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Impact of Fusion-Fission Hybrids on World Nuclear Future

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Abstract

Impact of Fusion-Fission Hybrids on World Nuclear Future

An investigation has been conducted to examine the impact of fusion-fission hybrids on world nuclear future. The primary objectives of this investigation have been: (1) to determine whether hybrids can allow us to meet the projected nuclear component of the world energy demand within current estimates of uranium resources without fast breeders, and (2) to identify the preferred hybrid concept from a resource standpoint.

The results indicate that hybrids have the potential to lower the world uranium demand to values well below the resource base. However, the time window for hybrid introduction is quite near and narrow (2000-2020). If historical market penetration rates are assumed, the demand will not be met within the resource base unless hybrids are coupled to the breeders.

The results also indicate that from a resource standpoint hybrids which breed their own tritium and have a low blanket energy multiplication are preferable.

Zusammenfassung

Beitrag von Fusions-Fissions-Hybridreaktoren zur zukünftigen Energiewirtschaft

Ziel dieser Untersuchungen war es die Auswirkungen von Fusions-Fissions-Hybridreaktoren auf die zukünftige Welt-Energiewirtschaft zu analysieren. Folgende Fragen wurden dabei untersucht:

(1) Können Fusions-Fissions-Hybridreaktoren im Rahmen der Energieprojektionen für die Zukunft und der vorhandenen Uranreserven den Schnellen Brüter ersetzen

(2) Welches Fusions-Fissions-Hybridreaktorkonzept ist das beste vom Standpunkt der Uranverfügbarkeit.

Als Ergebnis ergibt sich, daß Fusions-Fissions-Hybridreaktoren das Potential haben, den Uranverbrauch soweit zu verringern, daß die heute bekannten Uranreserven ausreichen. Jedoch müßten dazu die Fusions-Fissions-Hybridreaktoren bereits zwischen den Jahren 2000-2020 auf kommerzieller Basis eingeführt werden. Wenn historisch abgesicherte Markteindringkurven für bereits im Einsatz befindliche Energietechnologien auf das Fusions-Fissions-Hybridsystem angewandt werden, reichen die heute bekannten Uranreserven nicht aus; es sei denn die Fusions-Fissions-Hybridreaktoren werden mit dem Schnellen Brüter gekoppelt. In allen Fällen müßten jedoch Fusions-Fissions-Hybridreaktoren zum Einsatz kommen, die ihr eigenes Tritium brüten und eine niedrige Blanket-Multiplikation haben.

This work was performed in cooperation

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SYNOPSIS

An investigation has been conducted to examine the impact of fusion-fission hybrids on world nuclear future and how they may be integrated into the fission industry. The primary objectives of this investigation have been: (1) to determine whether hybrids can allow us to meet the projected nuclear component of the world energy demand within current estimates of uranium resources with or without fast breeders, and (2) to identify the preferred hybrid concept from a resource standpoint.

This study focuses on the time period between the present and the year 2075. Different scenarios where Th/U or U/Pu fusion-fission hybrids are coupled to different fission reactors (light water denatured, heavy water denatured, plutonium high converters, and plutonium fast breeders) have been examined. In addition, two reference scenarios where LWRs are coupled to either plutonium fast breeders or high converters have been examined. The annual and cumulative uranium requirements for these different scenarios up to the year 2075 have been determined assuming INFCE's low demand projection of world nuclear capacity. These uranium requirements correspond to the optimum time-dependent shares of the different reactor types in each scenario which were obtained using the strategy optimization code SOP-KA. The analyses have been performed for different hybrid design parameters, hybrid and breeder introduction dates, and market penetration constraints.

In all the hybrid scenarios, the tritium required for hybrid start-up is assumed to be produced in power-generating dedicated fission reactors with tritium production rates equal to those of Savannah-river-type reactors. For U/Pu systems, the possibility of producing the tritium in fast breeders has also been examined. For each hybrid scenario, four variations have been examined corresponding to whether the hybrid has a high or low blanket energy multiplication and whether the tritium required to fuel the hybrid is bred by the hybrid itself or by the dedicated fission reactors.

Values of the cumulative uranium demand for the different scenarios have been compared with recent estimates of the reasonably assured and estimated additional uranium resources with recovery costs up to 130 $/kg U.

The main conclusions of this study are:

(1) From a resource standpoint, hybrids which breed their own tritium fuel and have a low blanket energy multiplication are preferable. The resource penalty associated with tritium breeding outside the hybrid is quite severe and is equivalent to a delay in hybrid introduction until a sufficient number of tritium producers is built.

(2) Hybrids have the potential to lower the cumulative uranium demand to values well below the resource base. However, the time window for hybrid introduction is quite near and narrow (2000-2020).

(3) If breeders or plutonium high converters are not used, hybrids must be introduced early (2000) and must penetrate the market rapidly if the projected nuclear component of the energy demand is to be met within the resource base. If delayed till 2020, the demand can be met only if hybrids are coupled to the breeders and if both reactor types are allowed to penetrate the market rapidly.

(4) Traditional market penetration constraints are too restrictive so that hybrids will not "do the job" unless they are simultaneously introduced with the breeders in the year 2000.

(5) The use of hybrids results in a significant reduction in the maximum annual uranium demand. Values of 0.11 and 0.17 million tonnes per year have been obtained for U/Pu and Th/U scenarios respectively when hybrids are introduced in the year 2000. The corresponding values for an introduction date of 2020 are 0.17 and 0.26 million tonnes per year. The demand disappears entirely after 35-40 years from hybrid introduction. This means that uranium accessibility for large consumers with little resources of their own will not be the main problem; adequacy of the resource base remains to be the primary issue.

(6) When Th/U hybrids with low blanket multiplication are coupled to denaturated light or heavy water reactors, a relatively small hybrid capacity will be required because of their high support ratio. Hybrids and tritium producers may be placed within secure boundaries while the supported converters would be available to countries which need them. The minimum outside/inside ratio obtained in these scenarios ranges from 7.7 to 10.0 for LWRDs and HWRDs, respectively.

When the above conclusions are coupled with the current status of fusion research and projected progress milestones, one cannot escape the conclusion that the development and deployment of hybrids does not diminish or eliminate the need for fast breeders.

ABSTRACT

An investigation has been conducted to examine the impact of fusion-fission hybrids on world nuclear future. The primary objectives of this investigation have been: (1) to determine whether hybrids can allow us to meet the projected nuclear component of the world energy demand within current estimates of uranium resources with or without fast breeders, and (2) to identify the preferred hybrid concept from a resource standpoint.

The results indicate that hybrids have the potential to lower the world uranium demand to values well below the resource base. However, the time window for hybrid introduction is quite near and narrow (2000-2020). If historical market penetration rates are assumed, the demand will not be met within the resource base unless hybrids are coupled to the breeders.

The results also indicate that from a resource standpoint hybrids which breed their own tritium and have a low blanket energy multiplication are preferable.

I. INTRODUCTION

It is generally recognized that for nuclear fission to provide a substantial fraction of the world energy needs for more than only a few decades, the natural fissile content of uranium ore resources must be supplemented [1,2]. Current projections of the nuclear component of world energy demand and estimates of uranium resources leave no doubt that a worldwide shortfall of fissile fuel early in the next century will be highly likely. The shortfall can be averted by early and rapid introduction of fast breeder reactors. However, safety and weapons-proliferation concerns, both real and imaginary, have hampered deployment of the plutonium-fueled liquid metal fast breeder reactor in several key countries [1,3,4]. An intensive search for alternative breeder and near-breeder reactors, along with nuclear fuel cycles which do not allow easy access to weapons grade materials has been undertaken [1]. In addition, considerable interest has recently been generated in fusion-fission hybrid concepts as a potentially-attractive method for producing fissile fuel and a vehicle for early introduction of fusion [5,6]. The idea is to surround the fusion reaction region with a blanket of fertile material so that the fusion neutrons would convert the fertile isotopes Th-232 or U-238 to U-233 or Pu-239 respectively.

The fissile material produced in the hybrid can be burned in fission reactors or it can be partially burned in-situ releasing considerably more energy than that generated by fusion. Thus, hybrids can nicely couple the "fast neutron-rich but energy-poor" DT fusion process with the "energy-rich but neutron-poor" fission process. Neutron multiplication in the hybrid blanket through (n,2n), (n,3n), and (n,fission) reactions makes it possible for the total number of breeding captures per DT fusion neutron to be considerably larger than unity. This means that even if hybrids are made to breed their own tritium fuel, large quantities of fissile materials can still be produced per unit of fusion energy [7].

The most attractive feature of the hybrid concept is that it may allow fusion to make an early and significant contribution to the world energy needs [5,6]. The fission energy produced in the supported fission reactors and in the hybrid blanket itself makes it possible to relax the fusion gain requirements in the hybrid. Reduced gain and plasma confinement parameters in magnetic fusion devices, and low driver efficiency or target gain in inertial confinement fusion may be tolerable. Hence, it is reasonable to expect that hybrids can be deployed much earlier than pure fusion devices and possibly open the way for them.

Fusion-fission hybrids have potentially much higher fuel production rates per unit thermal power than fast breeders [8]. Neutronic analyses and conceptual reactor studies have shown that a U/Pu hybrid can produce enough plutonium to fuel as many as six LWRs of equivalent thermal power on a steady-state basis [9]. The support ratio is **even higher for Th/U hybrids because U-233 is a more efficient** fuel for thermal fission reactors and because in the hybrid blanket Th-232 has a much lower fast-fission cross section than U-238. This is significant not only from an economic viewpoint but also from the standpoint of hybrid ownership and proliferation concerns. In a scheme similar to that outlined by Feiveson and Taylor [4], the hybrids may be placed within internationally-monitored, physically-secure "fuel production centers" while the converter reactors using the produced ^{233}U would be operated on the so-called denatured fuel cycle and would be available to countries that need them [9,10]. This scheme will be feasible only if the generating capacity "outside the fence" is much larger than that inside. In addition, the hybrids' large fuel production rates may make it economically feasible to operate them off-line; this will be an important consideration for first generation hybrids with expectably low plant availability.

1. 1. Objectives

The literature abounds with studies of fusion-fission hybrids [5-16] ranging from detailed multi-dimensional neutronic analyses of hybrid blankets to conceptual hybrid reactor designs for different fusion drivers. Little work, however, has been done to realistically examine the impact of fusion-fission hybrids on world nuclear future and how they affect the uranium demand if current long-term projections of the nuclear energy component are to be met. To this end, this study has been undertaken. The primary objectives of this investigation have been: (1) to determine whether hybrids can allow us to meet the projected nuclear component of the world energy demand within current estimates of uranium resources with or without fast breeders, (2) to determine whether there is a "time window" for hybrid introduction and how such a window is affected by market penetration constraints, (3) to identify the preferred hybrid concept from a resource standpoint (i.e. fuel vs. power producing hybrids, with or without tritium breeding for both Th/U and U/Pu Systems), and finally, (4) to quantify the impact of hybrids on proliferation as measured by the ratio between capacities outside and inside the fence.

It should be emphasized that this study focuses primarily on the question of resource adequacy; assessment of the technical and commercial feasibility of hybrids and other advanced reactors is beyond the scope of this investigation.

II. METHODOLOGY

II.1. Nuclear Demand Projections

This study focuses on the time period between the present and the year 2075. It is assumed that pure fusion reactors will not contribute significantly to the world energy needs till the end of that period. This assumption will not alter the results of this investigation for the period between the present and the point when pure fusion actually penetrates the market and represents a commercially-significant share (>1%) of the installed capacity.

Several forecasts of world nuclear generating capacity have recently been published (Table 1). The accuracy of these forecasts is difficult to assess inasmuch as they depend on economic, social, and political constraints. The uncertainty, as measured by the percent difference between the high and low demand projections, is quite large and increases with time, being about 50% in the year 2000 and more than 100% in 2025 (Fig. 1). With this caveat in mind, this investigation is based on INFCE's low demand projection of world nuclear capacity extrapolated to the year 2075 (Table 2). This forecast is the most recent and is based on estimates made by individual countries of their projected energy needs. The use of such low forecast will not alter the general conclusions of this investigation. Estimates of the cumulative uranium consumption to be determined on the basis of this low demand projection represent lower bounds and are, therefore, optimistic.

II.2. Hybrid Coupling Scenarios

The annual and cumulative world uranium demand for the different scenarios shown in Fig. 2 up to the year 2075 have been determined. The optimum time-dependent shares of the different reactor types have been determined using the strategy optimization code SOP-KA [17] (Appendix B). These time-dependent shares are determined so that the projected demand (Fig. 1) is met and the cumulative uranium consumption at 2075 is minimized. The analyses have been made for different hybrid, breeder, and advanced reactors introduction dates, market penetration scenarios, and hybrid design parameters.

Scenarios I and II in Fig. 2 are reference cases where LWRs are coupled to either Pu high converters (HC) or fast breeders (FBR). The LWRs can be converted to burn plutonium, if it is available, only after the FBRs or HCs enter the market. Scenarios III and IV are for Th/U hybrids (HYB) coupled to either light or heavy water denatured reactors (LWRD, HWRD), while scenarios V and VI are for U/Pu hybrids coupled to either Pu high converters or fast breeders along with LWRs. For the Th/U systems, the LWRs built before hybrid introduction are assumed to operate in a once-through mode (OT) and may be converted to LWRDs when U-233 bred by the hybrids becomes available. For scenarios V and VI, the LWRs may be converted to burn plutonium if it is available only after the hybrids and breeders (or HCs) enter the market.

In all the hybrid scenarios (III through VI), the tritium required for hybrid startup is produced in power-generating dedicated fission reactors (SR) with production rates equal to those of Savannah-river-type reactors. For U/Pu systems (V and VI), the possibility of replacing the SRs with tritium-producing fast breeders (FBRT) has also been examined. For each hybrid scenario (III through VI), four hybrid designs have been examined corresponding to whether the hybrid is primarily a fuel or power producer (i.e. low or high blanket energy multiplication) and whether the tritium required to fuel the hybrid is bred by the hybrid itself or by the dedicated fission reactors (SRs or FBRTs); this results in a total of 26 scenarios.

The main design parameters for the different fission reactors used in this investigation, namely, LWR (OT), LWR (Pu), LWRD, HWRD, HC, FBR, SR, and FBRT are given in Tables 3 through 5. The design parameters for the different hybrids are given in Appendix A; these are based on numerous neutronic calculations reported in the literature [9-15]. The fissile breeding rates for the different hybrids examined in this study represent upper bounds for the values reported in the literature, and hence, the estimated uranium demand values will be somewhat optimistic (i.e. low).

II.3. Market Penetration

The effect of market penetration constraints for the different reactor types (HYB, FBR, SR, FBRT, HC, and HWRD) on the cumulative uranium consumption of the different scenarios shown in Fig. 2 has been determined. Three market penetration constraints have been examined; these are shown in Figs. 3 and 4 for introduction dates of 2000 and 2020 respectively. The introduction date has traditionally been defined as the point when a reactor type represents a commercially-significant share (1%) of the installed capacity [18]; here, however, it is defined as the time when the first commercial reactor is built.

Constraint A in Figs. 3 and 4 allows a reactor type to fully-penetrate the market within ten years from the time of introduction. Full penetration is defined as the point when the maximum allowable introduction rate is equal to the sum of the rate of replacement for decommissioned reactors and the rate of increase of projected capacity. Constraint A is clearly too optimistic and is used only to determine the potential, i.e. a lower bound on uranium requirements, for the different scenarios. A similar constraint has been used by INFCE to determine the potential of different breeder fuel cycles [1].

Constraint B in Figs. 3 and 4 is representative of historical market penetration scenarios. It is based on a logistic substitution model for competing options [18] where the time-dependent market share f(t) is given by the relation:

$$\log \{f(t)/[1 - f(t)]\} = \alpha t + \beta \qquad (1)$$

where t is time and α and β are constants to be obtained from historical trends of energy substitution systems. The growth in market share as represented by Eq. (1) applies from the point of introduction t_o till the point when a new alternate option captures a commercially-significant share (1%) of the market. Beyond that point the market share for the first option begins a period of logistic decline until it is eliminated [18]. In this study we assume that Eq. (1) applies throughout the period of interest. Based on historical growth data for different energy systems, the parameter α was selected to be 0.03 which is somewhat high [18] so that constraint B represents a somewhat accelerated penetration. The parameter β was selected so that $f(t_o)$ is equal to 0.001.

Constraint C in Figs. 3 and 4 is a simple linear model representative of "planned" penetration. Most of the results to be presented here utilize constraints A and B. Numerical values for the maxumum penetration rates are given in Table 6.

II.4. Uranium Resources

A comparison has been made between the cumulative uranium requirements of the different scenarios examined and recent estimates of world uranium resources [1,21]. Uranium resources are classified according to their recovery cost and probability of existence. Table 7, taken from reference [1], lists estimates of the world's "reasonably assured", "estimated additional", and "speculative" uranium resources with cost of recovery up to 130 $/kgU. The reasonably assured resources (RAR) in these categories amount to 2.36 MTU, while the estimated additional resources (EAR) are 2.29 MTU. The term "reserves" is equivalent to the reasonably assured resources with recovery cost less than 80 $/kgU.

It is difficult to estimate uranium resources with recovery costs higher than those listed in Table 7 since exploration has, heretofore, been aimed at deposits containing more than 0.1% uranium. Environmental constraints and real mining costs may limit utilization of lower grade ores. Prudent planning should be based on the sum of RAR and EAR and should not include the speculative resources. It is this sum which will be compared with estimates of the cumulative uranium demand for the different scenarios examined in this study.

III. RESULTS AND DISCUSSION

III.1 Identification of Preferred Hybrid Concept

Calculations have been made to identify the preferred hybrid concept from a resource standpoint. The two variables of interest here are blanket energy multiplication and tritium breeding, i.e. (1) whether hybrids should produce primarily fissile fuel or power (low M vs. high M), and (2) whether hybrids should breed their own tritium fuel or not.

Figure 5 is a plot of the cumulative uranium consumption as a function of time for scenario VI with either a high or low blanket multiplication hybrid. **Here, U/Pu hybrids are coupled to fast breeders and** light water reactors. Savannah river type reactors are used to provide start-up tritium for the hybrid, however, the hybrid breeds its own tritium fuel. The hybrids, breeders, and tritium producers are assumed to be introduced in the year 2000 with market penetration constraint C. The hatched band in Fig. 5 represents the sum of the reasonably assured (RAR) and estimated additional (EAR) uranium resources with recovery costs up to 130 \$/kgU. The band width is ± 20% of EAR (Table 7).

Figure 5 shows that in both the low and high blanket multiplication cases the cumulative uranium consumption increases with time and begins to level off at some point beyond the introduction date of the hybrids and breeders reaching an asymptotic value at 2075. This behavior is reasonable since as hybrids and breeders are gradually introduced, enough LWRs will have to be built to meet the balance of the demand. These LWRs will require natural uranium to fuel them until a sufficient number of hybrids and breeders is built.

Figure 5 shows that from a resource standpoint a low blanket multiplication is preferred. Similar results have been obtained for other scenarios, introduction dates, and penetration constraints. This result is reasonable since a low - M hybrid produces more fissile material per unit thermal power than a hybrid with high blanket multiplication.

Figure 6 is a plot of the cumulative uranium consumption as a function of time for scenario IV where the tritium fuel is produced by either the hybrid itself or by Savannah-river type reactors (SR). In both cases, the start-up tritium is provided by SRs. Here, Th/U hybrids are coupled to HWRDs and if excess U-233 is available some of the once-through LWRs may be converted to LWRDs. The hybrids, HWRDs, and SRs are assumed to enter the market in the year 2000. Constraint C is applied to the hybrids and SRs only.

The results in Fig. 6 exhibit a similar behavior as those in Fig. 5; the cumulative uranium consumption increases with time until enough hybrids are built to support the converters. At that time it begins to level off and ultimately reaches an asymptotic value. Figure 6 clearly shows that, from a resource standpoint, it is preferable that hybrids breed their own tritium. The reason for this behavior is that a large number of SRs will be required to provide tritium for the hybrids; nearly 13 GWt of SRs is required to provide enough tritium for 1 GW of fusion power. This means that the rate of hybrid penetration into the market will be limited by the rate at which SRs can be built. Similar results have been obtained for other scenarios, introduction dates, and penetration constraints.

Based on the above results, we conclude that from a resource standpoint the preferred hybrid concept should breed its own tritium fuel and have a low blanket multiplication. There may be other reasons (primarily technological simplicity) for first-generation hybrids not to breed their own tritium. However, the resource penalty associated with this option is quite severe and is equivalent to a delay in hybrid introduction until a sufficient number of tritium producers is built. For the remainder of this study, only low-M hybrids which breed their own tritium will be examined. For these hybrids, the source of start-up tritium will have little impact on the cumulative uranium consumption since only a few of these reactors will be required. In the results to follow, Savannah-river-type reactors are used for that purpose.

III.2 Potential Impact of Hybrids on Uranium Demand

Figure 7 shows the cumulative uranium consumption as a function of time for the different scenarios examined in this study (Fig. 2). Here, the hybrids, breeders, high-converters, and tritium producers are assumed to enter the market in the year 2000. Market penetration constraint A has been used so that these results represent the lowest possible uranium demand values (i.e. potential limit) for the different scenarios. It is clear that hybrids (scenarios III through VI) have the potential to lower the cumulative uranium demand to values well below the resource estimates. The uranium demand values for the U/Pu scenarios (V and VI) are lower than those for Th/U scenarios (III and IV) since they take credit for the plutonium produced in pre-hybrid LWRs. The uranium demand values for scenarios V and VI are essentially the same since the relatively unconstrained market penetration by the hybrid results in an abundance of plutonium. For Th/U scenarios, the use of HWRDs in conjunction with the hybrids (scenario IV) results in slightly lower uranium demand than the case when LWRDs are used (scenario III) because of their higher conversion ratio.

Results similar to those in Fig. 7 for an introduction date of 2020 are shown in Fig. 8. For comparison, the results for scenario II with breeder introduction in the year 2000 are superposed on Fig. 8. Such comparison is reasonable since the hybrid development program is at least twenty years behind that for the breeder. It is clear from Fig. 8 that delaying hybrid introduction till 2020 would make it impossible to meet the nuclear component of the demand within the known uranium resources. It is also clear that the breeder alone can "do the job" if introduced sufficiently early. It should be emphasized that the results in Fig. 8 are based on market penetration constraint A so that these estimates of the cumulative uranium demand are the lowest to be expected for an introduction date of 2020. Scenarios V and VI are the only options with potential uranium demand only slightly higher than the resource base.

III.3. Effect of Market Penetration Constraints on the Cumulative Uranium Demand

The results presented in Figs. 7 and 8 represent lower bounds on the cumulative uranium consumption for the different scenarios because of the relatively-unrestricted market penetration assumed (constraint A). The computations have been repeated for historical market penetration constraints (constraint B in Figs. 3 and 4). These results are shown in Figs. 9 and 10 for introduction dates of 2000 and 2020 respectively.

Figure 9 shows that if hybrids and advanced reactors are to be introduced in the year 2000 and allowed to penetrate the market under historical constraints (constraint B in Figs. 3 and 4), the demand can be met within the known resource base only if hybrids are to be coupled to fast breeders (scenario VI). If the introduction date is delayed till 2020 (Fig. 10) the cumulative uranium demand for all hybrid scenarios would be considerably larger than the resource base. The uranium demand values for U/Pu hybrid scenarios V and VI are lower than those for Th/U scenarios III and IV since the former take credit for the plutonium produced in pre-hybrid LWRs. In all cases, however, it appears that traditional market penetration constraints will be too restrictive if breeders alone are introduced in the year 2000 or if hybrids and breeders are simultaneously introduced in 2020.

III.4. Annual Uranium Demand

In addition to the cumulative uranium demand values presented above, the variations of the annual uranium demand with time for the different scenarios have been computed. The annual demand values are of importance to major consuming countries with scarce resources of their own. For these countries, such as western Europe and Japan, uranium accessibility, i.e. the ability to buy their uranium needs on the open world market, is of concern.

Figure 11 shows the annual uranium demand for scenario IV where Th/U hybrids are coupled to HWRDs. The results are shown for hybrid introduction dates of 2000 and 2020 where market penetration constraint B is used in both cases. Figure 11 shows that before hybrid introduction the annual uranium demand rises monotonically to match the increased nuclear capacity (once-through LWRs). After hybrids are introduced, the annual uranium demand continues to rise at a slower rate until a sufficient number of hybrids and HWRDs are built so that their combined capacities along with the converted LWRDs would compensate for the increased nuclear capacity. Beyond that point the annual demand begins to drop as once-through LWRs are decommissioned (or converted to LWRDs) and reaches zero nearly 35 years after hybrid introduction. The peak annual demand values are 0.17 and 0.26 million tons per year for introduction dates of 2000 and 2020 respectively.

Results nearly identical to these shown in Fig. 11 have been obtained for scenario III where Th/U hybrids are coupled to LWRDs. The peak annual demand values are 0.17 and 0.26 million tons per year for introduction dates of 2000 and 2020 respectively. These values are quite reasonable and indicate that uranium accessibility on the open world market for major consuming countries is not the main problem; rather, the problem is still the adequacy of the resource base.

Figure 12 shows the annual uranium demand for scenario VI where U/Pu hybrids are coupled to fast breeders. The hybrids and breeders are assumed to enter the market simultaneously at either 2000 or 2020 with penetration constraint B (Figs. 3 and 4). These results are somewhat different from those in Fig. 11 inasmuch as they are characterized by double-peaked variation in the annual demand. The drop after the first peak results from utilizing the plutonium produced in pre-hybrid LWRs to start newly built FBRs or fuel those LWRs which have been converted to burn plutonium. The second peak is reached nearly twenty years after hybrid and breeder introduction. By that time enough of these reactors would have been built to compensate for the increased nuclear capacity. The uranium demand then decreases with time as more LWRs are decommissioned or converted to burn plutonium. The uranium demand drops to nearly zero approximately forty years after hybrid and breeder introduction. The peak annual demand values are 0.11 and 0.17 million tons per year for introduction dates of 2000 and 2020 respectively. These are somewhat lower than those for the Th/U scenarios III and IV primarily because of the plutonium credit from LWRs.

Results similar to those in Fig. 12 have been obtained for scenario V where U/Pu hybrids are coupled to plutonium high converters. Again, a double-peaked behavior is obtained with maximum values of 0.11 and 0.17 million tons per year for introduction dates of 2000 and 2020 respectively.

III.5. Time-Dependent Shares of Different Reactors

The results presented in Figs. 11 and 12 can be best understood by examining the time-dependent shares of the different reactor types. Figure 13 describes the time evolution of scenario IV where Th/U hybrids are coupled to HWRDs. These hybrids have a low blanket multiplication and breed their own tritium fuel. Power producing Savannah-river-type reactors are used to provide start-up tritium for the hybrids. The hybrids are introduced in the year 2000 with market penetration constraint B.

Figure 13 gives the time-dependent shares of the different reactor types. These are the values obtained using the strategy optimization code SOP-KA and result in the minimum possible cumulative uranium consumption by the year 2075 subject to the above stated constraints. The upper line in Fig. 13 represents the projected nuclear capacity in Table 2. The regions between different lines represent capacities of the indicated reactor types.

As can be seen from Fig. 13, as U-233 producing hybrids penetrate the market gradually, HWRDs are built to burn the U-233. However, once-through LWRs continue to be built after hybrids are introduced to meet the balance in the increased capacity. As more hybrids enter the market, additional HWRDs are built to meet the increased demand and replace decommissioned once-through LWRs. Also, by the year 2020 excess U-233 begins to accumulate so that some of the once-through LWRs are converted to LWRDs.

It is interesting to note that throughout the period of interest the necessary hybrid capacity is relatively small and becomes considerably lower than the constraint imposed by market penetration after roughly twenty years from its introduction. The maximum installed hybrid capacity for this scenario is nearly 220 GWe and occurs at 2050. This is an advantage of Th/U hybrids because of their high support ratios; this issue will be discussed below. The number of SR reactors required for start-up tritium for the hybrids is extremely small (exaggerated on Fig. 13). The maximum SR capacity for the scenario shown in Fig. 13 is nearly 15 GW and occurs at 2030.

Results similar to those shown in Fig. 13 for scenario III are shown in Fig. 14. Here, Th/U hybrids are coupled to LWRDs. Again, the maximum hybrid capacity is relatively small being about 285 GWe at 2055. The maximum SR capacity is nearly 17 GWe at 2030.

The high support ratios obtained with Th/U hybrids are clearly illustrated in Fig. 15 where the ratio between capacities outside and inside "the fence" is plotted as a function of time for both scenarios III and IV. These results are based on the data in Figs. 13 and 14. For both these scenarios it is assumed that the hybrids and tritium producers (SRs) will be placed within secure boundaries while all other reactors will be available to countries which need them. The outside/inside ratio drops from a value of infinity at the point of hybrid introduction (year 2000 in this case) to a broad minimum value 40-50 years from that point. The support ratio initially decreases as more hybrids enter the market and later rises slightly as enough U-233 is accumulated to run newly installed converters without building more hybrids. The minimum outside/inside ratios in Fig. 15 are approximately 7.7 and 9.9 for scenarios III and IV respectively.

Results similar to those shown in Figs. 13 and 14 for U/Pu scenarios V and VI are shown in Figs. 16 and 17 respectively. In these figures, the initial sudden drop in the LWR capacity results from converting some of them to burn plutonium. The LWR capacity continues to increase beyond the point of hybrid introduction because of its gradual market penetration. As enough hybrids and breeders (or HCs) are built, the LWR capacity decreases as the reactors decommissioned at the end of their lifetimes are replaced by breeders (or HCs). It is clear from Figs. 16 and 17 that a larger number of hybrids will be required for U/Pu systems than for Th/U (Figs. 13 and 14); this is a direct result of their lower support ratio. The maximum hybrid capacities are nearly 1325 GWe at 2075 for both scenarios V and VI compared to 285 and 220 GWe for scenarios III and IV respectively. The maximum SR capacities in Figs. 16 and 17 are nearly 23 GWe at 2055; these are extremely small so the use of tritium-breeding fast reactors (FBRTs) instead of SRs would not alter the results.

IV. CONCLUSIONS

Based on the results of this investigation the following conclusions can be drawn:

(1) From a resource standpoint, hybrids which breed their own tritium fuel and have a low blanket energy multiplication are preferable. The resource penalty associated with tritium breeding outside the hybrid is quite severe and is equivalent to a delay in hybrid introduction until a sufficient number of tritium producers is built.

(2) Hybrids have the potential to lower the cumulative uranium demand to values well below the resource base. However, the time window for hybrid introduction is quite near and narrow (2000-2020).

(3) If breeders or plutonium high converters are not used, hybrids must be introduced early (2000) and must penetrate the market rapidly if the projected nuclear component of the energy demand is to be met within the resource base. If delayed till 2020, the demand can be met only if hybrids are coupled to the breeders and if both reactor types are allowed to penetrate the market rapidly.

(4) Traditional market penetration constraints are too restrictive so that hybrids will not "do the job" unless they are simultaneously introduced with the breeders in the year 2000.

(5) The use of hybrids results in a significant reduction in the maximum annual uranium demand. Values of 0.11 and 0.17 million tonnes per year have been obtained for U/Pu and Th/U scenarios respectively when hybrids are introduced in the year 2000. The corresponding values for an introduction date of 2020 are 0.17 and 0.26 million tonnes

per year. The demand disappears entirely after 35-40 years from hybrid introduction. This means that uranium accessibility for large consumers with little resources of their own will not be the main problem; adequacy of the resource base remains to be the primary issue.

(6) When Th/U hybrids with low blanket multiplication are coupled to denaturated light or heavy water reactors, a relatively small hybird capacity will be required because of their high support ratio. Hybrids and tritium producers may be placed within secure boundaries while the supported converters would be available to countries which need them. The minimum outside/inside ratio obtained in these scenarios ranges from 7.7 to 10.0 for LWRDs and HWRDs, respectively.

When the above conclusions are coupled with the current status of fusion research and projected progress milestones, one cannot escape the conclusion that the development and deployment of hybrids does not diminish or eliminate the need for fast breeders.

V. ACKNOWLEDGEMENTS

We acknowledge with thanks, discussions with members of the Fusion Engineering Program at the University of Wisconsin, particularly those with Professors R. W. Conn and G. L. Kulcinski. Mr. C. Broeders of the Nuclear Research Center in Karlsruhe has conducted studies on tritium production in LMFBR-type reactors; we are grateful for that information.

VI. REFERENCES

1. International Nuclear Fuel Cycle Evaluation (INFCE) Working Group V on Fast Breeders, Final Report, IAEA Vienna 1980

2. W. Häfele, "World Energy Resources, Demand and Supply of Energy and the Prospects for the Fast Breeder," International Symposium on Design, Construction and Operating Experience with Demonstration Liquid Metal Fast Breeder Reactors, IAEA-SM-225/71, Bologna, Italy (April 1978).

3. H.H. Hennies, P. Jansen, and G. Kessler, "A West German Perspective of the Need for the Plutonium-Fueled LMFBR," Nuclear News, pp. 69-76 (June 1979).

4. H.A. Feiveson and T.B. Taylor, "Security Implications of Alternative Fission Futures," Bulletin of Atomic Scientists, 31, 10 (December 1976).

5. H.A. Bethe, "The Fusion Hybrid," Nuclear News, pp. 41-44 (May 1978).

6. E. Teller, "Fission or Fusion?," ANS Trans., 33, 214 (November 1979).

7. J.A. Maniscalco, "Fusion-Fission Hybrid Concepts for Laser-Induced Fusion," Nuclear Technology, 28, 98 (January 1976).

8. P. Fortescue, "Comparative Breeding Characteristics of Fusion and Fast Reactors," Science, 196, 1326-1329 (June 1977).

9. J.A. Maniscalco, L.F. Hansen, and W.O. Allen, "Scoping Studies of ^{233}U Breeding Fusion-Fission Hybrid," Proc. Third ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, CONF-780508, Vol. 1, pp. 159-169, Santa Fe (May 1978).

10. S.I. Abdel-Khalik, "Coupling Between Fusion-Fission Hybrids and the Fission Industry," Proc. Third US/USSR Symposium on Fusion-Fission Hybrids, Princeton (January 1979).

11. R.W. Conn, S.I. Abdel-Khalik, G.A. Moses, et al., "SOLASE-H, a Laser Fusion Hybrid Study," UWFDM-270, University of Wisconsin (May 1979).

12. M.H. Ragheb, S.I. Abdel-Khalik, M. Youssef, and C.W. Maynard, "Lattice Calculations and Three-Dimensional Effects in a Laser Fusion-Fission Reactor," Nuclear Technology, 45 (2), 140-152 (1979).

13. J.D. Lee, "Nuclear Design of the LLL-GA U_3Si Blanket," Proc. Third ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, CONF-780508, Vol. 1, 219, Santa Fe (May 1978).

14. D.L. Chapin, et al., "Evaluation of Potential Blanket Concepts for a Demonstration Tokamak Hybrid Reactor," Proc. Third Topical Meeting on the Technology of Controlled Nuclear Fusion, CONF-780508, Vol.1, 230, Santa Fe (May 1978).

15. F.H. Tenney, et al., "A Systems Study of Fusion-Fission Reactors," Princeton Plasma Physics Laboratory, PPPL-1450, (Nov. 1978).

16. R.W. Moir, et al., "Interim Report on the Tandem Mirror Hybrid Study," UCID-18078, Lawrence Livermore Laboratory, (Aug. 1979).

17. P. Klumpp, "Die Bedeutung von Leichtwasserreaktor - Hochkonvertern für den Natururanbedarf der Bundesrepublik Deutschland - Analyse möglicher Strategien des Übergangs von Leichtwasserreaktoren zu Schnellen Brütern," Diplomarbeit, University of Karlsruhe (March 1979).

18. C. Marchetti, N. Nakicenovic, "The Dynamics of Energy Systems and the Logistic Substitution Model", RR-79-13, IIASA, Austria (December 1979)

19. C. Broeders, unpublished results

20. J.L. Crandall (Compiler), "The Savannah River High Flux Demonstration," DP-999, E.I. DuPont (June 1965); See also: T.B. Rhinehammer and L.J. Wittenberg, MLM-2419, Monsanto (Oct. 1978).

21. OECD/IAEA, "World Uranium Potential - An International Evaluation," OECD Report (Dec. 1978).

TABLE 1

Forecasts of World Nuclear Capacity [16]

Source	Date	Capacity at year's end, GWe	
		Year 2000	Year 2010
EIA	Oct. 1978	700-850-1050	970-1180-1450
INFCE	Oct. 1978	831-1207	1150-1670
AECL/WEC	July 1978	1142	1580
ERG/WEC	July 1978	967-1284	1340-1780
OECD/IAEA	Dec. 1977	1000-1890	1380-2620
WAES	May 1977	913-1772	1260-2450

TABLE 2

World Nuclear Demand Projection Used in this Study*

Year	Capacity (GWe)	Year	Capacity (GWe)	Year	Capacity (GWe)
1980	145	2015	1475	2050	2550
1985	245	2020	1650	2055	2700
1990	375	2025	1795	2060	2850
1995	550	2030	1950	2065	3000
2000	830	2035	2100	2070	3150
2005	1080	2040	2250	2075	3300
2010	1295	2045	2400		

---

*Centrally Planned Economy Areas Not Included.

TABLE 3 Design Parameters for (1 GWe) Light and Heavy Water Reactors [1]

Parameter	LWR				HWR
	Once-Through	Uranium Recycle	Pu Burner	Denatured	Denatured
Discharge Burnup, MWd/kg	33	33	33	35	16
Conversion Ratio	0.59	0.60	0.71	0.78	0.93
Initial Core Loading Per GWe					
kg ^{233}U	0	0	0	1582	1648
kg ^{235}U	1800	1800	153	24	24
kg Fissile Pu	0	0	2147	0	0
kg Total Heavy Metal	79700	79700	79700	79700	113000
Equilibrium Annual Loading$^{(a)}$					
kg ^{233}U	0	0	0	722	831
kg ^{235}U	804	804	50	62	52
kg Fissile Pu	0	0	1003	0	0
kg Heavy Metal	25100	25100	25100	23500	56100
MT U$^{(b)}$	148	148	0	0	0
MT SWU$^{(b)}$	119	119	0	0	0
Equilibrium Annual Discharge$^{(a)}$					
Per GWe-yr$^{(a)}$					
kg ^{233}U	-	0	0	435	729
kg ^{235}U	-	216	27	62	52
kg Fissile Pu	-	163	646	57	32
kg Heavy Metal	-	24300	24300	22700	55200
MT U$^{(b)}$	-	33	0	0	0
MT SWU$^{(b)}$	-	6	0	0	0
Lifetime Requirements$^{(c)}$					
kg ^{233}U	-	0	0	8970	3540
kg Fissile Pu	-	-4830	11200	-1690	-944
MT U$^{(b)}$	4470	3490	0	0	0
MT SWU$^{(b)}$	3610	3450	0	0	0

[a] Assumed 75% capacity factor

[b] Assumed 0.2% tails assay

[c] 30-year requirements adjusted by end-of-life credit and by 1% not immediately recoverable material each in fabrication and reprocessing.

TABLE 4 Design Parameters for (1 GWe) Breeders and Pu High Converters

	Breeders		
	FBR	FBRT(a)	HC
Breeding (Conversion) Ratio	1.32	1.0(b)	0.95
Initial Core Loading Per GWe			
kg Fissile Plutonium	3158	3200	8300
kg Total Heavy Metal	90,000	90,000	84,000
Equilibrium Annual Loading(c)			
kg Fissile Plutonium	1481	1500	1400
kg Heavy Metal	32,000	32,000	14,000
Equilibrium Annual Discharge(c)			
kg Fissile Plutonium	1694	1500	1345
kg Heavy Metal	31,200	31,200	13,200
kg Tritium	0	2.0	0
Net Annual Gain(c)			
kg Fissile Plutonium	213		
kg Tritium		2	

---

[a] Additional details may be found in Reference [19].

[b] Does not account for tritium breeding.

[c] Assumed 70% capacity factor.

TABLE 5 Design Parameters for Power-Producing (1GWe) Savannah-River-Type Reactors

Initial Core Loading Per GWe Natural Uranium Equivalent (Ton)	612
Equilibrium Annual Loading (b) Natural Uranium Equivalent (Ton)	164
Annual Tritium Production (kg) (b)	9.0 (c)

---

[a] An overall thermal efficiency of 32% is assumed.

[b] Based on 70% capacity factor.

[c] Corresponds to 4.1 kg/GWt-year of full time operation (for more details see [20]).

TABLE 6: Market Penetration Constraints

MAXIMUM ALLOWABLE CAPACITIES (GWe) TO BE BUILT WITHIN EACH 5-YEAR PERIOD*

PERIOD	Introduction Date = 2000			Introduction Date = 2020		
	A	B	C	A	B	C
2000-05	82	7	12	-	-	-
05-10	143	10	12	-	-	-
10-15	∞	15	18	-	-	-
15-20		22	18	-	-	-
20-25		31	23	50	8	23
25-30		46	23	100	13	23
30-35		71	47	∞	19	35
35-40		100	60		27	48
40-45		139	78		40	60
45-50		186	91		57	73
50-55		240	109		88	109
55-60		303	122		123	122
60-65		364	150		168	159
65-70		423	185		223	185
70-75		476	216		287	216

---

[*] Figures include replacement of decommissioned reactors. A 30-year reactor life is assumed.

TABLE 7

Uranium Resources Outside Centrally Planned Economy Areas, MT U (from [1])

Cost of recovery ($/kgU)	Type of resources		
	Reasonably Assured Resources	Estimated Additional Resources	Speculative Resources
less than 80 $/kgU	1.73 (reserves)	1.47	} 6.6 - 14.8
80-130 $/kgU	0.63	0.82	

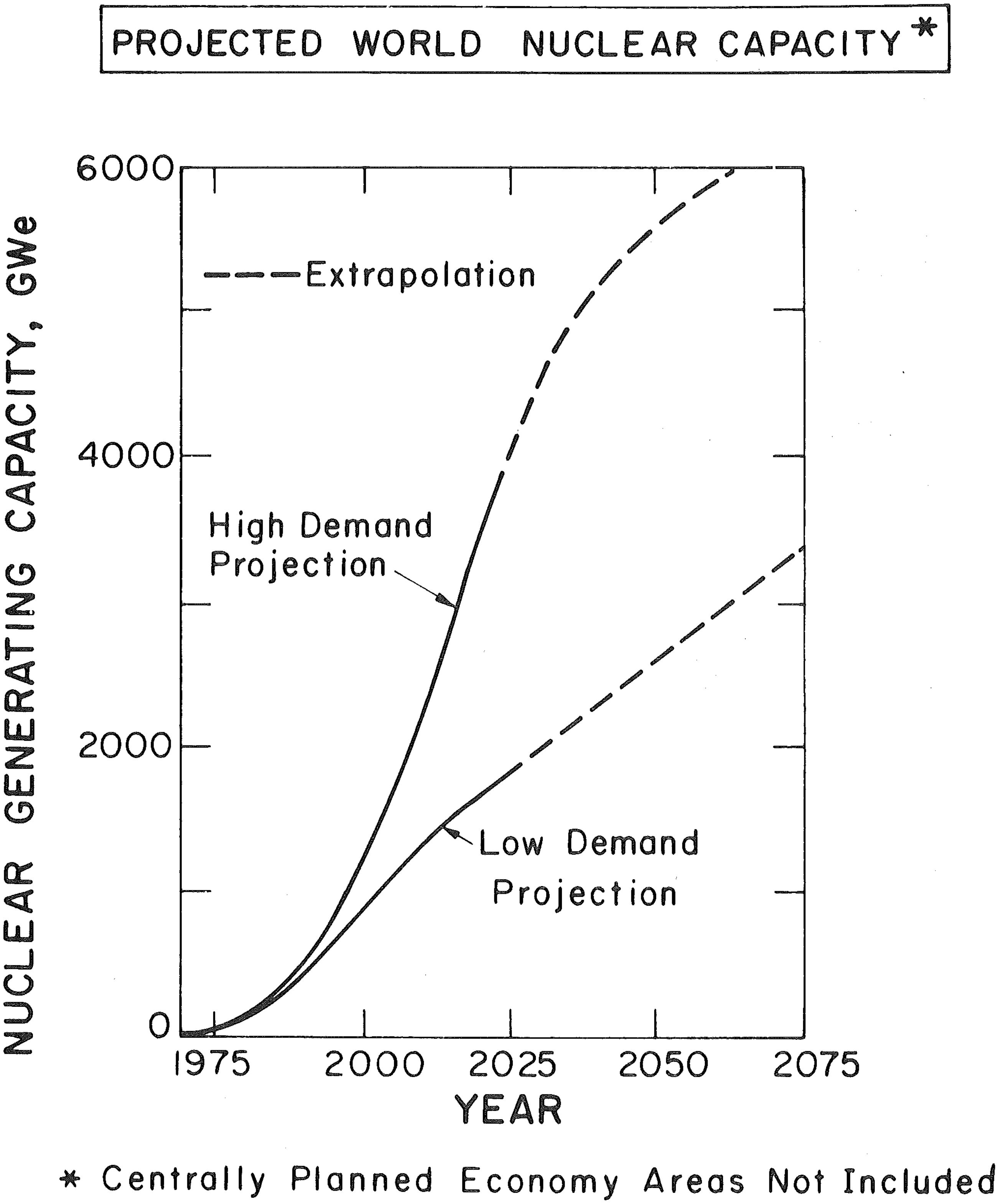

Figure 1. Projected World Nuclear Capacity [1]. The Low Demand Projection has been used in this Study.

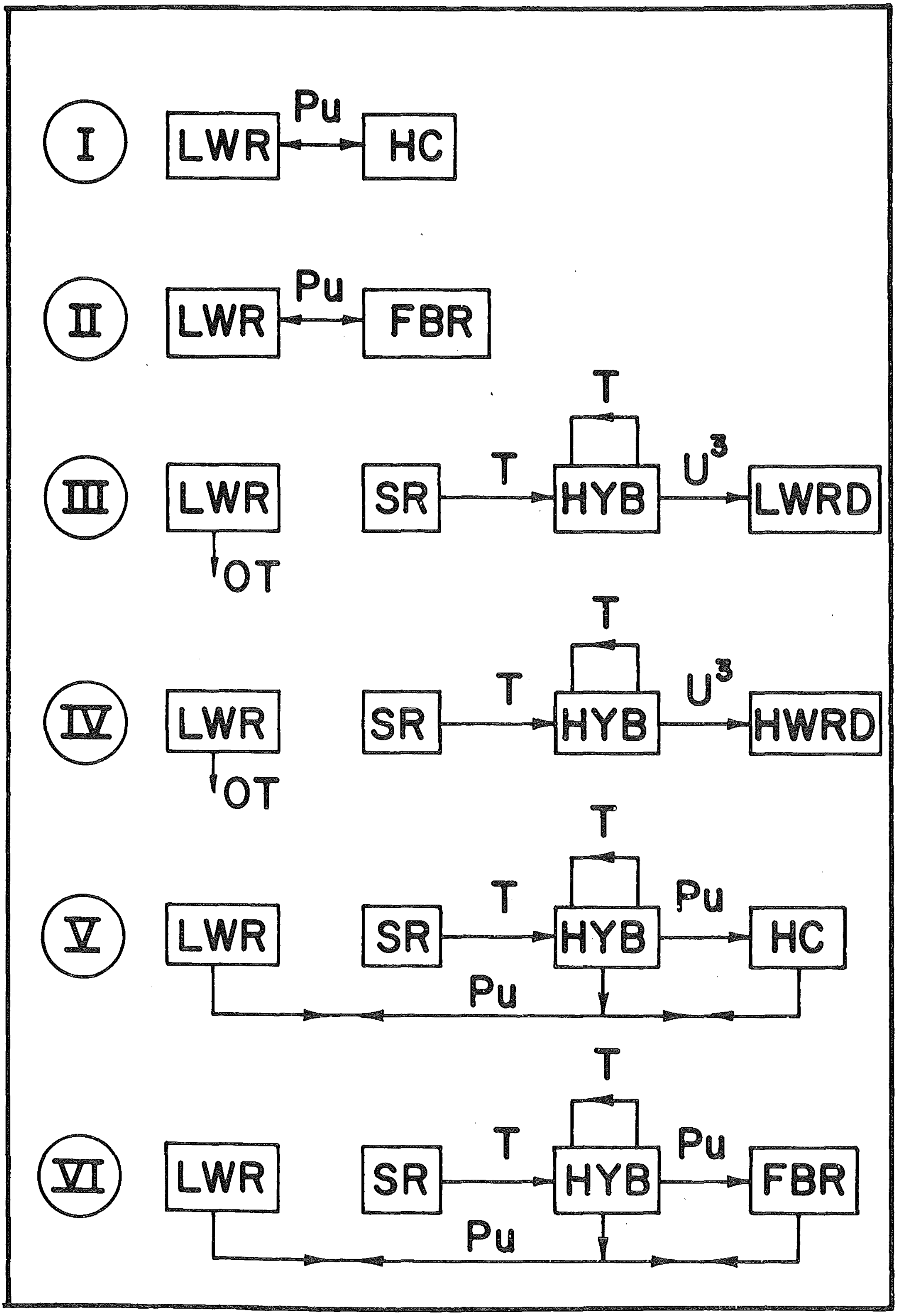

Figure 2. Schematic Diagram of the different Scenarios Examined in this Study.

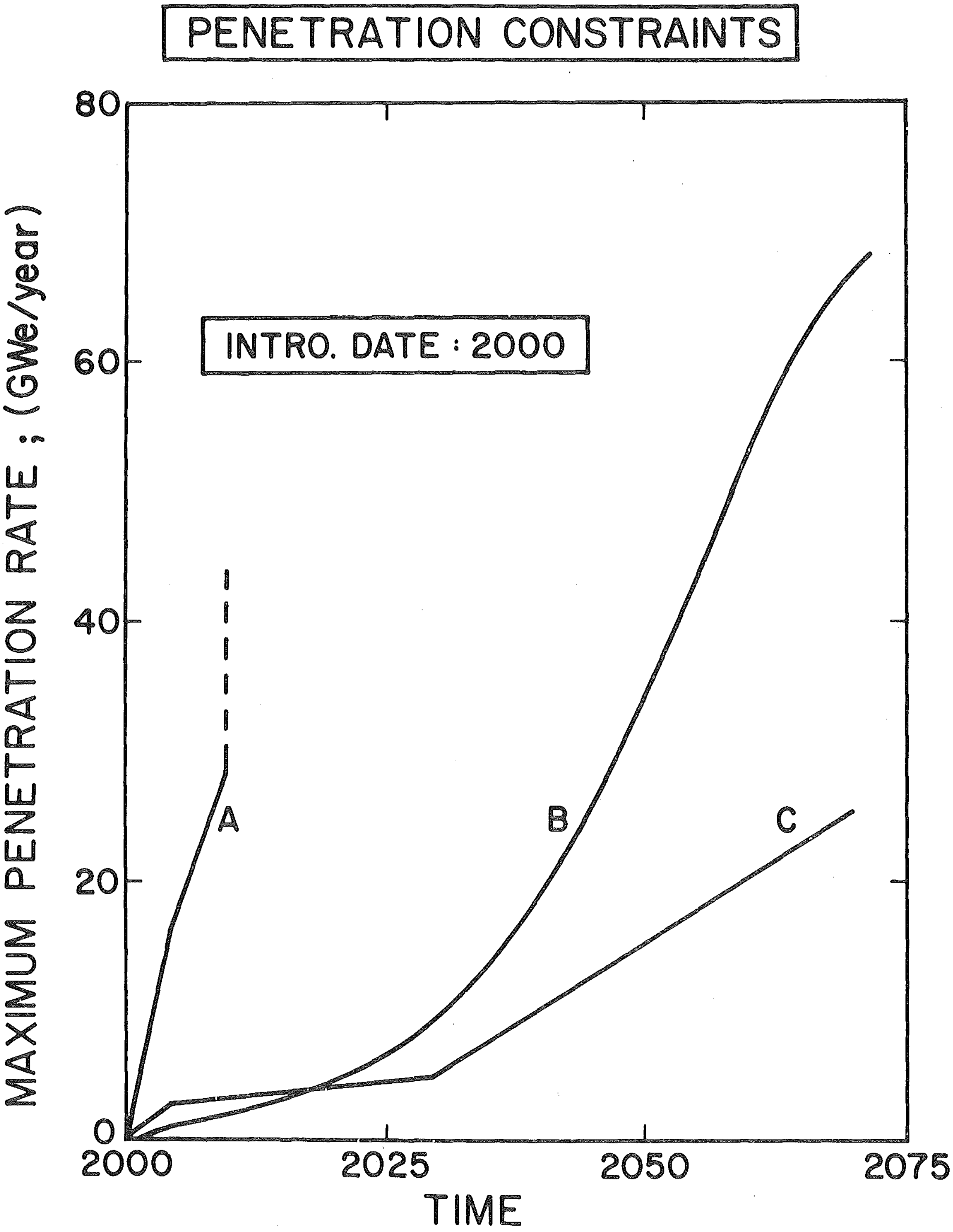

Figure 3. Market Penetration Constraints for an Introduction Date of 2000.

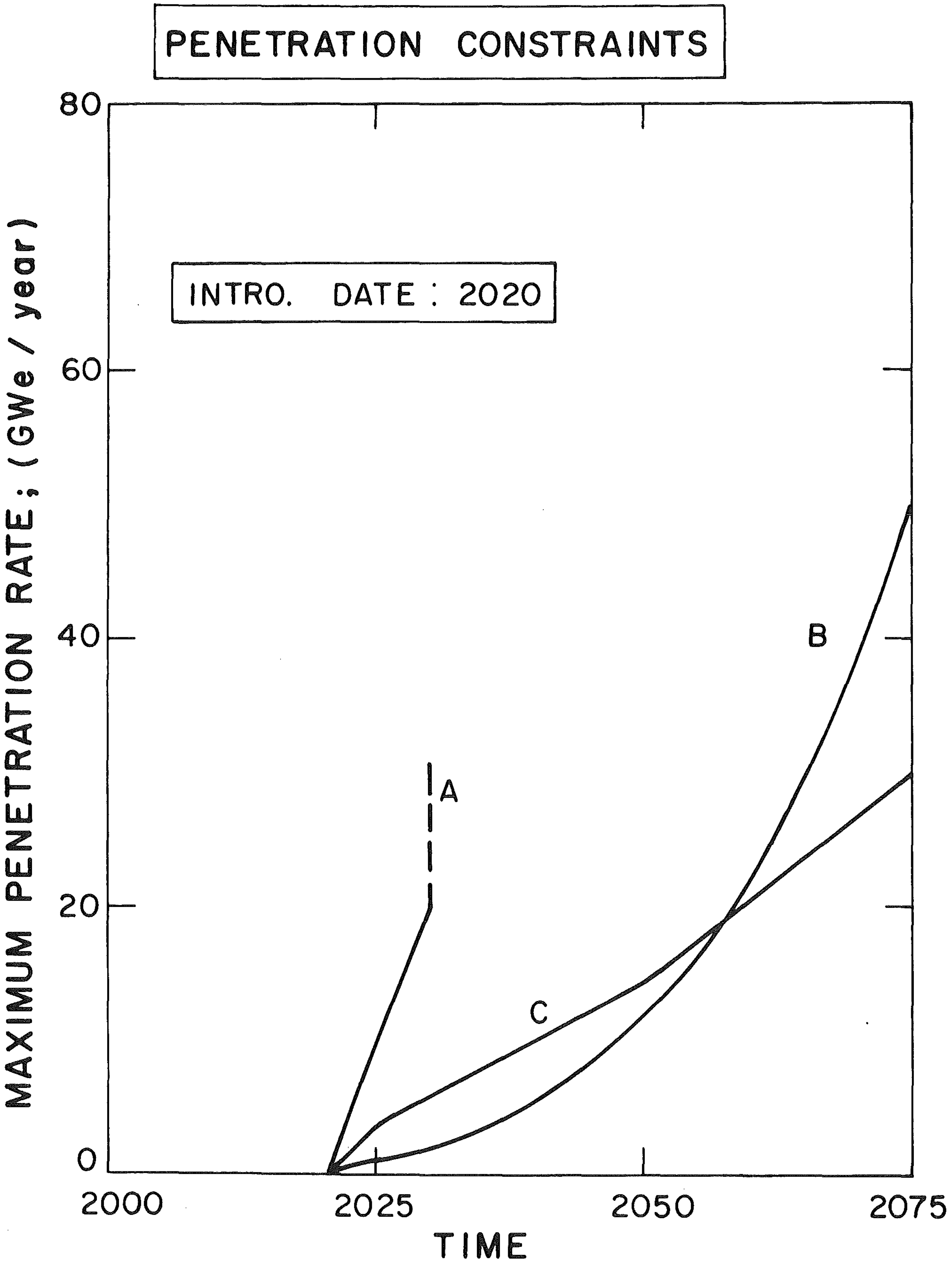

Figure 4. Market Penetration Constraints for an Introduction Date of 2020.

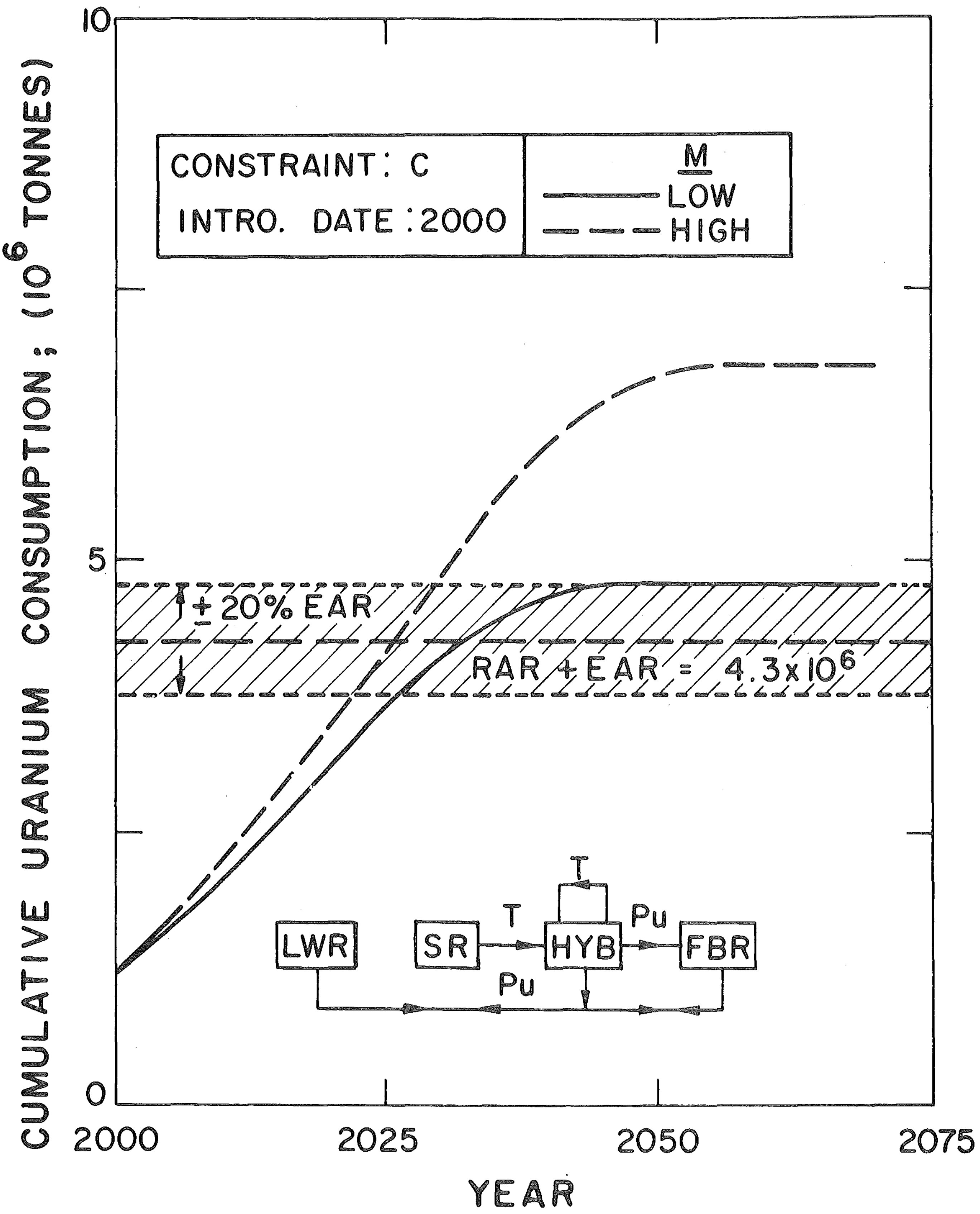

Figure 5. Variation of the Cumulative Uranium Consumption with Time for Scenario VI with High and Low Blanket Multiplication.

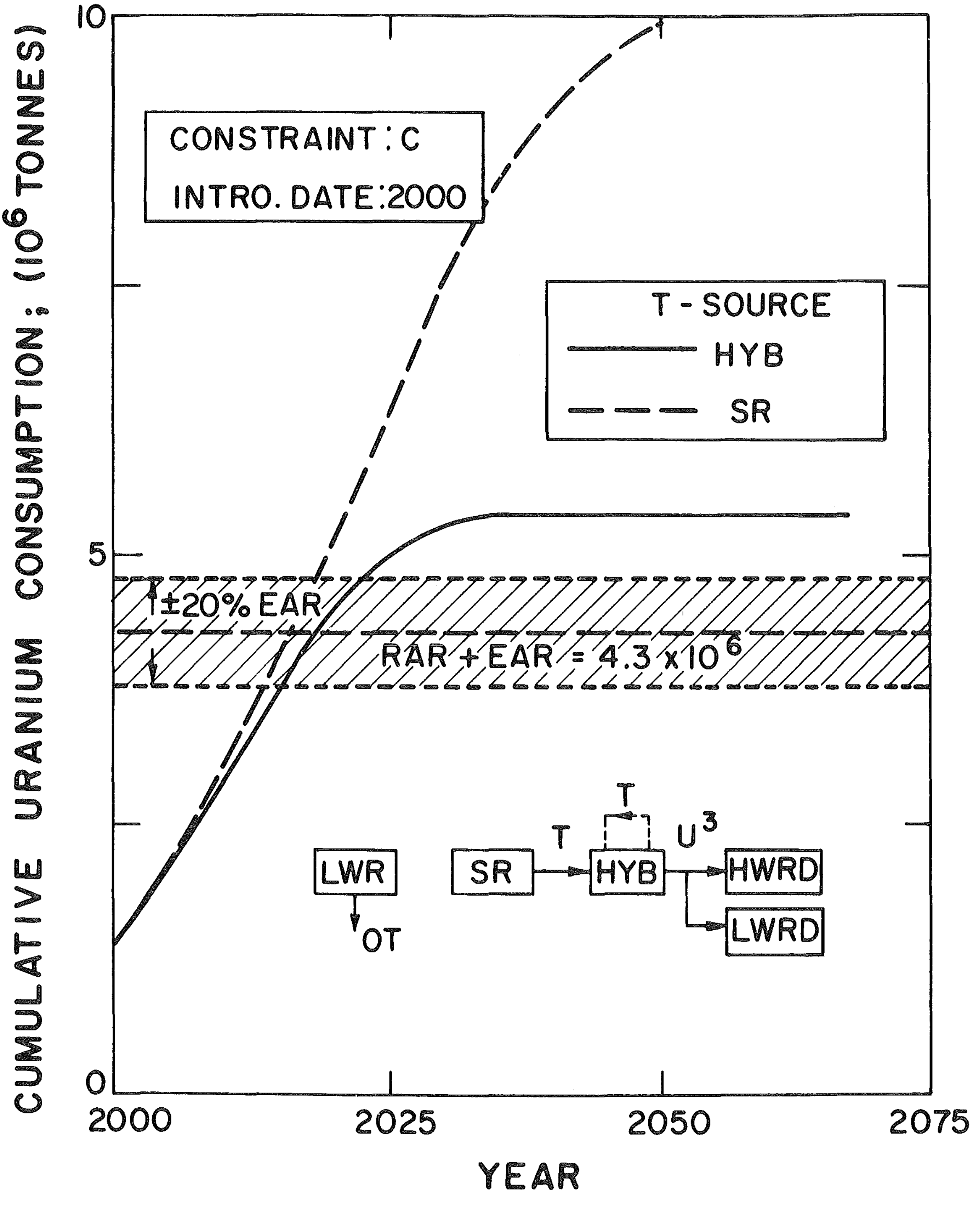

Figure 6. Variation of the Cumulative Uranium Consumption with Time for Scenario IV with and without Tritium Breeding in the Hybrid.

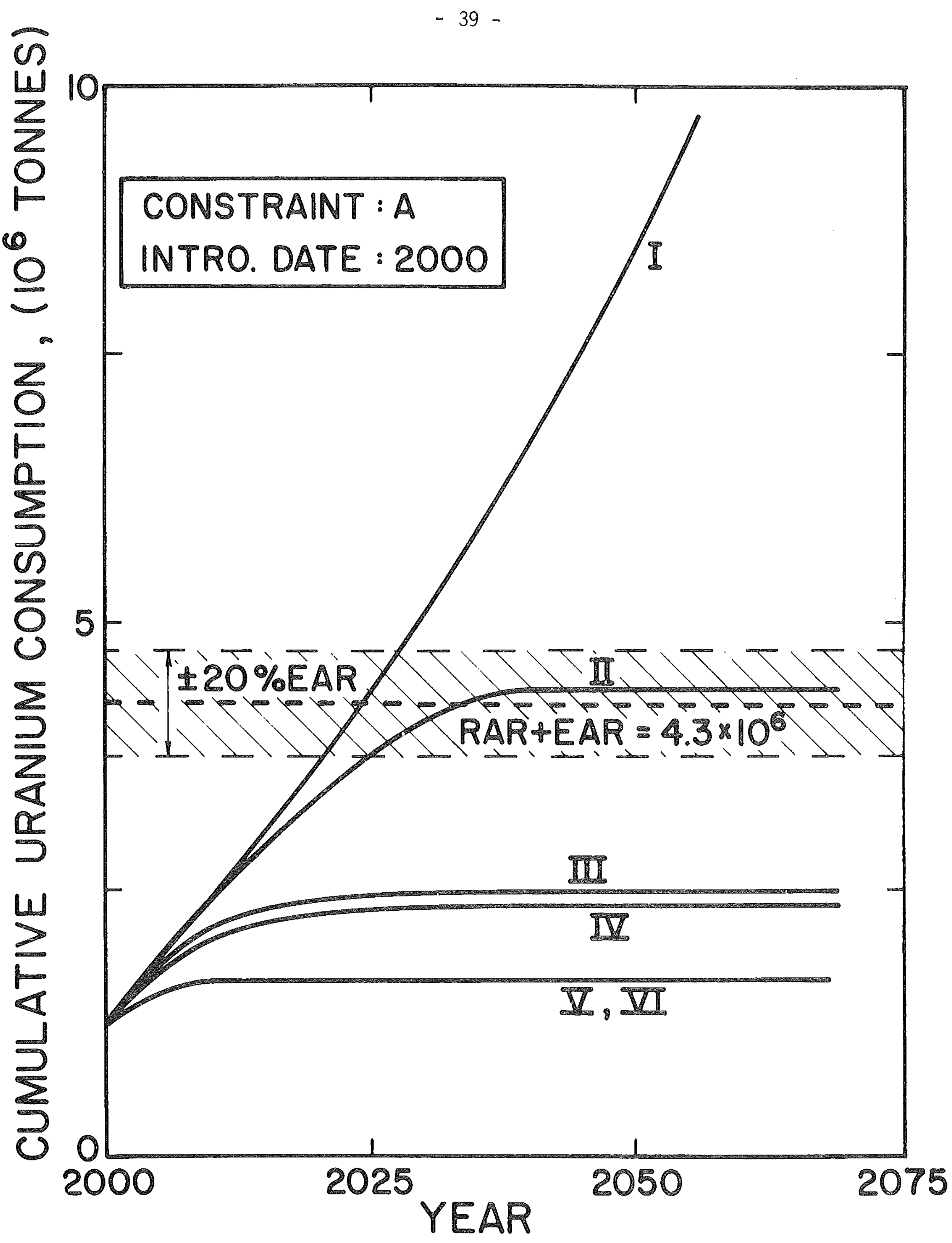

Figure 7. Variation of Cumulative Uranium Consumption with Time for the Different Scenarios shown in Fig. 2. (These represent the lowest possible values since Constraint A is used with introduction date of 2000).

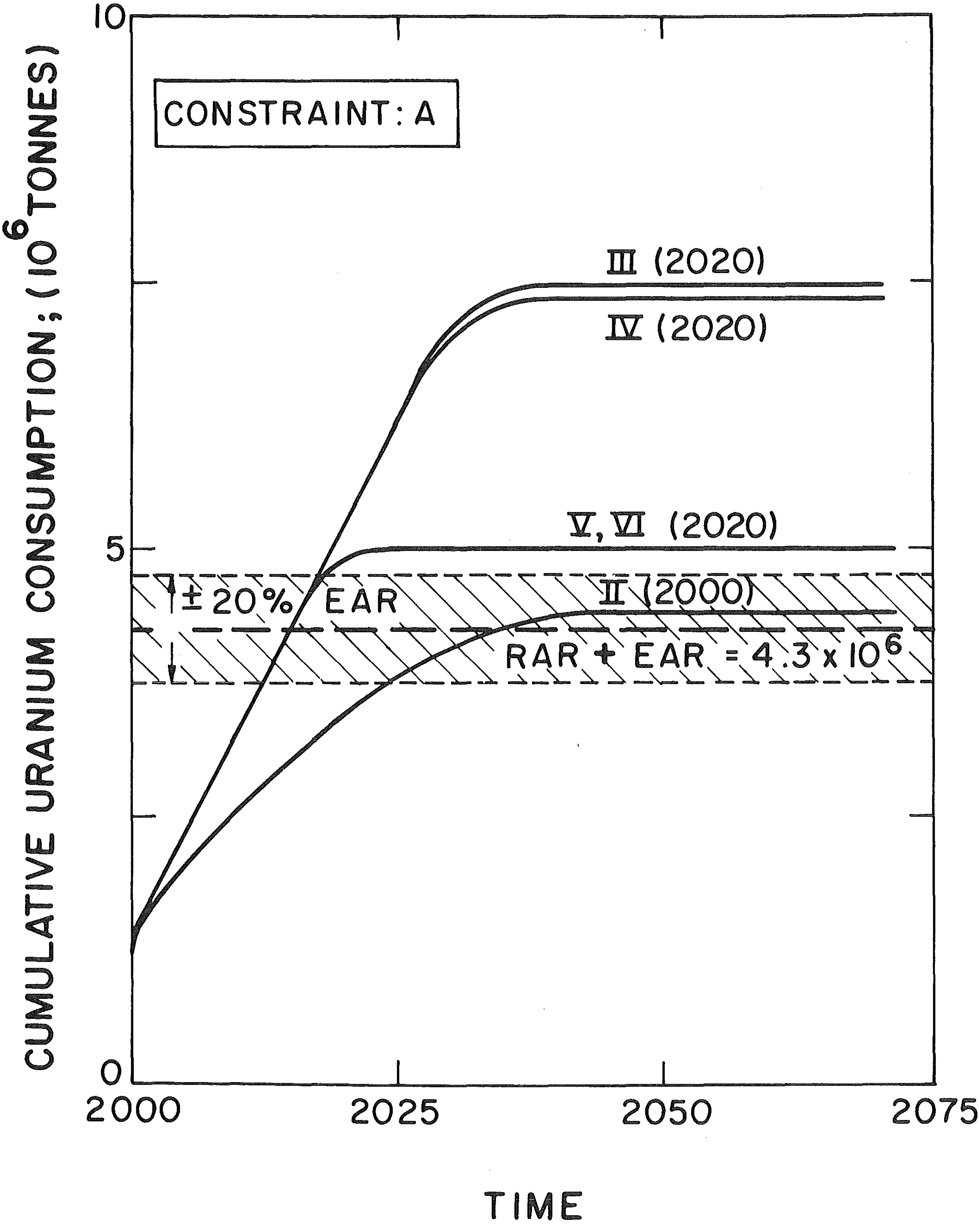

Figure 8. Comparison Between Breeder Scenario II and Hybrid Scenarios III-VI for Constraint A with Introduction Dates of 2000 and 2020 Respectively.

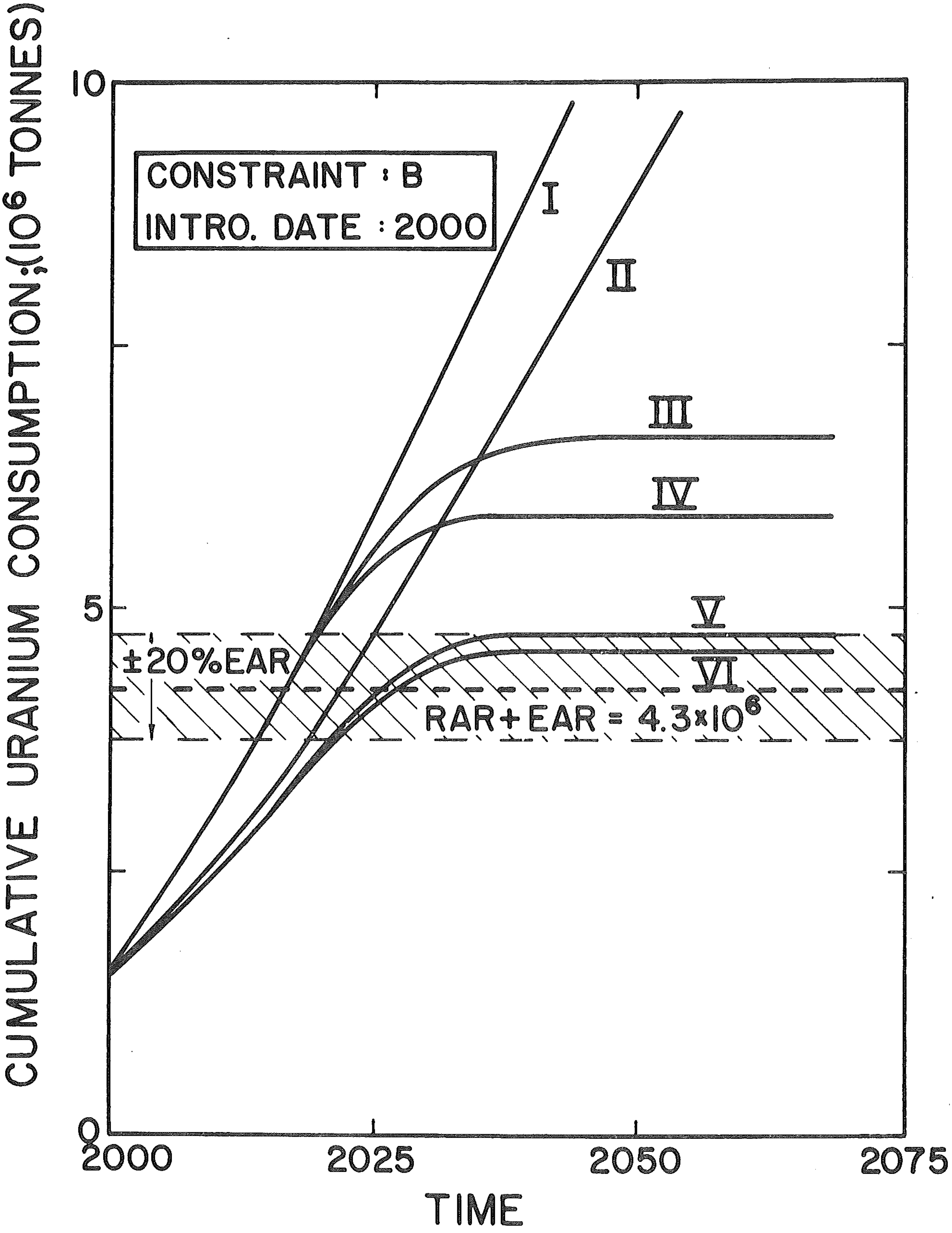

Figure 9. Cumulative uranium consumption for the different scenarios shown in Fig. 2 for realistic market penetration constraints (B) with Introduction Date = 2000.

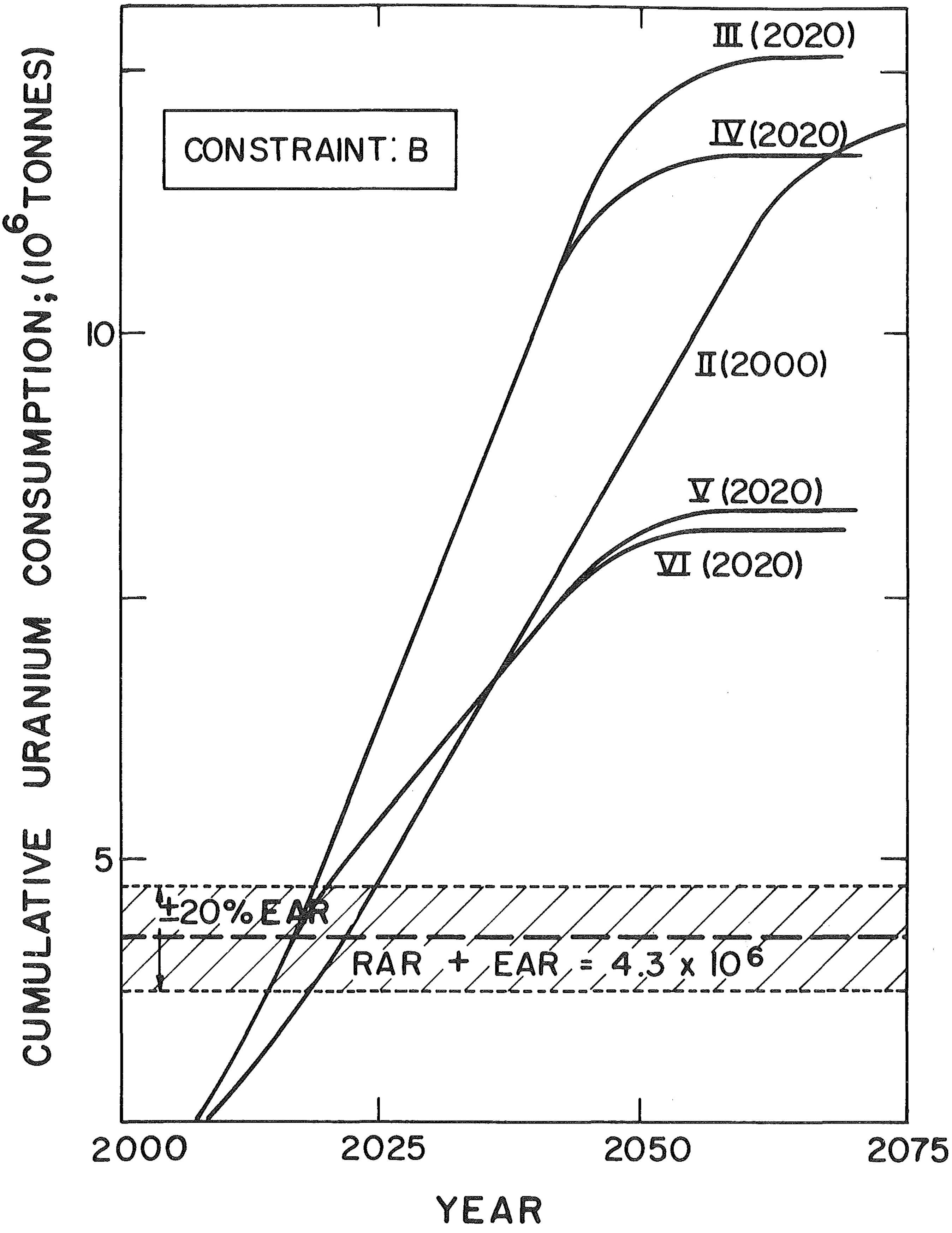

Figure 10. Results Similar to Those in Fig. 8. for Market Penetration Constraint B.

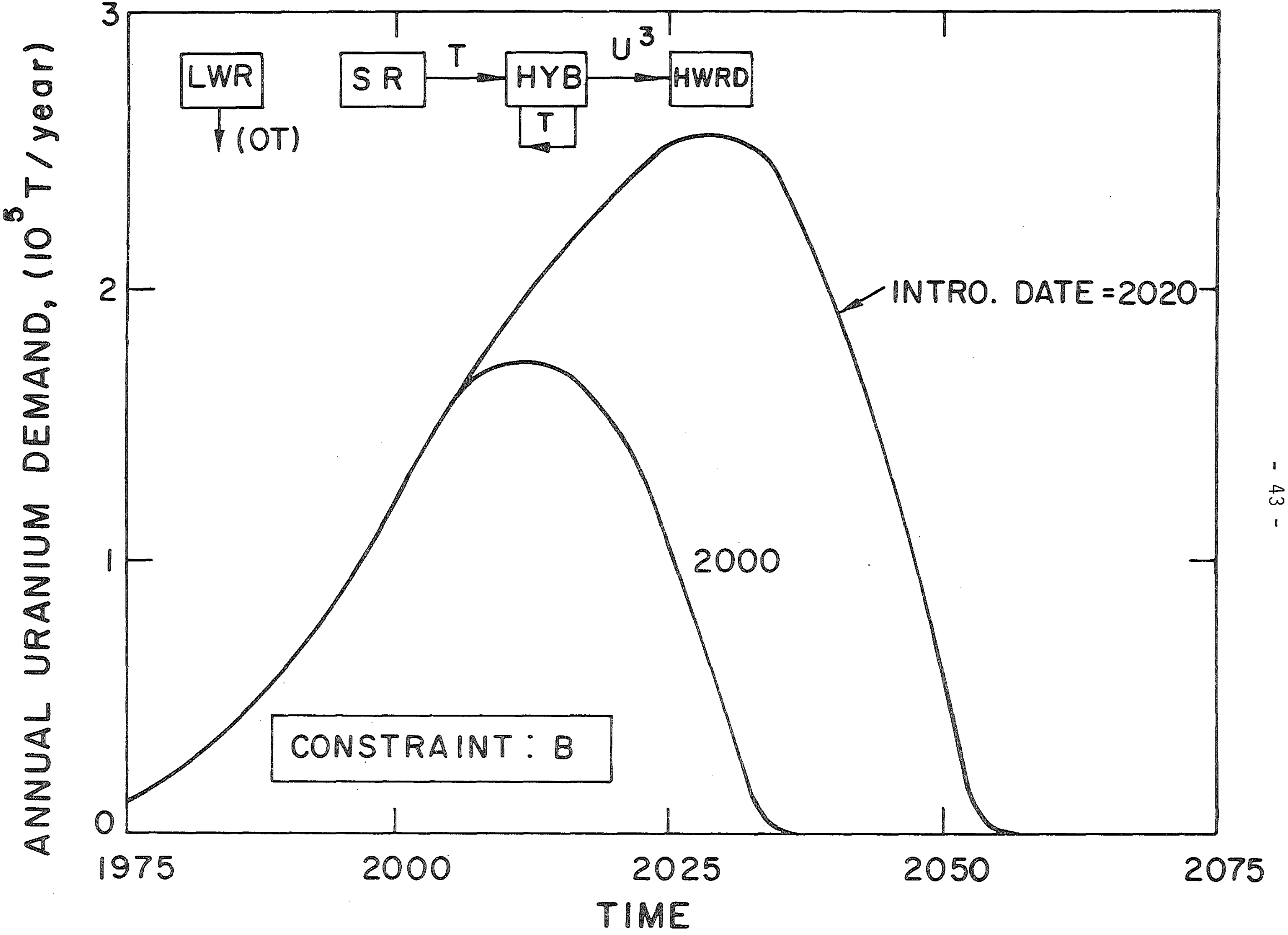

Figure 11. Variation of Annual Uranium Demand with Time for Scenario IV for Hybrid Introduction Dates of 2000 and 2020. (Market Penetration Constraint B has been used.)

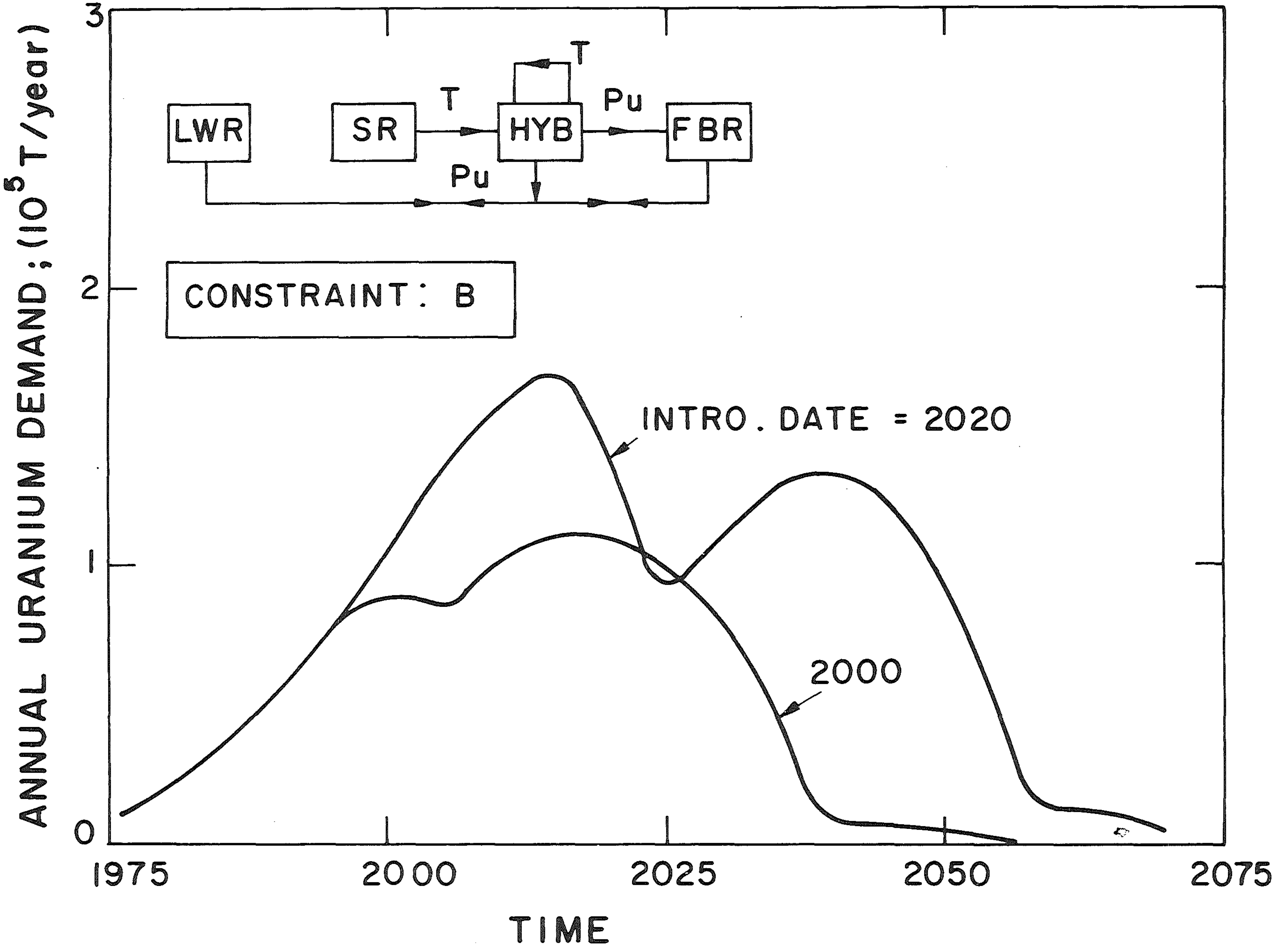

Figure 12. Variation of Annual Uranium Demand with Time for Scenario VI for Simultaneous Introduction of Hybrids and Breeders in 2000 and 2020 (Market Penetration Constraint B has been used).

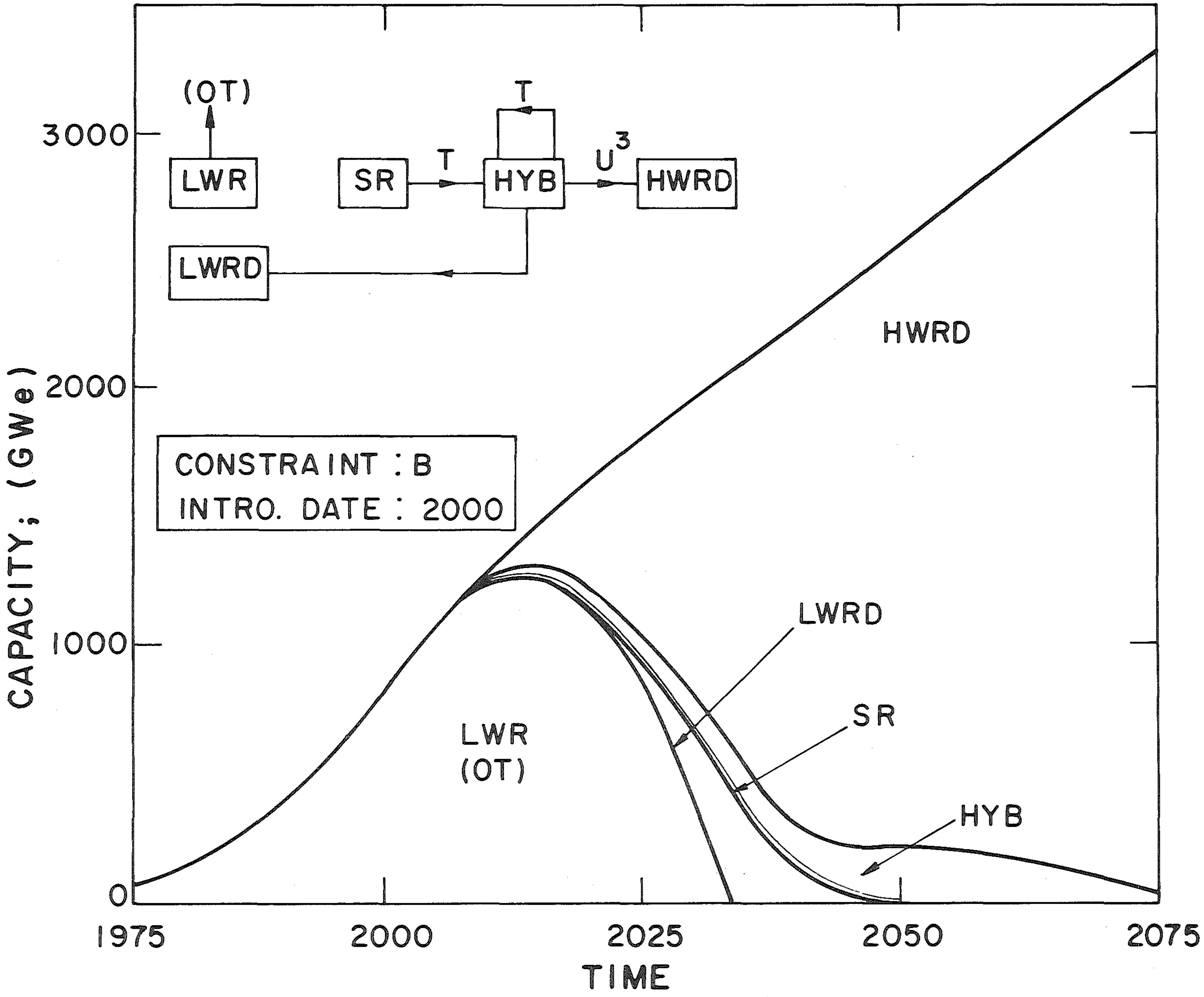

Figure 13. Optimum Time-Dependent Shares of Different Reactor Types for Scenario IV. (The SR region has been slightly exaggerated.)

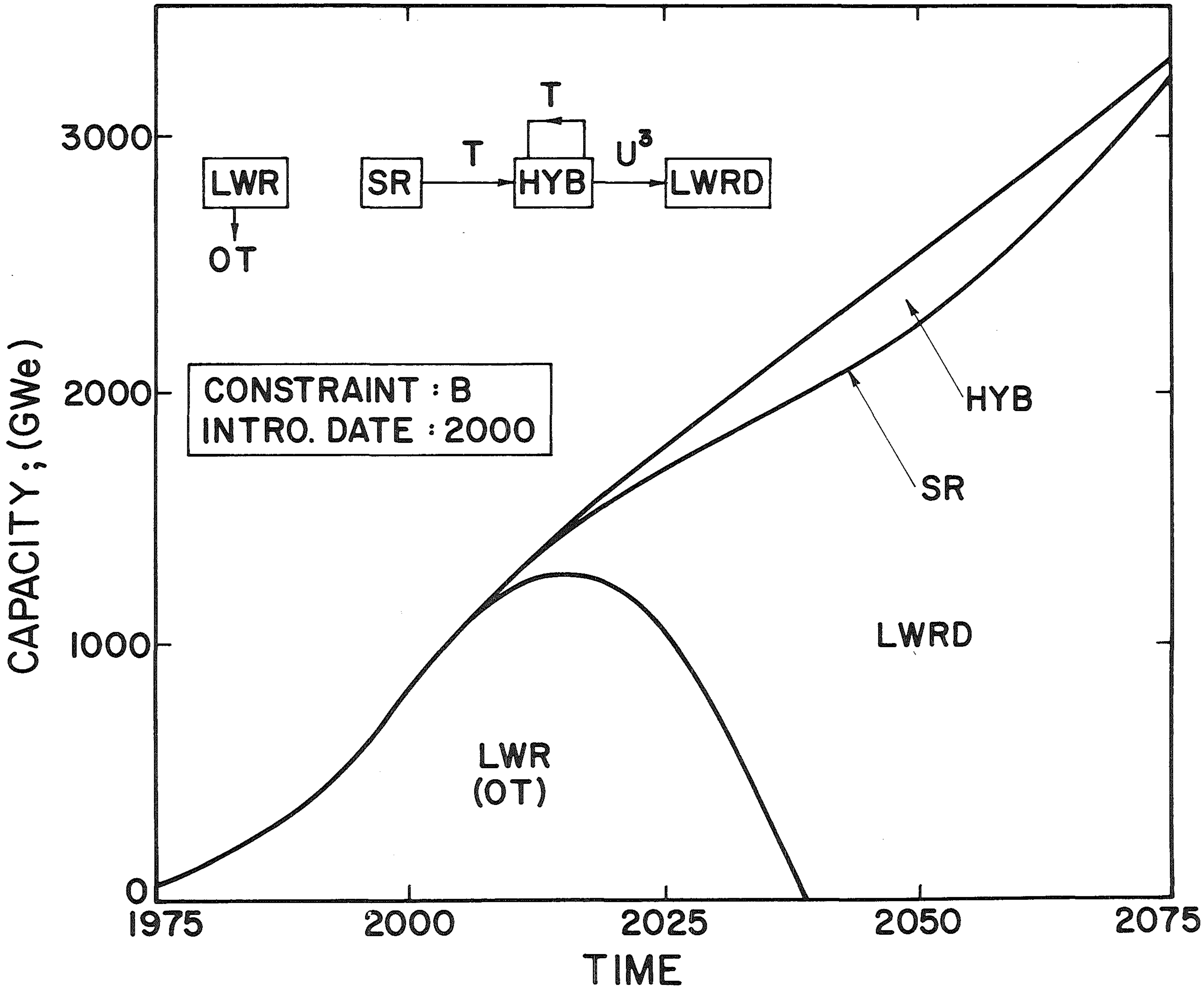

Figure 14. Optimum Time-Dependent Shares of Different Reactor Types for Scenario III. Hybrids are introduced in year 2000 with Constraint B.

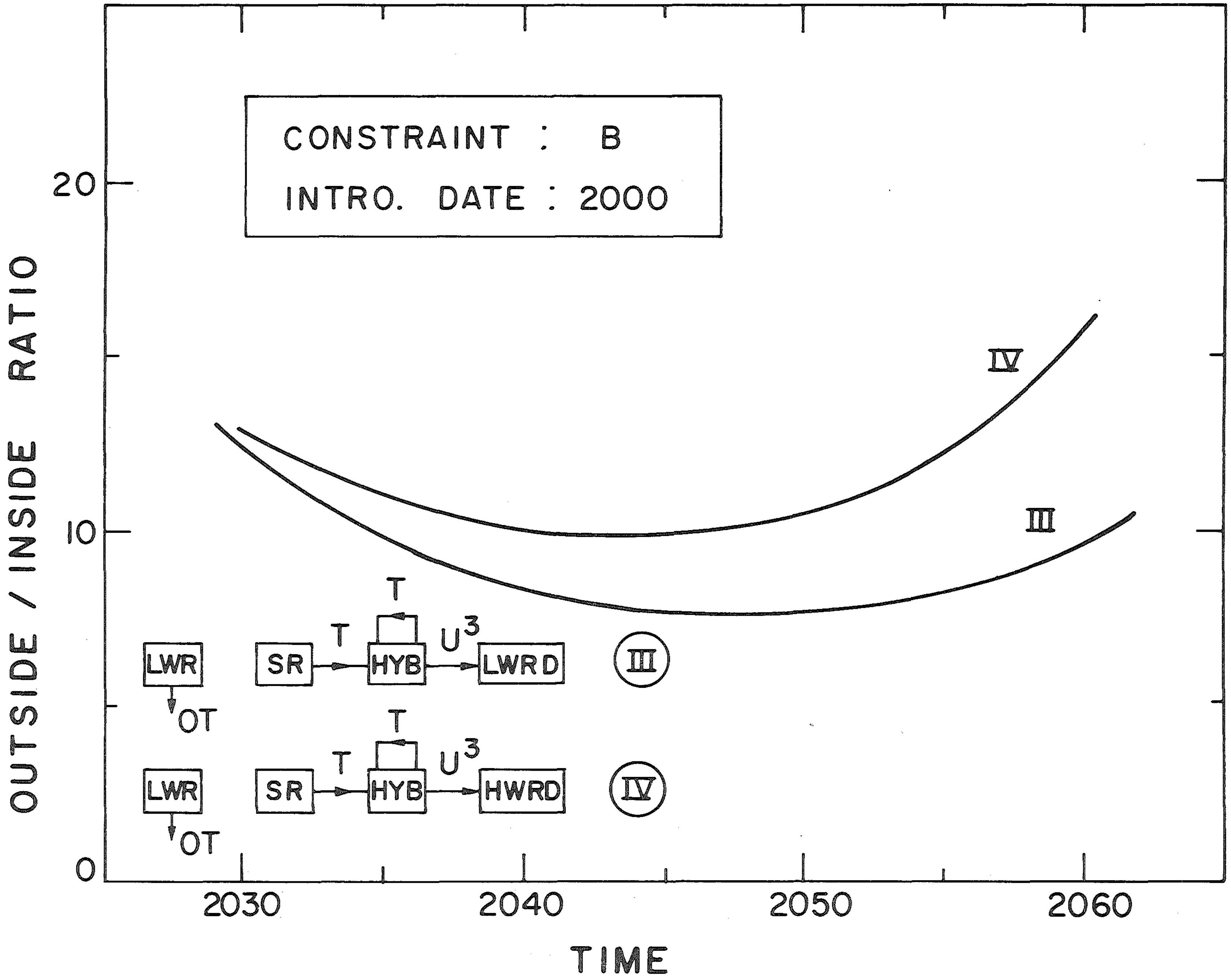

Figure 15. Variation of the outside/inside ratio with time for scenarios III and IV. (Outside = HYB+SR; Inside = all others.) These results correspond to those shown in Figs. 13 and 14.

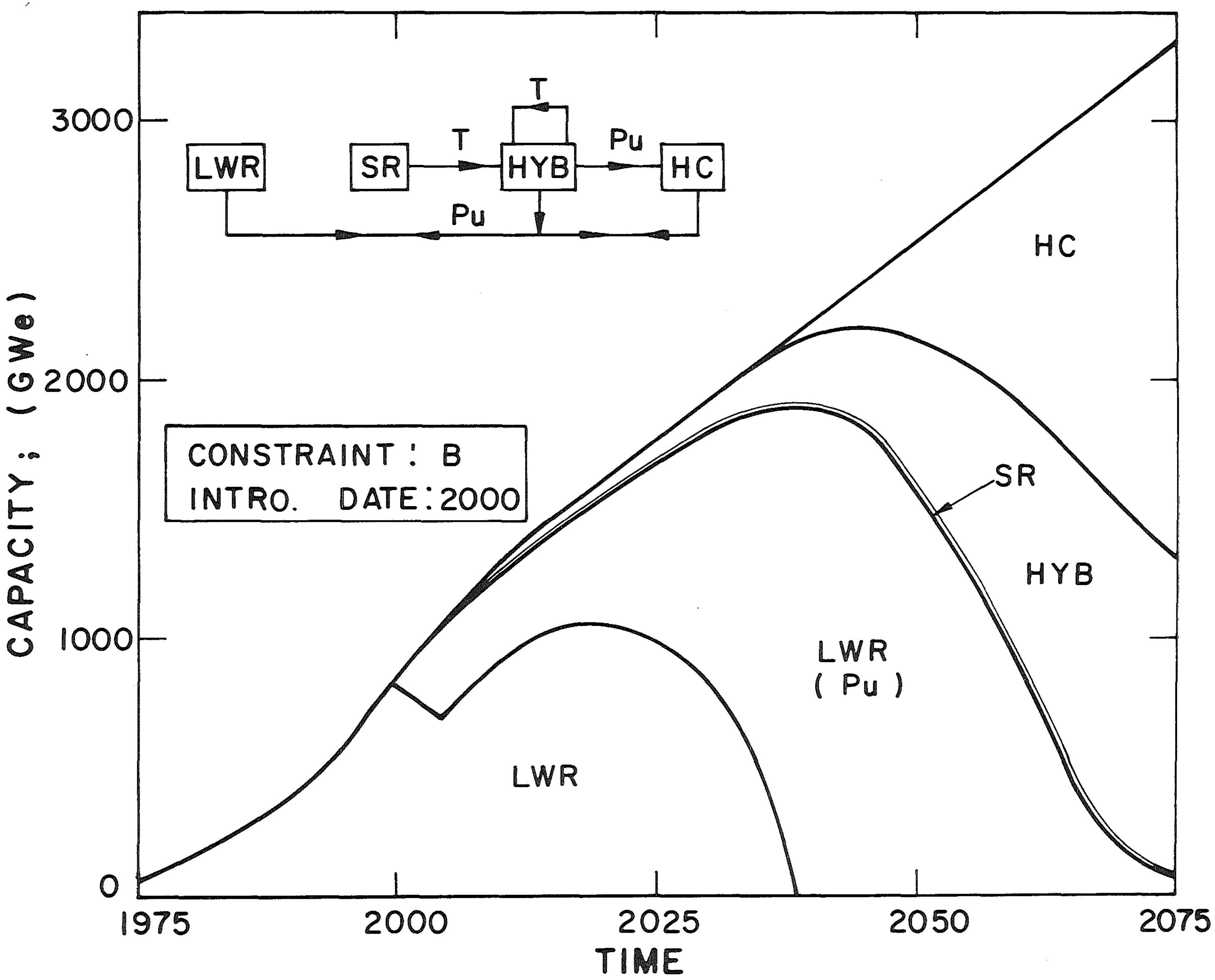

Figure 16. Optimum Time-Dependent Shares of Different Reactor Types for Scenario V. Hybrids are introduced in year 2000 with Constraint B.

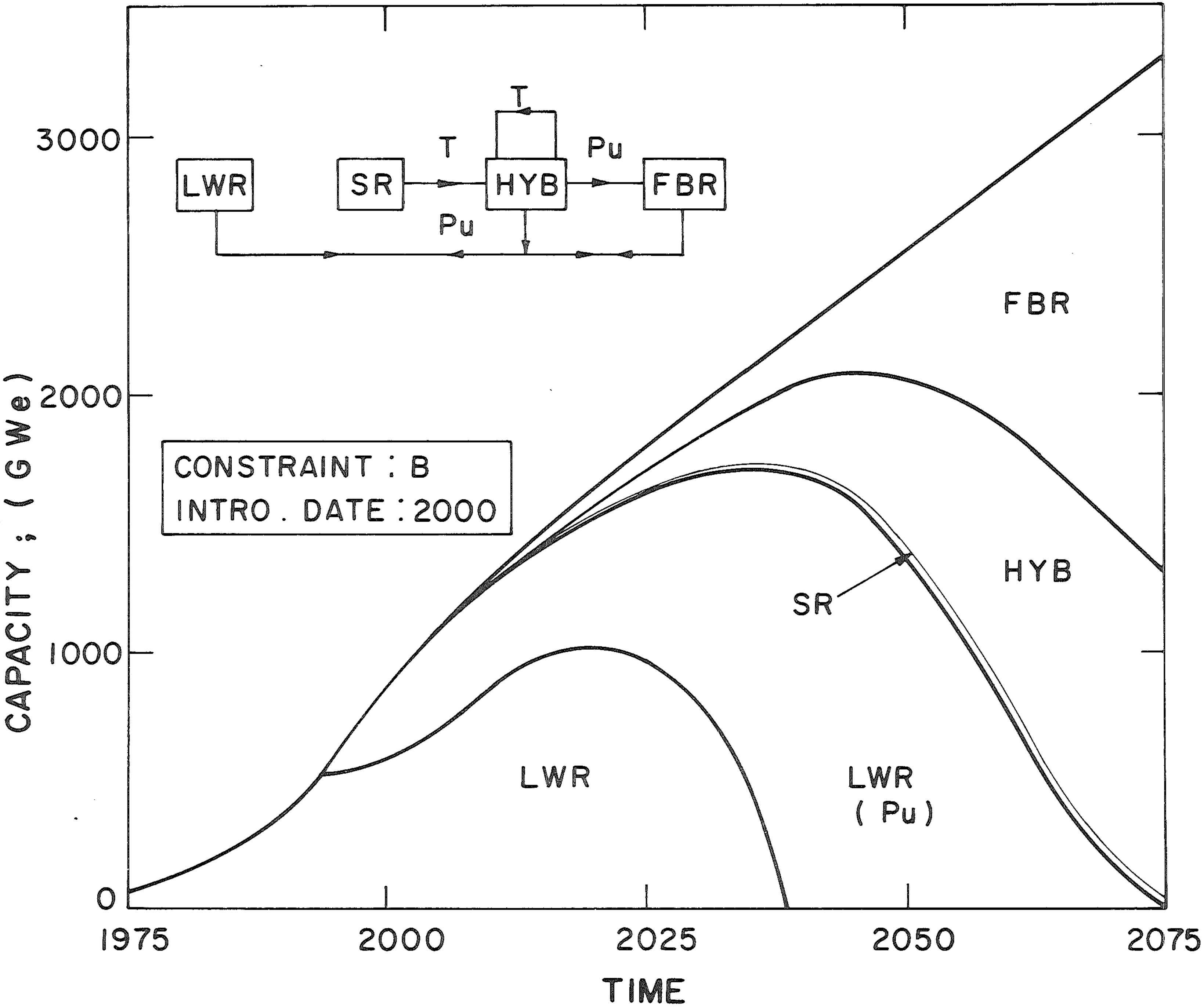

Figure 17. Optimum Time-Dependent Shares of Different Reactor Types for Scenario VI. Hybrids and Breeders are Introduced in Year 2000 with Constraint B.

APPENDIX A

HYBRID DESIGN PARAMETERS

In order to determine the preferred hybrid concept from a resource viewpoint, four hybrid designs have been examined for each of the Th/U and U/Pu cycles. These designs correspond to whether the hybrid is primarily a fuel or power producer (i.e., low or high blanket energy multiplication) and whether or not the hybrid breeds its own tritium. The main design parameters for these eight hybrid designs are given in Tables A-1 through A-4. These parameters are based on numerous neutronic calculations reported in the literature [9-15]. The hybrid fissile breeding rates used in this study represent upper bounds on the values reported in the literature, and therefore, the estimated cumulative uranium consumption figures are optimistically low.

The data given in Tables A-1 through A-4 are normalized to 1 GW of fusion power; they may however be renormalized to any reactor size using the intrinsic breeding rates given in the tables. The net electrical output is given for three values of the product $\eta_D G$ of the driver efficiency and fusion gain (or Q), namely 2, 5, and 10. Unless otherwise specified, the results presented in this report pertain to $\eta_D G = 5.0$.

For all hybrids, it is assumed that 75% of the fusion power is carried by the D-T fusion neutrons. The remaining 25% is in the form of photons and ions so that the total thermal power of the hybrid P_{th} is given by:

$$P_{th} = P_f\{0.25 + 0.75\ M\} \qquad \text{(A-1)}$$

where P_f is the fusion power and M is the blanket energy multiplication. The recirculating power fraction f_p is given by:

$$f_p = 1/[\eta_{th}\ \{1 + \eta_D G[0.25 + 0.75\ M]\}] \qquad \text{(A-2)}$$

where η_{th} is the thermal efficiency of the hybrid power cycle; a value of 0.40 has been selected. The net electrical output of the hybrid P_e will therefore be given by:

$$P_e = P_{th}\eta_{th}[1-f_p] \quad . \qquad \text{(A-3)}$$

For all hybrids, a tritium inventory of 5 kg/GW is assumed which is conservatively low. For Th/U hybrids (Tables A-1 and A-2), the low and high blanket multiplication values selected are 1.5 and 5.0, respectively. The corresponding number of breeding captures per D-T fusion event is 1.5 and 1.75, respectively, so that for hybrids which breed their own tritium the number of fissile atoms (U-233) produced per D-T fusion event are 0.50 and 0.75, respectively. The corresponding values for hybrids with no tritium breeding are 1.50 and 1.75, respectively.

For U/Pu hybrids (Tables A-3 and A-4), the low and high blanket multiplication values selected are 5.0 and 50.0, respectively. The corresponding number of breeding captures per D-T fusion event are 2.5 and 5.2, respectively, so that for hybrid with a tritium breeding ratio of unity the number of fissile atoms (Pu-239) produced per D-T fusion event are 1.5 and 4.2, respectively. The corresponding values for hybrids with no tritium breeding are 2.5 and 5.2, respectively.

For hybrids with high blanket multiplication the initial fissile loading is based on a 4% fissile enrichment and a thermal power density of 100 W/cm^3 in the fuel zone of the hybrid blanket. It is assumed that 40% by volume of the fissile breeding blanket is occupied by fuel material; the remaining sixty per cent is occupied by the coolant and structure.

TABLE A-1: Design Parameters for Th/U Hybrids with Low Blanket Multiplication With or Without Tritium Breeding

PARAMETER	Tritium Breeding	
	Yes	No
Blanket Multiplication	1.5	
Fissile Breeding Ratio	0.5	1.5
Tritium Breeding Ratio	1.0	0.0
Tritium Inventory (kg)	5.0	
Fusion Power (MW)	1000	
Thermal Power (MWt)	1375	
Gross Elect. Output (MWe)	550	
Net Elect. Output (MWe): $\eta_D G = \begin{cases} 2 \\ 5 \\ 10 \end{cases}$	180 375 460	
U-233 Production Rate (ton/y)(a)	2.17	6.50
Required Tritium (kg/y)(a)	0	56.1
Initial Fissile Loading (ton)	0	0

(a) Figures are based on 100% capacity factor; a 70% capacity factor is assumed.

TABLE A-2: Design Parameters for Th/U Hybrids with High Blanket Multiplication With and Without Tritium Breeding

<table>
<tr><th colspan="2" rowspan="2">PARAMETER</th><th colspan="2">Tritium Breeding</th></tr>
<tr><th>Yes</th><th>No</th></tr>
<tr><td colspan="2">Blanket Multiplication</td><td colspan="2">5.0</td></tr>
<tr><td colspan="2">Fissile Breeding Ratio</td><td>0.75</td><td>1.75</td></tr>
<tr><td colspan="2">Tritium Breeding Ratio</td><td>1.0</td><td>0.0</td></tr>
<tr><td colspan="2">Tritium Inventory (kg)</td><td colspan="2">5.0</td></tr>
<tr><td colspan="2">Fusion Power (MW)</td><td colspan="2">1000</td></tr>
<tr><td colspan="2">Thermal Power (MWt)</td><td colspan="2">4000</td></tr>
<tr><td colspan="2">Gross Elect. Output (MWe)</td><td colspan="2">1600</td></tr>
<tr><td rowspan="3">Net Elect. Output (MWe): $\eta_D G =$</td><td>2</td><td colspan="2">1155</td></tr>
<tr><td>5</td><td colspan="2">1410</td></tr>
<tr><td>10</td><td colspan="2">1500</td></tr>
<tr><td colspan="2">U-233 Production Rate (ton/y)[a]</td><td>3.25</td><td>7.58</td></tr>
<tr><td colspan="2">Required Tritium (kg/y)[a]</td><td>0</td><td>56.1</td></tr>
<tr><td colspan="2">Initial Fissile Loading (ton)</td><td>6.6</td><td>6.6</td></tr>
</table>

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[a] Figures are based on 100% capacity factor; a 70% capacity factor is assumed.

TABLE A-3: Design Parameters for U/Pu Hybrids with Low Blanket Multiplication With and Without Tritium Breeding

PARAMETER	Tritium Breeding	
	Yes	No
Blanket Multiplication	5.0	
Fissile Breeding Ratio	1.5	2.5
Tritium Breeding Ratio	1.0	0.0
Tritium Inventory (kg)	5.0	
Fusion Power (MW)	1000	
Thermal Power (MWt)	4000	
Gross Elect. Output (MWe)	1600	
Net Elect. Output (MWe): $\eta_D G$ = 2	1155	
5	1410	
10	1500	
Plutonium Production Rate (ton/y)(a)	6.66	11.1
Required Tritium (kg/y)(a)	0	56.1
Initial Fissile Loading (ton)	0	0

(a) Figures are based on 100% capacity factor; a 70% capacity factor is assumed.

TABLE A-4: Design Parameters for U/Pu Hybrids with High Blanket Multiplication With and Without Tritium Breeding

PARAMETER	Tritium Breeding	
	Yes	No
Blanket Multiplication	50.0	
Fissile Breeding Ratio	4.2	5.2
Tritium Breeding Ratio	1.0	0.0
Tritium Inventory (kg)	5.0	
Fusion Power (MW)	1000	
Thermal Power (MWt)	37,750	
Gross Elect. Output (MWe)	15,100	
Net Elect. Output (MWe): $\eta_D G = 2$	14,600	
Net Elect. Output (MWe): $\eta_D G = 5$	14,900	
Net Elect. Output (MWe): $\eta_D G = 10$	15,000	
Plutonium Production Rate (ton/y)(a)	18.7	23.1
Required Tritium (kg/y)(a)	0	56.1
Initial Fissile Loading (ton)	66	66

(a) Figures are based on 100% capacity factor; a 70% capacity factor is assumed.

APPENDIX B

THE STRATEGY OPTIMIZATION CODE (SOP-KA)

SOP-KA is a computer code developed at the Nuclear Research Center in Karlsruhe (FRG). The code is used to determine the optimum time dependent shares of different nuclear power reactor types subject to a specified set of constraints so that a given functional can be optimized. The constraints are primarily the overall power demand projection, maximum market penetration rates for different reactors, availability of fuel cycle facility capacities, availability of fissile materials, and reactor lifetime. The functional to be optimized may be the cumulative uranium consumption over the period of interest (as is the case in this study), or the overall system costs, etc. Annual and cumulative balances are made for the different variables, i.e. materials, costs, etc., taking into account any lead or lag times which may be specified for each variable in each reactor type. Standard Linear Programming Software (IBM-MPSX/370) is used to determine the optimum mix of the different reactors as well as the time histories of the different variables over the period of interest. In the following, the methodology used in SOP-KA is briefly described. Additional details may be found in [17].

The time span of interest is divided into N consecutive periods of length p (recommended value p = 5 years). The projected nuclear capacity for these different periods is given the symbol P(n) where n = 1, 2..., N + 1. Let X(r,n) be the capacity of reactor type r during period n. Hence,

$$\sum_{r} X(r,n) = P(n) \qquad (1a)$$

where $$X(r,n) \geq 0 \qquad \text{(1b)}$$

and $$X(r,n) = 0 \text{ for } n < t_o(r) \qquad \text{(1c)}$$

where $t_o(r)$ is the introduction time of reactor type r measured in periods. The variables X and P are measured in the same units (e.g. GWe) and account for the load factor.

Let $Z(r,n)$ be the reactor additions of type r during period n. Hence, for all r and n,

$$X(r,n) - X(r,n-1) + Z(r,n-L_r) = Z(r,n) \qquad \text{(2a)}$$

$$Z(r,n) \geq 0 \qquad \text{(2b)}$$

$$X(r,j) \text{ , } Z(r,j) = 0 \quad \text{for } j \leq 0 \qquad \text{(2c)}$$

where L_r is the lifetime of reactor type r in periods. $Z(r,n-L_r)$ represents the potentially necessary additions while $[X(r,n) - X(r,n-1)]$ is the actual change in capacity which may be negative. Condition (2b) is necessary to guarantee the lifetime for each reactor.

Additional simple constraints on $X(r,n)$ and $Z(r,n)$ can be specified according to introduction times or introduction rates of different reactor types. These constraints can be stated as equalities or inequalities whichever is more convenient.

Let m be an index for a specific fuel cycle demand to be measured in F units, where F represents tonnes, cubic meters, curies, etc. For a given reactor type r, the following variables are defined:

$I(r,m) \equiv$ inventory in F/GWe.

$L(r,m) \equiv$ annual reload in F/GWe-year.

$D(r,M) \equiv$ annual discharge in F/GWe-year.

$E(r,m) \equiv$ end-of-life inventory discharge in F/GWe.

and $U(r,m) \equiv$ surplus in F/GWe-year.

The cumulative fuel cycle demand $K(m,n)$ of material m till the end of period n measured in F units (e.g. tonnes of natural uranium consumed up to period n) will therefore be given by:

$$K(m,n) = K(m,n-1) + \sum_r \left\{ I(r,m) \times Z(r,m) \right.$$

$$+ E(r,m) \times Z(r,n-L_r)$$

$$+[U(r,m) + L(r,m) + D(r,m)]$$

$$\left. \times [X(r,n) + X(r,n-1)] \times \frac{p}{2} \right\} \qquad (3a)$$

$$K(m,n) \geq 0 \qquad (3b)$$

$$K(m,0) = 0 \quad . \qquad (3c)$$

Equation (3b) guarantees availability of material m if the needs ($I(r,m)$ and $L(r,m)$) are negative and the discharges ($D(r,m)$ and $E(r,m)$) are positive. This allows multi-stage introduction of several symbiotic reactor systems. For example I(FBR, Pu) could be the negative of the plutonium fuel cycle inventory for a fast breeder reactor while U(FBR,Pu) is the positive of the yearly plutonium surplus of the breeder and U(LWR,Pu) is the annual plutonium production of a light water reactor. The maximum additions of breeder capacity will then be limited by plutonium availability. To calculate the natural uranium demand (e.g. for light water reactors), I and L have to be positive while D and E are negative; this poses no additional restrictions on the reactor split since $|E| < |I|$

and $|D| < |L|$.

Equation (3a) can be extended to include any lead times δ_I for $I(r,m)$, lag times δ_D and δ_E for $D(r,m)$ and $E(r,m)$, and lead or lag times δ_L for $L(r,m)$. These lead and lag times should not exceed p. The general form of Eq. (3a) can then be written as [17]:

$$\begin{aligned} K(m,n) = K(m,n-1) + \sum_r \Bigg\{ & I(r,m) \;\left[\left(1-\frac{\delta_I}{p}\right) Z(r,n) \right. \\ & \left. + \left(\frac{\delta_I}{p}\right) Z(r,n+1)\right] + E(r,m) \;\left[\left(1-\frac{\delta_E}{p}\right) Z(r,n-L_r) \right. \\ & \left. + \left(\frac{\delta_E}{p}\right) Z(r,n-L_r-1)\right] + U(r,m) \;\left[\left(1-\frac{\delta_U}{p}\right) X(r,n) \right. \\ & \left. + \left(\frac{\delta_U}{p}\right) X(r,n-2) + X(r,n-1)\right] \frac{p}{2} \\ & + D(r,m) \;\left[\left(1-\frac{\delta_D}{p}\right) X(r,n) + \left(\frac{\delta_D}{p}\right) X(r,n-2) + X(r,n-1)\right] \frac{p}{2} \\ & + L(r,m) \;\left[\left(1-\frac{\delta_L}{p}\right) X(r,n-1) + \frac{\delta_L}{p} X(r,n+1) + X(r,n)\right] \frac{p}{2} \Bigg\} \qquad (3.1a) \end{aligned}$$

The annual fuel cycle demand $A(m,n)$ of material m at the end of period n in units of F/year (e.g. tonnes of natural uranium per year) is given by:

$$A(m,n) = [K(m,n+1) - K(m,n-1)]/2p \quad . \qquad (4)$$

Additional constraints on $A(m,n)$ and $K(m,n)$ may be specified. Equations (1) through (4) can be supplemented to allow reactor retrofitting by introducing a new reactor type which replaces the old one and takes into account the already-used portion of reactor lifetime.

The above equations are solved using IBM-MPSX/370 linear programming package. One can select a goal function which provides for maximum penetration of a given reactor(s) type (e.g. maximum breeder introduction, limited only by the power demand projection, plutonium availability, and light water reactor lifetime). Alternatively, one can determine the optimum time-dependent shares of the different reactor types so that the cumulative uranium demand for the period of interest is minimized. The latter approach is used in this study.

A brief description of the input and a sample output are given below.

B.1 The Input

1. A problem identification name, the period length and number of periods to be investigated, the starting year for the first period, and the number of power reactor types under investigation.
2. The power demand projection for the end of each period.
3. For each power reactor type, the following data should be provided: the period for the first introduction, the lifetime, optimal additional restrictions for the installed capacity or power additions at specified periods, and the number of fuel cycle demand calculations.
4. For each power reactor type and each type of fuel cycle demand calculation, the following data should be provided: the inventory needs, the reloads and discharges, the end of lifetime discharges, and the corresponding lead or lag times.
5. A flag to indicate whether optimization is required or not.

B.2 The Output

The following is a sample output representing the case for scenario

III in Fig. 2 with hybrid introduction in the year 2000 according to market penetration constraint A (Fig. 3). The first three pages show the user supplied inputs. The projected capacity is first given followed by parameters for the different reactors. OT, LD, SR, and HY represent once-through LWRs, denatured LWRs, Savannah-river type tritium producers, and hybrids respectively. UNAT, UCOM, U3BI, and TRIT represent the natural uranium demand, the natural uranium committed, U-233, and tritium respectively. AB is the inventory in tonnes, with lead time FZ years. NL is the annual reload in tonnes with lead (or lag) time VZ in years. Positive VZ values indicate lead times. EL is the annual discharge in tonnes with lag time WZ in years. UE is the annual surplus in tonnes with lag time EZ years. EE is the end-of-life inventory discharge in tonnes with lag time WZ years.

The optimum time-dependent capacities of the different reactor types are listed on page 65 of the output. The reactor additions for each reactor type within each five-year period are given on page 66. Page 67 contains the decommissioned capacities for each five-year period followed by reactor modifications on pages 68 and 69. The annual demands of each variable are listed on page 70. HILF is a dummy variable and should be ignored. Finally the cumulative mass balances are given on page 71.

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Strategy   SR HY(ALL/U3/L) LWR                                  Page 1
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ENERGY DEMAND (GWE):

1975   1980   1985   1990   1995   2000   2005   2010   2015   2020

  60    145    245    375    550    830   1080   1295   1475   1650


2025   2030   2035   2040   2045   2050   2055   2060   2065   2070

1795   1950   2100   2250   2400   2550   2700   2850   3000   3150


2075   2080

3300   3450


FUEL CYCLE DATA

AB:  INITIAL CORE LOADING          FZ:  FABRICATION TIME
NL:  RELOAD (YEAR)                 VZ:  FZ - DELAY
EL:  DISCHARGE (YEAR)              WZ:  TIME FOR REPROCESSING
UE:  EXCESS (YEAR)                 EZ:  FZ - BURN-IN
EE:  FINAL DISCHARGE

DEFINITIONS:   E FOR = / G FOR >= / L FOR <=



REACTOR OT:
         AB     FZ     NL    VZ     EL    WZ     UE    EZ     EE    WZ

UNAT    40.0  2.3   138.0  1.8    0.0  0.0    0.0  0.0    0.0  0.0
UCCM  4180.0  8.0     0.0  0.0    0.0  0.0    0.0  0.0    0.0  0.0


OPERATING TIME (YEARS)             30
BEGINNING YEAR:                  1970
RESTRICTIONS FOR                    0
ADDITIONAL REACTORS:
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STRATEGY   SR HY(ALL/U3/L) LWR                                  PAGE 2
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REACTOR LD:

         AB     FZ      NL     VZ      EL     WZ      UE     EZ      EE     WZ

U33I -0.917 0.0 -0.681 0.0   0.402 2.0   0.000 0.0   0.917 2.5

OPERATION TIME (YEARS):          0     (COMBINATION WITH LAST
                                        REACTOR OF WHICH LD>0)
BEGINNING YEAR:               2000
RESTRICTION FOR ADDITIONAL       0
REACTORS:


REACTOR SR:

         AB     FZ      NL     VZ      EL     WZ      UE     EZ      EE     WZ

LNAT   448.5 2.3   164.0 1.8     0.0 0.0     0.0 0.0 -448.5 2.5
TRIT   0.000 0.0   0.000 0.0   0.000 0.0   0.009 1.0   0.000 0.0

OPERATING TIME (YEAR):          30
BEGINNING YEAR:               2000
RESTRICTIONS FOR                 0
ADDITIONAL REACTORS:
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STRATEGY   SR HY(ALL/U3/L) LWR                                      PAGE 3
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 REACTOR HY:

         AB    FZ     AL    VZ     EL    WZ     UE    EZ     EE    WZ

HILF    0.00  0.0    1.00  0.0    0.00  0.0    0.00  0.0    0.00  0.0
TRIT   -0.01  0.0    0.00  0.0    0.00  0.0    0.00  0.0    0.00  0.0
U3BI    0.00  0.0    0.00  0.0    0.00  0.0    4.04  3.0    0.00  0.0

OPERATING TIME (YEARS):          30
BEGINNING YEAR:                2000
RESTRICTION FOR                   2
ADDITIONAL REACTORS:

 2005      2010

  82 L     143 L

AIMING FUNCTION (CUMULATED MASS, YEAR, WEIGHT):

UNAT

2085 1.0E+00

HILF

2085 1.0E-03
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STRATEGY    SR HY(ALL/U3/L) LWR                               PAGE 4
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REPARTITION OF REACTORS (GWE):


             1975       1980       1985       1990       1995

CT        6.000E+01  1.450E+02  2.450E+02  3.750E+02  5.500E+02
LD        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
SR        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
HY        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00


             2000       2005       2010       2015       2020

CT        8.300E+02  7.745E+02  1.223E+02  0.000E+00  0.000E+00
LD        0.000E+00  1.620E+02  8.861E+02  9.397E+02  1.115E+03
SR        0.000E+00  6.096E+01  6.096E+01  6.096E+01  6.096E+01
HY        0.000E+00  8.250E+01  2.257E+02  4.744E+02  4.744E+02


             2025       2030       2035       2040       2045

CT        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
LD        1.260E+03  1.415E+03  1.708E+03  2.001E+03  2.400E+03
SR        6.096E+01  6.096E+01  0.000E+00  0.000E+00  0.000E+00
HY        4.744E+02  4.744E+02  3.919E+02  2.487E+02  0.000E+00


             2050       2055       2060       2065       2070

CT        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
LD        2.550E+03  2.700E+03  2.850E+03  3.000E+03  3.150E+03
SR        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
HY        0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00


             2075       2080

CT        0.000E+00  0.000E+00
LD        3.300E+03  3.450E+03
SR        0.000E+00  0.000E+00
HY        0.000E+00  0.000E+00
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STRATEGY    SR HY(ALL/U3/L) LWR                                PAGE 5
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 ADDITIONAL REACTORS/PERIOD:

                1975         1980         1985         1990         1995

OT           6.000E+01    8.500E+01    1.000E+02    1.300E+02    1.750E+02
LD           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
SR           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
HY           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00

                2000         2005         2010         2015         2020

OT           2.800E+02    4.548E+00    0.000E+00    0.000E+00    0.000E+00
LD           0.000E+00    1.620E+02    1.568E+02    3.133E+01    3.050E+02
SR           0.000E+00    6.096E+01    0.000E+00    0.000E+00    0.000E+00
HY           0.000E+00    8.250E+01    1.432E+02    2.487E+02    0.000E+00

                2025         2030         2035         2040         2045

CT           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
LD           3.200E+02    4.350E+02    4.600E+02    4.500E+02    4.300E+02
SR           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
HY           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00

                2050         2055         2060         2065         2070

CT           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
LD           4.550E+02    4.700E+02    5.850E+02    6.100E+02    6.000E+02
SR           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
HY           0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00

                2075         2080

CT           0.000E+00    0.000E+00
LD           5.800E+02    6.050E+02
SR           0.000E+00    0.000E+00
HY           0.000E+00    0.000E+00
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STRATEGY    SR HY(ALL/U3/L) LWR                            PAGE 6
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REACTOR-DECOMMISSIONING/PERIOD:

              1975        1980        1985        1990        1995

OT         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

              2000        2005        2010        2015        2020

OT         0.000E+00   6.000E+01   8.500E+01   1.000E+02   0.000E+00
LD         0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.300E+02
SR         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

              2025        2030        2035        2040        2045

OT         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD         1.750E+02   2.800E+02   1.665E+02   1.568E+02   3.133E+01
SR         0.000E+00   0.000E+00   6.096E+01   0.000E+00   0.000E+00
HY         0.000E+00   0.000E+00   8.250E+01   1.432E+02   2.487E+02

              2050        2055        2060        2065        2070

OT         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD         3.050E+02   3.200E+02   4.350E+02   4.600E+02   4.500E+02
SR         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY         0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

              2075        2080

OT         0.000E+00   0.000E+00
LD         4.300E+02   4.550E+02
SR         0.000E+00   0.000E+00
HY         0.000E+00   0.000E+00
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STRATEGY   SR HY(ALL/U3/L) LWR                               PAGE 7
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ADDITIONAL REACTORS/PERIOD FOR COMBINATION:

             1975        1980        1985        1990        1995

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2000        2005        2010        2015        2020

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   5.673E+02   2.226E+01   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2025        2030        2035        2040        2045

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2050        2055        2060        2065        2070

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2075        2080

CT        0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00
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STRATEGY   SR HY(ALL/U3/L) LWR                                  PAGE 8
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REACTOR-CHANGE OF COMBINATION/PERIOD IN COMBINATION:

             1975        1980        1985        1990        1995

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2000        2005        2010        2015        2020

CT        0.000E+00   0.000E+00   5.673E+02   2.226E+01   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2025        2030        2035        2040        2045

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2050        2055        2060        2065        2070

CT        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00

             2075        2080

CT        0.000E+00   0.000E+00
LD        0.000E+00   0.000E+00
SR        0.000E+00   0.000E+00
HY        0.000E+00   0.000E+00
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STRATEGY   SR HY(ALL/U3/L) LWR                                PAGE 9
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YEARLY MASS BALANCE (IN 1000 KG):

              1975        1980        1985        1990        1995

UNAT       1.318E+04   2.579E+04   4.131E+04   6.184E+04   9.205E+04
UCOM       7.106E+04   8.360E+04   1.087E+05   1.463E+05   2.341E+05
U3BI       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
TRIT       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HILF       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00


              2000        2005        2010        2015        2020

UNAT       1.209E+05   8.448E+04   2.080E+04   9.997E+03   9.997E+03
UCOM       3.802E+03   0.000E+00   0.000E+00   0.000E+00   0.000E+00
U3BI      -2.971E+01  -7.072E+01   1.912E+02   9.870E+02   1.542E+03
TRIT      -2.194E-01   5.799E-02  -1.129E-01   5.486E-01   5.486E-01
HILF       0.000E+00   8.250E+01   2.257E+02   4.744E+02   4.744E+02


              2025        2030        2035        2040        2045

UNAT       9.997E+03   6.398E+03   0.000E+00   0.000E+00   0.000E+00
UCOM       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
U3BI       1.494E+03   1.464E+03   1.207E+03   6.961E+02  -2.086E+02
TRIT       5.486E-01   5.486E-01   1.097E-01   0.000E+00   0.000E+00
HILF       4.744E+02   4.744E+02   3.919E+02   2.487E+02   0.000E+00


              2050        2055        2060        2065        2070

UNAT       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
UCOM       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
U3BI      -7.658E+02  -8.260E+02  -8.514E+02  -8.868E+02  -9.268E+02
TRIT       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
HILF       0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00


              2075        2080

UNAT       0.000E+00   0.000E+00
UCOM       0.000E+00   0.000E+00
U3BI      -9.769E+02  -1.017E+03
TRIT       0.000E+00   0.000E+00
HILF       0.000E+00   0.000E+00
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STRATEGY  SR HY(ALL/U3/L) LWR                                  PAGE 10
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 CUMULATIVE MASS BALANCE (IN 1000 KG):

                 1975         1980         1985         1990         1995

UNAT       4.157E+04    1.389E+05    3.066E+05    5.644E+05    9.490E+05
UCOM       4.180E+05    8.736E+05    1.492E+06    2.337E+06    3.770E+06
U3BI       0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
TRIT       0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00
HILF       0.000E+00    0.000E+00    0.000E+00    0.000E+00    0.000E+00

                 2000         2005         2010         2015         2020

UNAT       1.481E+06    1.995E+06    2.258E+06    2.335E+06    2.385E+06
UCOM       3.099E+06    3.087E+06    3.087E+06    3.087E+06    3.087E+06
U3BI       0.000E+00    0.000E+00    0.000E+00    3.058E+03    9.389E+03
TRIT       0.000E+00    0.000E+00    5.643E-01    0.000E+00    2.743E+00
HILF       0.000E+00    2.063E+02    9.768E+02    2.727E+03    5.099E+03

                 2025         2030         2035         2040         2045

UNAT       2.435E+06    2.476E+06    2.479E+06    2.465E+06    2.465E+06
UCOM       3.087E+06    3.087E+06    3.087E+06    3.087E+06    3.087E+06
U3BI       1.703E+04    2.444E+04    3.111E+04    3.586E+04    3.709E+04
TRIT       5.486E+00    8.229E+00    9.875E+00    1.015E+01    1.015E+01
HILF       7.471E+03    9.843E+03    1.201E+04    1.361E+04    1.423E+04

                 2050         2055         2060         2065         2070

UNAT       2.465E+06    2.465E+06    2.465E+06    2.465E+06    2.465E+06
UCOM       3.087E+06    3.087E+06    3.087E+06    3.087E+06    3.087E+06
U3BI       3.466E+04    3.073E+04    2.655E+04    2.220E+04    1.766E+04
TRIT       1.015E+01    1.015E+01    1.015E+01    1.015E+01    1.015E+01
HILF       1.423E+04    1.423E+04    1.423E+04    1.423E+04    1.423E+04

                 2075         2080

UNAT       2.465E+06    2.465E+06
UCOM       3.087E+06    3.087E+06
U3BI       1.291E+04    7.933E+03
TRIT       1.015E+01    1.015E+01
HILF       1.423E+04    1.423E+04
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