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ADVANCED FUEL CYCLE AND REACTOR CONCEPTS

SUB-GROUPS A AND B

RESOURCE REQUIREMENTS FOR ALTERNATIVE REACTOR DEPLOYMENT STRATEGIES

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RESOURCE REQUIREMENTS FOR ALTERNATIVE REACTOR DEPLOYMENT STRATEGIES

Introduction

The purpose of this paper is to estimate and compare resource requirements and other fuel cycle quantities for alternative reactor deployment strategies. This paper examines from global and national perspectives the interaction of various fuel cycle alternatives described in the previous U.S. submissions to Working Groups 4, 5, 8 and Subgroup 1A/2A. Nuclear energy forecasts of Subgroup 1A/2A are used in the calculation of uranium demand for each strategy. These uranium demands are then compared to U.S. estimates of annual uranium producibility. Annual rather than cumulative producibility was selected because it does not assume preplanned stockpiling, and is therefore more conservative. The strategies attempt to span a range of nuclear power mixes which could evolve if appropriate commercial and governmental climates develop.

This paper gives a summary of important nonproliferation considerations because civilian nuclear power programs are accompanied by proliferation risk. This risk arises mainly from the access these programs may provide to materials, facilities, and knowledge that could contribute to the acquisition of nuclear explosives. The proliferation threats include possible national or subnational misuses and involve weapons related activities. Decisions on whether to seek nuclear weapons are based on various political and military incentives and disincentives that are beyond the scope of this paper. However, it is important to ensure that nuclear power programs, as they evolve, do not present a significant opportunity for proliferation. A major step forward in this regard would be to limit access to weapons grade nuclear material or material from which weapons grade plutonium or uranium can easily be acquired. This suggests improved institutional arrangements and safeguards for enrichment and/or reprocessing facilities.

This paper does not address such factors as regulation, public and utility attitudes, or economics, although these factors have significant effects on the market penetration of new technology. Neither does it attempt to quantify the risks associated with any particular nuclear power strategy nor the societal effects associated with the success or failure of timely technological progress.

The paper is divided into three sections. The first section briefly summarizes the results. The second section gives the results of the analyses from both a global and a single country perspective. The third section describes the strategies which have been simulated and the assumptions which have been used for the global analysis.

During the preparation of this analysis additional recommendations regarding the definition of strategies became available from Subgroup 1A/2A. In addition, other working groups have defined still different reactor deployment strategies. Thus, some of the strategies discussed here may vary slightly from others being evaluated by INFCE. In general the actual numerical results of these simulations are much less important than the trends shown by the analysis, and it is believed the trends shown by this analysis will also be apparent in the analyses to be performed by the IAEA for Subgroup 1A/2A.

I. SUMMARY

Projections of annual and cumulative uranium requirements are made for various global nuclear power scenarios. Scenarios are based on INFCE Subgroup 1A/2A projections of nuclear power demand. Resource requirements are compared with projections of uranium producibility submitted by the U.S. to Subgroup 1B. Projections are also made of the resource requirements for reactor systems suitable for small countries with a newly developing nuclear power capability. The following conclusions are drawn from this evaluation:

- For the low nuclear energy demand forecast, current converter reactor technology operating in a once-through mode would be adequate to keep annual uranium demand within the upper estimates of uranium producibility until about 2025. Evolutionary improvements in converter technology can be implemented as economics dictate to serve as a hedge against long-term annual uranium production constraints and unanticipated increases in nuclear power growth.

- For the high nuclear energy demand forecast, no single technology provides complete assurance of adequate resource availability through the year 2025, including the strategy based on Pu-limited breeder deployment. Hence, improvements in converter fuel utilization will be important in assuring that there will be an adequate supply of uranium, even if breeders are rapidly deployed. In particular, improvements in once-through reactor and fuel cycle technology, including enrichment technology, could provide for increasing improvements in resource utilization beginning in the near-term. Since LWR once-through systems

are inherently the most resistant to proliferation, the improved once-through systems will extend the period available to develop measures to reduce the proliferation risks associated with advanced systems.

- Systems based on thorium and the recycle of denatured* U-233 have uranium requirements that are comparable to, or less than, those for systems based on Pu recycle. Although the recycle systems have not been developed, they are potential alternatives for long-term nuclear system development.

- For a country with a newly developing nuclear system, the use of improved once-through technologies can keep uranium requirements at levels comparable to self-generated thermal recycle of Pu or U-233 without the large fuel cycle investments and proliferation concerns of thermal recycle systems. If denatured U-233 fuels become available, those same converter reactors could utilize bred U-233 to further reduce resource requirements.

- For a nuclear system which intends to utilize FBRs, large commitments of LWR spent fuel to thermal recycle could constrain FBR deployment.

- R&D strategies should include institutional alternatives such as international or multinational fuel cycle centers.

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*Diluted with U-238 so as to require isotopic separation to produce weapons useable material.

II. Results

The results of the strategy analyses addressing uranium consumption are presented in this section. Also provided are estimates of key fuel cycle facility requirements where appropriate.

The discussion of the results is divided into two parts. Part A is a global analysis. The effects of various nuclear technologies on global consumption of uranium are considered. The cases considered are advanced once-through, thermal recycle, and fast breeder introduction in conjunction with once-through reactors. The interactions between fuel cycles which may occur in the evolution of nuclear power are discussed The strategies and assumptions used in the global analysis are defined in Section III.

Part B considers cases similar to those of individual countries initiating nuclear power programs. The analysis examines the ability of converter reactor technologies to meet postulated energy needs within the constraints of an assumed nuclear growth rate and resource availability.

A. Results of the Global Analysis

Four of the major single technology options being considered by INFCE which would reduce future uranium requirements are:

- Improving current once-through reactors and fuels.
- Reducing enrichment tails assay.
- Thermal recycle.
- Fast breeder reactors.

Each of the above strategies represent a single technology approach to reducing resource requirements. In reality no single approach can be assumed to be adequate or practical from the viewpoint of the various national situations existing now and in the future.

In Figures 1L and 1H uranium requirements for the improved once-through options are compared with current once-through LWR technology and the uranium producibility estimates.* The top curve which represents current LWR technology provides a point of reference. The next curve represents uranium consumption for a 15% reduction in LWR resource requirements beginning in 1990. The 15% improved LWR is representative of what could be achieved over the near-term with improvements in fuel technology which would allow higher spent fuel discharge exposures. Programs to develop and demonstrate this level of performance have been started in the U.S., and by 1990 it is anticipated the necessary technology will be available for all LWRs.

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*See page 51 for further definition.

FIGURE 1L. ANNUAL URANIUM CONSUMPTION FOR ONCE-THROUGH STRATEGIES AND LOW DEMAND

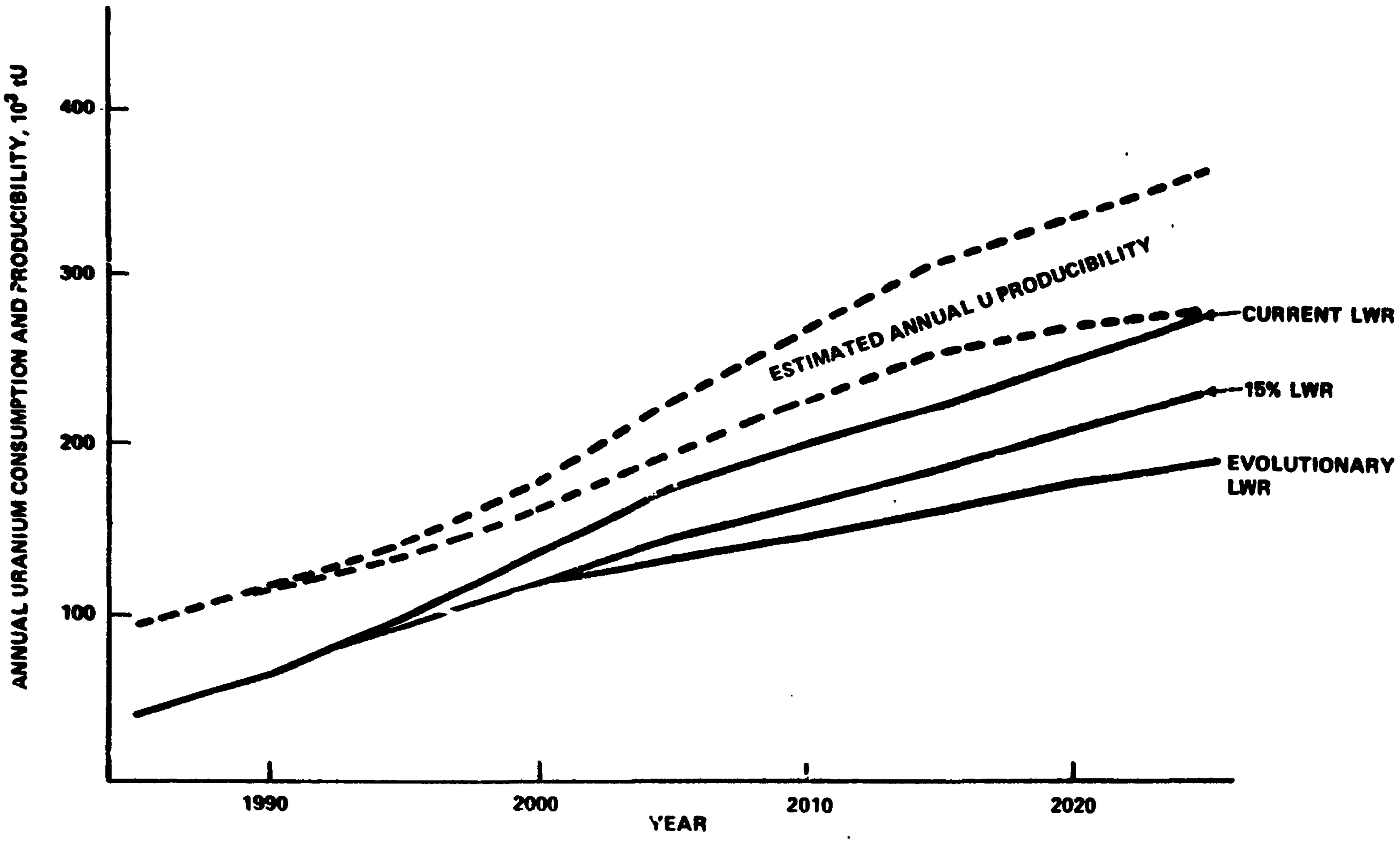
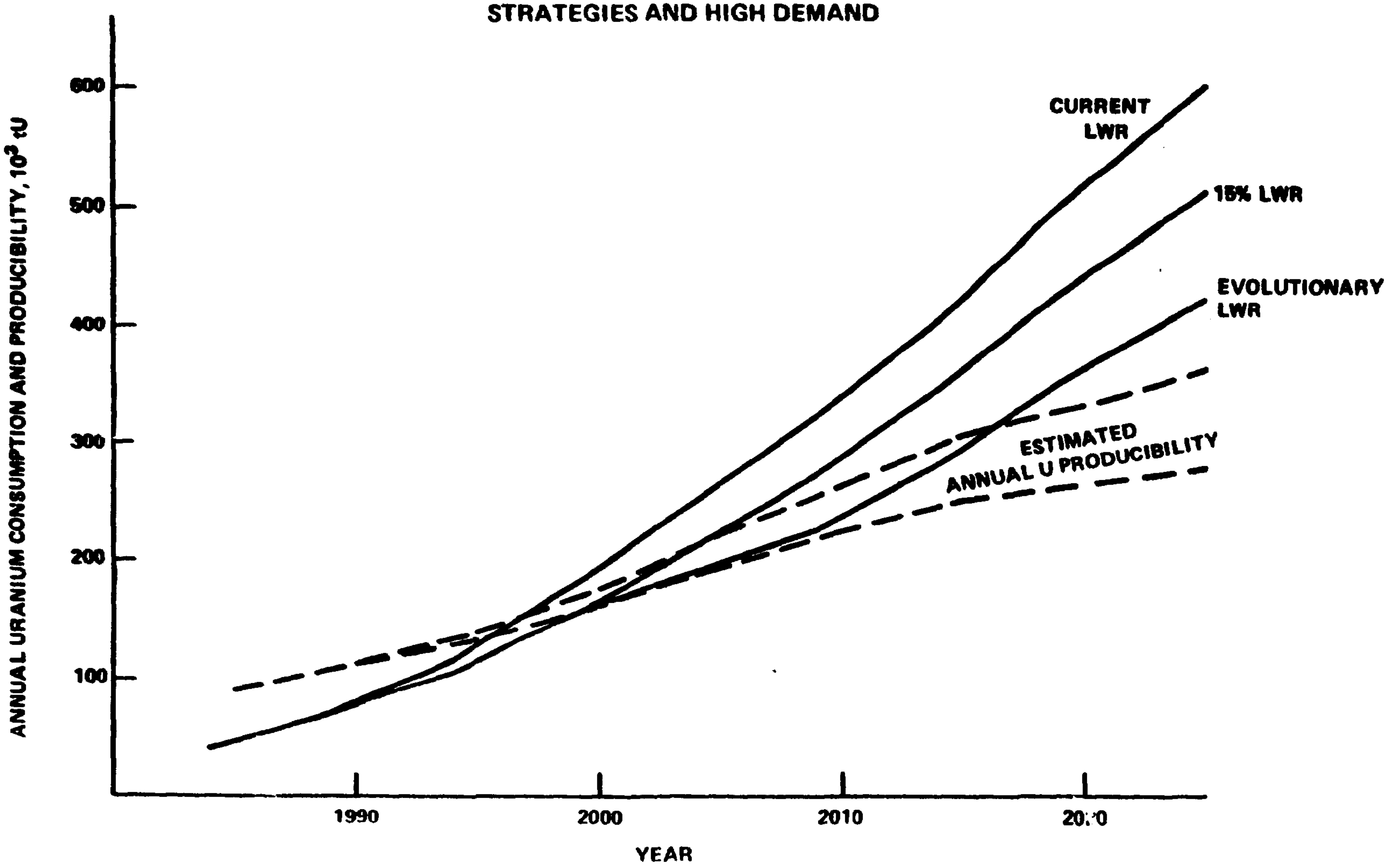


FIGURE 1H. ANNUAL URANIUM CONSUMPTION FOR ONCE-THROUGH STRATEGIES AND HIGH DEMAND



Second generation LWR improvements are represented in the figures by the "evolutionary LWR" strategy. New LWRs are assumed to achieve a 30% reduction in uranium requirements beginning in the year 2000 as compared to current technology. The evolutionary LWR strategy is seen to significantly extend the time when uranium demand exceeds producibility.

Figures 2L and 2H compare uranium requirements with uranium producibility estimates for the above once-through systems assuming reduced-tails. The introduction of reduced tails assumes that technology will be available in 2010 to reduce enrichment plant tails assay to 0.05% and to strip to 0.05% the stockpile of tails that were previously produced at higher assay. The long-term effect of the advanced enrichment technologies would be to achieve nearly a 20% reduction (compared to 0.2% enrichment tails assay) in annual uranium requirements for a system consisting primarily of LWRs. Comparable effects could be realized in many of the other strategies. The reduced tails schedule presented in Section III assumes more advanced enrichment technologies will become available in the future, and that adequate safeguards can be developed for those technologies. Enrichment tails assay is normally changed as a reaction to enrichment supply and demand and the changing price of uranium. Assuming the price of uranium continues to increase and enrichment technology continues to advance, the assumed tails assay schedule may represent a realistic estimate.

In Figures 3L and 3H uranium requirements for recycle options are compared with the evolutionary LWR once-through requirements. The recycle strategy is one in which it is assumed all LWR reactors operate on self-generated recycle by 2025. Improvements in once-through technology could also be applied to Pu

FIGURE 2L ANNUAL URANIUM CONSUMPTION FOR ONCE-THROUGH STRATEGIES WITH REDUCED TAILS. (RT)

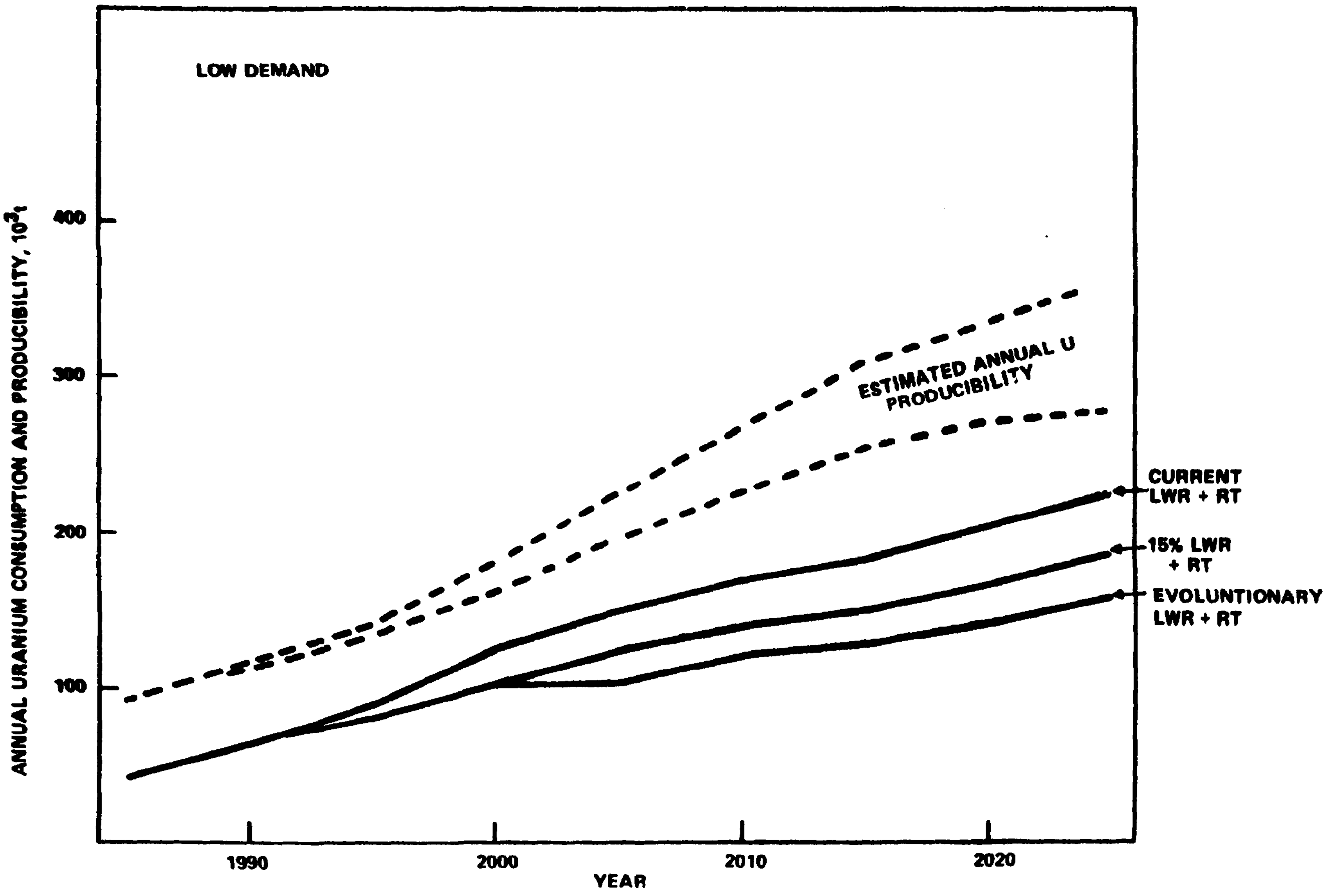


FIGURE 2H ANNUAL URANIUM CONSUMPTION FOR ONCE-THROUGH STRATEGIES WITH REDUCED TAILS (RT)

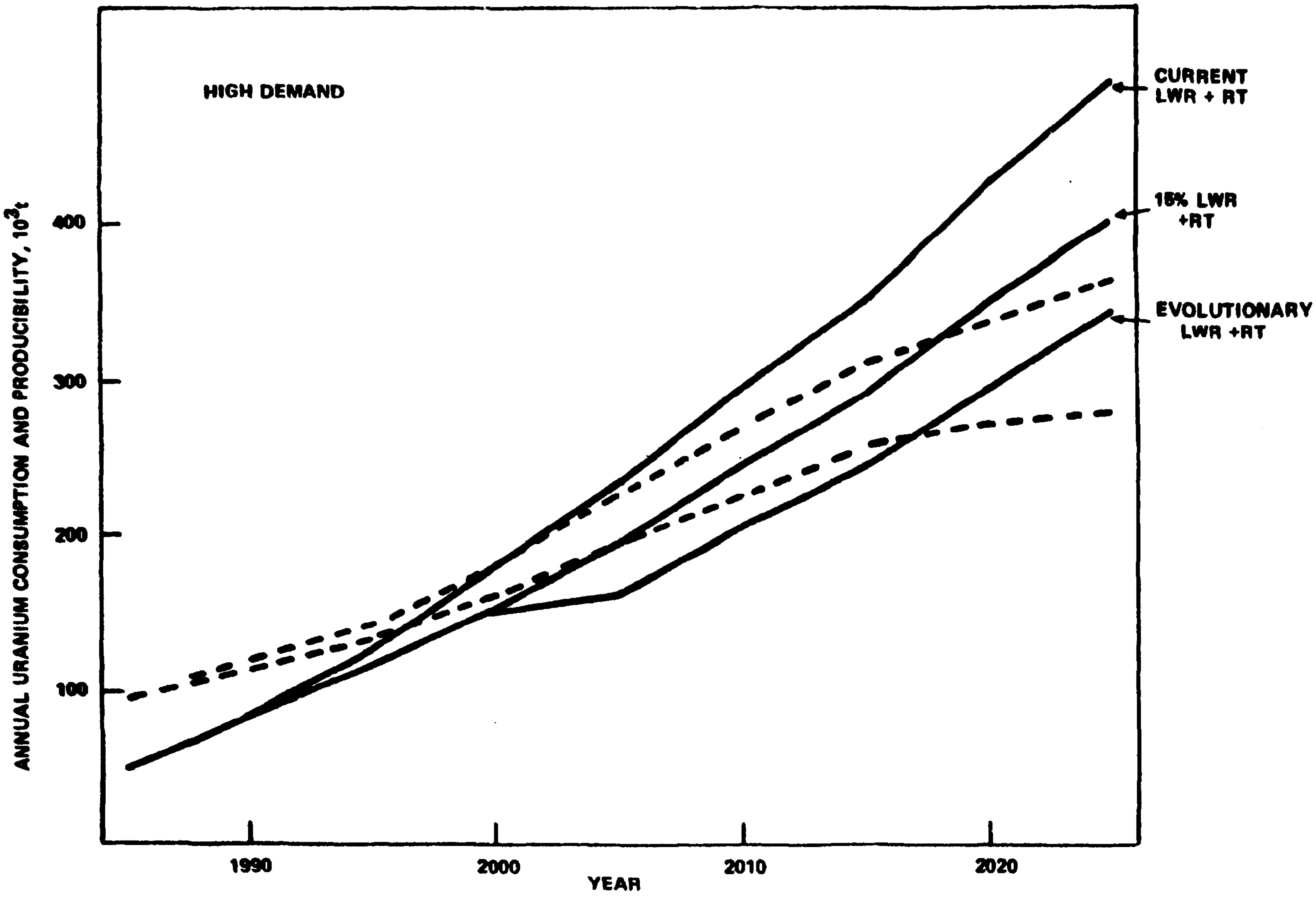


FIGURE 3L. ANNUAL URANIUM CONSUMPTION FOR EVOLUTIONARY LWR ONCE-THROUGH AND RECYCLE OPTIONS

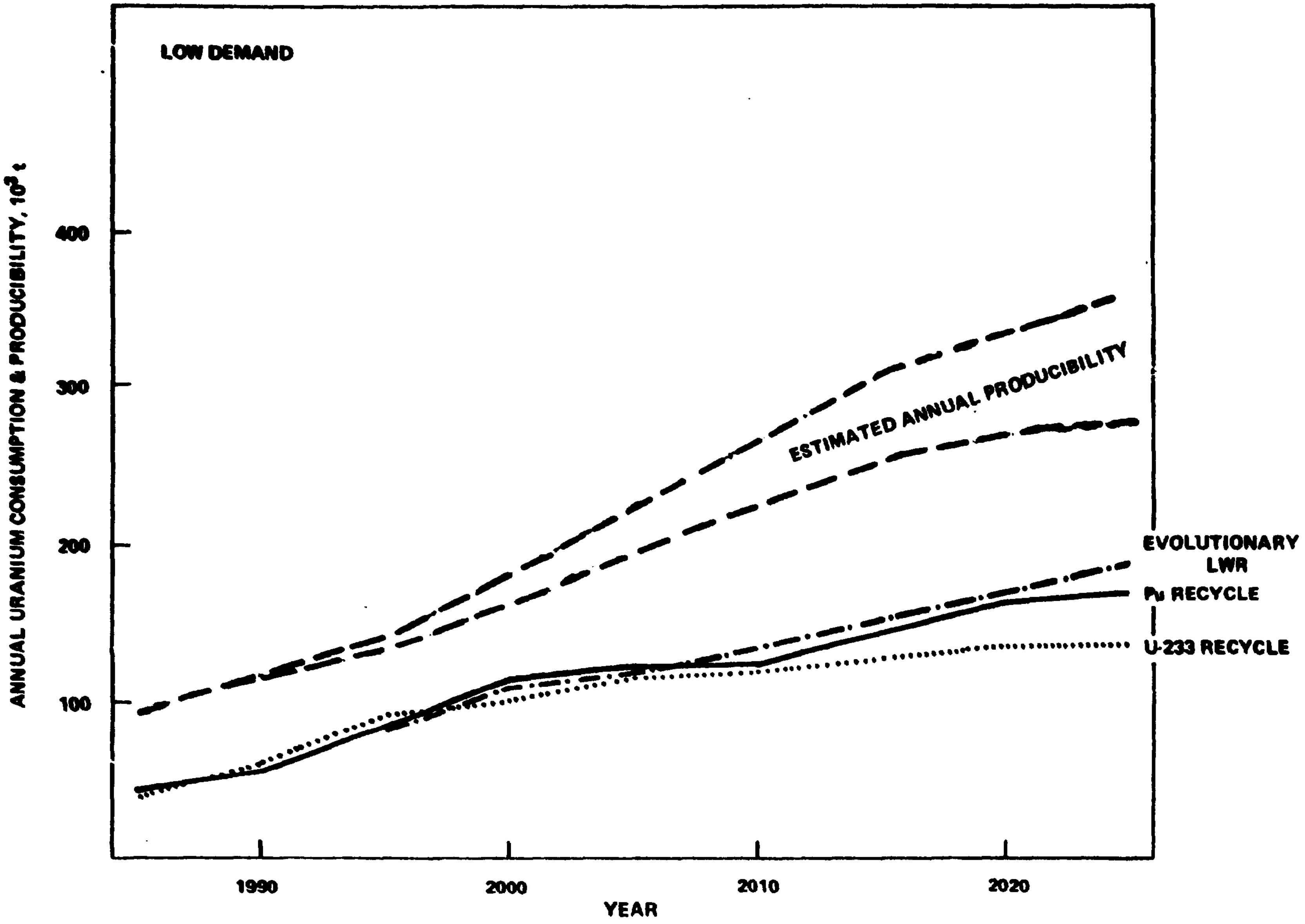
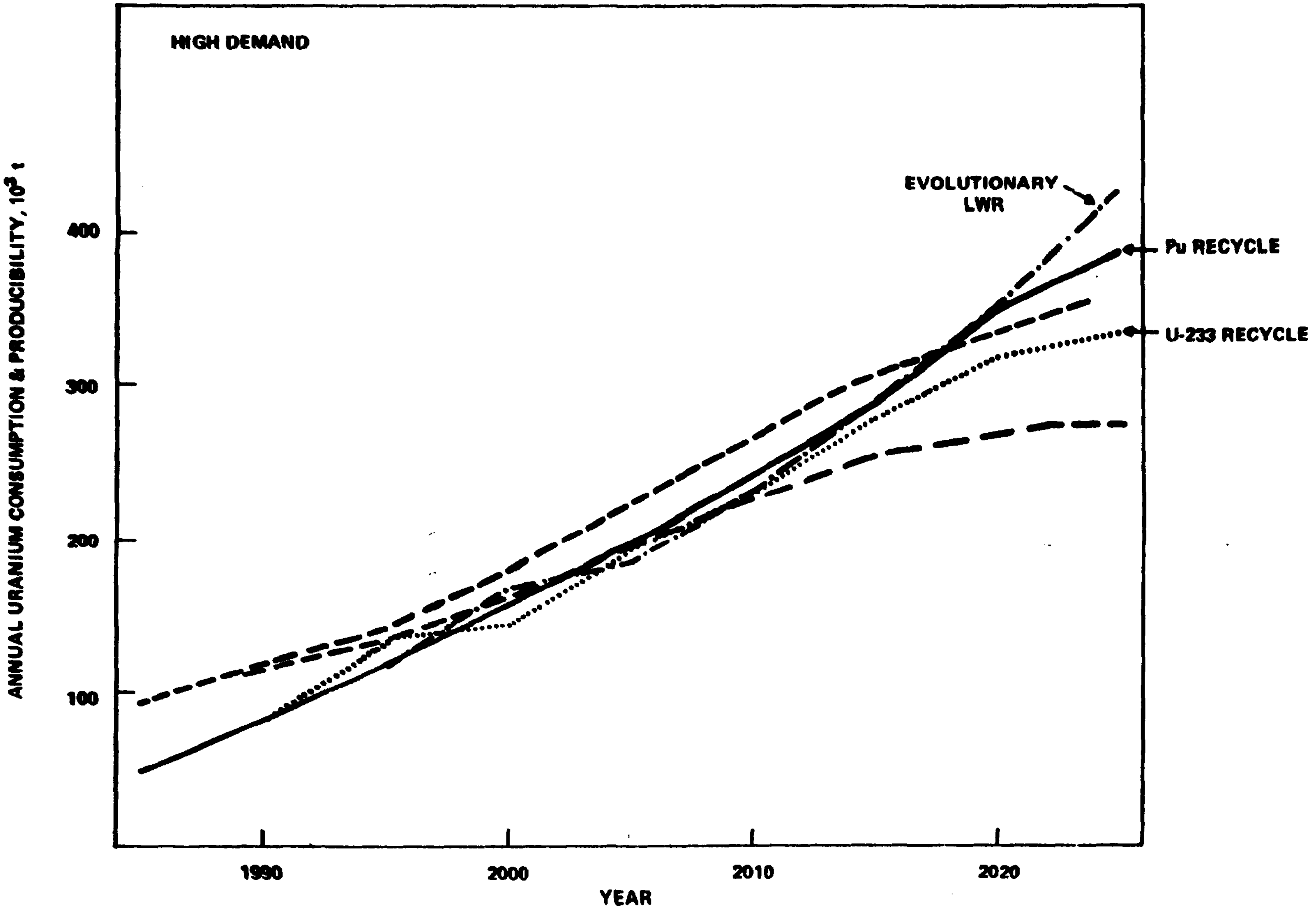


FIGURE 3H. ANNUAL URANIUM CONSUMPTION FOR EVOLUTIONARY LWR ONCE-THROUGH AND RECYCLE OPTIONS



recycle, realizing an additional reduction in resource requirements, depending upon the extent to which recycle is used in the system. With either of these recycle strategies, annual uranium supply may become inadequate around the year 2005, assuming high demand. In a low demand situation total global uranium supply does not appear to be a problem for any of the strategies in the INFCE time period.

Development and deployment of a thermal recycle strategy would require large capital investments for fuel fabrication and reprocessing facilities and would require higher nuclear safeguards costs than comparable once-through reactor strategies. Approximately eighty 1500 MTU plants would be required by 2025. During the deployment of this strategy 4 or 5 of these plants would have to be built every year, each costing more than 1 billion dollars. The improved once-through strategies would require one-time investments in R&D which are likely to be less than the cost of deploying recycle. Additional costs of the once-through strategies as compared to thermal recycle could include greater enrichment capacity requirements and the cost associated with spent fuel management, although the waste management costs for thermal recycle will also be significant.

Each of the above strategies could contribute to increased security of fuel supply, but each has its drawbacks. Both the evolutionary once-through strategy and the recycle strategies could extend known resources and delay the arrival of uranium shortfalls, but over the long-term would be inadequate for the high energy demand case.

Recycle and once-through strategies both present proliferation concerns which must be addressed. Figure 4 shows, for the high energy demand forecast, fissile plutonium accumulated outside of reactors for LWR once-through systems as well as recycle. This figure shows that recycle reduces the accumulated plutonium outside of reactors, but converts it from an unseparated form to a separated form. The distribution of plutonium for the thermal recycle strategy (including that in reactor) is shown in more detail in Figure 5. Significant quantities of plutonium are still available and because it is in a much more vulnerable and difficult to safeguard form, the overall vulnerability is increased.

For a recycle system the safeguarding of plutonium in bulk form within reprocessing and fuel refabrication facilities will require the development of additional improved technical and institutional measures beyond those developed for the safeguarding of spent fuel from once-through reactors.

Long-Term Strategies with FBRs

Since the fast breeder reactor (FBR) potentially offers the maximum energy from a given amount of uranium, it is assumed that among the advanced reactor concepts requiring reprocessing the FBR will receive the most development effort. Figure 6 shows the annual resource requirements for the high energy forecast demand and the base FBR strategies.* Given the high energy forecast, the breeder can only help to overcome uranium shortages in the long run, i.e., 30 years or more after commercialization. The high FBR deployment strategy becomes Pu limited in about 2010. The medium and low strategies,

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*FBR strategies are used only with the high energy demand forecast since they are not needed with the low energy demand forecast during the period of this study.

FIGURE 4. CUMULATIVE FISSILE PLUTONIUM QUANTITIES OUTSIDE OF REACTORS FOR THE ONCE-THROUGH LWR AND Pu RECYCLE STRATEGY

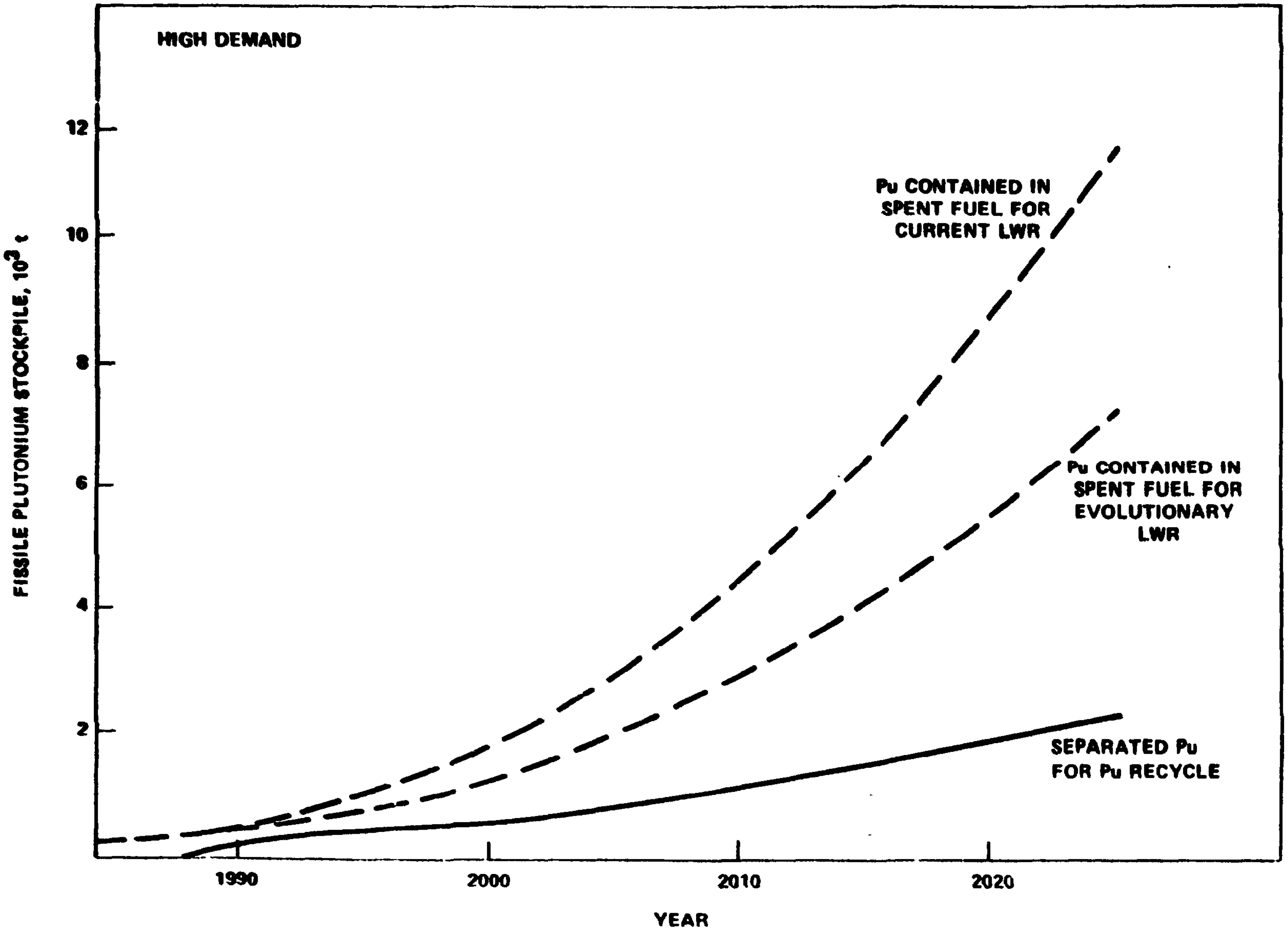


FIGURE 5 FISSILE PLUTONIUM QUANTITIES AT VARIOUS LOCATIONS FOR THE LWR Pu RECYCLE STRATEGY

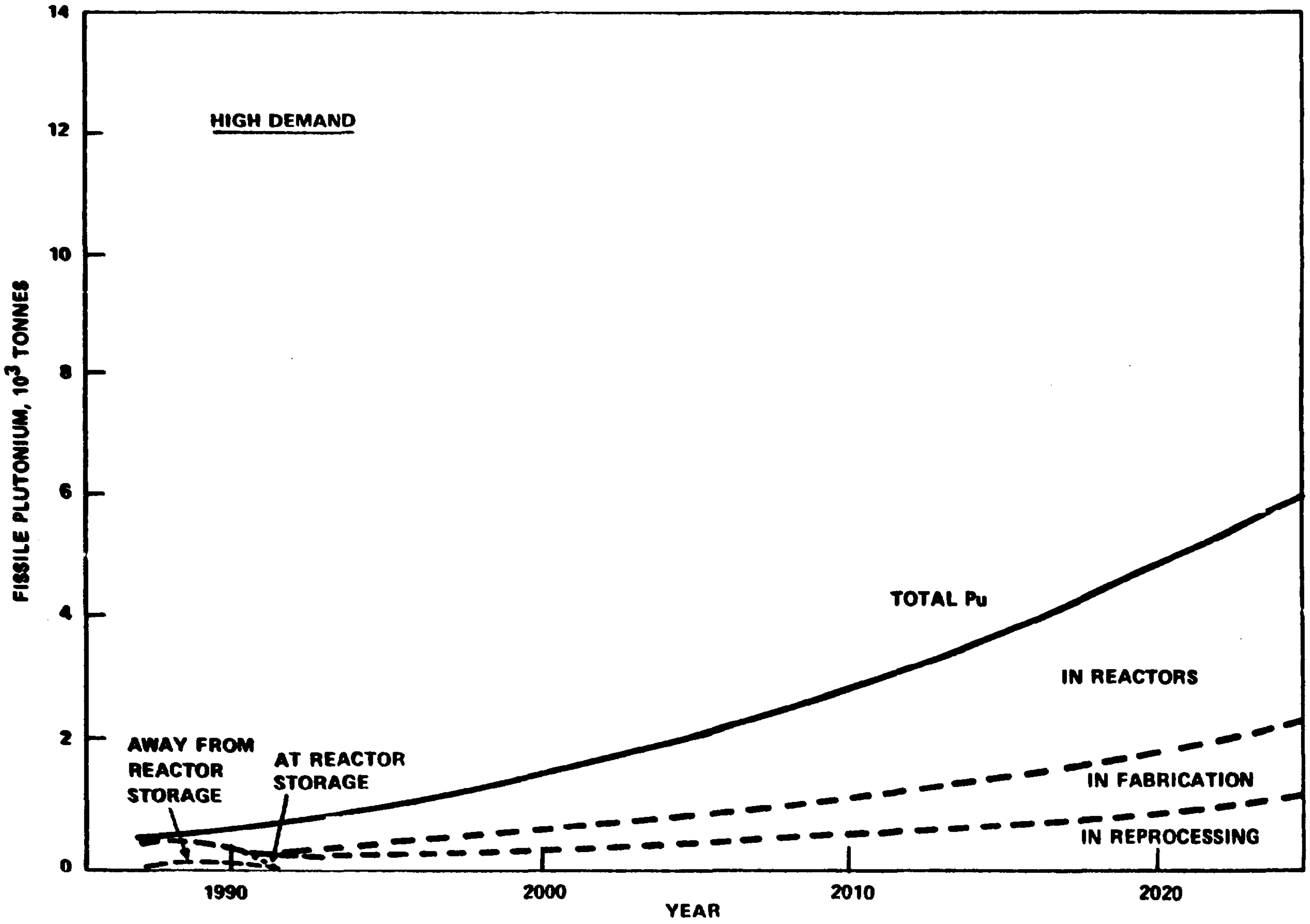
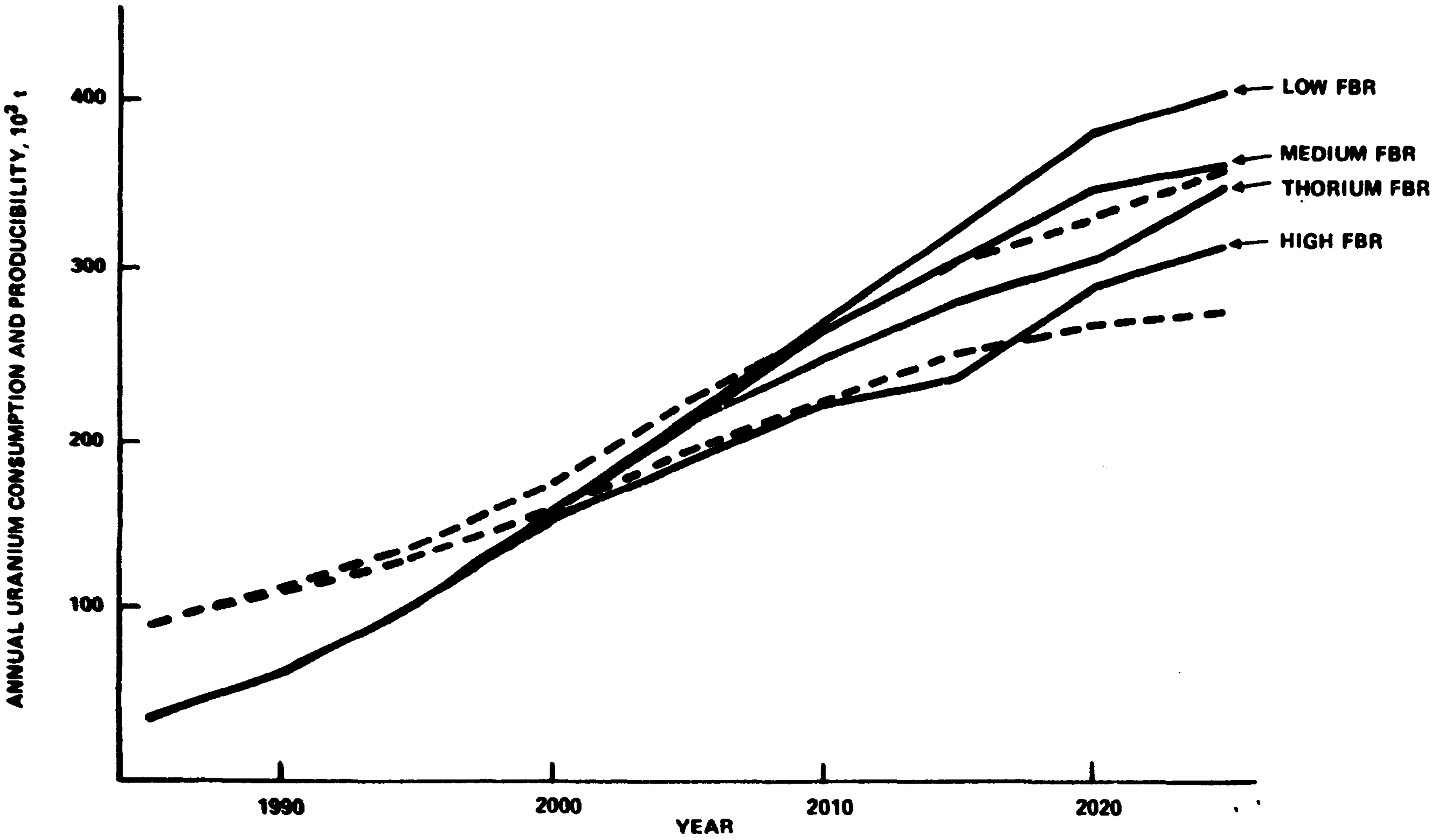


FIGURE 6 ANNUAL URANIUM CONSUMPTION FOR ALTERNATIVE FBR DEPLOYMENT STRATEGIES WITH HIGH DEMAND

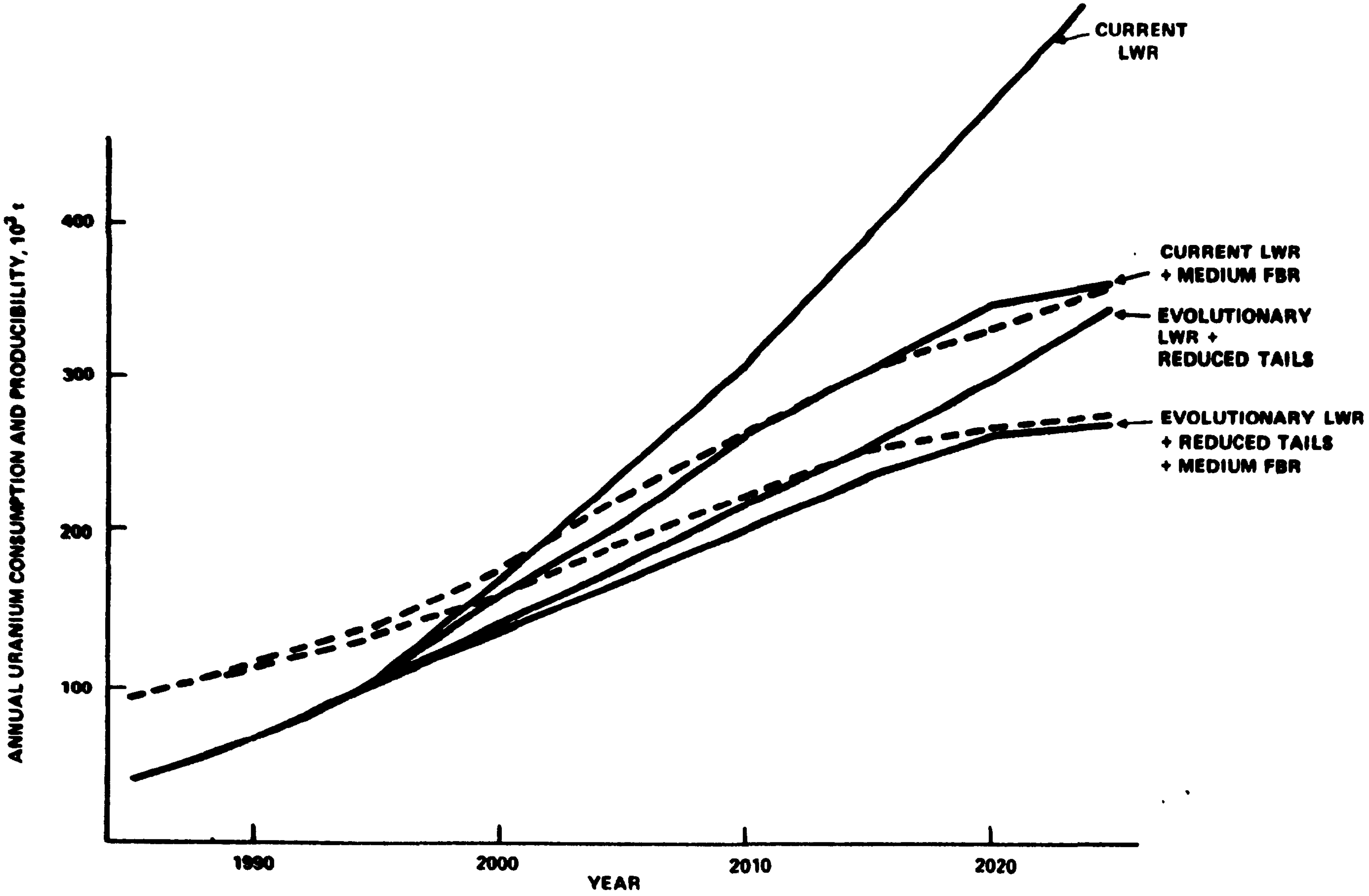


which appear to be more likely than the high deployment strategy, are not Pu limited. In general, the year 2025 limit of this study does not allow the ultimate effects of any of the FBR strategies to be demonstrated.

For the low, medium and high FBR strategies, converter reactors would constitute about 80, 70 and 60% of the respective reactor mixes in 2025. Thus, a large portion of the system would receive only limited benefits from the breeders prior to 2025, and for converter reactor operators there would still exist large incentives to improve the fuel utilization of their systems. This is demonstrated in Figure 7 in which the evolutionary LWR and reduced tails are used in conjunction with the medium FBR deployment strategy. Together these improvements reduce annual uranium consumption by almost 30% by 2025 as compared to the breeder strategy without any LWR system improvements. As shown in Figure 7, the LWR improvements with reduced tails and medium FBR deployment can keep uranium demand below the producibility constraints.

A study of the effect that thermal recycle could have on the theoretical maximum FBR deployment rate has been made. It was assumed that thermal recycle is initiated in 100% of the LWRs beginning in 1990 and continued until 2010 for the high energy demand forecast. During this time the constraints on breeder deployment are as described in the high FBR deployment scenario, that is, the rate of deployment of FBRs is limited only by plutonium availability after 2005. In this strategy it is assumed that the pre-1990 stockpiles are used to load the thermal reactors up to their equilibrium self generated recycle loadings. The breeders are then deployed using that part

FIGURE 7 ANNUAL URANIUM CONSUMPTION FOR MEDIUM FBR DEPLOYMENT AND ONCE-THROUGH SYSTEM IMPROVEMENTS WITH HIGH DEMAND



of the spent fuel stockpile not used in recycle reactors. In addition, it is conservatively assumed that all plutonium discharged from recycle reactors can be used in breeders. This study showed that by 2010 only about one-fourth the number of FBRs could be deployed with thermal recycle as compared to no recycle, with the relative number increasing to about 80% by 2020. The study also showed that the cumulative uranium requirement in 2025 is higher for recycle as compared to the no recycle case.

As in the case of thermal recycle, the safeguarding of bulk quantities of Pu in fuel cycle facilities will be of major concern for the FBR strategies. Figure 8 shows the accumulation of Pu outside of reactors for LWR once-through systems and the medium FBR strategy with high energy demand forecast. This figure shows that breeders do not assure lower out of reactors plutonium inventories. And, because the plutonium is present in a more vulnerable form (separated vs. unseparated) new technical and institutional initiatives will be required to deal with the plutonium in the breeder strategy. The distribution of plutonium for the medium FBR strategy (including that in reactors) is shown in more detail in Figure 9. Because of the later need for reprocessing and refabrication facilities for the FBR in comparison to the thermal recycle strategy (compare Figures 5 and 9) there is less plutonium in the most vulnerable parts of the fuel cycle for the FBR strategy until about 2010.

Thorium-Based Strategy Considerations

The primary alternatives to once-through fuel cycle systems considered by WG-8 are based on the use of thorium and the recycle of U-233 in converter reactors.

Since the neutronic properties of U-233 are optimum in a thermal neutron environment, the use of thorium will have different relevance to thermal and

FIGURE 8 FISSILE PLUTONIUM QUANTITIES OUTSIDE OF REACTORS FOR THE MEDIUM FBR INTRODUCTION STRATEGY ON THE Pu/U CYCLE AND FOR LWR ONCE-THROUGH STRATEGIES

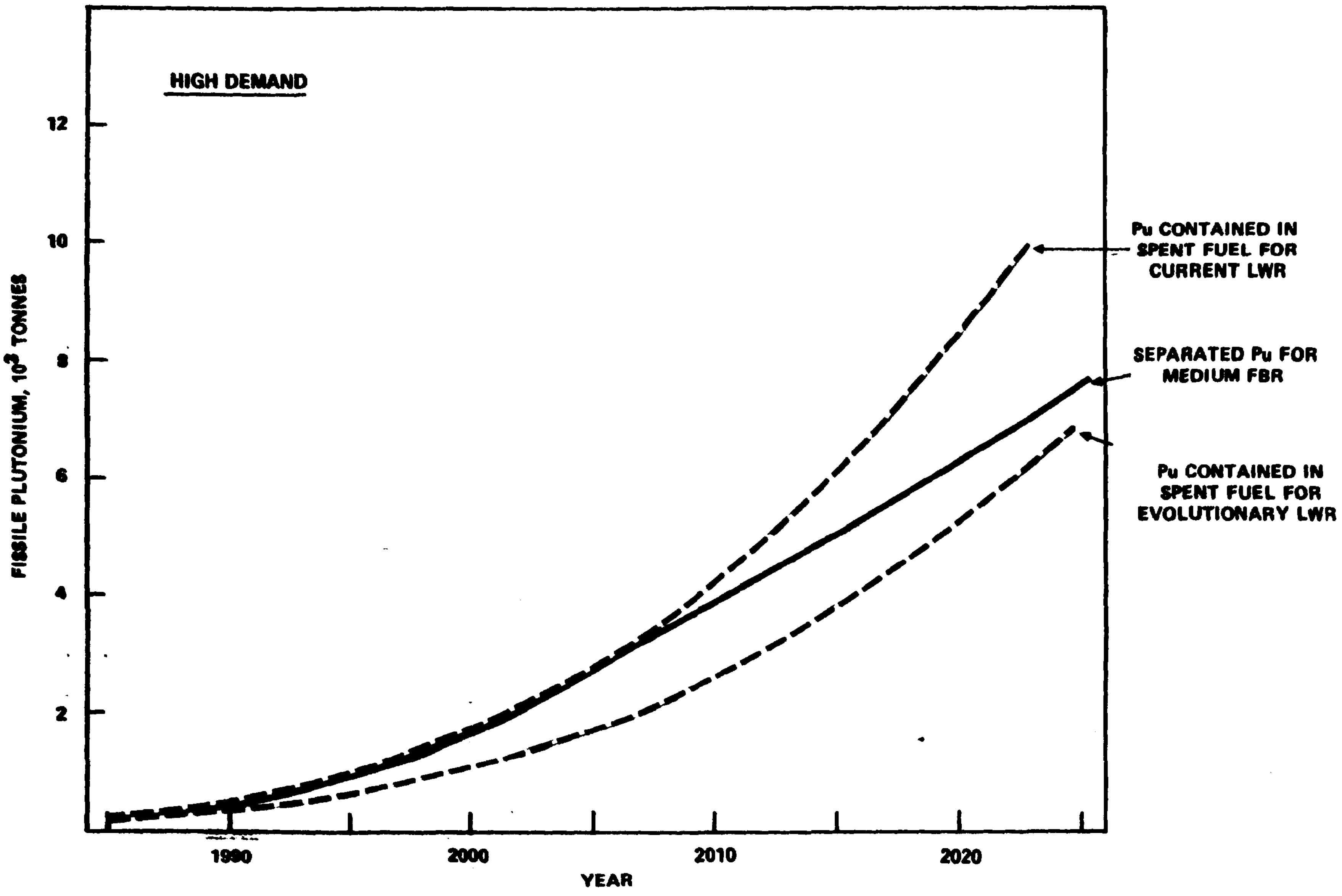
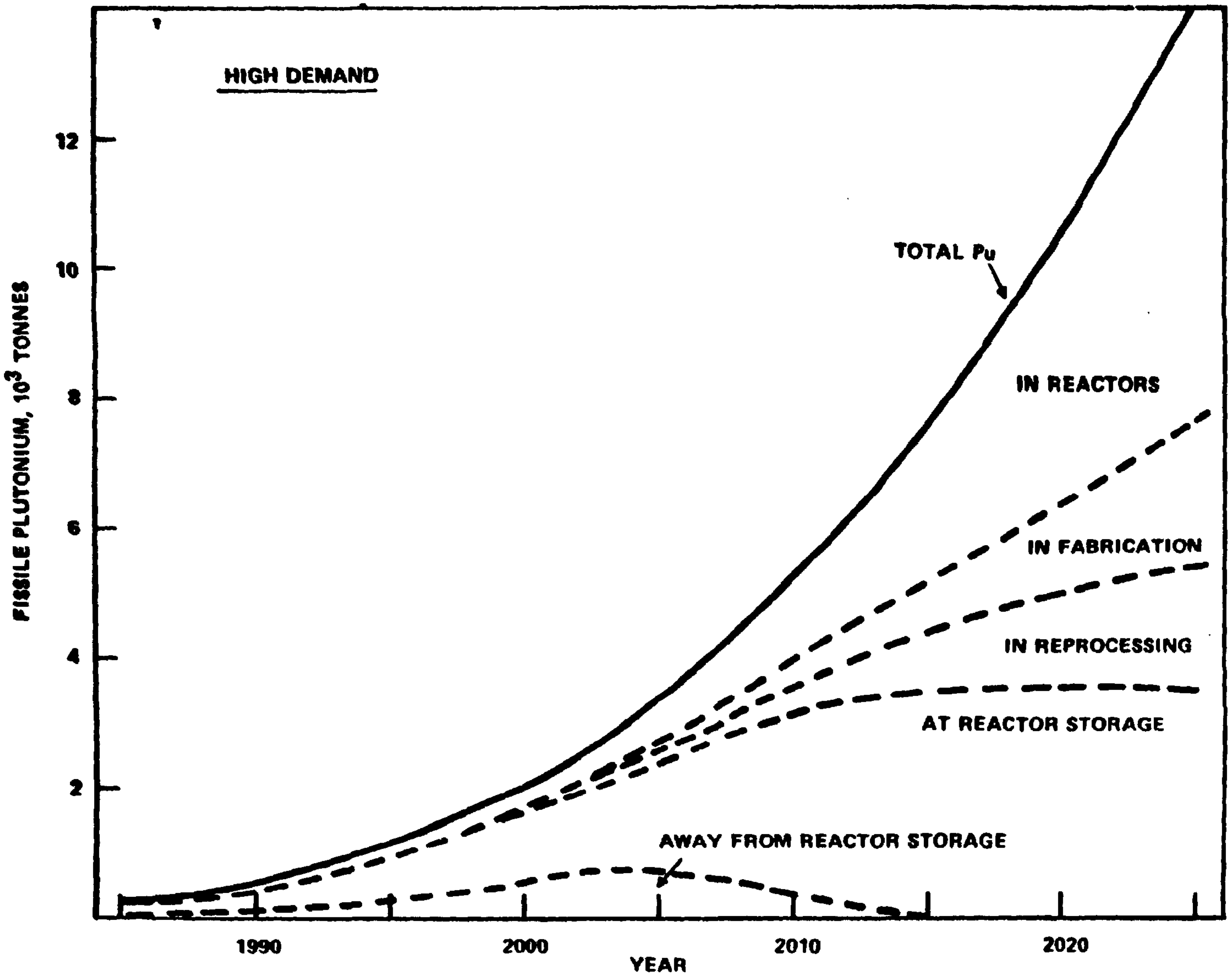


FIGURE 9 FISSILE PLUTONIUM QUANTITIES AT VARIOUS LOCATIONS FOR THE MODERATE FBR INTRODUCTION STRATEGY ON THE Pu/U CYCLE



fast reactors. For thermal reactors, the availability of U-233, produced from either thermal or fast reactors, offers the potential for the evolution of more resource utilization efficient systems than use of U/Pu cycles.

For fast breeders, thorium blankets could become a feasible option if the costs are reasonable and if the appropriate institutional arrangements are implemented. If breeders should be developed on a large scale to produce fuel for converter reactors, a market in U-233 could develop in which breeders and converters would develop a symbiotic relationship. In an equilibrium situation breeders could use Pu from conventional reactors to breed U-233 from thorium in the blankets of breeder reactors. The bred U-233 would in turn be denatured with U-238 and used as fuel for converters. Implementation of such a system would depend upon several variables including the availability and price of uranium, the relative capital and fuel cycle costs of converter and breeder reactors, and the ability to develop the appropriate safeguards. Figure 6 shows a symbiotic strategy* in which plutonium fueled FBRs with thorium blankets produce U-233 which is then denatured for use in converter reactors.

Figures 3L and 3H show a strategy in which denatured U-233 recycle is widely deployed. Although this technology is less mature and could not be deployed before about 2000, by about the year 2010 it could reduce resource requirements below that required for Pu recycle. This particular strategy was based on LWRs primarily, but resource requirements could be reduced further if other advanced converters such as HWRs or HTRs were more widely deployed.

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*The equilibrium benefits of symbiotic systems can be displayed only by extending the time frame of the study beyond 2025.

In Figure 10 are shown the reprocessing requirements for the strategy with thorium blanketed breeders, which has the medium FBR deployment rate. Even with this relatively limited number of FBRs, more than eighty 1,500 Te/year plants would be required by 2025. During the deployment of this strategy, 4 or 5 of these plants would have to be built every year, each costing at least $1 billion.

Although a thorium fuel cycle will require more R&D beyond that which will be done to develop the conventional uranium fuels, programs have been initiated which could result in commercial feasibility after the year 2000. As nuclear power continues to evolve, options must be considered which could meet fuel supply and nonproliferation objectives for the spectrum of national situations.

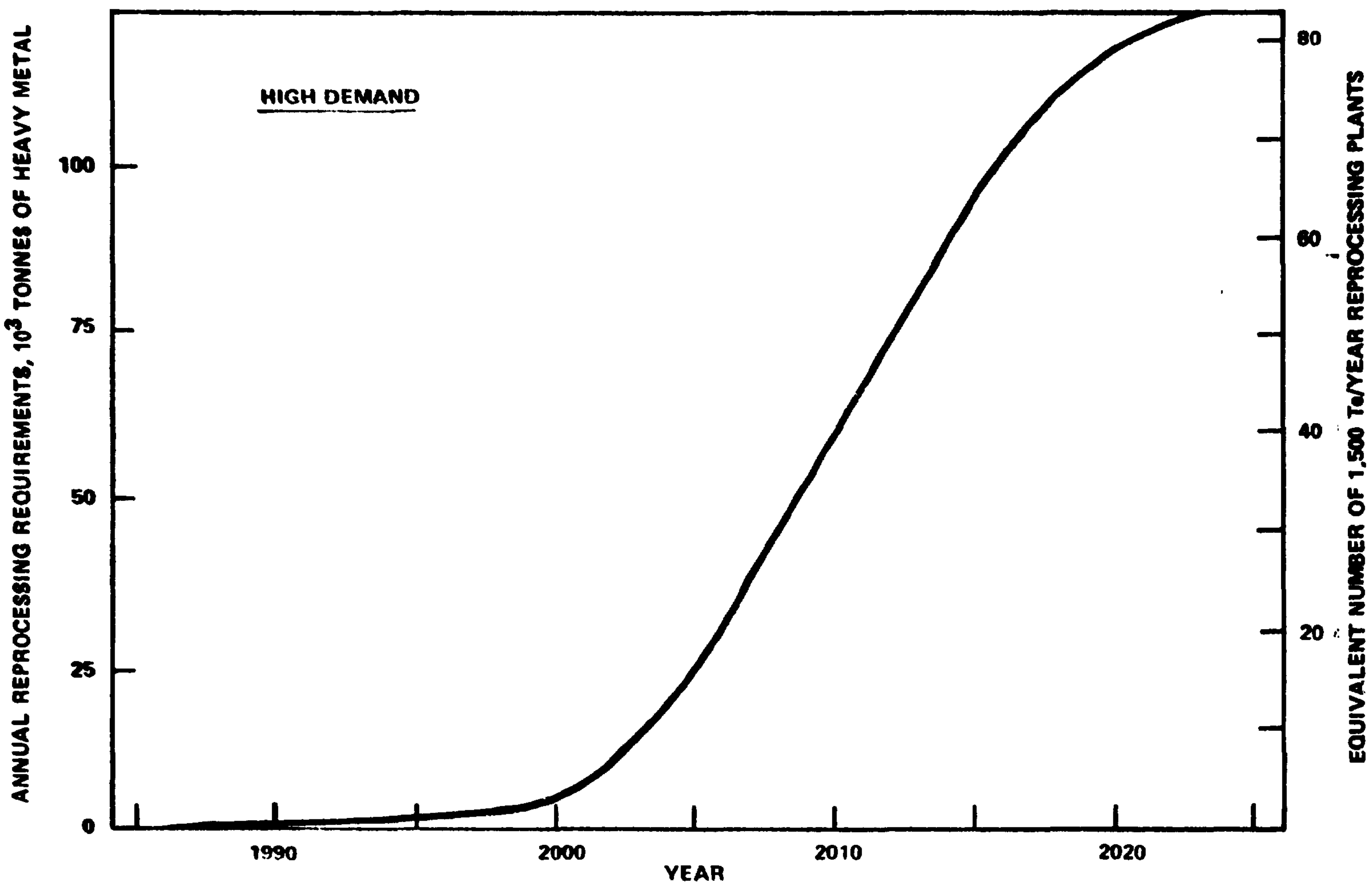
The proliferation resistance attributes of thorium-based fuel cycles may be summarized as follows:

- <u>Fresh fuel</u>

  (a) In the case of fresh fuel consisting of thorium and highly enriched uranium or plutonium, weapons usable material can be obtained without isotopic separation and, depending on the nature of the fuel, possibly without chemical separation.

  (b) If denatured uranium is used (e.g., less than 20% U-235 or less than 12% U-233), isotopic separation (which in itself requires several chemical conversions) would be required to obtain weapons useable material. The isotopic barrier to diversion may decrease in future decades if enrichment capabilities become more widely available.

FIGURE 10 ANNUAL REPROCESSING REQUIREMENTS FOR THE MEDIUM FBR INTRODUCTION STRATEGY ON THE Pu/U/Th FUEL CYCLE



(c) The radiation from U-232 daughters also makes U-233 a somewhat more difficult material to handle and process than plutonium or uranium enriched only with U-235.

- Spent fuel

  If reactor fuel contains any significant amount of U-238, plutonium will unavoidably be produced during reactor operation and it can be recovered from the spent fuel through chemical reprocessing. If the thorium is all intimately mixed with sufficient U-238, isotopic separation would be required to obtain weapons-usable U-233 or U-235, as noted above for fresh fuel. In cycles using uranium highly enriched in U-235, the isotopic composition of separated uranium is likely to be such as to make it suitable for use in weapons.

- Reprocessing/enrichment facilities

  These are the most vulnerable and difficult-to-safeguard facilities. The proliferation resistance of these facilities in thorium-based fuel cycles is generally similar to that for plutonium-based fuel cycles.

With particular institutional arrangements, such as restricting sensitive portions of the fuel cycle to multinationally controlled centers, the proliferation resistance of denatured thorium-based fuel cycles could be substantially improved and would provide higher proliferation resistance than the plutonium-uranium MOX-based fuel cycles, though somewhat lower than the LWR once-through fuel cycles. Without such arrangements the proliferation resistance of the denatured thorium-based cycles would be poor.

Thorium-based fuel cycles which require highly enriched uranium introduce large additional proliferation vulnerabilities which make them generally less proliferation resistant than plutonium-uranium MOX based cycles, assuming similar institutional arrangements for both cycles.

B. Special Needs of Countries Initiating Nuclear Power Programs

Introduction

Requirements for nuclear resources and services have generally been addressed from a global perspective. However, one of the principle charters of INFCE is to consider the special needs of developing countries with respect to nuclear power. Therefore, this section considers some aspects of nuclear power development in single states. In particular, key resource and service requirements have been estimated for various technical options which are likely to be considered for deployment by a nation with newly developing systems. By estimating the two independent variables--the expected demand for and perceived availability of nuclear resources and services--one can identify strategies that might be appropriate for developing nuclear programs.

Analysis

The analysis assumes a linear growth in nuclear power capacity of 1 GWe/yr starting at the arbitrary date 1985. The results are relatively insensitive to the choice of starting date, the only major uncertainty being the price of uranium. It has been assumed that only one reactor type is introduced in each case. Such a growth would be an ambitious one for most developing countries, however the scenarios are simple enough so that the results may be scaled to either higher or lower deployment rates without complex calculations. The reactor resource requirements are the same as those listed in Table 6 in Section III. These requirements are those associated with current, or near current, thermal reactor technologies. Fast breeder reactors have not been included in the analysis since most nations initially entering a nuclear power program would not have the technological base to select this option. The nuclear strategies considered in this section are given in Table 1, and the reactor types used in the analysis are given in Table 2.

The enrichment tails assay was set at 0.2% in all cases. In addition, calculations using the reduced tails schedule given in Section III were made for the LWR once-through strategies.

Results

1. Once-Through Strategies

The cumulative uranium consumption for the once-through strategies are presented in Figures 11 and 12 for the LWR and HWR respectively. In addition the annual enrichment requirements are shown in Figure 13. The evolutionary LWR, case 3, and the evolutionary HWR, case 5, offer similar resource utilization characteristics when uranium alone is considered. However, the amount of enrichment that is required in these two cases is significantly different. In 2020, for example, the evolutionary LWR requires approximately 3×10^6 kg-SWUs per year; the evolutionary HWR requires approximately 0.8×10^6 kg-SWUs per year. Systems with even lower uranium requirements that are comparable in their use of uranium are the advanced LWR (evolutionary LWR and reduced tails) once-through and the HWR utilizing slightly enriched uranium (SEU). In 2020 the advanced LWR once-through requires approximately 8×10^6 kg-SWU per year.

The effect of the reduced tails schedule on the uranium utilization of the 15% improved LWR has also been studied. The result is a decrease of approximately 16% in cumulative uranium consumption by 2025. There is a corresponding increase in required cumulative enrichment services of a factor of approximately 1.8.

Table 1

Reactor Strategies for the Single-Country Analysis

Once-Through Strategies

1. LWR-U5(LE)/U only
2. LWR-U5(LE)/U+15% only
3. Evolutionary LWR:
    - o 1985 - 2000 LWR-U5(LE)/U+15%
    - o After 2000 - LWR-U5(LE)/U+30%
4. HWR-U5(NAT)/U only
5. Evolutionary HWR:
    - o 1985 - 2000 HWR-U5(NAT)/U
    - o Post-2000 HWR on SEU
6. HWR-U5(SEU)/U only

Thermal Recycle

7. LWR Pu Recycle
    - o 1985 - 2025 LWR-U5(LE)
    - o 2000 - Pu recycle introduced
    - o 2010 - Sufficient reprocessing capacity on line to reprocess all spent fuel
8. HWR on denatured U-233/thorium fuel;
    - o 1985 - 2000 HWR-U5(NAT)/U
    - o 2000 - 2025 HWR-U5(DEN)/U8/Th/U3(SGR)
    - o 2000 - Sufficient reprocessing capacity available to reprocess annual spent fuel discharge.

Table 2

Reactor Types Used in the Single-Country Analysis

LWR-U5(LE)/U: A current technology Light Water Reactor with lightly enriched (about 3%) U-235 fuel.

LWR-U5(LE)/U+15%: A Light Water Reactor with lightly enriched U-235 fuel which requires 15% less U_3O_8 than current LWRs.

LWR-U5(LE)/U+30%: A Light Water Reactor with lightly enriched U-235 fuel which requires 30% less U_3O_8 than current LWRs.

HWR-U5(NAT)/U: A current technology Heavy Water Reactor which uses natural uranium fuel.

HWR-U5(SEU)/U: A Heavy Water Reactor which uses slightly enriched (about 1.2%) U-235 fuel.

HWR-U5(DE)/U8/Th/U3(SGR): A Heavy Water Reactor which begins operation with denatured U-235 fuel in thorium and recycles the U-233 which it produces in later cycles. Make-up requirements are provided by denatured U-235.

FIGURE 11 CUMULATIVE URANIUM CONSUMPTION FOR LWR ONCE THROUGH STRATEGIES: 1GWe/YEAR STARTING IN 1985

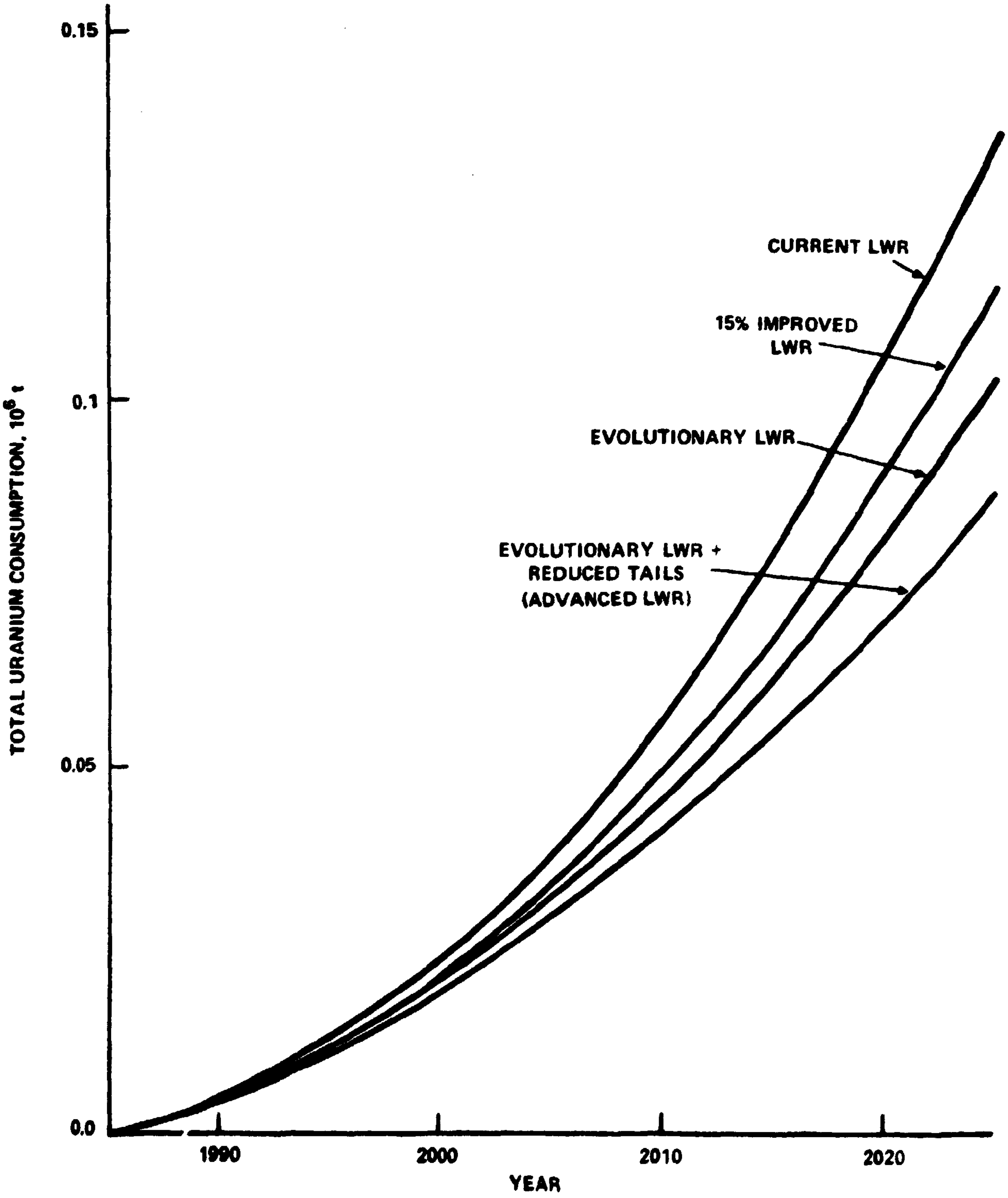


FIGURE 12 CUMULATIVE URANIUM CONSUMPTION FOR HWR ONCE THROUGH STRATEGIES: 1GWe/YEAR STARTING IN 1985

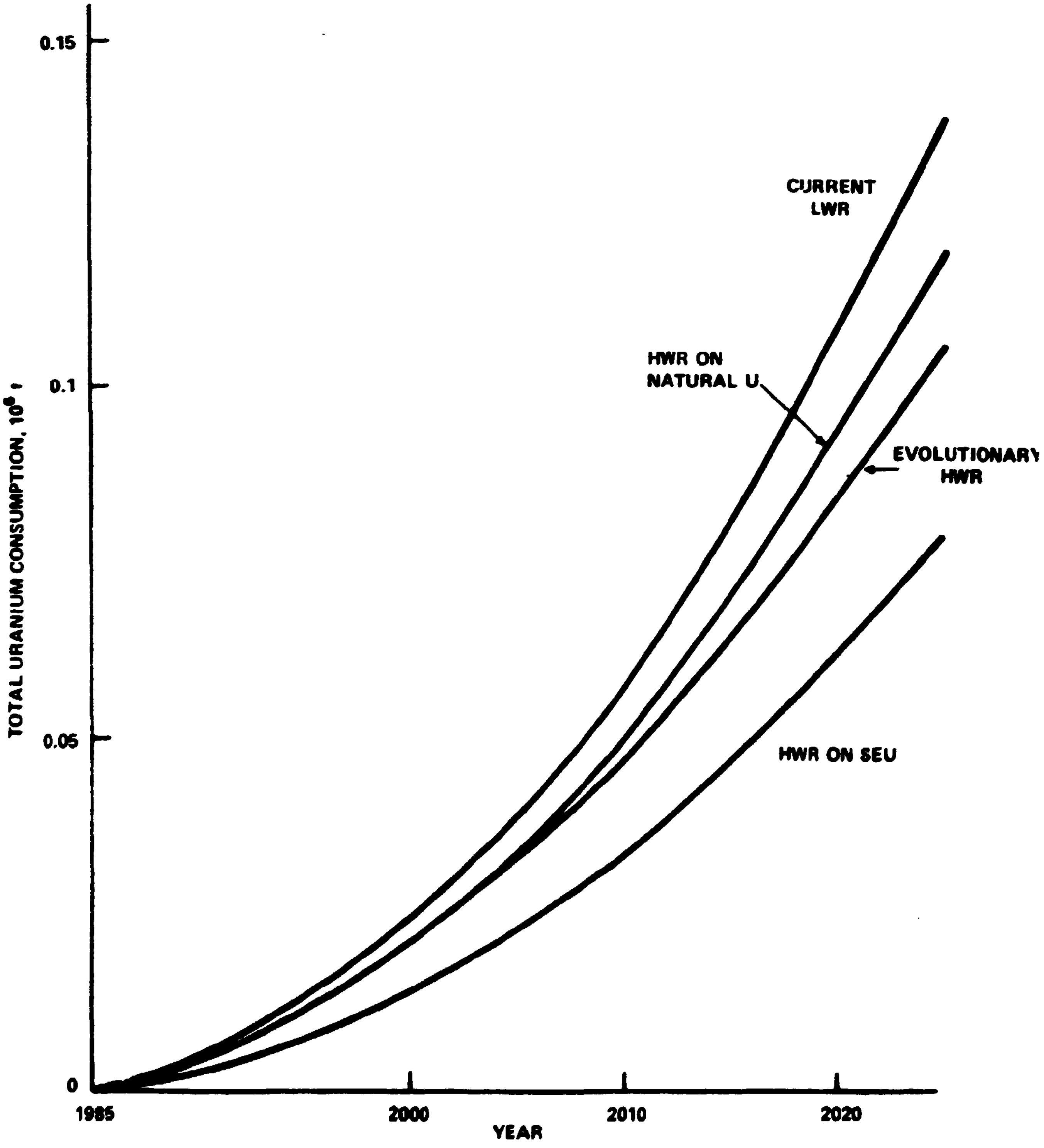
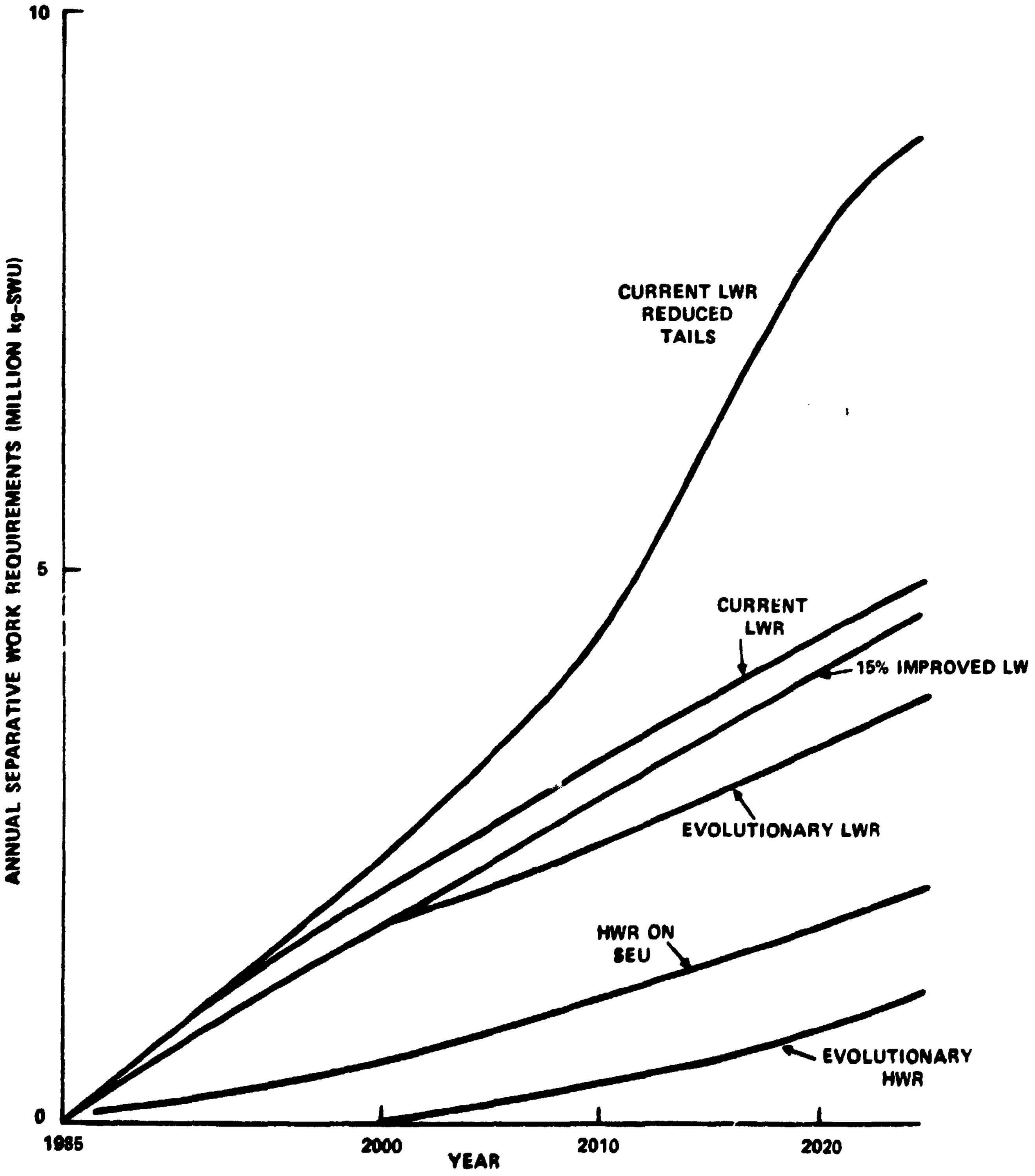


FIGURE 13 ANNUAL ENRICHMENT REQUIREMENTS FOR ONCE THROUGH STRATEGIES: 1GWe/YEAR STARTING IN 1985



It should be pointed out that the enrichment tails assay is a function of, among other things, the price of uranium and the amount of enrichment capacity that is available. It is unlikely that a single country will be able to control the tails assay schedule that is in effect.

Figure 14 compares estimates of the spent fuel storage requirements for the LWR and HWR. Because of the HWR's high annual discharges, a natural uranium HWR system would require about 200% more spent fuel storage capacity.

Overall, improved LWRs and HWRs on the once-through cycle offer the potential for significant reductions in uranium requirements, although particular strategies could create particular problems in enrichment requirements or spent fuel disposal. Similar results would be possible with other advanced converters such as HTRs.

2. Thermal Recycle Strategies

The cumulative uranium consumption for the thermal recycle strategies are shown in Figure 15; Figure 16 shows the annual separative work requirements. From a uranium utilization standpoint traditional plutonium recycle in standard LWRs and denatured uranium/thorium self-generated recycle in HWRs have similar characteristics. The annual separative work requirements with the LWR recycle are higher until around 2020 because the HWR is assumed to operate with natural uranium from 1985 to the year 2000.

Recycle strategies have more serious proliferation problems than once-through systems. Traditional Pu recycle suffers from having significant amounts of separated plutonium at various points in the recycle stages. In addition

FIGURE 14 CUMULATIVE QUANTITIES OF SPENT FUEL: 1GWe/YEAR STARTING IN 1985

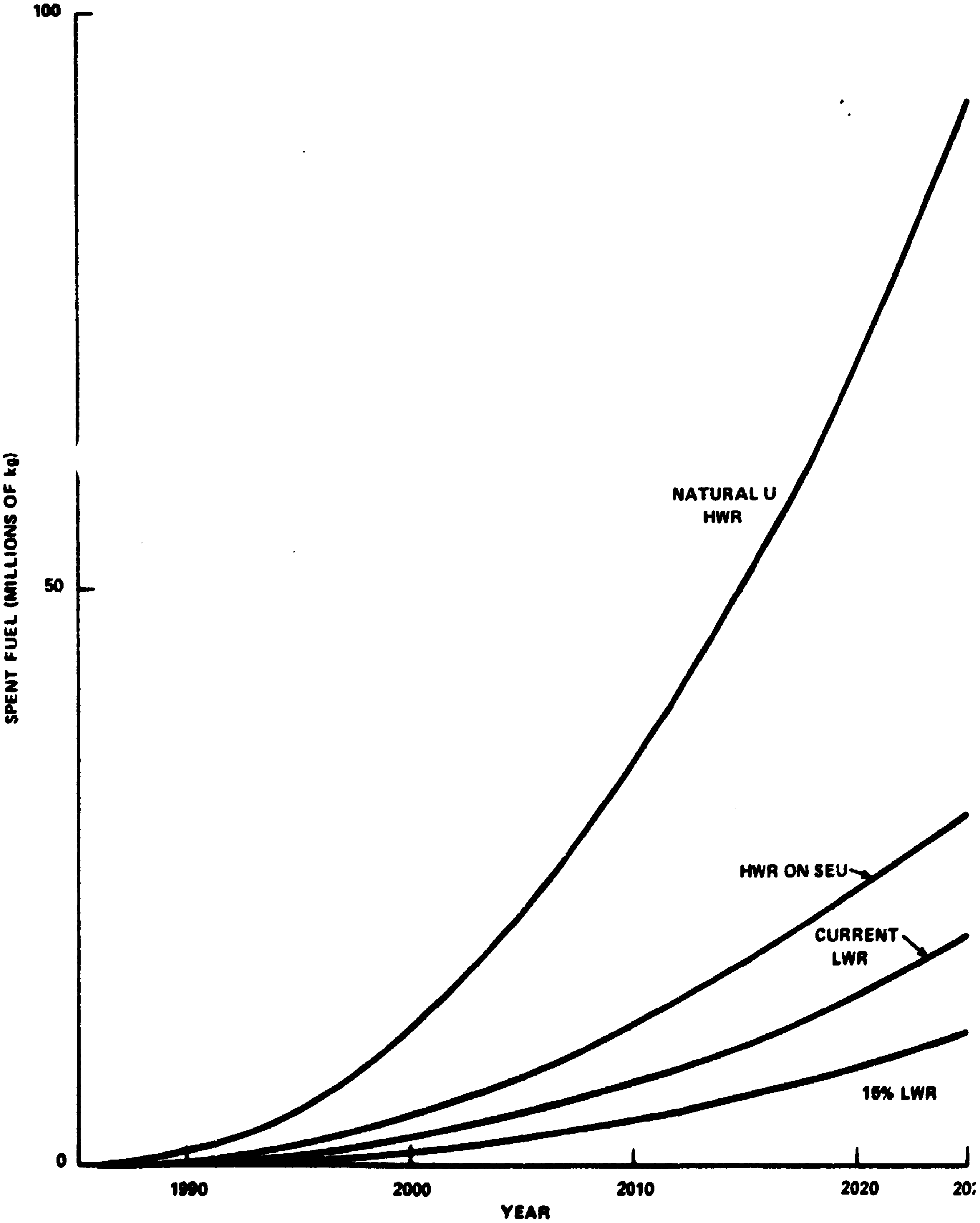


FIGURE 15 CUMULATIVE URANIUM CONSUMPTION FOR THERMAL RECYCLE STRATEGIES 1GWe/YEAR STARTING IN 1985

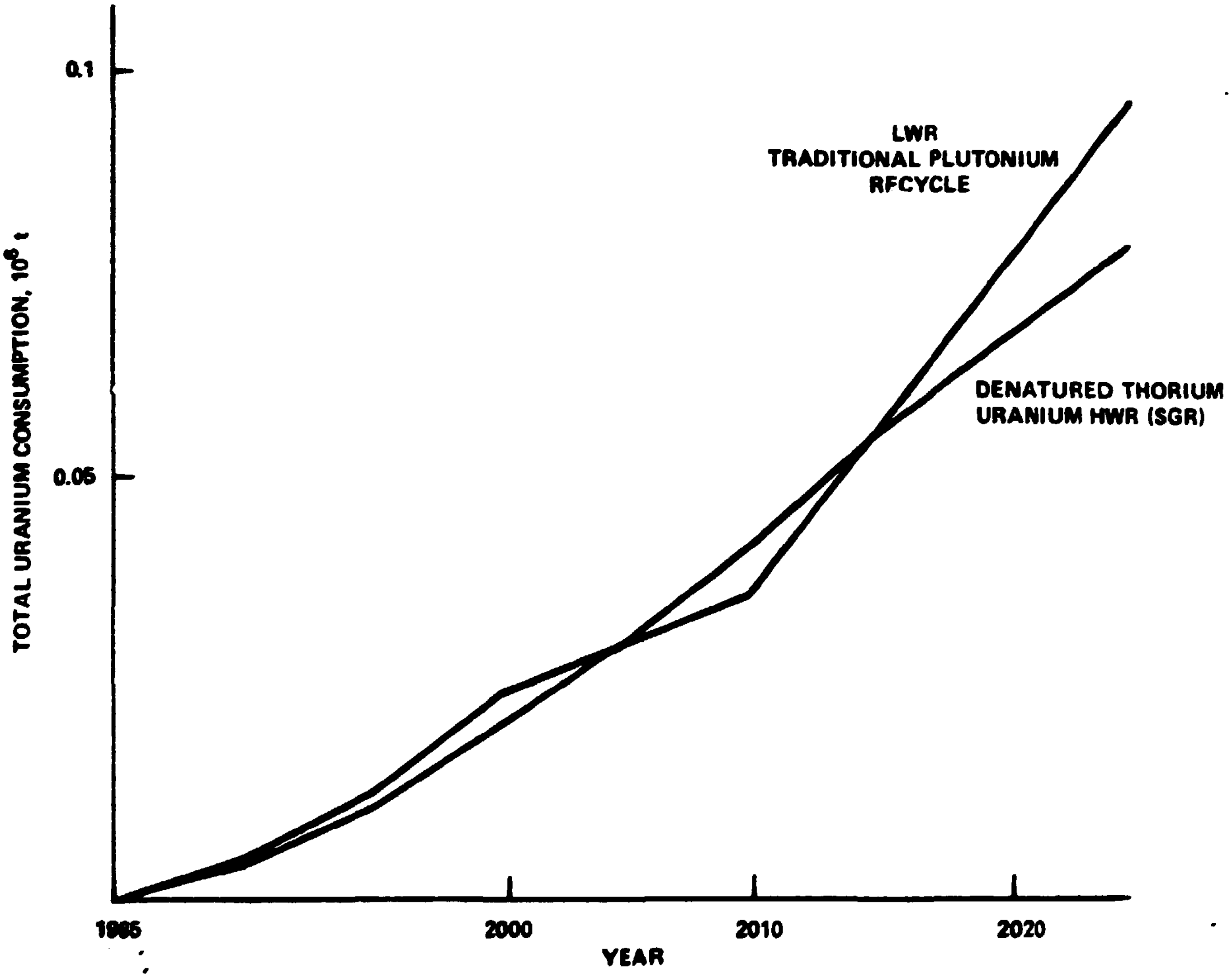
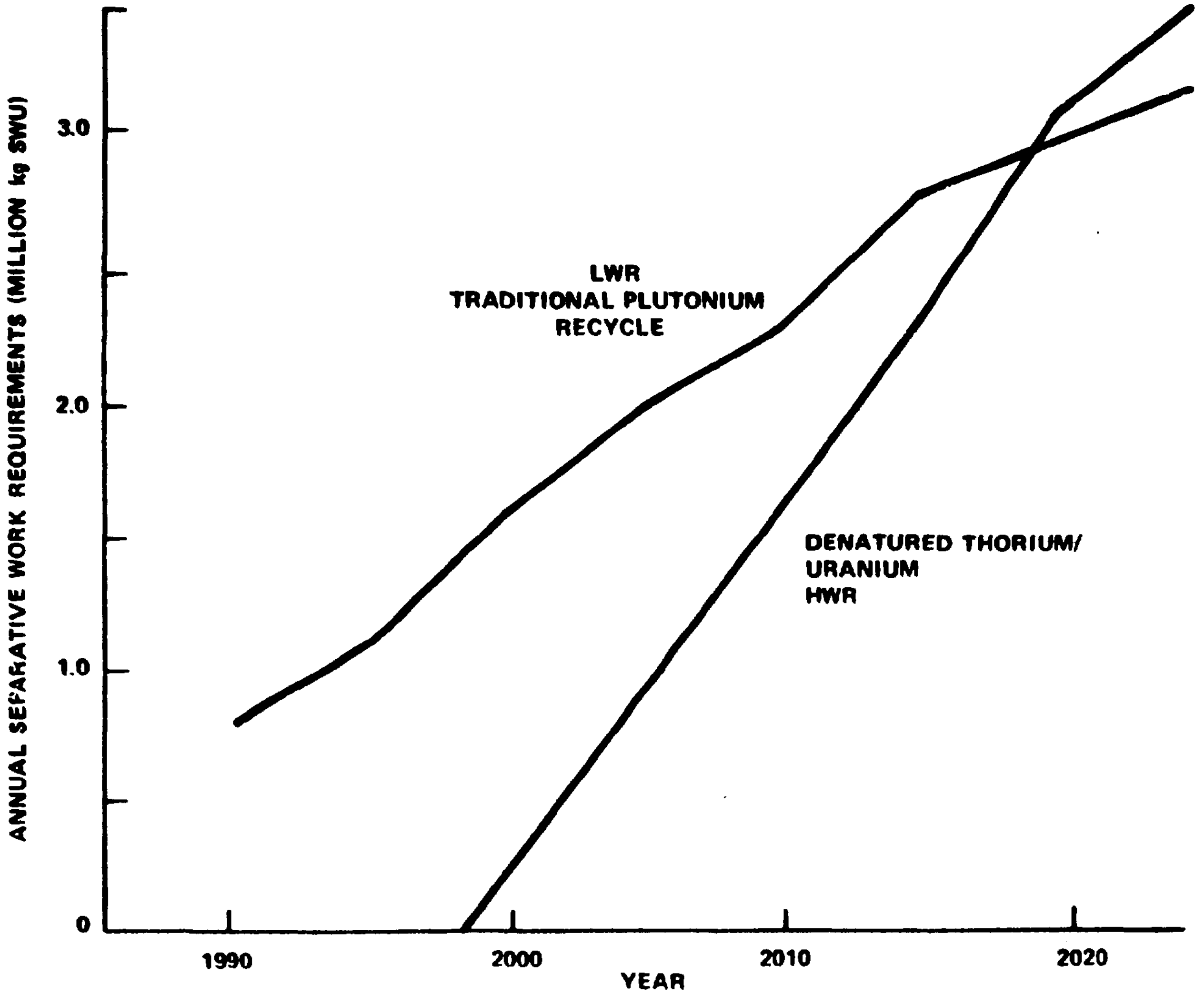


FIGURE 16 ANNUAL ENRICHMENT REQUIREMENTS FOR THERMAL RECYCLE STRATEGIES: 1GWe/YEAR STARTING IN 1985



mixed oxide (MOX) fuel is a part of the front end of the fuel cycle. This fresh fuel contains plutonium that can be readily separated out chemically and used to fabricate nuclear weapons. In contrast, denatured uranium/thorium fuel would require both chemical and isotopic separation. Another possible advantage of denatured U/thorium fuel is that there is significantly less fissile plutonium in the reprocessing phase of the fuel cycle than in traditional Pu recycle. It is probably necessary to consider, on a case by case basis, thermal recycle from a proliferation resistance and fuel assurance point of view. If a nation has access to significant thorium resources and fuel cycle services a denatured uranium/thorium fuel cycle should be considered as a possible alternative to U/Pu recycle. If such resources are not available the advanced once-through LWR and the evolutionary HWR once-through strategies are clearly viable options from a resource utilization point of view.

The enrichment and reprocessing capacity that is required for both thermal recycle strategies by 2025 is given in Table 3.

In order to develop a hedge against a large increase in uranium prices, a nation considering the initiation of a nuclear power program might deploy uranium-fueled advanced converters of a type so designed as to be convertable later to uranium/thorium burners, and join in cooperative efforts to develop thorium-based nuclear fuels. This would permit the benefits of reasonably priced nuclear power to accrue in the near-term, while ensuring against a possible large increase in uranium prices in the long-term.

Table 3

Required Enrichment and Reprocessing Capacity

Strategy	Enrichment Capacity	Reprocessing Capacity
	(Kg-SWU/Y)	(MTHM/Y)
Standard LWR	3.2×10^6	1040
Denatured Thorium HWR	3.5×10^6	1840

III. Elements of the Analysis

Eight different reactor deployment strategies were simulated for both the High and Low WOCA* forecasts of nuclear generating capacity which were developed by INFCE Subgroup 1A/2A at their 16-17 October 1978 meeting. These forecasts are shown in Table 4. They may be considered as defining a probable range of values; the fact that the real value may lie outside of that range cannot be excluded. These forecasts are illustrations of possible bounding scenarios so the representative high and low values for fuel cycle requirements may be derived. Because of these uncertainties calculations were carried out for both the low and high nuclear capacity forecasts.

The reactor systems which were included in the analysis are listed in Table 5, and their lifetime resource requirements are summarized in Table 6. All reactors were assumed to operate at a 70% capacity factor over their 30 year operating lives. Reactor mixes as indicated in the INFCE Questionnaires (IQ) are assumed up to the year 2000. The year 2000 reactor mixes are shown in Table 4.

Simulations were made with two different assumptions of the enrichment plant tails assay. As a reference value, it is assumed tails remain at 0.2% U-235. In addition, a reduced tails strategy is assumed to be introduced with the following schedule:

Reduced Tails Assay Schedule

0.2% before 1990

0.15% from 1990 to 2000

0.10% from 2000 to 2010

0.05% after 2010 plus the stripping of the previous inventories of tails.

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*WOCA is an acronym for countries other than those with centrally planned economies.

Table 4

Projected Installed Nuclear Capacity (GWe)

Year	INFCE Low	INFCE High
1985	245	274
1990	373	462
1995	550	770
2000	850	1200
2005	1100	1650
2010	1300	2150
2015	1450	2700
2020	1650	3350
2025	1800	3900

INFCE Questionnaire Forecasts in 2000

Reactor	GWe Low	 High
LWR	717.9	1042.8
HWR	73.5	101
HTR	3.6	3.6
AGR	16.8	23
FBR	20.4	36.9

Table 5

Reactor Types Used in the Simulations

LWR-U5(LE)/U: A current technology Light Water Reactor with lightly enriched (about 3%) U-235 fuel.

LWR-U5(LE)/U+15%: A Light Water Reactor with lightly enriched U-235 fuel which requires 15% less U_3O_8 than current LWRs.

LWR-U5(LE)/U+30%: A Light Water Reactor with lightly enriched U-235 fuel which requires 30% less U_3O_8 than current LWRs.

LWR-U5(DE)/U/TH: A Light Water Reactor which uses denatured (enrichment less than 20% U-235) U-235 fuel in fertile thorium.

LWR-U3(DE)/U8/TH/U3(SGR): A Light Water Reactor which begins operation with denatured (enrichment less than or equal to 20% U-235) U-235 fuel in thorium and recycles the U-233 which it produces in later cycles. Make-up requirements are provided by denatured U-235. A self-generated recycle system.

LWR-Pu/U(SGR): A Light Water Reactor which uses recycle plutonium and uranium equivalent to the amount which it discharges. The remainder of fissile requirements are supplied by enriched uranium. A self-generated recycle system.

HWR-U5(NAT)/U: A current technology Heavy Water Reactor which uses natural uranium fuel.

HWR-U5(SEU)/U: A Heavy Water Reactor which uses slightly enriched (about 1.2%) U-235 fuel.

HWR-U5(DE)/U8/Th/U3(SGR): A Heavy Water Reactor which begins operation with denatured U-235 fuel in thorium and recycles the U-233 which it produces in later cycles. Make-up requirements are provided by denatured U-235. A self-generated recycle system.

*FBR-Pu/U/U/U-HET OX: A Fast Breeder Reactor with a heterogeneous mixed (plutonium and uranium) oxide core and depleted uranium radial and axial blankets.

*FBR-Pu/U/Th/Th-HET OX: A Fast Breeder Reactor with a heterogeneous mixed (plutonium and uranium) oxide core an thorium radial and axial blankets.

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*All calculations assume a two year out-of-reactor plutonium turnaround.

Table 6

30-Year Lifetime Resource Requirements by Reactor Type*

Reactor Type	U_3O_8 tU/GWe	Enrichment (10^3 kg-SWU/GWe)	Net Fissile Pu Discharge (kg/GWe)	ThO_2 tTh/GWe
Once-Through Cycle:				
LWR-U5(LEU)/U	4,406	3,429	5,248	-
LWR-U5(LEU)/U+15%	3,727	3,237	3,797	-
LWR-U5(LEU)/U+30%	3,089	2,651	3,080	-
HWR-U5(NAT)/U	3,810	-	10,260	-
HWR-U5(SEU)/U	2,515	844	4,363	-
With Recycle:				
LWR-U5(LEU)/U**	3,344	3,245	5,248	-
LWR-U5(LEU)/U+15%**	3,072	3,125	3,797	-
LWR-U5(LEU)/U+30%**	3,721	2,677	3,080	-
LWR-Pu/U(SGR)***	3,008	2,594	1,150	-
LWR-U5(DE)/U8/Th/U3(SGR)	2,745	3,372	1,809	15.2
LWR-U3(DE)/U/Th	-	-	1,910	13.6
HWR-U5(NAT)/U**	3,537	-	10,260	-
HWR-U5(SEU)/U**	2,535	844	4,363	-
HWR-U5(DE)/U8/Th/U3(SGR)	1,712	2,019	692	19.2
FBR-Pu/U/U/U-Het Ox	-	-	8,619	-
FBR-Pu/U/Th/Th-Het Ox	-	-	-6,860	19.2

*Standard Tails Composition (0.2%)
Lifetime Average Capacity Factor (70%)
1% Fuel Fabrication Loss
1% Reprocessing Loss
**Once-Through Reactors with a uranium credit.
***Estimated

This simulates the use of advanced enrichment technologies after the year 1990.

Reactor Deployment Strategies

Each of the reactor deployment strategies is described below. The strategies, and the specific reactor types employed to implement those strategies, were selected as being representative of potential deployment mixes and were not intended to preclude other reactor types. These are base strategies to which additional improvements may be added. For example, the reduced tails schedule or an improved LWR may be added to an FBR strategy. The spectrum of changes as applied to both demand scenarios for a given strategy is displayed in the figures. The words in brackets key the strategies to the curves presented in Section II.

Once-Through Strategies:

(1) Unimproved LWR Once-Through (O/T): [Current LWR]

This case assumes no new reactor types or fuel cycle improvements are commercially introduced.

- o LWR/HWR/FBR reactor mix pre-2000 as in the INFCE Questionnaire (IQ) response (Table 4).
- o Post-2000 all new capacity is the unimproved LWR or the HWR on natural uranium operated in once-through mode, deployed in the year 2000 ratio determined by the IQ (approximately 10% HWRs).
- o All pre-2000 FBR's continue to end of their useful lives and are then replaced with LWRs and HWRs.

- o All LWRs and HWRs have present characteristics without improvements.
- o The PWR/BWR mix for LWR's is 2:1.

(2) Phased introduction of 30% LWR improvements: [Evolutionary LWR]

This strategy assumes improvements in LWR uranium utilization are phased in over a 10 year period to 2000, at which time all new LWRs would have lifetime U_3O_8 requirements 30% less than current LWRs. Improved HWRs are assumed to be deployed beginning in year 2000. It is representative of strategies that give an overall 30% improvement to the once-through fuel cycle.

- o LWR/HWR/FBR reactor mix pre-2000 as per IQ.
- o Current LWRs are deployed to 1990.
- o All new LWRs from 1990 to 2000 are 15% improved LWRs. All existing LWRs are backfitted with this improvement during this decade.
- o Current HWRs are deployed to 2000.
- o All new reactors after 2000 are 30% improved LWRs and HWRs on SEU deployed in the 9 to 1 ratio.

(3) Introduction of 15% LWR improvement: [15% LWR]

This case is similar to case 2 except that the 30% improved LWRs are not introduced.

Thermal Recycle Strategies:

(4) LWR Pu Recycle: [Pu Recycle]

This case assumes that thermal recycle is adopted and no additional breeders are built after year 2000. The LWR/HWR reactor mix is the same as in all of the previous cases. Plutonium recycle is assumed to be introduced in 1990 in self-generated recycle LWRs. HWRs on SEU are introduced in 2000.

- Current LWR remains in system at all times.
- Thermal recycle introduced in 1990.
- Current HWR remains in system until phased out by retirements.
- HWR on SEU introduced in 2000.

(5) LWR and HWR Recycle Based on Thorium Cycles: [U-233 Recycle]

This is an alternative scenario to (4) in which Th is used as a fertile material to produce U-233 which would be given widescale deployment in a denatured form. Self-generated recycle of denatured U-233 would be introduced in HWRs after 2000.

- LWR on denatured fuel would be deployed in 1990 to initiate production of a U-233. In 2000 these reactors would initiate denatured U-233 recycle.
- Current HWR in system until phased out by retirements.

o New HWRs would be operated on self-generated, denatured U-233 recycle beginning in 2000.

Fast Breeder Reactor (FBR) Strategies:

(6) Low FBR Introduction on the PU/U cycle: [Low FBR]

For both the high and low nuclear energy demand forecast a 12% per year (compound) increase in the rate at which breeders are deployed is assumed. (This is equivalent to a doubling of the rate of FBR additions every 6 years). Based on the INFCE Questionnaire answers for the period 1999-2000, 4.52 GWe of FBRs are projected to be installed for the high nuclear demand. For the low nuclear demand projection 1.87 GWe of FBRs are projected to be installed. This increase is continued until deployment becomes Pu or installed reactor capacity limited. The amount of installed capacity projected for breeders is given below.

Low Strategy FBR Capacity (GWe)

Year	High Demand	Low Demand
2000	37	20
2005	69	33
2010	126	56
2015	226	98
2020	402	170
2025	712	300

(7) Medium FBR Introduction on the Pu/U Cycle: [Medium FBR]

For the low energy demand forecast the deployment rate 1999-2000 is 4.52 GWe of FBRs, while for the high energy demand forecast the deployment rate is 7.16 GWe. Using a 6 year doubling time, as was done above, the amount of installed capacity projected for the FBR is given below.

Medium Strategy FBR Capacity (GWe)

Year	High Demand	Low Demand
2000	37	20
2005	88	51
2010	178	109
2015	336	209
2020	615	385
2025	1108	658

(8) High FBR Introduction: [High FBR]

Subgroup 1A/2A has defined the following very rapid breeder deployment scenario that can be used as a high benchmark case:

- Reactor mix pre-2000 as in the INFCE Questionnaire response except that, in anticipation of strong incentives for FBR, the year 2000 installed FBR capacity is assumed to be increased by approximately 35% from Questionnaire response (i.e., to 50 GWe).

- FBR introduced in 2000.

- HWR on SEU introduced in 2000.

- FBR installation rate increases 30% per year until 2005; thereafter deployment is limited only by plutonium availability in spent fuel (no reprocessing constraint).

- Non-FBR capacity additions are at same proportions as in 2000.

- The resulting breeder deployment rates are shown below:

High Strategy FBR Capacity (GWe)

Year	High Demand	Low Demand
2000	50	20
2005	186	40
2010	500	69
2015	766	191
2020	1230	420
2025	1490	658

(9) Thorium Cycle - FBR Introduction: [Th FBR]

This case assumed that a thorium blanketed fast breeder reactor is deployed at the low rate for the high energy demand forecast. The number of breeders deployed is the same as in strategy 6. In this case after 2005 U-233 would be burned in denatured LWRs. After 2000 HWRs would operate on denatured self generated U-233 recycle.

URANIUM PRODUCIBILITY

U.S. proposed estimates of uranium producibility are compared with the results of the calculations discussed above. Excluding those countries with centrally planned economies, the producibility of Reasonably Assured Resources (RAR) and Estimated Additional Resources (EAR) of uranium at a forward cost of less than \$50/lb U_3O_8 will peak near the year 2000 at about 110,000 to 130,000 annual tonnes U. The producibility from all sources in 2025 will be a multiple of this equalling between about 275,000 to 350,000 annual tonnes U. The cumulative production from IUREP speculative resources through 2025 could be 2.5 to 4 million tonnes U. The projected uranium producibility schedule used in the results section is given in Table 7.

It must be emphasized that the projections given are for uranium at a forward cost of less than \$50/lb U_3O_8. Since these projections are based on today's knowledge of uranium resources, they can be considered as a lower limit of production capabilities and they serve only as a departure point for discussion.

Table 7

Long-Term Annual Resource Production Capability

Calendar Years and Thousands of Tonnes U
(and Short Tons U_3O_8)

	1985	1990	1995	2000	2005	2010	2015	2020	2025
Low Producibility	93 (121)	113 (147)	133 (173)	161 (209)	194 (252)	223 (290)	252 (328)	267 (347)	277 (360)
High Producibility	94 (122)	115 (150)	139 (181)	177 (230)	224 (291)	264 (343)	306 (398)	331 (430)	359 (467)

Numbers in brackets are Short tons U_3O_8