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Some Comments on

THE IMPACT OF THERMAL NEAR BREEDERS ON URANIUM UTILIZATION

by

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Thermal reactors designed to operate on self-sufficient Th/^{233}U fuel cycles have marginal breeding gains and they cannot produce any appreciable excess fissile material. Self sufficiency is possible only with ^{233}U as the fissile material, and self-sufficiency from the beginning of life requires an external supply of ^{233}U. If other fissile materials (^{235}U or ^{239}Pu) are used for the initial loading, a few transition cycles are required to reach the equilibrium self-sufficient state. Some typical fuel utilization characteristics of thermal converters and near-breeders are shown in Table I. The initial core fissile inventory requirement is about 2000 kg for a 1000 MWe CANDU near-breeder and 2000-4000 kg are required for an LWBR depending upon fuel type (highly enriched uranium, slightly enriched uranium, or plutonium), specific power and design burnup.

The transition from the initial core to a self-sufficient equilibrium cycle is expected to be faster in a CANDU reactor than in a LWBR. The lifetime uranium requirement for a CANDU near-breeder is about 1100 short tons of U_3O_8 if enriched uranium feed is used. This requirement is doubled if the CANDU near-breeder is fueled by plutonium produced in the natural uranium fueled CANDU because about 0.5 gm of fissile plutonium is produced per gm of ^{235}U consumed. The lifetime uranium requirement for the LWBR ranges from about 1800 to 4000 short tons of U_3O_8, again depending on the fuel type, specific power and design burnup. Also shown in Table I for comparison are the characteristics of a high conversion HTGR, and a MSBR.

The most basic question asked of the thermal near-breeder is whether it could remove the need for the fast breeder. Because these thermal breeders are at best self-sufficient, and then only in their equilibrium condition, the total power capacity that can be installed will be limited if the uranium supply is limited. The final total capacity achieved depends upon system characteristics. For example, in the LWR uranium recycle case, about 180 kg of fissile plutonium per GW(e)-yr are produced in an LWR that consumes 163 ST of U_3O_8 per GW(e)-yr so $\sim$1.1 kg of plutonium are made available per short ton of U_3O_8 consumed. In a system made up of CANDU natural uranium reactors, $\sim$2.0 kg of plutonium are produced per short ton of uranium consumed. Thus, in power systems limited to just these reactor types and assuming equivalent inventories required for startup and transition to equilibrium cycle in the near-breeder reactors, a system made up of natural uranium and thorium cycle CANDU reactors could establish an equilibrium power generation capacity nearly twice that of the LWR-LWBR system. For a non-growth power system with a fixed equilibrium nuclear power capacity, thermal near-breeder reactors could possibly replace fast breeder reactors. For continually growing power systems, however, the need for fast breeder reactors with sufficient breeding capability is inevitable.

We have taken a brief look at the possible impact of thermal near-breeders in a growing power system--a simplified model of the U. S. nuclear power economy. The nuclear power growth rate assumed was that given in the Final Environmental Statement for LMFBR Program.[1] We used ALPS,[2] an LP optimization code, to compare the cumulative uranium requirements for the following four scenarios.

Case 1: LWR only

Case 2: LWR + Near-Breeder (1995 Introduction)

Case 3: LWR + LMFBR (1995 Introduction)

Case 4: LWR + Near-Breeder (1995 Introduction) + LMFBR (2015 Introduction)

The advanced reactor types are introduced starting 1995 with constraints on introduction rate and the Pu availability. Both the near-breeder and the LMFBR were assumed to be fueled initially with fissile Pu produced in LWRs. Pu was recycled in the LWR when the storage costs (assumed to be $500/kg-yr) exceeded the savings possible from reduced uranium requirements that would result from the introduction of additional near-breeders or LMFBRs at a later date. The U_3O_8 price was assumed to be the function of the cumulative consumption shown in Fig. 1.

The near-breeder characteristics were those of a CANDU on a Th-cycle with CR=1.0 at equilibrium. (Initial core inventory is 2000 kg/GWe and additional fissile makeup and external inventory requirements until the equilibrium is reached are 2300 kg/GWe.) The LMFBR was assumed to have an initial core inventory of 3000 kg/GWe and an external inventory of 1600 kg/GWe. (The corresponding compound doubling time was 15 years.)

The cumulative uranium requirements for the four scenarios listed above are presented in Fig. 2. Case 2, the near-breeder introduction case, shows uranium requirements that are reduced by about 20% compared to the LWR with Pu recycle. (This impact on the uranium consumption is about the same magnitude as that of self-generated Pu recycle in the LWR system.) Uranium requirements continue to increase after several decades of the near-breeder introduction and will do so as long as the total capacity demand increases. This is to be contrasted with the LMFBR case where the LWR capacity can be either replaced by the LMFBR (after 30-year plant lifetime) or fueled by the excess Pu produced in the LMFBR, and hence the cumulative uranium requirements eventually level off.

In Case 4, where near-breeders are first introduced then replaced by the LMFBR introduction after 20 years, the uranium requirements through year 2030 are similar to the case of near-breeder introduction only without LMFBR introduction.

The LWR capacity installed for various scenarios are presented in Fig. 3.

For a CANDU-based power economy, qualitatively same results are obtained (see Figs. 4 and 5) except that the uranium requirements for all scenarios are scaled down from the LWR-based power economy because of the increased Pu availability from CANDUs.

The key point remains, however, that in the U. S. only through the early introduction of a good breeder (such as the LMFBR) can a ceiling be put on uranium requirements that is consistent with current estimates of nuclear growth rates and uranium reserves.

It is of interest, however, that other system studies[3] (reproduced here in Figs. 6 and 7) have indicated a quite different impact for thermal near-breeders in an expanding power economy than we found in our studies. The referenced studies indicated that the uranium resource conservation realized by the introduction of the thermal near-breeder is about the same magnitude as it is for LMFBR introduction or even better. The two studies apparently directly contradict each other. The contradiction is simply explained by differences in the growth patterns assumed in the two studies. To see this it is useful to examine the relationship between the doubling time of the energy demand and the doubling capability of the breeder system.

Consider a growing power economy (see Fig. 8), where the total nuclear capacity growth rate is given by the energy doubling time, EDT, and the breeder reactor is characterized by the reactor doubling time, RDT, and the reactor specific inventory SI. For breeders introduced at time t_o, when the total nuclear capacity is GW_o, the cumulative requirement for the externally supplied fissile inventory of breeder reactors is given by

$$SI \cdot GW_o \cdot [(1 - \frac{EDT}{RDT})(e^{0.693t_e} - 1) + 0.693 \frac{EDT}{RDT} \cdot t_e] \qquad (1)$$

where $t_e = \frac{t-t_o}{EDT}$ (time in unit of EDT).

As the fissile inventory for the breeder reactors is provided by Pu produced in the converter reactors, Eq. (1) is proportional to the uranium requirements. Hence, the uranium requirement is a function of the ratio EDT/EDT. Figure 9 shows this relationship. For a very fast energy growth rate EDT/RDT is small, and the uranium requirements are almost independent of the breeder reactor doubling time. At the other extreme also, the case of no energy growth, EDT/RDT is large and the uranium requirements again are independent of the breeder reactor doubling capability. Realistic cases in the U. S. are expected to lie in between, however, and over the range from zero to slightly greater than unity uranium requirements are very sensitive to the precise magnitude of EDT/RDT. The nuclear capacity doubling times (EDT) assumed for our study and for Ref. 3 are compared in Table II, which explain the opposite conclusions indicated.

In our study the nuclear capacity doubling time increases continuously from 5 years in 1985 to 30 years in 2030. Hence, the uranium requirements for the LMFBR scenario tend to level off starting around 2020 when the ratio EDT/RDT starts to exceed 1.0 (see Fig. 9), whereas the uranium requirements for the near-breeder scenario diverge from the LMFBR scenario because of the continuing energy demand growth. In Ref. 3, on the other hand, the nuclear capacity doubling time is 5 years through 2000, 11 years from 2000 to 2030, and no further growth is assumed after 2030. Because the ratio EDT/RDT is very small through the year 2000, the uranium requirements are about the same for both near-breeder and LMFBR scenarios. The uranium requirements for the two scenarios diverge somewhat during the period 2000-2030 as EDT/RDT becomes larger, but after 2030 they level off quickly because of the assumption of no further energy growth. The ceiling on uranium requirements under the scenario is therefore mainly sensitive to initial core inventories rather than any doubling time properties of a breeder reactor.

These studies illustrate two points. First they highlight one of the problems that arises in quoting results from system studies. Plausible differences in input assumptions can lead to drastically different conclusions. Second, they underline the fact that under certain specific assumptions for nuclear electric power growth, thermal near-breeders can be shown to be equivalent in resource utilization to fast breeder systems. The answer to the question of whether thermal near-breeders do, in fact, provide a realistic alternative to fast breeders hinges on the realism of such assumptions.

Table I. Fuel Utilization Characteristics of Thermal Converters and Near-Breeders (1000 MWe)

	CANDU	LWBR	HTGR	MSBR
CR or BR	1.0	1.0	0.9	1.07
Initial Core Fissile[a] Inventory (kg)	2000	2000–4000	4800	1500
Annual Uranium Requirement (ST U_3O_8/yr)	0	0	35	0
Lifetime Uranium Requirement[b] (ST U_3O_8)	1100	1800–4000	2300	~ 0[c]

[a]Fissile Pu for CANDU, ^{235}U or fissile Pu for LWBR and ^{235}U for HTGR.

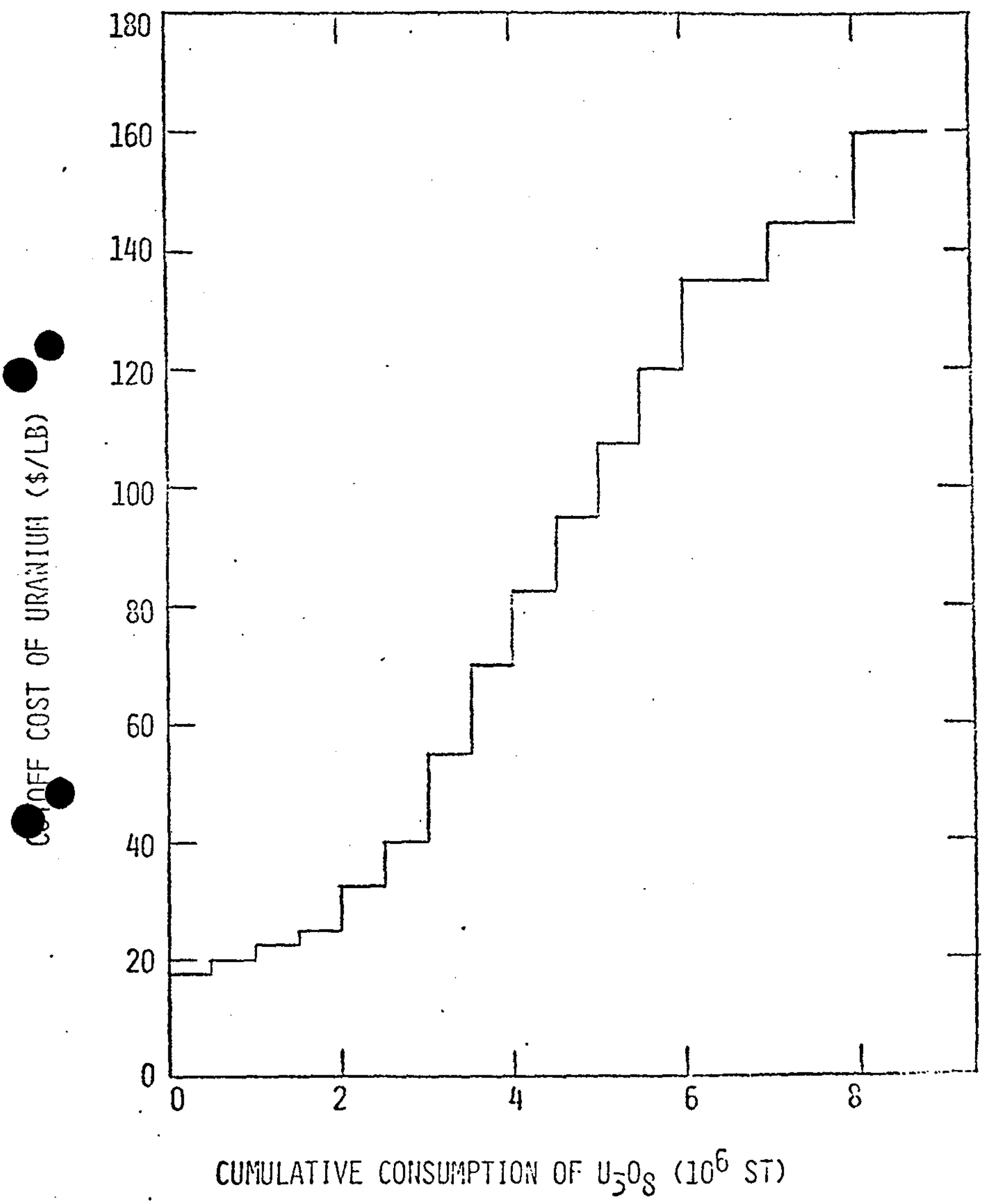
[b]U_3O_8 required to achieve equilibrium cycle plus annual feed (if required) for 30 years.

[c]Excess fissile production of 50 kg/yr is assumed to compensate the initial core inventory.

Table II. Comparison of Nuclear Capacity Doubling Time

Year	This Study	Ref. 3
1985	5	5
2000	12	5
2025	26	11
2030	30	No Growth

FIGURE 1



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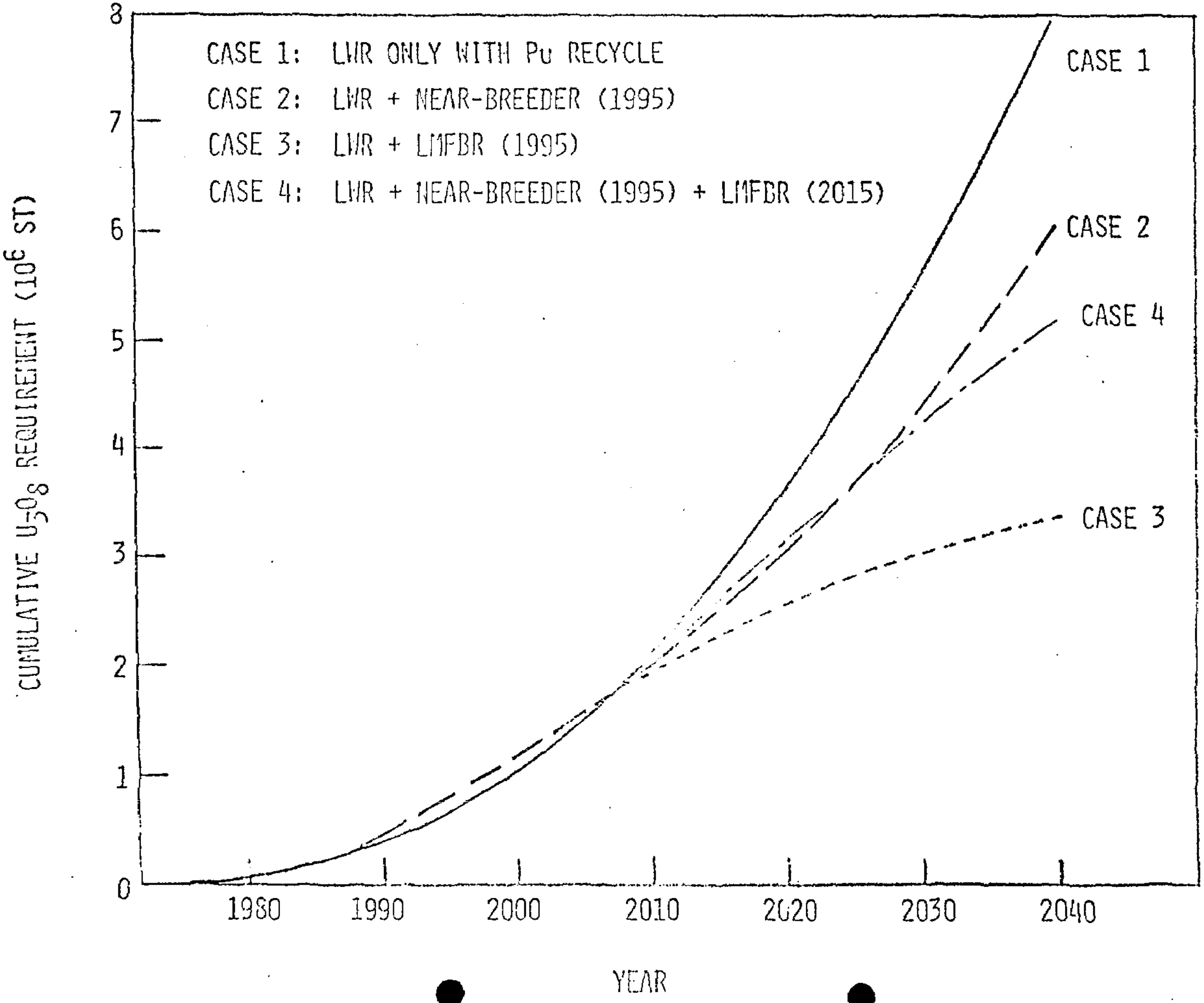
CASE 1: LWR ONLY WITH Pu RECYCLE
CASE 2: LWR + NEAR-BREEDER (1995)
CASE 3: LWR + LMFBR (1995)
CASE 4: LWR + NEAR-BREEDER (1995) + LMFBR (2015)
CASE 1
CASE 2
CASE 4
CASE 3
CUMULATIVE U_3O_8 REQUIREMENT (10^6 ST)
0
1
2
3
4
5
6
7
8
1980
1990
2000
2010
2020
2030
2040
YEAR

FIGURE 3

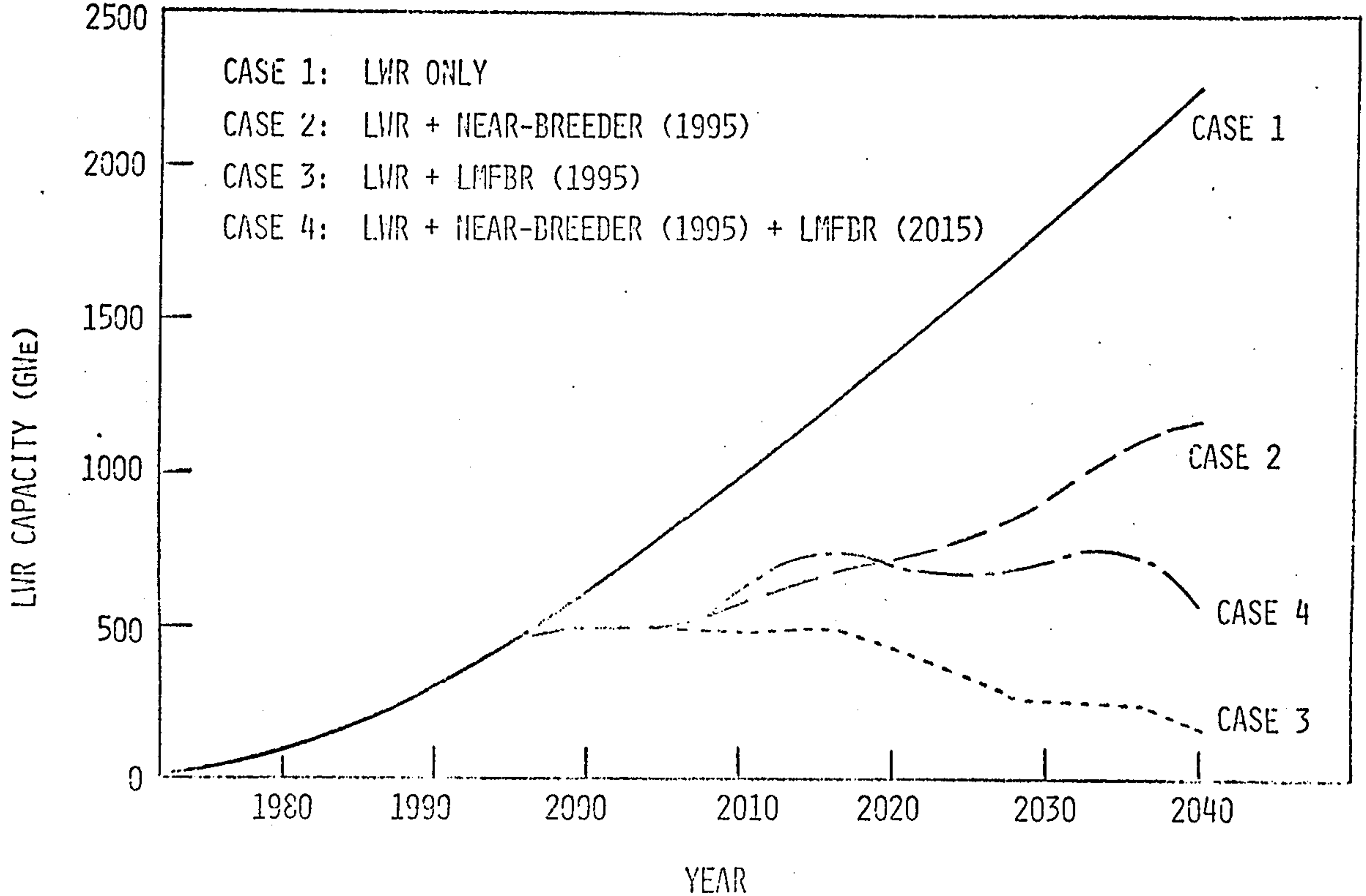

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FIGURE 4

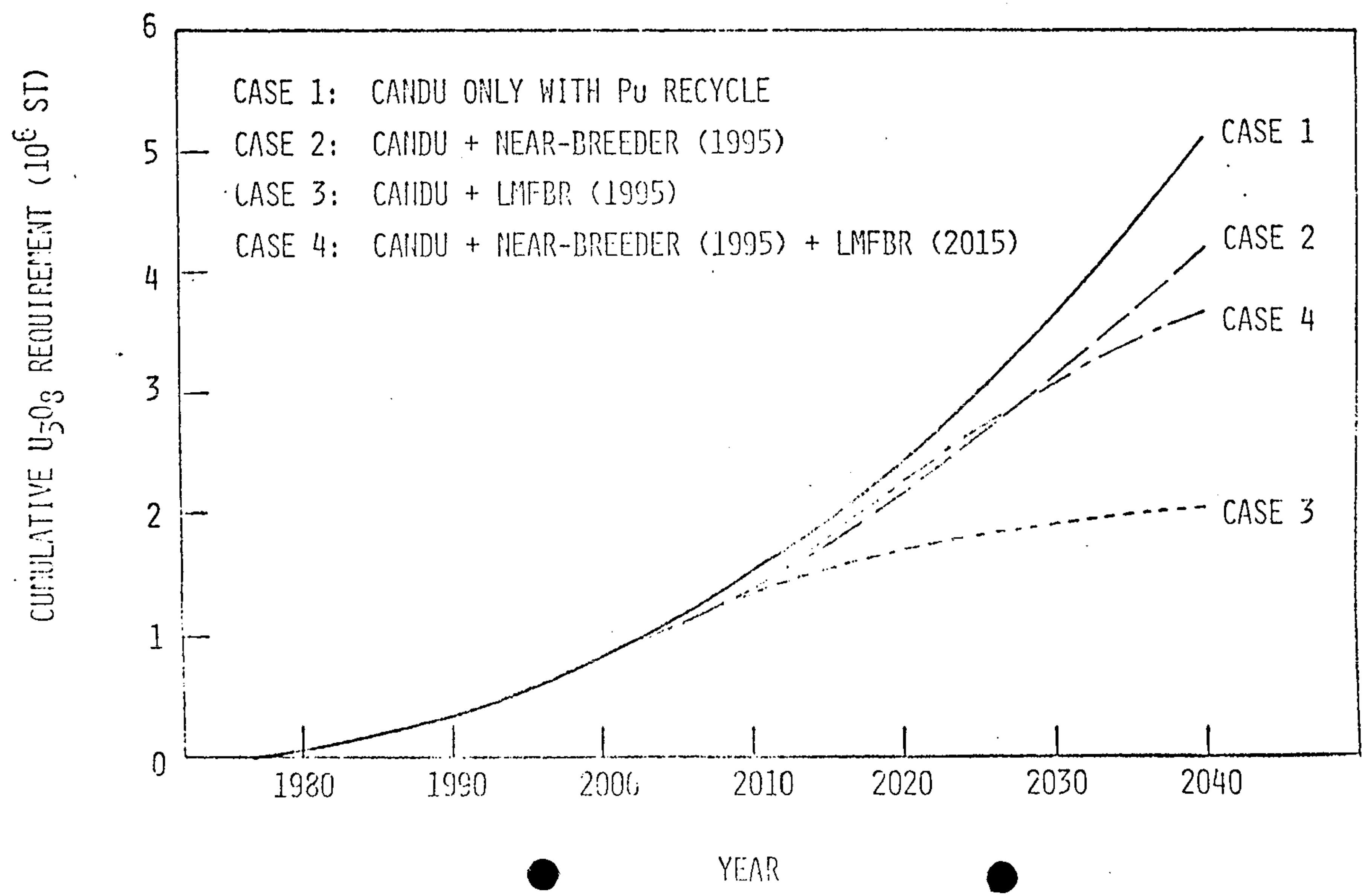

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FIGURE 5

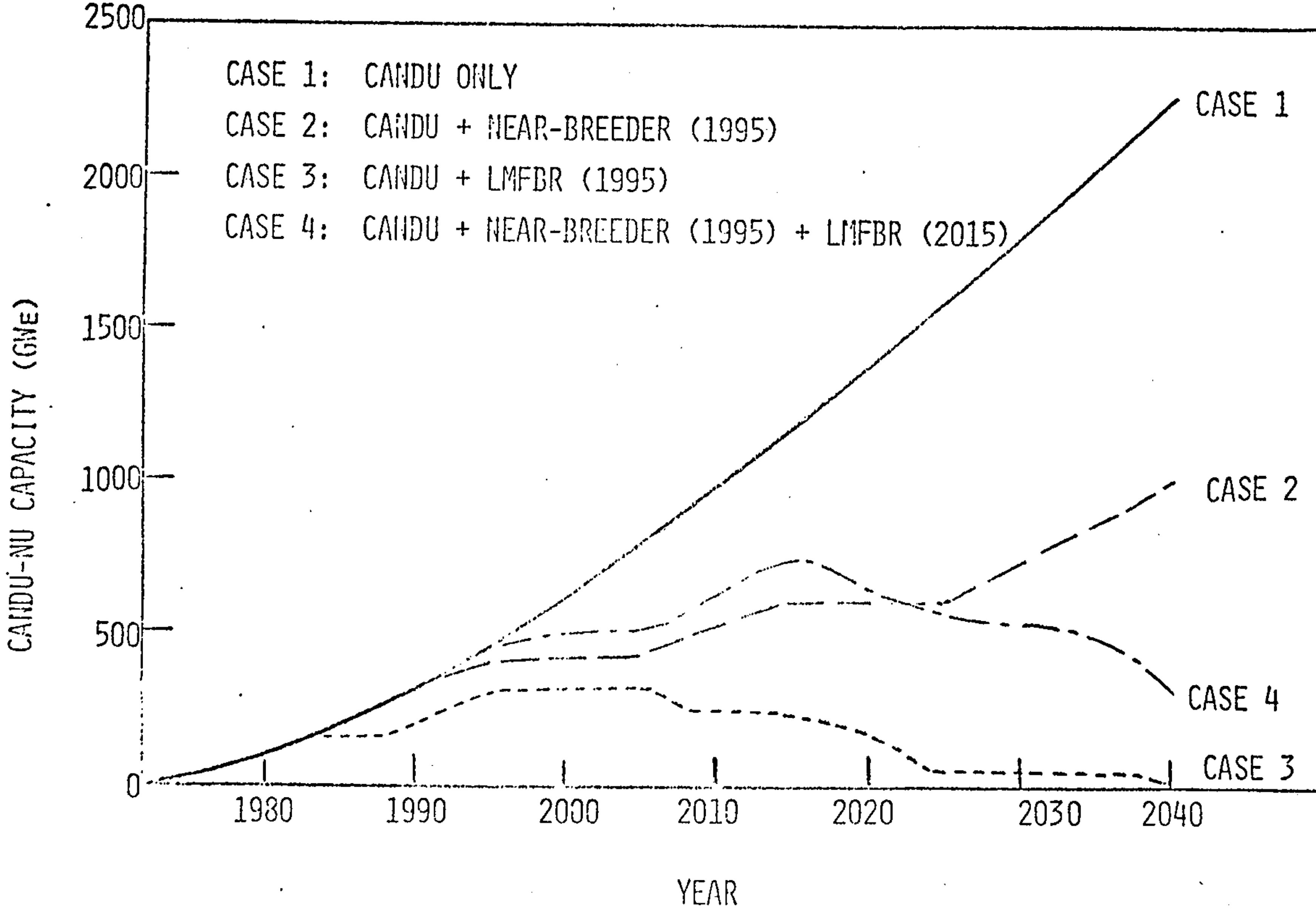

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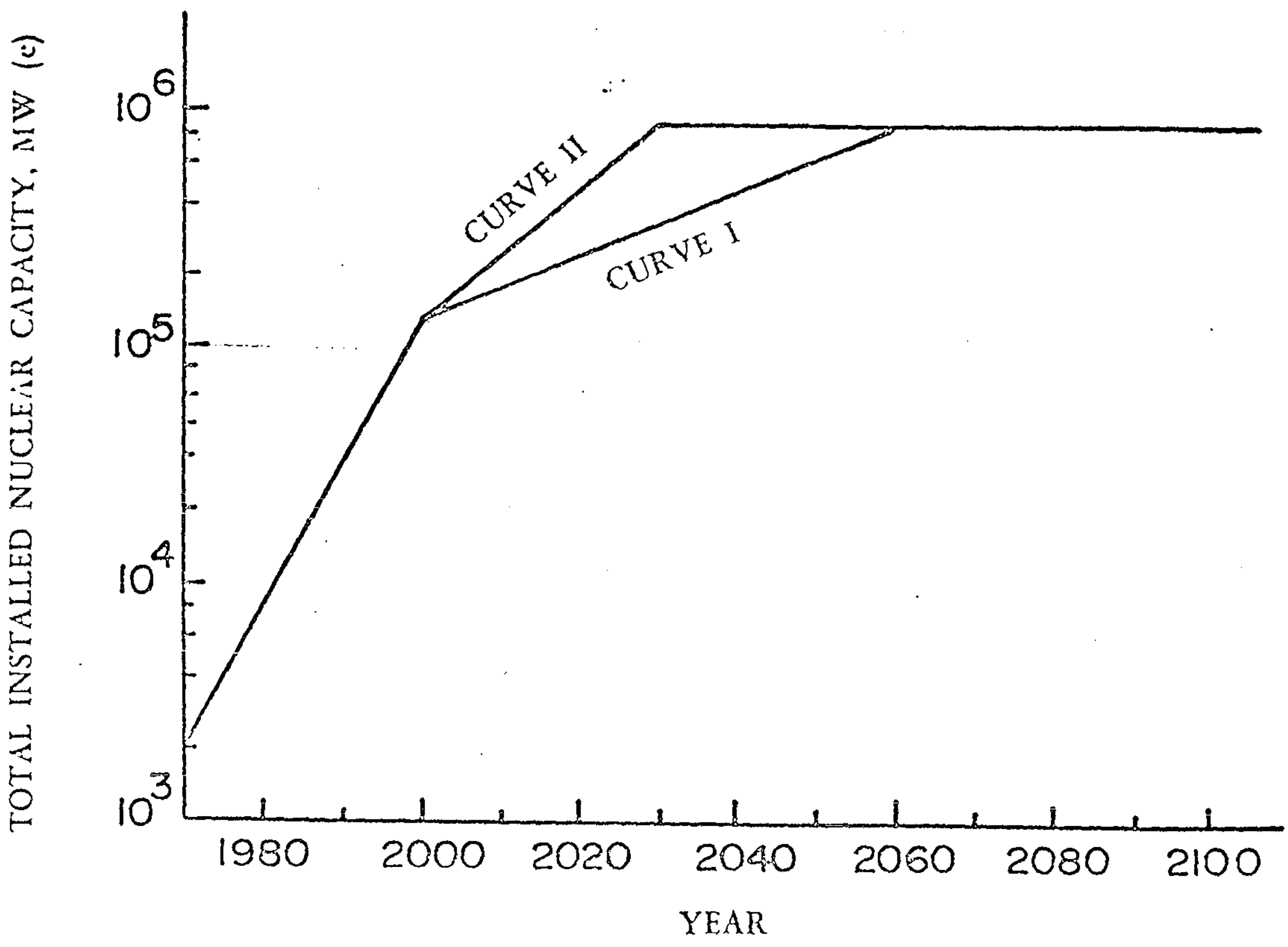
FIGURE 6

ASSUMED INSTALLED NUCLEAR CAPACITY GROWTH



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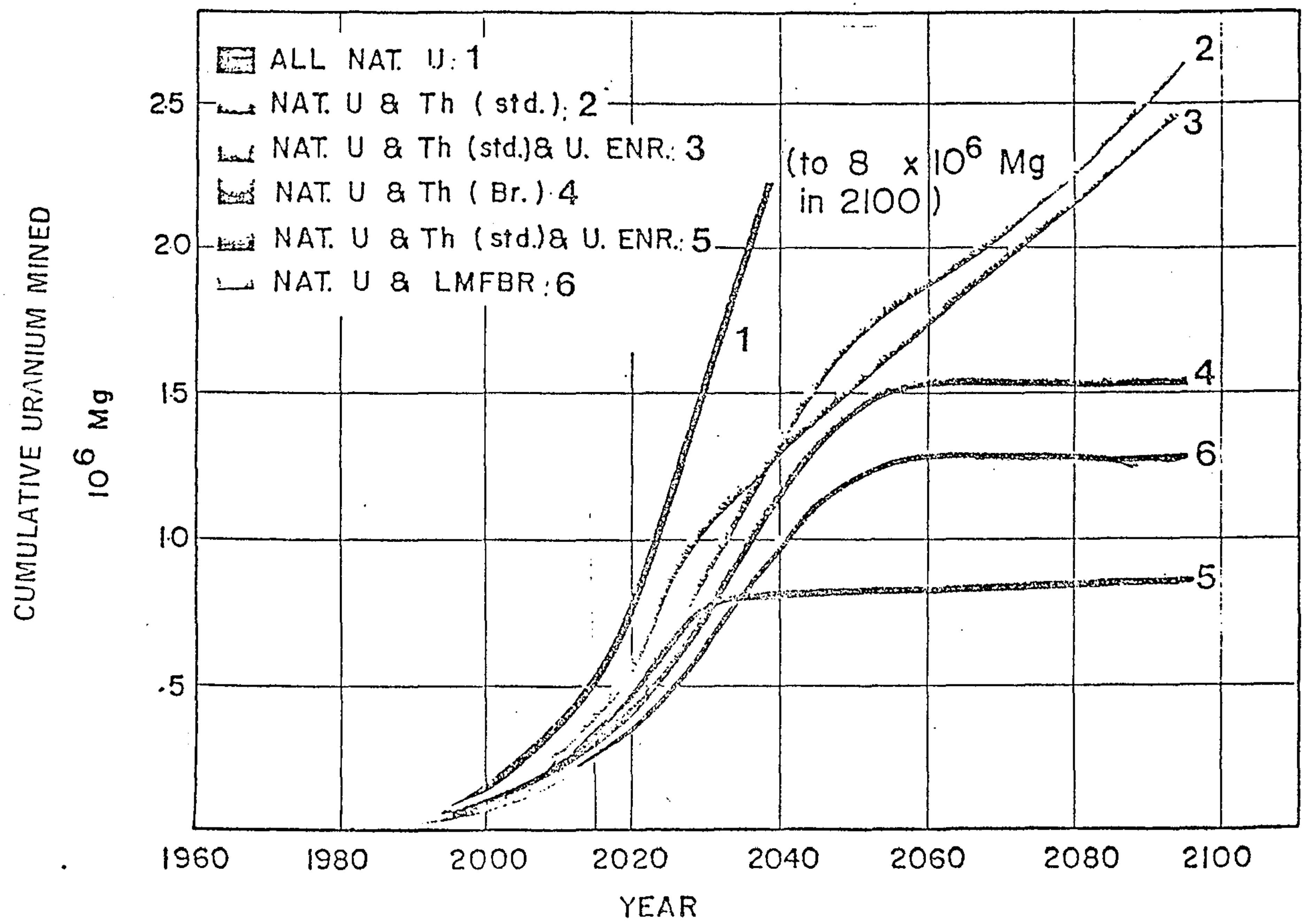
CUMULATIVE URANIUM MINED

GROWTH CURVE II



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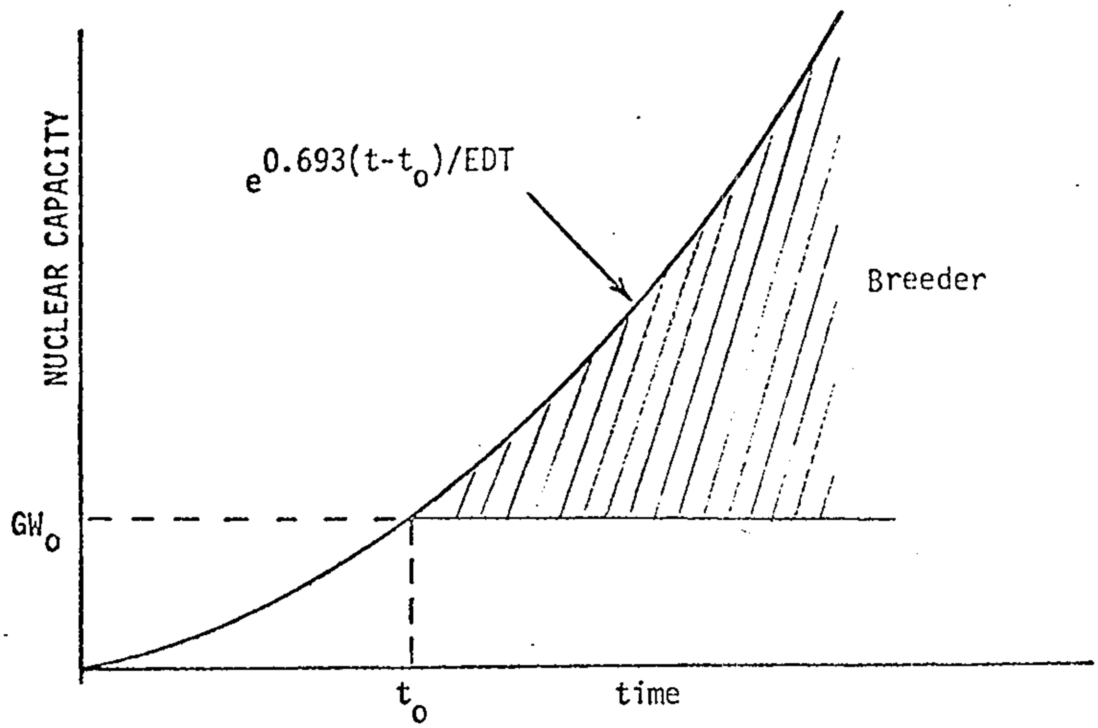


EXTERNALLY SUPPLIED FISSILE INVENTORY REQUIREMENT (∝ URANIUM REQUIREMENT) FOR A BREEDER SYSTEM IN A GROWING POWER ECONOMY

$$= SI \cdot GW_o \cdot \left[\left(1 - \frac{EDT}{RDT}\right)\left(e^{0.693\ t_e} - 1\right) + 0.693\ \frac{EDT}{RDT} \cdot t_e\right]$$

where

EDT = NUCLEAR CAPACITY DOUBLING TIME

RDT = BREEDER FISSILE DOUBLING TIME

SI = BREEDER SPECIFIC FISSILE INVENTORY

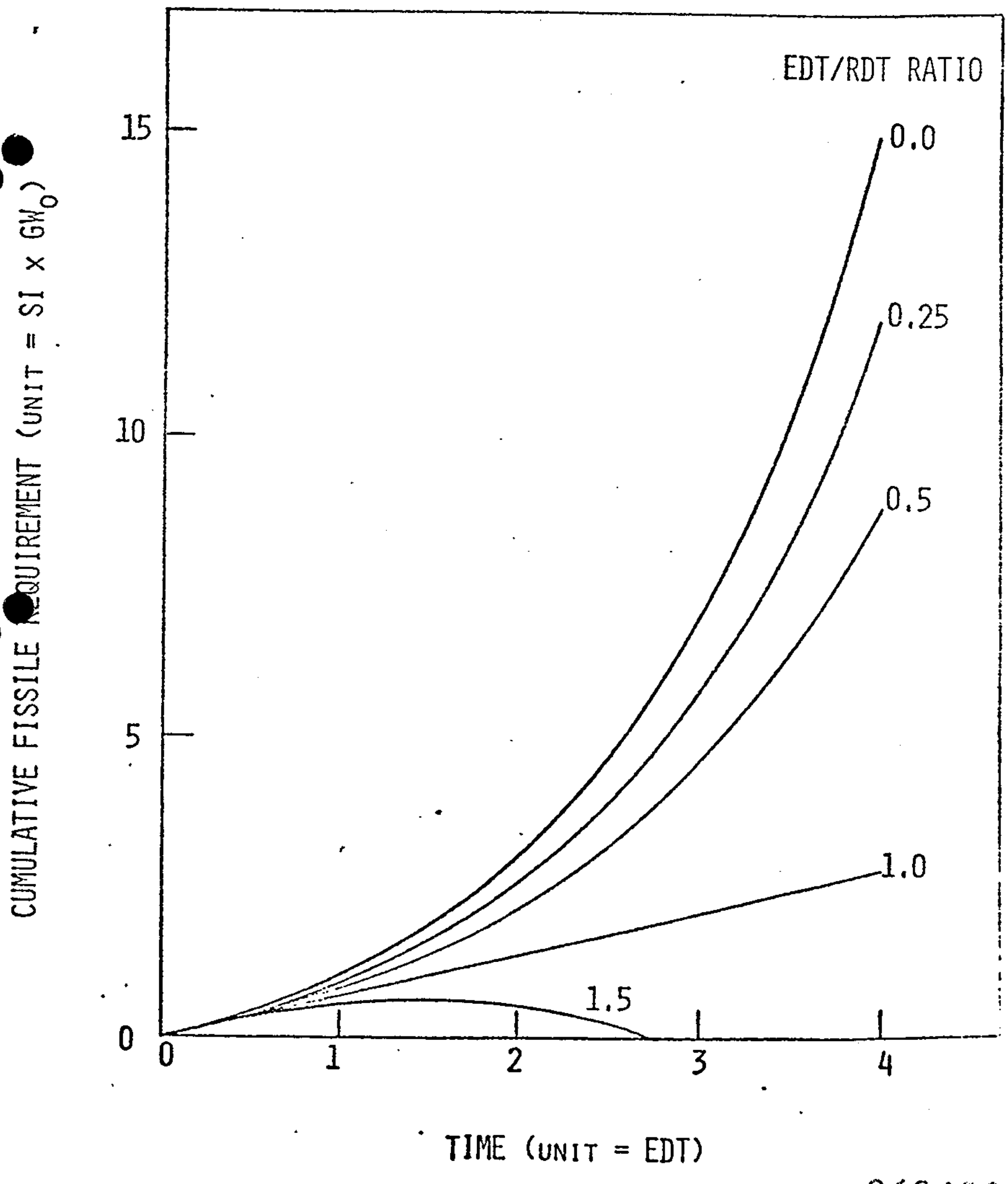
GW_o = NUCLEAR CAPACITY AT BREEDER INTRODUCTION DATE (t_o)

$t_e = \frac{t-t_o}{EDT}$ (time in unit of EDT)

FIGURE 8

FIGURE 9

BREEDER FISSILE REQUIREMENT (EXTERNAL SUPPLY)
AS A FUNCTION OF TIME AND EDT/RDT RATIO



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1. WASH-1535, Final Environmental Statement: LMFBR Program, Dec. 1975.

2. R. W. Hardie, W. E. Black, and W. W. Little, "ALPS, A Linear Programming System for Forecasting Optimum Power Growth Patterns," HEDL-TME-72-31, April 1972.

3. S. R. Hatcher, S. Banerjee, et al., "Thorium Cycle in Heavy Water Moderated Pressure Tube (CANDU) Reactors," presented at ANS Meeting, November 1975.