ORNL-TM-3525

Contract No. W-7405-eng-26

Gas-Cooled Reactor and Thorium Utilization Programs

AN EVALUATION OF PLUTONIUM USE IN HIGH-TEMPERATURE GAS-COOLED REACTORS

Paul R. Kasten
Leonard L. Bennett
W. E. Thomas

OCTOBER 1971

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

CONTENTS

AN EVALUATION OF PLUTONIUM USE IN HIGH-TEMPERATURE GAS-COOLED REACTORS

Paul R. Kasten
Leonard L. Bennett
W. E. Thomas

Abstract

High-temperature gas-cooled reactors (HTGRs) are generally proposed for operation on the thorium fuel cycle using highly enriched ^{235}U as initial and makeup fissile fuel, with recycle of the bred ^{233}U. However, development of a fuel recycle technology also inherently develops the ability to fabricate plutonium-fueled HTGR fuel elements. Thus, light water reactors (LWRs) which produce plutonium, fast breeder reactors (FBRs) producing excess plutonium (or ^{233}U), and HTGRs can work together. A systems analysis study was therefore performed to help clarify the role that HTGRs might play in utilizing plutonium from light water reactors in the near future and from FBRs at times when plutonium production exceeds breeder reactor requirements.

These investigations considered competition between LWRs, FBRs, HTGRs, and fossil plant types with HTGRs utilizing either ^{235}U or plutonium as the makeup fuel (the initial fissile fuel was ^{235}U for both cases). The effects of rising ore prices, separative work prices, values of bred fissile materials, and changing capital costs with time were included in the calculations. The basic tool used in these studies was a linear programming optimization model of the U.S. utility industry, which determines the optimum long-term expansion plan of the industry with minimum cost as the objective function.

In summary, the results of this study showed that (1) use of the plutonium-makeup fuel cycle permits HTGRs to have a much deeper penetration of the power market than use of the ^{235}U-makeup fuel cycle alone (1075 plants vs 493); (2) plutonium-makeup HTGRs are economically preferred over plutonium-fueled LWRs over the period of this study (1970-2015); (3) use of Pu-makeup HTGRs has no significant influence on the introduction and use of FBRs; (4) as the price of uranium ore rises and the price of plutonium decreases, it will eventually be necessary for HTGRs to operate with plutonium as the initial fissile fuel if they are to compete with LWRs fueled with uranium tails and plutonium; and (5) if FBRs produce excess fissile fuel it appears economically desirable that such fuel be ^{233}U for use in HTGRs.

BLANK PAGE

1. INTRODUCTION

High-temperature gas-cooled reactors (HTGRs) are generally proposed for operation on the thorium fuel cycle using highly enriched ^{235}U as initial and makeup fissile fuel, with recycle of the bred ^{233}U. However, development of a fuel recycle technology also inherently develops the ability to fabricate plutonium-fueled HTGR fuel elements. Thus, fast breeder reactors (FBRs) producing excess plutonium (or ^{233}U) and HTGRs can work together, as indicated in Fig. 1.

At the present time, HTGRs are being offered commercially to utilities on the basis of ^{235}U-thorium fueling and the assurance of the USAEC of reasonable costs for recovering the bred ^{233}U. Further, the AEC is supporting HTGR fuel recycle development whose purpose is to develop the technology required for economically recycling bred fuel from HTGRs. This technology would also permit economic fabrication of plutonium-fueled HTGR fuel elements.

Light water reactors presently built and under construction will in a few years provide large quantities of plutonium for use either in light water reactors, HTGRs or in fast breeder reactors. While it is generally agreed that plutonium is best used in fast breeder reactors, the time of introduction of these reactors on a commercial basis is far enough away that recycle of plutonium in light water reactors or in HTGRs is highly probable. The purpose of this study is to help clarify the role that HTGRs might play in utilizing plutonium from light water reactors in the near future and from FBRs at times when plutonium production exceeds breeder reactor requirements. Thus, investigations were performed of the competitiveness of the HTGR in meeting the long-term industry expansion needs, considering competition from other nuclear and fossil plant types; in particular, the influence of using plutonium as makeup fuel on that competitiveness was studied. Effects of rising ore prices, separative work prices, values of bred fissile materials, changing capital costs, etc., were included in the calculations. Classes of power plants in competition with the HTGR were assumed to be: fossil (represented by coal-fired plants), light water converters (represented by PWRs), and fast breeders (represented by LMFBRs). Each of these classes has other plant types, such as oil-fired, BWR, and GCFBR. Although not complete,

ORNL DWG 71-7053R

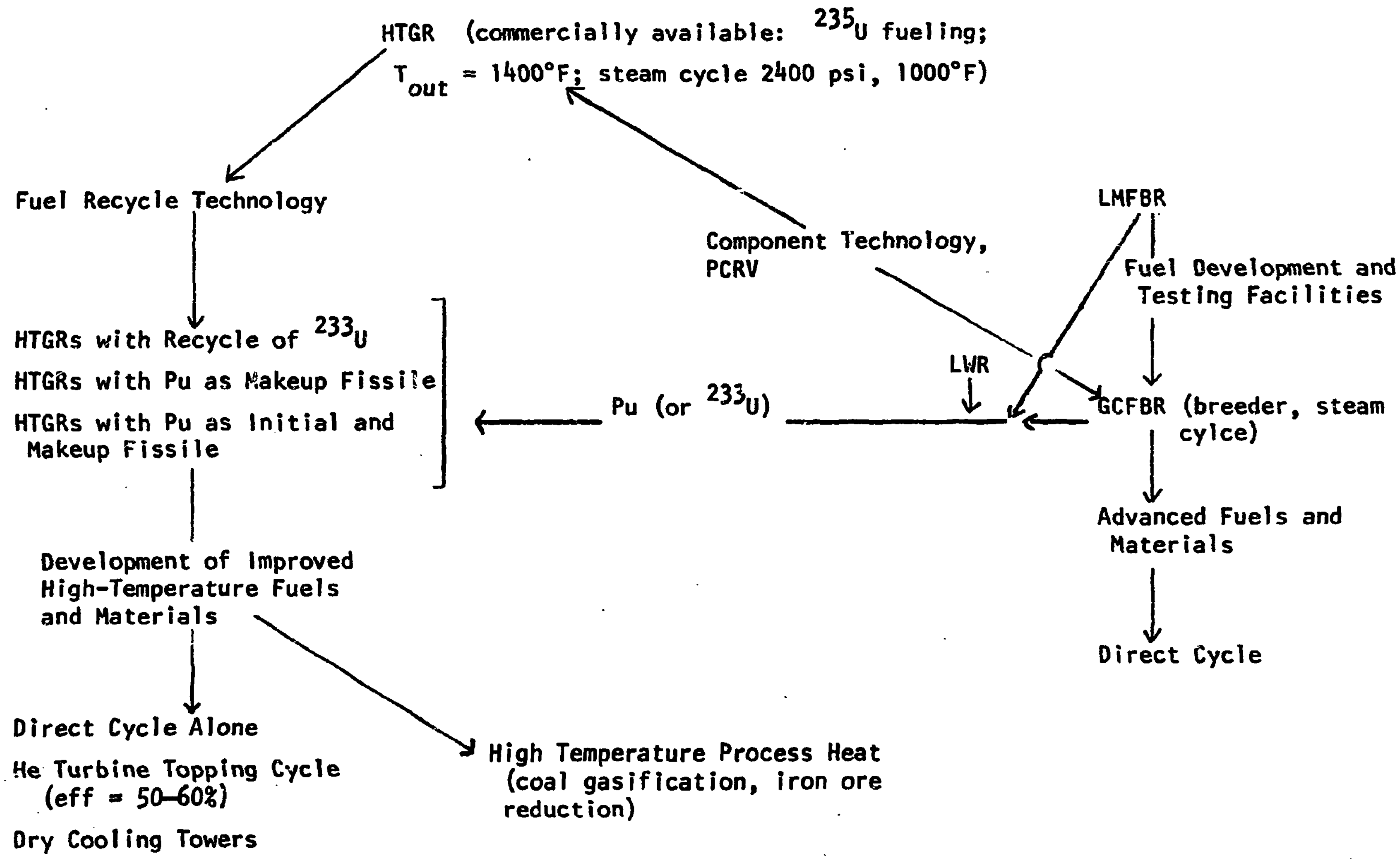

Fig. 1. Gas-Cooled Reactor Development.

the use of the selected representative types should permit a realistic evaluation of the relative economic competition faced by the HTGR.

The basic tool used in these studies was a linear programming optimization model of the U.S. utility industry, which determines the optimum long-term expansion plan of the industry. Previous work with similar models was carried out in the AEC Systems Analysis Task Force Studies (SATF) in 1967-1968. Results from this previous work were reported in USAEC Reports WASH-1098 and WASH-1126.

The computer model contains subroutines which project costs of fuel cycle services (such as fuel preparation, fabrication, processing, shipping, etc.) as a function of throughput of fuel from each reactor type. The description of the fuel cost models is contained in USAEC Report WASH-1099. Using cost data prepared by the fuel cost subroutines, and reactor mass balance data (largely obtained from previous task force studies), the long-term optimization of plant selections is carried out by a linear programming model that was written at ORNL, closely patterned after the Systems Analysis Task Force model written at PNL (now HEDL). A detailed description of the ORNL code, called ORSAC (for Oak Ridge Systems Analysis Code), is presented in ORNL-TM-3223.

2. GROUND RULES AND STUDY DESCRIPTION

Table 1 shows some of the ground rules chosen for this study. The period covered in the calculations was from January 1, 1970 through December 31, 2039. However, all reported costs and other results cover only the 45-year period through December 31, 2015. The additional 24 years was used to reduce the probability of end-effect error in the period of interest.

Table 2 indicates the sources of reactor characteristics and most of the fuel cycle data. The PWR data was prepared during the SATF studies and are generally described in WASH-1082. A total of 19 different PWR fuel cycles was used, including uranium-fueled cycles, plutonium plus natural uranium-fueled cycles, and plutonium plus depleted uranium-fueled cycles. The HTGR data prepared during the SATF

Table 1. Ground Rules for ORSAC Calculations

1.	Separative Work Price:	Thru 2-21-71	$26/kg
		Thru 12-31-71	$28.70/kg
		Thereafter	$32/kg
2.	Electrical Energy Demand:	From FPC 1970 National Power Survey	
3.	Discount Rate:	7%/year	
4.	HTGR Availability Date:	1978	
5.	LMFBR Availability Date	1986	

Table 2. Sources of Reactor Data Used in ORSAC Calculations

1. PWR data from WASH-1082
2. HTGR data from WASH-1085
3. LMFBR Data
   a) AI follow-on design 1986-1990
   b) GE follow-on design 1990-

studies are reported in WASH-1085; in addition, these data were supplemented by plutonium-makeup cycles calculated by ORNL and by Gulf General Atomic (GGA). The LMFBR data were prepared by Argonne, based on the 1000-Mwe LMFBR follow-on designs by Atomics International and General Electric. The AI design was selected as the "reference design" and introduced in 1986. The GE design was designated as an "advanced design," and was not introduced until 1990. Both designs were available after 1990.

3. FOSSIL FUEL PRICES

Figure 2 shows the distribution of coal prices used in the study. As shown here, the distribution of coal prices was divided into 13 segments having approximately equal energy fractions. The average price of coal from this distribution is about \$7.50/ton (about 32¢/MMBTU). In general, when nuclear energy becomes competitive with a given coal price, nuclear will capture the entire block shown. The coal prices were held constant during the study horizon.

4. URANIUM ORE PRICES

Uranium reserves were entered as a table of quantities available at a given price, as shown in Table 3. The effect of cumulative ore usage on uranium prices was automatically included in the optimization process.

Table 3. Uranium Ore Available at Given Prices

Thousands of Tons of U_3O_8	Average Price \$/lb U_3O_8
0 - 300	7.25
300 - 700	9.00
700 - 1100	11.25
1100 - 1500	13.75
1500 - 1800	17.50
1800 - 2100	22.50
2100 - 2300	27.50
2300 - 2500	32.50
2500 - 2800	37.50
2800 - 4000	42.50
4000 - 10000	50.00

Based on current domestic uranium reserves and estimates of additional available resources in recognized favorable geological environments.

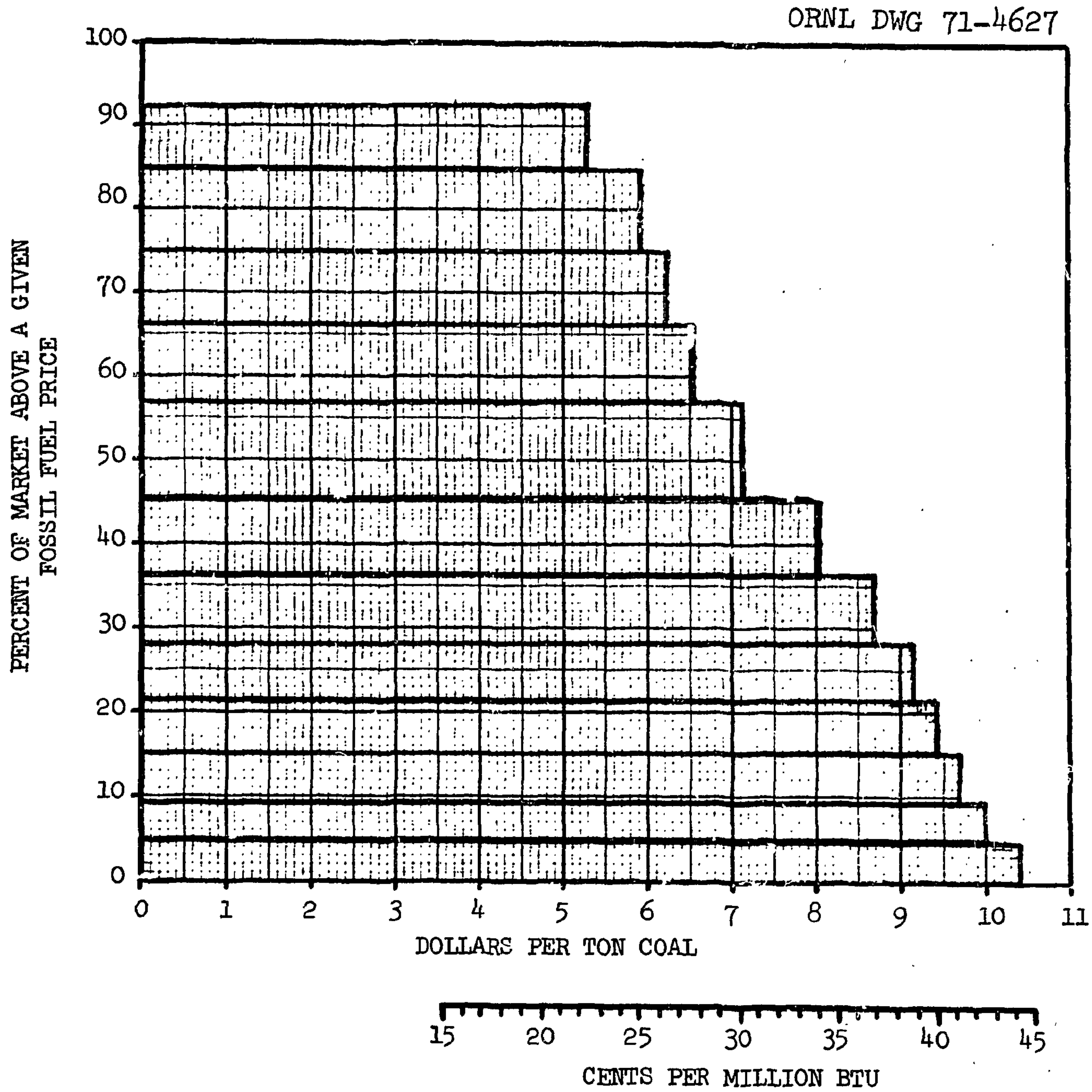

Fig. 2. Fossil Fuel Price Distribution Used in ORSAC Studies.

5. POWER PLANT CAPITAL COSTS

Capital costs were estimated as a function of plant size for each plant type included in the study. We then superimposed a projection of plant size as a function of time, plus a curve of cost reductions due to "learning." The final result was a curve of capital cost versus time for each of the plant types. These costs are shown in Fig. 3. The costs shown here are in constant 1970 dollars, and do not include any escalation during construction. The reduction with time is due to the combined effects of increase in plant size plus learning. A complete discussion of the capital cost estimates is presented in ORNL-TM-3243.

6. HTGR FUEL CYCLE DATA

Previous system analysis studies made by the USAEC have included plutonium-fueled LWRs, but have not considered plutonium makeup for the HTGR. Results from those studies have generally shown that large numbers of plutonium-burning LWRs are introduced when excess plutonium is produced by fast breeders. However, other studies have indicated that plutonium has a higher fuel value in the HTGR than in LWRs. Hence, it seemed appropriate to include plutonium-makeup HTGRs in system analysis studies.

The so-called reference design HTGR described in WASH-1085 was selected by ORNL for fuel cycle calculations with plutonium taking the place of highly enriched uranium (93.5% ^{235}U) as the purchased makeup material. However, ^{235}U was used for the initial loading and as part of the makeup material until ^{233}U had built up in the reactor (to simplify startup). The makeup plutonium composition was held constant with isotopic fractions typical of LWR discharge plutonium (60% ^{239}Pu, 24% ^{240}Pu, 12% ^{241}Pu, 4% ^{242}Pu). Since the HTGR was initially fueled with ^{235}U, this reactor type was not completely divorced from the diffusion plant. However, both ore and separative work requirements are greatly reduced, relative to use of the standard ^{235}U-makeup cycle. Table 4 presents 30-year fuel consumption data for the ^{235}U-makeup and the Pu-makeup cycles. The net consumptions imply conversion ratios of about 0.8 for the ^{235}U-makeup case and about 0.6 to 0.65 for the Pu-makeup case.

ORNL 71-4632

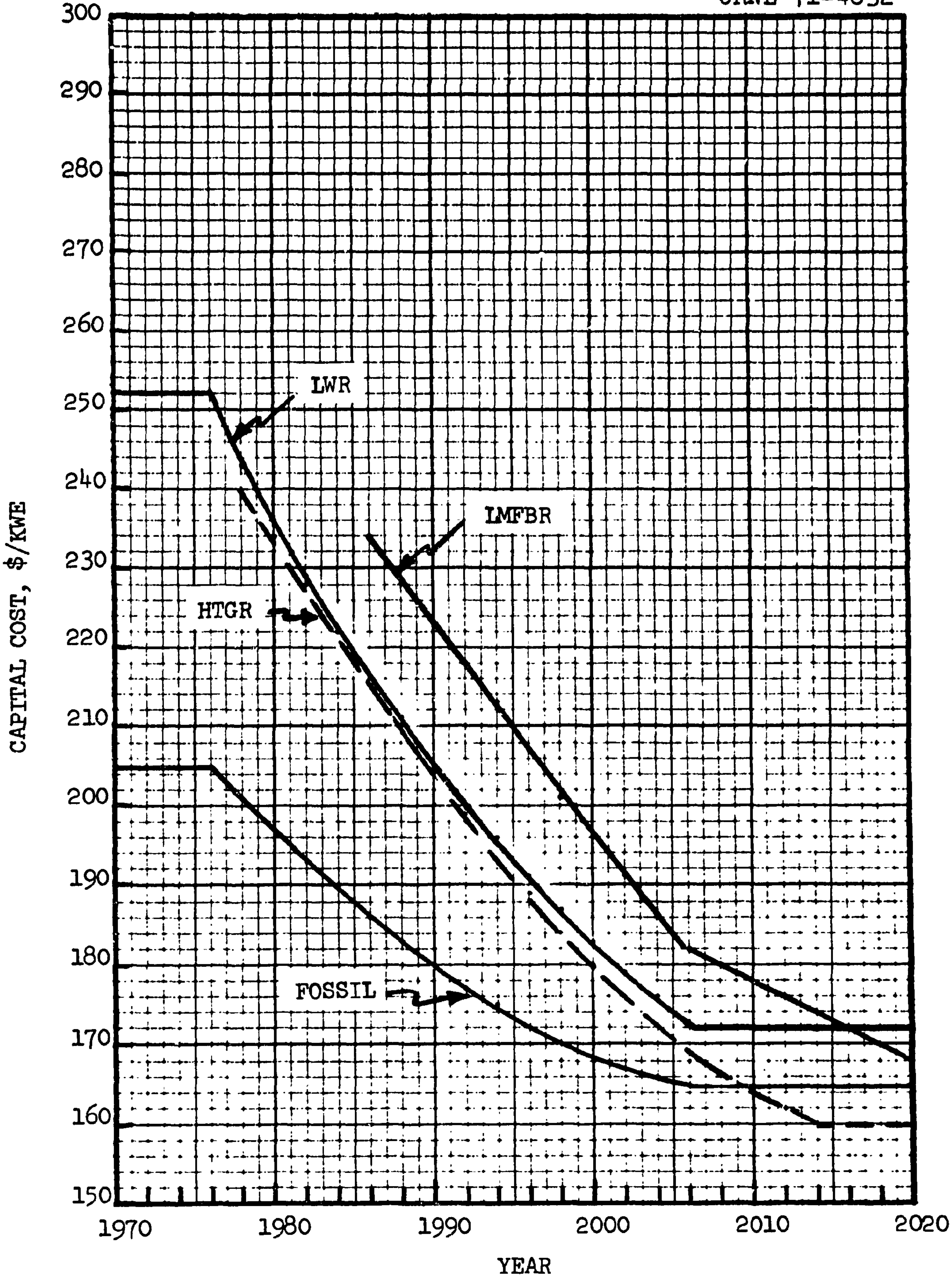

Fig. 3. Power Plant Capital Costs Used in ORSAC Calculations (All Costs are in Constant 1970 Dollars).

Table 4. Summary of 30-Year Fuel Requirements for a 1000-Mwe HTGR with Either ^{235}U-Makeup or Pu-Makeup

	Reference ^{235}U-Makeup Cycle	Plutonium Makeup Cycle
Total Makeup Feed, kgs		
^{235}U	8,055	1,990
Fissile Pu		8,685
Total Fuel Remaining[a] at End of 30 Years, kgs		
Fissile Pu		245
Bred ^{233}U	1,350	810
Bred ^{235}U	175	90
Makeup ^{235}U[b]	1,250	∿ 275
Net 30-Year Consumption, kgs		
Fissile Pu		8,440
Bred Uranium	-1,525	- 900
Makeup ^{235}U	6,805	1,715
TOTAL	5,280	9,255
30-Year Supply Requirements[c]		
Sep. Work, MTU	1908.5	471.5
U_3O_8, Short Tons	1470.7	472.4

[a]Includes final reactor loading plus fuel discharged from recycle, but which was still in the pipeline.

[b]Partially burned makeup ^{235}U is stored but is not recycled due to high ^{236}U content (no credit is taken for this material).

[c]With 0.2% ^{235}U in diffusion plant tails.

7. SUMMARY OF RESULTS

The items discussed in the preceding sections constituted the input to the linear programming model of the U.S. electric utility industry. All the plant types competed for the plant addition requirements to meet expansion needs of the industry. Table 5 presents a tabular summary of the optimum plant additions as obtained from the ORSAC calculation, while Fig. 4 presents the results graphically.

These results indicate that the HTGR is in fact the preferred system for using the plutonium made available from the fast breeders. In the earlier years, however, a Pu-fueled PWR is built in sizeable numbers. This selection of the PWR is caused by two factors.

1. The linear program model incorporated a constraint such that the maximum number of HTGRs which could be built in a given period was limited to twice the number which were built in the previous period, beginning with a maximum of two plants in the initial period.
2. The computer-selected PWR uses plutonium for only the first 4 years of operation, switching to enriched uranium for the final 26 years. Thus, the plutonium is tied up for only 4 years, compared with a 30-year commitment in the HTGR, for the cases considered.

A comparable ORSAC case was also run without the Pu-makeup HTGR included, and the results are shown in Fig. 5. As expected, fewer HTGRs were built in the 1970-2015 period. The LMFBR captures the major part of the new capacity requirements, while the Pu-fueled LWR is built to utilize the excess plutonium. For the ^{235}U-makeup case, the HTGR is built only during the period before the LMFBR is introduced, plus a few built to utilize the ^{233}U made available by retirements of older HTGRs. Table 6 compares the results of the two cases, one of which considered plutonium makeup to be possible, while the other considered ^{235}U makeup alone.

The above results also indicate that high-performance fast breeders will be built in about the same numbers independent of the use of plutonium-fueled HTGRs, and that they provide a major portion of the central station power plant needs. As FBRs are built in large numbers, large quantities of excess plutonium will be produced and a system to use this plutonium

Table 5. NUMBER OF 1000-MWE POWER PLANTS ADDED IN EACH TWO-YEAR PERIOD FROM 1970-2015

Two-Year Period Beginning	Number of Plants Added During Period						
	PWR		HTGR		LMFBR	Fossil	Total[2]
	U-fueled	Pu-fueled	U-fueled	Pu-fueled			
1970	11.3	0	n.a.[1]	n.a.	n.a.	39.7	51.
1972	30.8	0.6	n.a.	n.a.	n.a.	27.6	59.
1974	17.0	3.8	n.a.	n.a.	n.a.	29.2	50.
1976	8.2	6.7	n.a.	n.a.	n.a.	60.1	75.
1978	27.0	6.6	0	2.0	n.a.	31.4	67.
1980	33.4	12.2	0	4.0	n.a.	43.4	93.
1982	16.8	16.9	0	8.0	n.a.	36.3	78.
1984	56.7	0	16.0	0	n.a.	42.3	115.
1986	23.9	0	32.0	0	8.0	37.1	101.
1988	12.4	0	64.0	0	16.0	53.6	146.
1990	0	0	71.5	0	32.0	27.5	131.
1992	0	0	35.1	29.1	64.0	24.8	153.
1994	0	0	3.2	34.1	128.0	8.7	174.
1996	0	0	3.8	0	177.8	9.4	191.
1998	0	0	0	96.0	116.2	4.8	217.
2000	0	0	3.1	66.0	158.4	0	227.
2002	0	0	4.9	77.1	148.9	0	231.
2004	0	0	9.3	81.3	184.3	0	275.
2006	0	0	3.7	88.8	190.3	0	283.
2008	0	0	9.5	146.1	178.6	0	334.
2010	0	0	11.4	89.6	211.5	0	313.
2012	0	0	10.4	47.2	250.0	0	308.
2014	0	0	6.2	21.8	342.4	0	370.
Total Additions 1970-2015	238.	47.	284.	791.	2206.	478.	4042.

(1) This plant type was not available in the periods marked "n.a."

(2) Totals may not agree precisely with sum of individual values, due to round-off differences.

ORNL DWG 71-9244R

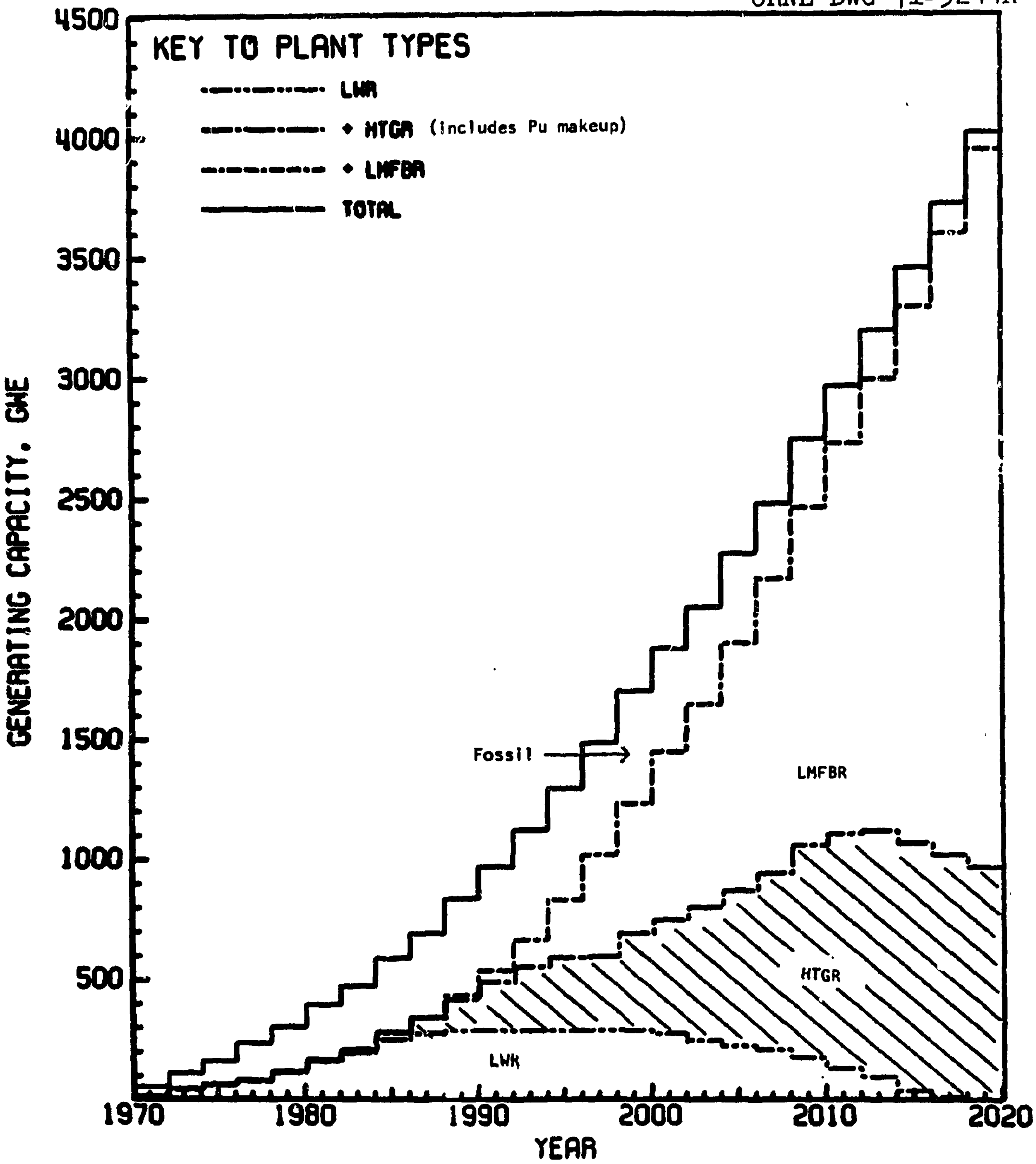

Fig. 4. Total Generating Capacity, GWE, as a Function of Reactor Type and Time Based on Table 5 (Including Additions and Retirements During Period.)

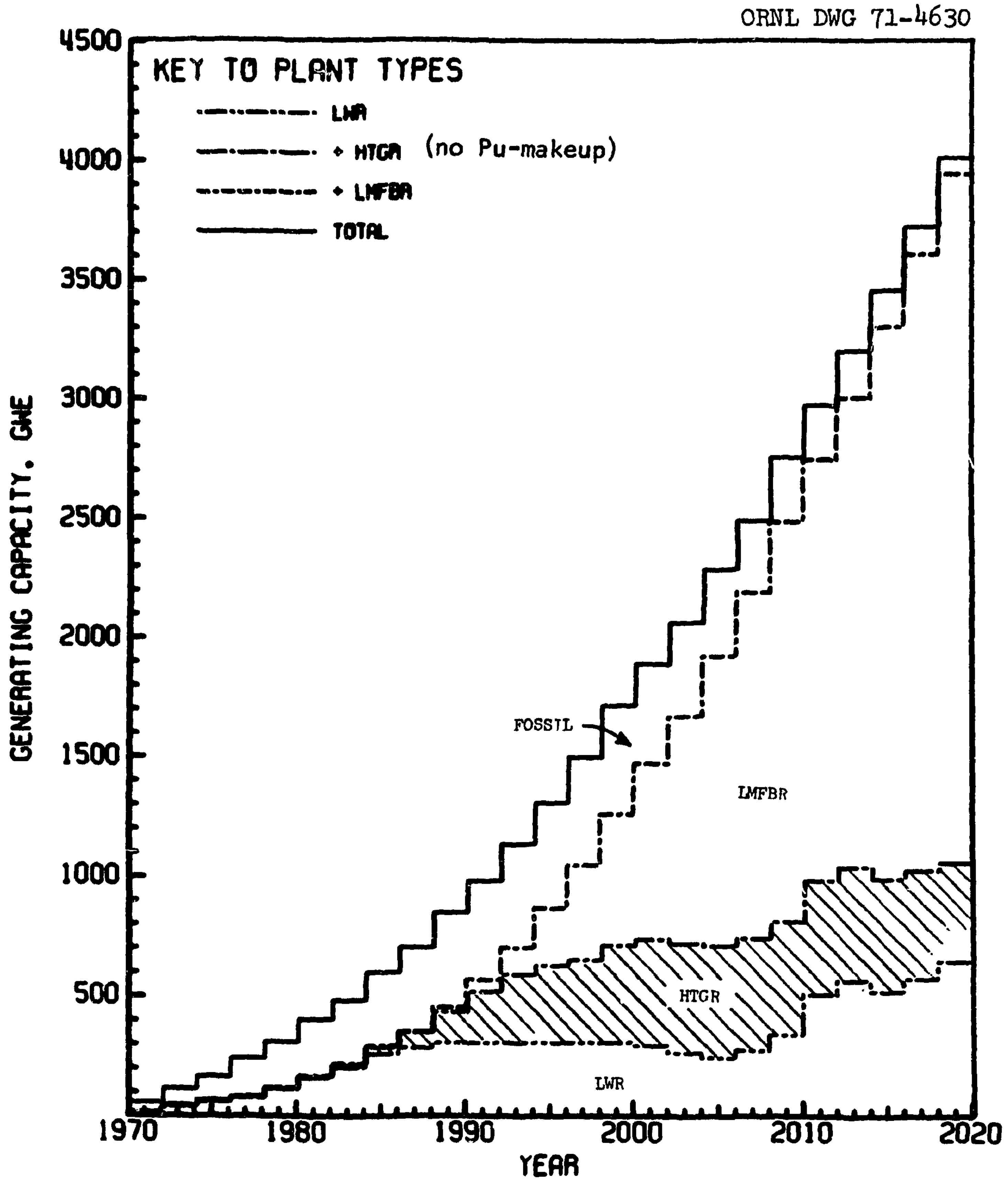

Fig. 5. Total Generating Capacity, GWE, As a Function of Reactor Type and Time, Excluding Use of the Pu-Makeup HTGR (Including Additions and Retirements During Period).

Table 6. Comparison of ORSAC Results With and Without Plutonium-Makeup HTGR — Total Number of 1000-Mwe Plants Built in 1970-2015 Period

	Pu-Makeup HTGR Included	Without Pu-Makeup HTGR
Light-Water Reactors		
Uranium Fueled	238.	220.
Plutonium Fueled	47.	547.
Total	285.	767.
HTGR		
Uranium Makeup	284.	493.
Plutonium Makeup	791.	
Total	1075.	493.
LMFBR	2206.	2331.
Fossil	478.	451.

will be needed. The favorable capital and fuel cycle cost for the HTGR makes that reactor a logical choice to fill this role, if the Pu-makeup cycle is made available. (This result is in agreement with fuel cycle calculations performed previously at Gulf General Atomic and at Oak Ridge National Laboratory, which indicated that the value of fissile plutonium is higher in HTGRs than in LWRs.) If the Pu-makeup cycle is not considered for the HTGR, then that reactor has a much smaller role in the optimum system expansion, and the plutonium fueled LWR becomes the dominant system to supplement the LMFBR.

Additional significant information obtained in this study concerns the trends in power costs for the various reactor systems with time, and the shadow price of fissile fuels. Figure 6 gives the power cost as a function of time for the different reactor types, considering various fuel cycles. For the cases calculated, the fast breeder reactor controls

ORNL DWG 71-7041

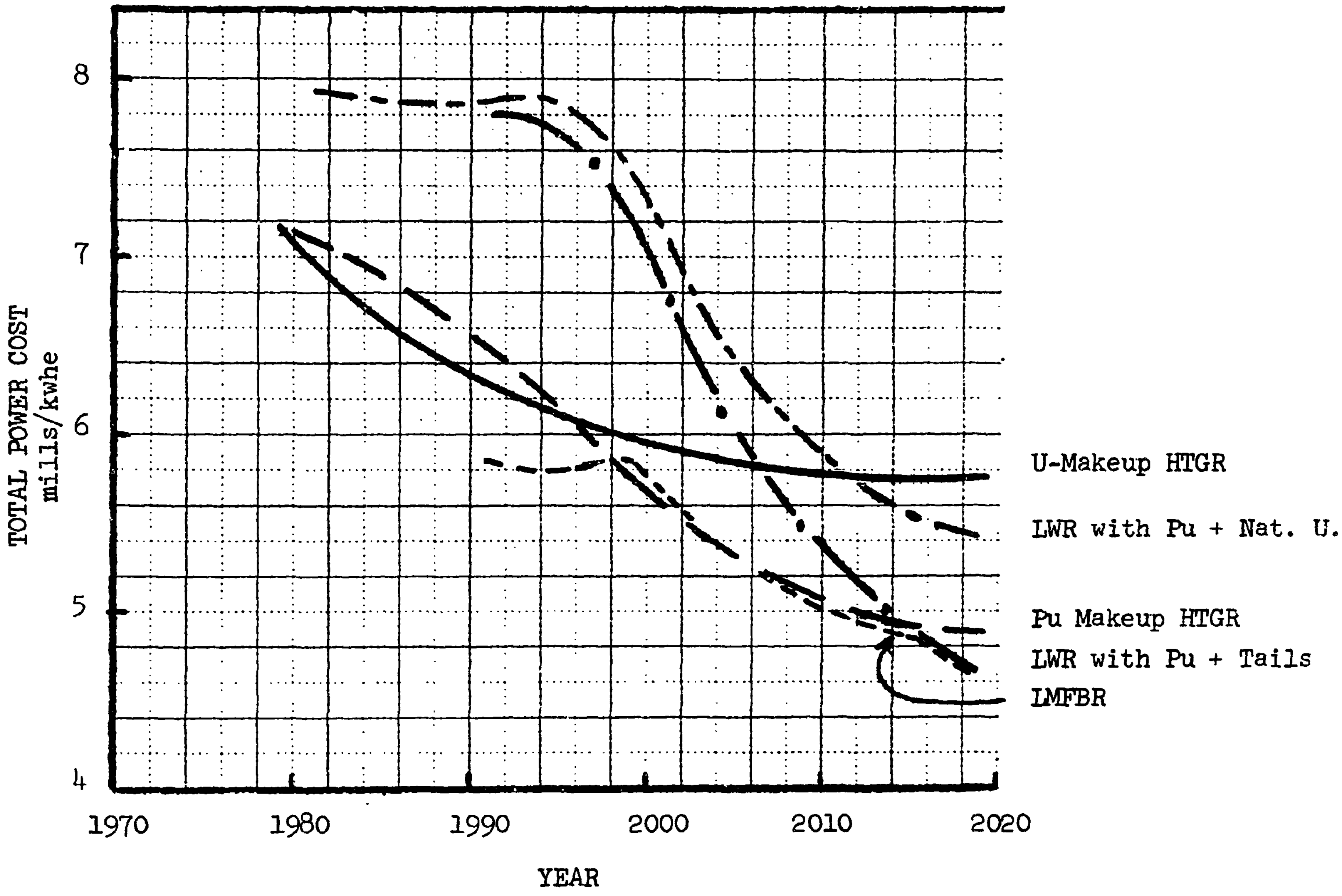

Fig. 6. Total Power Costs Vs Time

the power cost of the system, leading to FBR dominance in future years. Also, as the shadow price of plutonium falls, the power cost of the LWR fueled with Pu and depleted uranium falls significantly, becoming lower than power costs from the Pu-makeup HTGR about 2015. This is due to the increasing cost of uranium ore, causing the initial fueling cost of the HTGR to rise. At the same time, the initial fueling cost of the LWR is not influenced by the cost of uranium ore, since the value of tails material would not change significantly. If the HTGR were fueled with plutonium-thorium, however, the penalty associated with rising uranium ore prices would not occur. These results indicate that if plutonium-fueled HTGRs are to maintain dominance over plutonium-fueled LWRs in future years, use of plutonium as the initial as well as the makeup fissile fuel will be required. While this should be possible, specific studies of HTGRs fueled initially with plutonium need to be performed, considering the plutonium to be that produced by FBRs.

Figure 7 gives the shadow price of bred fissile materials as a function of time, and also the U_3O_8 price, for the case which considered the Pu-makeup HTGR. The increasing value of the fissile plutonium initially is due to its relatively high value in FBRs and the economic incentive to install FBR plants, while the decreasing value in future years is due to the production of excess plutonium by the large FBR capacity in existence at that time. The ^{233}U value vs time has in general the same type behavior as does plutonium; however, somewhat surprising is the relatively high value obtained for ^{233}U. This is due to the economic attractiveness of HTGRs, and the high value of ^{233}U relative to plutonium in HTGR plants. Also, it is significant that the value of ^{233}U remains relatively high in future years, which indicates that when FBRs start producing excess fissile fuel, that material should be ^{233}U. Figure 7 also indicates that even prior to the year 2000 there may be overall economic benefits if FBRs were to produce some ^{233}U for use in HTGRs.

8. CONCLUSIONS

In summary, the results of this study show that (1) use of the plutonium-makeup fuel cycle permits HTGRs to have a much deeper penetration of the power market than use of the ^{235}U-makeup fuel cycle

ORNL DWG 71-7050

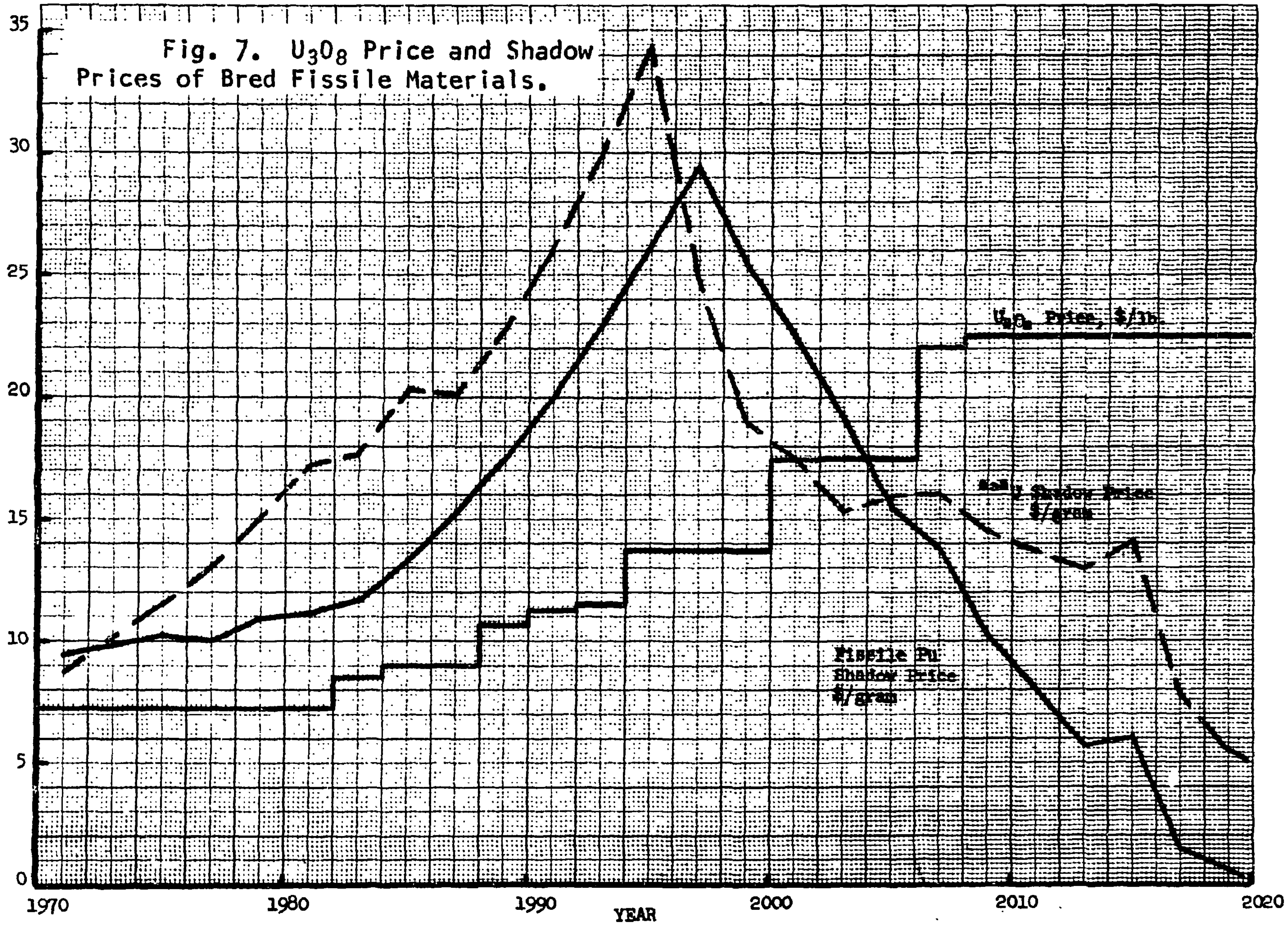

Fig. 7. U_3O_8 Price and Shadow Prices of Bred Fissile Materials.

alone; (2) plutonium-makeup HTGRs are economically preferred over plutonium-fueled LWRs over the period of this study; (3) as the price of uranium ore rises and the price of plutonium decreases, it will eventually be necessary for HTGRs to operate with plutonium as the initial fissile fuel if they are to compete with LWRs fueled with uranium tails and plutonium; (4) use of Pu-makeup HTGRs has no significant influence on the introduction and use of FBRs; and (5) if FBRs produce excess fissile fuel it appears economically desirable that such fuel be ^{233}U for use in HTGRs.

BIBLIOGRAPHY

1. Potential Nuclear Power Growth Patterns, USAEC Report WASH-1098, December 1970.

2. Cost-Benefit Analysis of the U.S. Breeder Reactor Program, USAEC Report WASH-1126, April 1969.

3. Reactor Fuel Cycle Costs for Nuclear Power Evaluation, USAEC Report WASH-1099 (to be published).

4. F. G. Welfare, et al., The Oak Ridge Systems Analysis Code (ORSAC) Users' Manual, USAEC Report ORNL-TM-3223, Oak Ridge National Laboratory, June 1971.

5. Current Status and Future Technical and Economic Potential of Light Water Reactors," USAEC Report WASH-1082, March 1968.

6. An Evaluation of High-Temperature Gas-Cooled Reactors, USAEC Report WASH-1085, December 1969.

7. H. I. Bowers and M. L. Myers, Estimated Capital Costs of Nuclear and Fossil Power Plants, USAEC Report ORNL-TM-3243, Oak Ridge National Laboratory, March 5, 1971.

APPENDIX

For completeness, the results for the case of no introduction of fast breeder reactors is given in Fig. A-1 (other bases are the same as in the body of this report). As shown, the HTGR dominates the future power market for such a condition based on the study performed. Also, results concerning separative work requirements and natural uranium ore requirements for various cases are given in Table A-1 and Figs. A-2 through A-4. Figure A-2 gives results for the case where only fossil fuel and LWR plants are installed; Fig. A-3 considers fossil fuel, LWR, and HTGR (U-fueled) plants to be available for construction; while Fig. A-4 considers fossil fuel, LWR, HTGR (U-fueled) and LMFBR plants available for construction. The mined ore and separative work requirements for Case No. 73 (same as Case No. 63 except the plutonium-makeup HTGR was considered in the solution) were essentially the same as the results given in Fig. A-4.

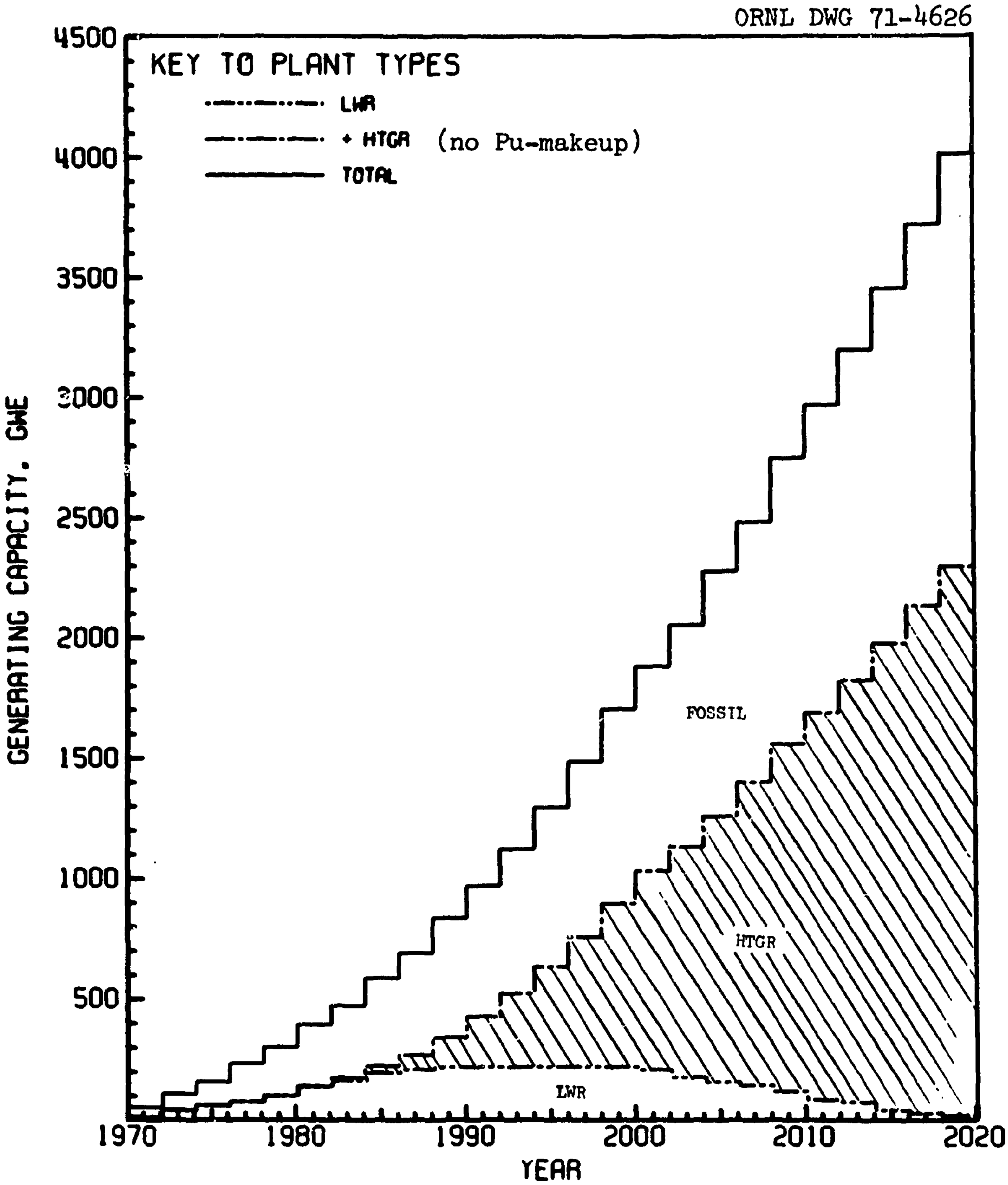

Fig. A-1. Total Generating Capacity, GWE, If LMFBRs are not Included (Including Additions and Retirements During Period).

Table A-1. Uranium Ore Requirements and Separative Work Requirements for Various Cases

Case Number	41	61	63	73
Plants Included	Fossil LWR	Fossil LWR HTGR-U	Fossil LWR HTGR-U LMFBR	Fossil LWR HTGR-U LMFBR HTGR-Pu
<u>Uranium Consumption and Price</u>				
Thousands of tons of U_3O_8 used thru 2019	3020	3540	1980	2060
U_3O_8 Price thru 2019				
Maximum	42.50	42.50	22.50	22.50
Average	20.00	23.30	12.65	13.05
Separative work (kilotonnes/yr)				
Maximum	87.	200.	62.	59.
Ave. thru 2019	46.	75.	30.	32.

ORNL DWG 71-9247

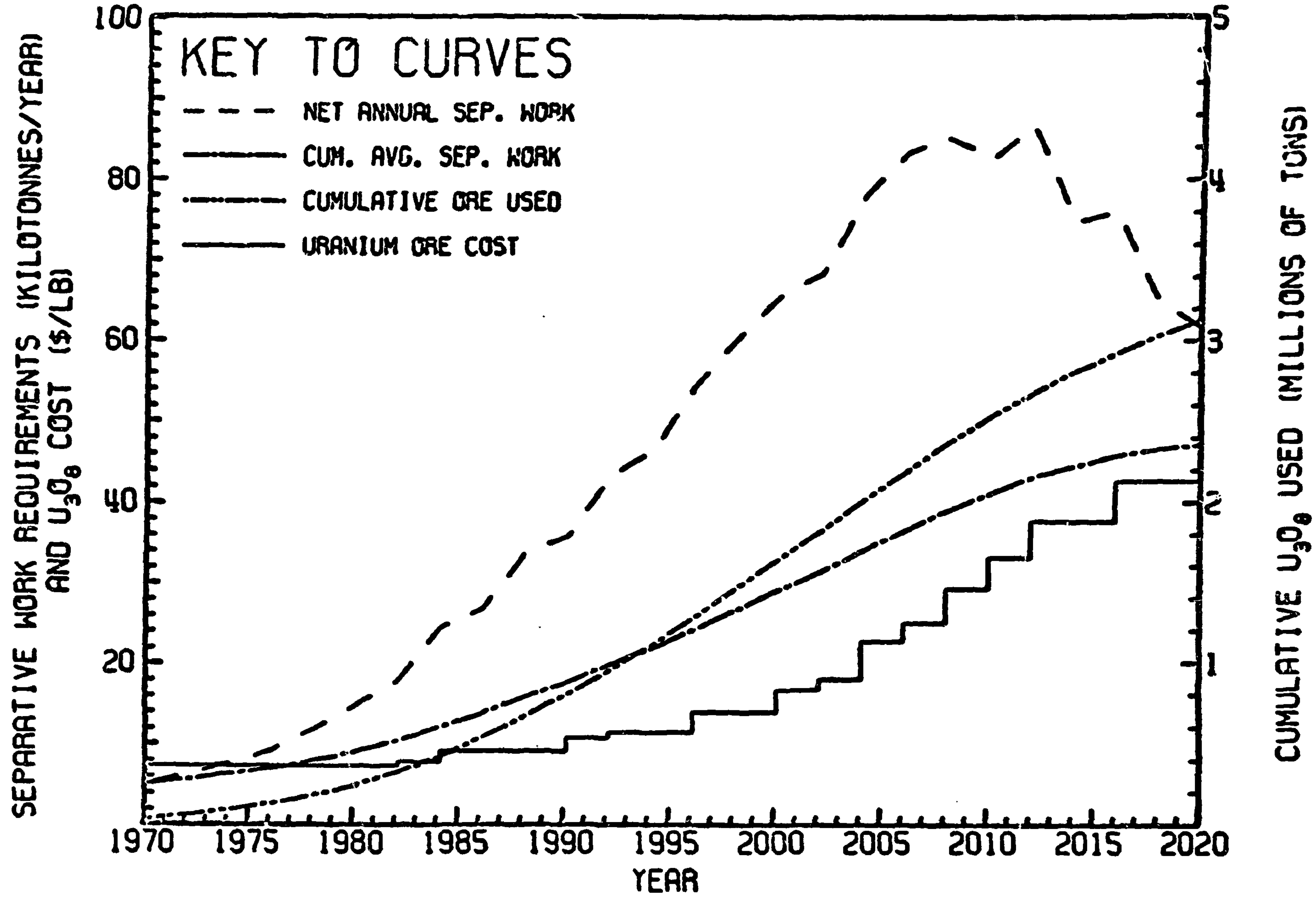

Fig. A-2. Separative Work Requirements and U_3O_8 Cumulative Use and Cost, For Use of LWR + Fossil Plants Only (Case No. 41).

ORNL DWG 71-9245

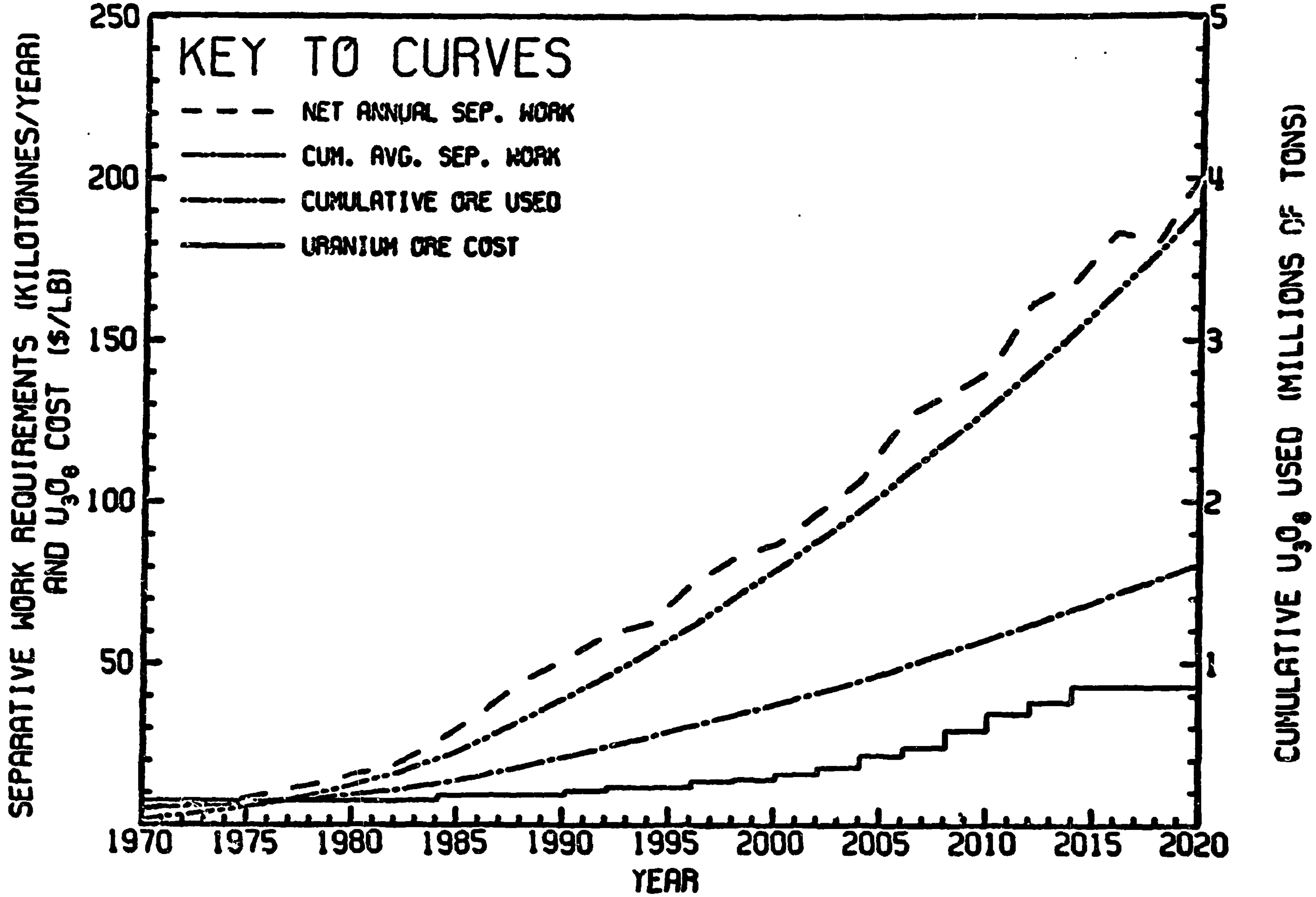

Fig. A-3. Separative Work Requirements and U_3O_8 Cumulative Use and Cost, For Use of Fossil + LWR + U-Fueled HTGR (Case No. 61).

ORNL DWG 71-9246

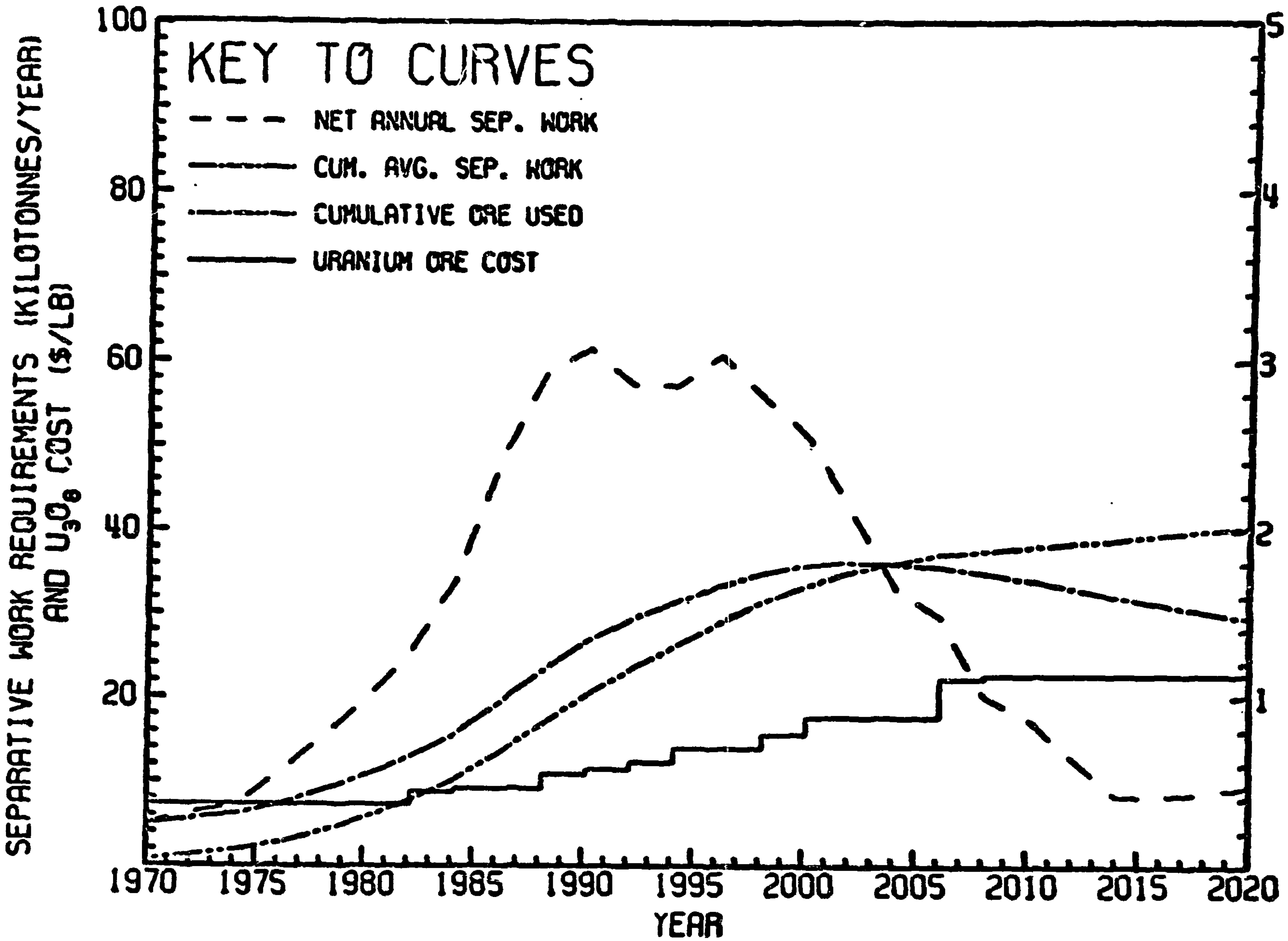

Fig. A-4. Separative Work Requirements and U_3O_8 Cumulative Use and Cost, For Use of Fossil + LWR + U-Fueled HTGR + LMFBR (Case No. 63). (Case No. 73 is also well approximated by these curves.)