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The Plutonium Utilization in Thermal and Fast Reactor in Japan

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1. Introduction

Japan has had a growing interest in utilization of nuclear power for peaceful uses for a long time. Since 1954, when the Japanese Government first appropriated a research fund for nuclear power projects, there have been active research and development carried out on nuclear power programs by government, concerned industries and universities. The expectation of utilizing the nuclear power in Japan is to reduce a strong dependence on imported hydrocarbons from outside of Japan (~90 % of primary energy supplies depends on import as of 1973), aggravated by the inadequacy of her domestic energy resources.

In energy supply area, the operation of 1,000 MW(e) nuclear power plant for one year is roughly correspond to 1,400,000 kl of oil consumption per year, if it is converted on the basis of the thermal equivalency. Therefore, if the nuclear power program shows the delay of as much as 25,000 MW(e) from the target, the import of oil should be increased by 35,000,000 kl in order to compensate the consequences of this nuclear delay. Thus, the electric power companies in Japan initiated full-fledged nuclear power generation in about 1966. The rapid growth of nuclear power program is still continuing and expected more to do so in Japan.

2. Nuclear Power Program and Fuel Cycle Requirements

As of June 1976, there are 12 nuclear power plants in operation in Japan with the total power ourput of 6.6 GW(e), and 12 are under construction, representing the total additional power output of 10 GW(e). A long-term program[1] for nuclear power program prepared in 1976 by the Japanese government is as follows. In 1975, the nuclear power generation installed capacity was 6.6 GW(e) and its percentage in total electricity production was 7.5 %; by 1985, the nuclear will be 49 GW(e) and its percentage will be 27.6 %; by 1990, the nuclear will be 90 GW(e) and its percentage will be about 35 %; by 2,000, the nuclear will hit 170 GW(e) mark and its share will well exceed 50 %. This is summarized in Table 1.

This long term nuclear power program of Japan is extensive but not too excessive ones compared with other developed countries. According to the EEI report,[2] for example, the Japanese share of nuclear power generating capacity to that of the world nuclear is about constant of 8 % over the period between 1975 to 2000.

The current Japanese nuclear power plants are mainly consisted from light water reactors of either PWR or BWR, and there exists a conservative tendency of the electric power companies who will choose the reactor type from their past experiences on construction and operation. Therefore, it is safe to say that the light water reactors will be their major choices for time-being, unless some extreme situations occur such as shortage of enriched uranium fuel supply, severe economic penalty, etc. If, in Japan, the total nuclear power generating capacity is assumed to be supplied only from light water reactors, the natural uranium required to operate these nuclear power plants, which will meet the long-term Japanese program, would amount to about 500,000 t of U_3O_8.

The accurate assessment of uranium resources and expansion of its supply will require the further efforts of many countries, but the largest known resources are in Australia, Canada, the South Africa and the U.S. The South America, and Asiatic countries are playing much lesser roles in uranium resources.

Current estimates of reasonably assured reserves and estimated additional resources at US$15 and US$30 per pound of U_3O_8 cost levels are shown in Table 11. The total uranium reserves of the world at reasonable price level is seemed to be about 8,000,000 t of U_3O_8.[3]
The Japanese share of the nuclear power generation capacity to the world nuclear power generation capacity is about 8 % as indicated in Table 1, and if we could say that Japan, who has very minimal amount of natural uranium reserves, could hold on to the corresponding amount of natural uranium from world uranium market to the level of the share of nuclear power generation capacity without disturbing the interests of other countries, the possible Japanese share would so be about 600,000 t of U_3O_8. This amount of natural uranium will well be consumed before the turn of century by Japan, if the Japanese nuclear power generation will be depended only on light water reactors. Therefore, Japan has been studying several reactor strategies to fulfill the need of her nuclear power program.

The apparent conclusion to reduce the requirement of natural uranium is to utilize fast breeder reactors in long term and light water reactors with plutonium recycle in near term. However, heavy water reactor possesses very good specific characteristics of Japan's need, such as;

(1) the amount of natural uranium required for generating unit electricity would be 1/2 to 1/3 of light water reactor.

(2) this reactor could be operated not only with feeding natural uranium but also with using slightly enriched fuel either by ^{235}U or plutonium, without changing the designs of fuel assemblies and control rods.

In view of the above specific features of heavy water reactor, Japan has been paying special effort to develop the heavy water moderated, boiling water cooled, plutonium-uranium oxide fuelled reactor (ATR).[4] The development of this type of reactor is now being carried out not only in Japan but also in Canada, UK, and Italy. Currently in Japan, a prototype reactor, named "FUGEN", of 165,000 kW(e) is under construction and it is expected to achieve criticality in March 1978. The reactor characteristics of ATR are summarized in Table III in comparison with other type reactors.

Plutonium recycle into light water reactors is not the new concept at all, but has never materialized in a commercial way. However, the technological problems have well been studied and the current technological conclusions are as follows.

(1) Recycle of self-generated plutonium into the light water reactor is the most promising method. In this case, there is no need to make the design change of fuel subassemblies and control methods.

(2) From the basic differences of control rod systems between PWR and BWR, PWR prefers to use the system of all plutonium contained fuel rods in a subassembly,"All Pu type", and BWR, in contrary, prefers to use the system of plutonium contained and non-plutonium contained fuel rods being dispersed throughout a subassembly,"Pu Island type".

(3) Whole core loading of plutonium contained fuel into light water reactor of which the core is designed for UO_2 fuel will encounter a control system difficulty.

Fast breeder reactor development in Japan, it is very actively conducted. The details is given in other paper.[5]

Keeping the above in mind, the reactor strategies which have been investigated are selected as follows;

Case 1: Fulfill the program only by light water reactors (Uranium cycle), [Reference case]

Case 2: Use the combination of light water reactors (Uranium cycle), and fast breeder reactors.

Case 3: Use the combination of light water reactors (Uranium cycle), light water reactors (plutonium recycle), and fast breeder reactors.

Case 4: Use the combination of light water reactors (Uranium cycle), plutonium fuelled heavy water reactors (ATR), and fast breeder reactors.

Besides these four basic combinations of reactor types, other factors; such as the share of each reactor type, the date of commercial introduction of each reactor type, the rate of introduction of such reactor, and the date of stopping further introduction of such reactor; will significantly increase the number of cases to be investigated. In this paper, therefore, the following three asumptions have been made for the sake of simplifying the discussion.

(1) The commercial introduction of fast breeder reactor will begin in 1990. The deployment of fast breeder reactor will be limited to 1,000 MW(e) per year for first five years and only 50 % of the new requirements and the replacement of retiring light water reactors should be fulfilled by fast breeder reactors. After year 2000, all new installations will be fast breeder reactors. This incubation period for the introduction of fast breeder reactors is considered to be necessary to divert Japanese nuclear industries from light water reactors to fast breeder reactors.

(3) Plutonium recycle into light water reactors will begin in 1985. The mode of plutonium recycle will be limited to the self-

generated-plutonium-recycle-scheme, and there will be no specifically designed light water reactors in which plutonium will be burnt. Fast breeder reactor is always given the top priority to use the plutonium, and the only remaining plutonium is recycled into light water reactors.

(3) Start of the commercial utilization of the Advanced Thermal Reactors is assumed to be in 1985. From the same reasons applied to tne introduction of fast breeder reactors, the pace of introducing ATR is limited to 1,000 MW(e) per year for first five years. Then, the gradual increase of ATR is maintained until the share of ATR within Japanese nuclear power generating capacity will hit 10 % at year 2,000. From there on, no new ATR will be introduced.

The reactor strategies to meet the nuclear power program are illustrated in Fig. 1. Some typical results of evaluation for each reactor strategies are shown in Figs. 2 and 3 and Table IV. It is apparent from these results that:

(1) Introduction of fast breeder reactor is inevitable to resolve the natural uranium supply problem, and the plutonium utilization in thermal reactor will further improve the natural uranium supply situation.

(2) The requirement of separative work unit is significantly reduced by the introduction of fast breeder reactor, and further reduction of separative work unit requirement is expected by plutonium utilization in thermal reactors.

(3) Reprocessing requirement is also significantly reduced by the introduction of fast breeder reactor, and plutonium utilization in thermal reactors does not significantly change the reprocessing requirement.

(4) Accumulation of excess plutonium not in reactor use is formidable for the reference case, and plutonium utilization in fast breeder and thermal reactors is significantly improve the situation of excess accumulation of unused plutonium, and the appropriate choice of the combination of reactor types allow to minimize the amount of unused plutonium.

In summary, the utilization of plutonium in thermal and fast reactors is the necessity in Japan. The maximum natural uranium requirement will be reduced to about 400,000 t U_3O_8 as indicated in Table IV, and this amount is only about 5 % of the known and estimated world natural uranium reserves.

3. Strategies of Plutonium Utilization

It is concluded in the previous section that the utilization of plutonium in thermal and fast breeder reactors is inevitable in Japan. We, then, have to assume that the plutonium to be utilized in thermal and fast reactors is to come from discharged fuel from light water reactors at least for time being. In order, therefore, to obtain plutonium from discharged fuels, the reprocessing is the must.

There is, however, little in present world politics to encourage us now to proceed to the reprocessing of spent fuels from light ware reactors. Many reactor operators are forced to store the spent fuels at the temporary storage pools. This has been the case because of;

(1) there are no commercial reprocessing plants in operation as of November, 1976,

(2) there is strong fear of the proliferation of separated plutonium into the ill use, and it is assumed that there is no really effective technical means to prevent the proliferation at present.

The temporary storage of spent fuels in a pool sounds simple solution to meet the current reprocessing situation. But if the temporary storage should become to be extended beyond the current scope and become to the permanent storage, then the storage itself will become technically, economically and environmentally problem area. At present, most of the spent fuels from operating reactors are being stored on-site pools, but in some cases in the U.S. the off-site storage of spent fuel is being seriously considered. It is estimated that, during next decade, significant additional off-site storage will be required.

According to GE's estimate,[6] the capital costs of off-site storage will amount to US$30 to US$70 thousand a ton, depending on facility sizes. This estimate, together with estimates of operating costs, leads to conclude that long term spent fuel storage will increase the fuel cycle cost by as much as one-half to three-quarters of a mill per kW.h. This cost translates into US$4 to $6 million per year per GW(e) nuclear power plant and so it is not negligible. The permanent storage of radioactive waste in contrary, which is separated from the reprocessing of spent fuels, is much easier technically, economically and environmentally, because it is being designed to do so from the beginning. The refinement and removal of plutonium and other actinides from wastes make it easier for the wastes management.

The problem of proliferation is serious. There is concern of the potential for the added nuclear weapons proliferation if plutonium industries become widespread. However, unless abundant alternate energy sources and technologies are available to everybody, the world would be competing in very near future for limited energy sources which are currently available. This dangerous situation may be more fearful and realistic than the fear of proliferation of plutonium. Thus, it seems more sensible to develop means to make the benefits out of plutonium as a source of energy on a basis that the more definite technologies of utilizing plutonium would minimize the potential of proliferation and the in-reactor plutonium inventory is more preferable than the excess plutonium stored in the vault. In any event, the tighter safeguarding of plutonium is the prerequisite to all above conclusious.

From economical reasons, from waste management standpoint, and from non-proliferation reasons, we should conclude that the strategy of plutonium utilization in thermal and fast reactors is favorable. Thus, the establishment of plutonium industries in Japan is strongly supported by government.

The first step of establishing the plutonium industries in Japan is to support the plutonium utilization program in thermal reactors, on the basis that this technology would support for the rapid deployment of fast breeder reactors at later time.

The programatic schedule directly related to plutonium utilization in thermal and fast reactors are indicated in Table V.[7] The development of plutonium fuel fabrication facilities was the initial effort of Japan. The small scale plutonium fuel laboratory, which is not indicated in Table V, has been in operation for more than 10 years, and two plutonium fuel fabrication laboratories of 10 t/a and 3 t/a capacities for thermal reactor fuel and fast reactor fuel, respectively, have been in operation over 5 years. The experiences gained through the operations of those facilities are now being applied to the design works of 50 t/a and 10 t/a plutonium fuel fabrication pilot plants, which supply the necessary fuel for thermal and fast breeder reactors respectively. These pilot plants will soon be followed by the commercial scale plutonium fuel fabrication plants of 200 t/a for thermal reactors and of 50 t/a for fast reactors. For those pilot and production plants, the construction cost is estimated as about US$300 million.

The necessary plutonium for the plutonium utilization program should come from reprocessing plants. A small scale reprocessing plant of 200 t/a capacity is now ready to start its operation sometime in early 1977. Two large scale commercial reprocessing plants of 1,200 t/a each are scheduled to come into operation in 1986 and 1993, respectively. The construction costs for these three reprocessing plants are estimated as US$500 million.

The other related facilities such as plutonium nitrate conversion facilities, plutonium vaults, etc., are also scheduled to operate concurrently with related facilities. The estimated construction costs for these facilities are about US$170 million.

As indicated in Table V, the plutonium utilization in thermal and fast reactors do need a long lead time before their realizations. Especially, the design, construction and preoperational phases of fuel cycle facilities need considerable amount of time. It is most likely to be five to ten years. Therefore, the fuel cycle related facilities including fuel reprocessing to plutonium fuel fabrication should be started at very early stage of the program. In the past, the reactor development had enjoyed the most of research and development, but the tide has changed and the fuel cycles should be given the most attentions. Otherwise, the program schedule shown in Table V could not be met.

4. Conclusions

In this paper, an analysis on plutonium utilization strategies has been made using a Japanese situation as an example. The drawn conclusions were followings:

(1) Effective and early utilization of plutonium in thermal and fast reactors is inevitable to reduce the amount of necessary natural uranium of which the national nuclear power program can

be carried. It is especially true for the countries where the technologies exist but the resources do not exist.

(2) Early decision on the scenerio of plutonium utilization in thermal and fast reactors is truely necessary. For the case of plutonium recycle in thermal reactor, there is no time left before the scenerio decision.

(3) Based on the decided scenerio, the technology developments for reactors and for fuel cycles are necessary to be started immediately. The emphasis should be given to the fuel cycles area.

(4) Since everything is depended upon the availability of plutonium as for the source of energy, the early operation of reprocessing plant is very necessary. There exist some controversies between promotion of reprocessing and prevention of proliferation of plutonium. However, we do need to recognize the reality of that the world will face the prospect of competing for ever diminishing world supplies of oil and gas near the turn of the century.

(5) Earlier establishment of fuel cycle facilities is necessary, and this will permit the rapid deployment of fast breeder reactors in later date.

The above dawn conclusions are very applicable not only to Japan but also the countries where the energy related resources are scarce but the technologies exist or will exist.

Achieving the goal of plutonium utilization in thermal and fast reactors, the international understanding and cooperation are vital, and there is a special need to arrive at international and domestic procedures to minimize potential problems of weapons proliferation.

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Table I Japan's Long Term Nuclear Generating Installed Capacity (1976 Projection)

Year	1975	1980	1985	1990	2000
Nuclear Capacity [1] (million kW(e))	6.60	16.60	49.36	90	170
Share of Nuclear to [1] Total Electric Generation of Japan (%)	7.5	13.8	27.6	~35	~50
Share of Japanese [2] Nuclear to World Nuclear (%)	7.4	7.3	8.6	8.0	8.0

Table II Uranium Resources of the World, Tons U_3O_8, January 1976

	Reasonably Assured Reserves t U_3O_8	Estimated Additional Reserves t U_3O_8
\$ 15/lb U_3O_8	1,540,000	1,270,000
\$ 30/lb U_3O_8	2,400,000	2,450,000
Sub Total	3,940,000	3,720,000
Total World	7,660,000	

Table III Major Reactor Characteristics of Plutonium Fuelled Thermal Reactors

	Pu-Recycle Light Water Reactor	Pu-Fuelled D_2O Reactor (ATR)	CANDU
Natural Uranium Requirement kg U/MW(e)·a	117.7	29.2	95.1
Separative Work Unit Requirement kg SWU/MW(e)·a	70.7	—	—
Reprocessing Requirement kg fuel/MW(e)·a	28.8	33.6	147.9

All the requirements are based on the load factor of 75%

Table IV Accumulative Requirement and Differences of Resources Required by 2000

	CASE 1 Reference Case		CASE 2 LWR + FBR (U)		CASE 3 LWR + FBR (U, Pu)		CASE 4 LWR + ATR + FBR (U) (Pu)	
	Accumulative to 2000	Difference with Case 1	Accumulative to 2000	Difference with Case 1	Accumulative to 2000	Difference with Case 1	Accumulative to 2000	Difference with Case 1
Natural Uranium (U_3O_8) $\times 10^2 t$	48.8	—	43.4	5.4	39.1	9.7	38.6	10.2
Separative Work $\times 10^4 t$ of SWU	18.8	—	16.8	2.0	15.7	3.1	15.4	3.4
Reprocessing $\times 10^3 t$	43.0	—	44.1	▲ 1.1	44.1	▲1.1	44.5	▲1.5
Pu in Storage (t)	284	—	116	168	51	233	36	248

▲ Shows the negative effect

Table V Program Schedule related to Pu Utilization

	1976 · 1980 · 1985 · 1990 · 1995 · 2000	Construction Cost *
Pu in thermal reactors	S/A Test 1/3 Core Pu in light water reactor ATR Proto type operation Commercial Use of ATR	—
Pu in fast reactors	Experimental reactor in operation Proto type fast rsactor in operation Commercial Use of fast reactor	—
Pu fuel fabrication (thermal reactor)	10 t/a Laboratory in operation 50 t/a pilot plant in operation 200 t/a production plant in operation	166 m $
Pu fuel fabrication (fast reactors)	3t/a Laboratory in operation 10t/a pilot plant in operation 50 t/a production plant in operation	140 m $
Reprocessing Plant (thermal reactors)	200 t/a plant in operation 1200 t/a plant in operation 1200 t/a plant in operatinn	500 m $
Pu Conversion	6 kg/d plant, then 40 kg/d plant	50 m $
Pu Vault	5t vault, then 30t vault	113 m $

* 1976 value

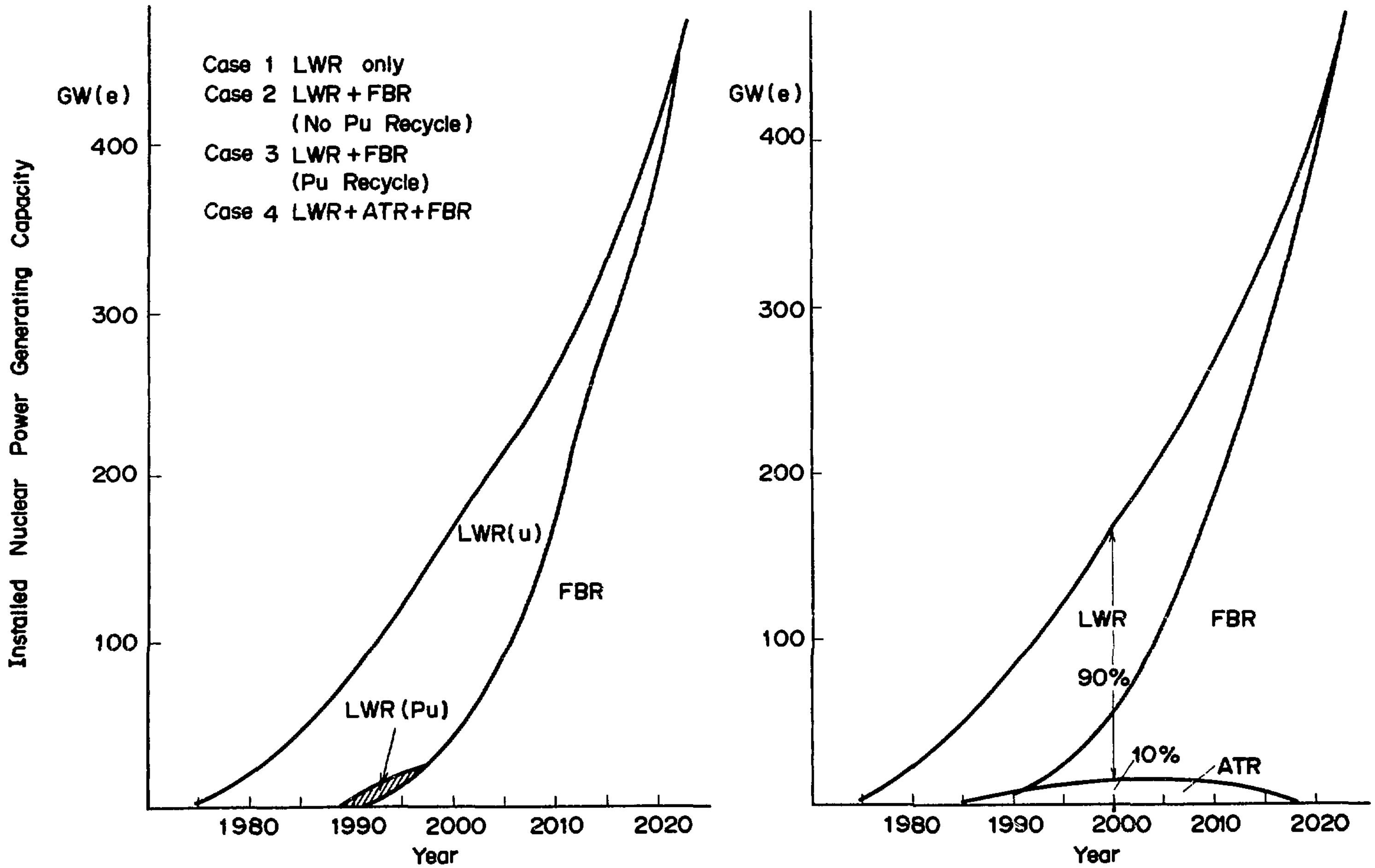

Fig. 1 Senerios of the Combination of Reactor Types

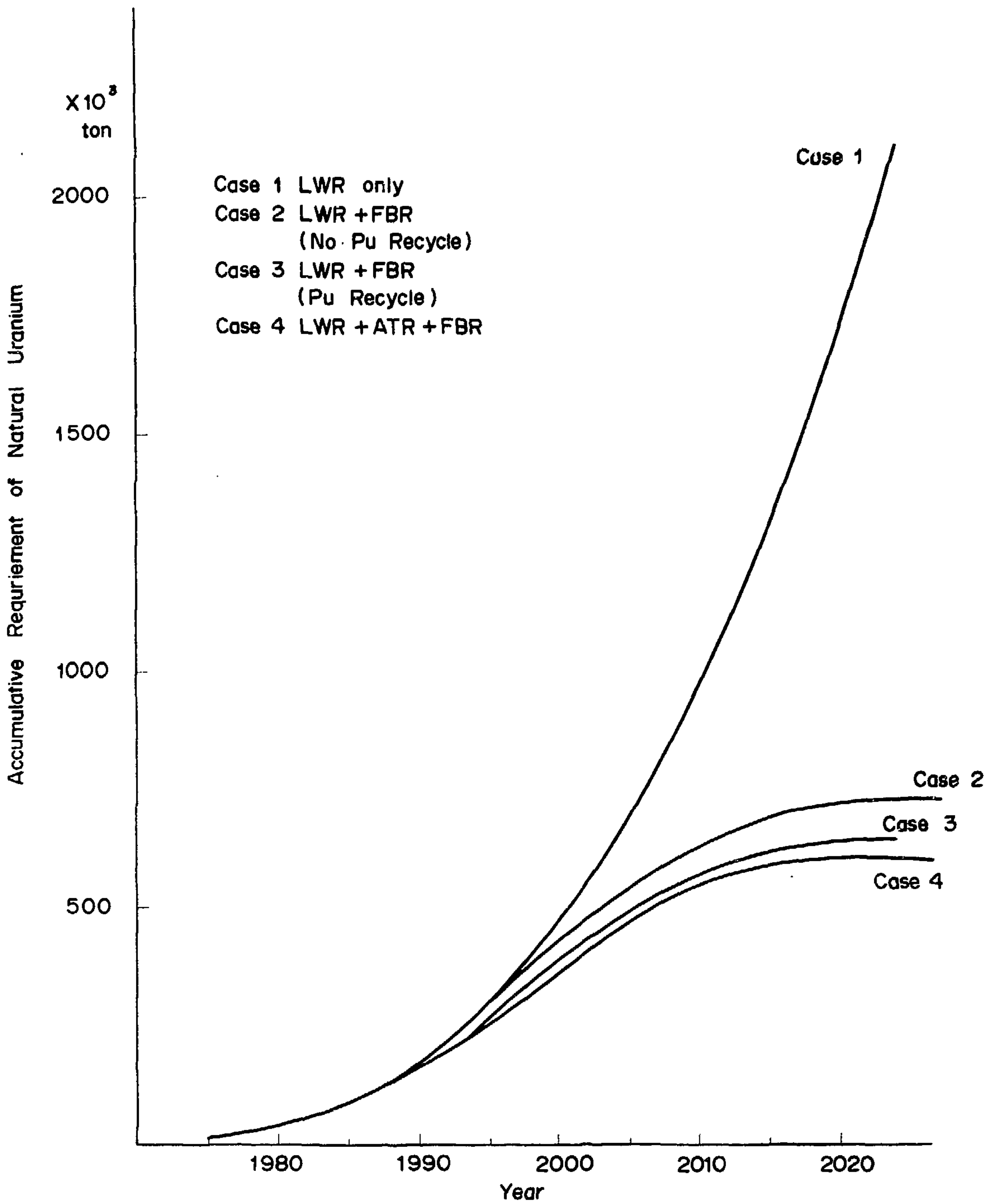

Fig. 2 Accumulative of Natural Uranium

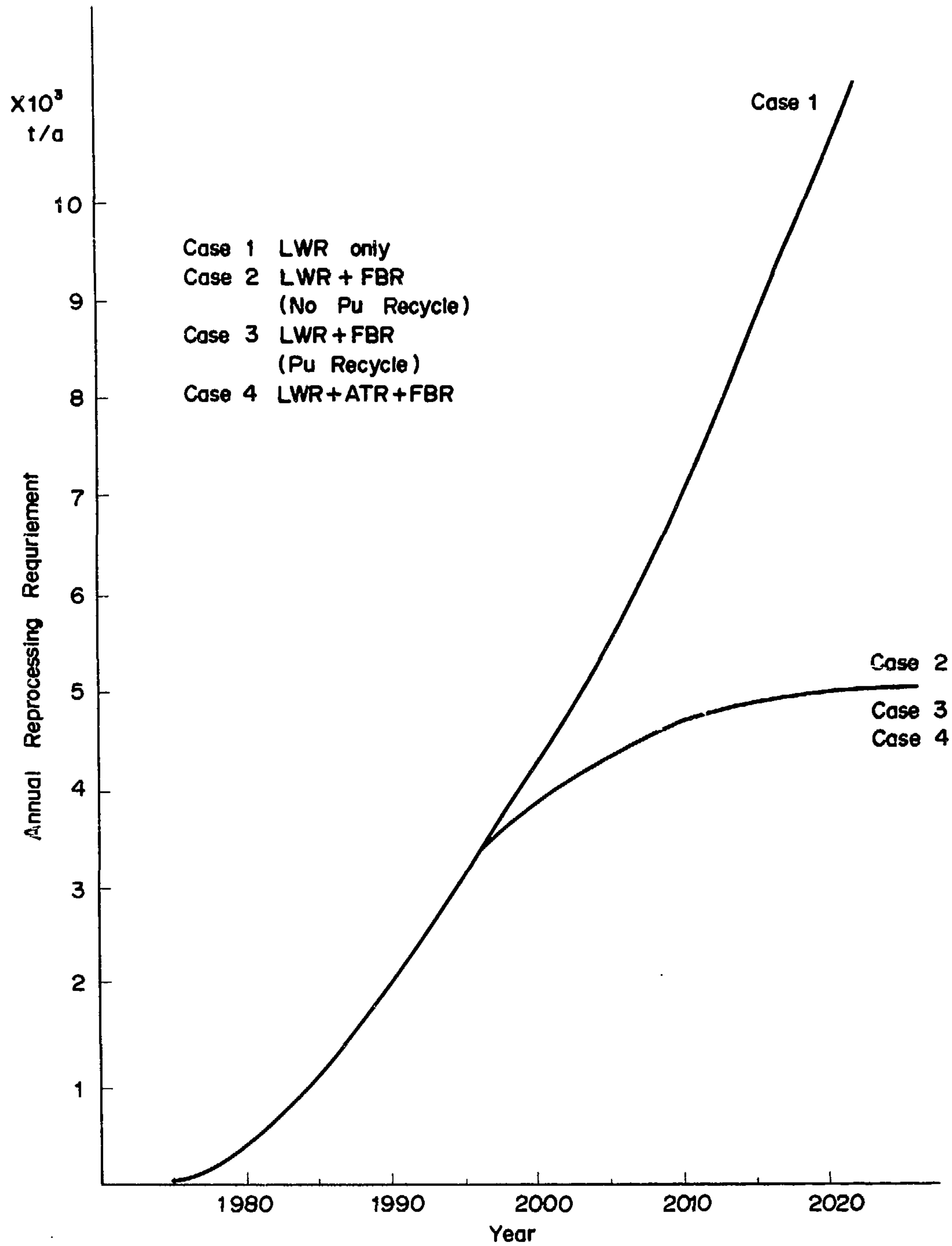

Fig. 3 Annual Reprocessing Requirement