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PREDICTION OF THE ECONOMICALLY OPTIMUM TIME TO INITIATE RECYCLE FOR THE HIGH-TEMPERATURE GAS-COOLED REACTOR INDUSTRY USING COMPUTER PROGRAM DELAY

F. J. Furman, R. B. Pratt, and A. L. Lotts

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F. J. Furman, R. B. Pratt, and A. L. Lotts

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ABSTRACT

The planning of "Big Science" projects requires accurate predictions of the worth of the resultant technology. The optimum time to pursue such a program must be decided so that the effort does not culminate years before it is needed, or worse, years after it was needed. This study is intended to provide economic information for the planning of the recycle technology development of high-temperature gas-cooled reactors.

Cost as a function of throughput curves for fuel fabrication, spent fuel storage, and waste storage was calculated. This information was combined by computer program DELAY, with the mass balances for 1000 Mw(e) HTGR's operating with and without benefit of fuel recycle, with assumed growth curves, and with start dates for fuel recycle operations. This was done to calculate total present worthed costs for fueling an HTGR industry as a function of when fuel recycle operations are started. Sensitive parameters were varied to determine the effect of inaccuracies in the input data. Inspection of the results reveals that recycle operations should begin 5 to 8 years after the first 1000 Mw(e) HTGR begins operations. The economic penalty for delay in starting recycle operations was found to be as great as $30 million/year.

INTRODUCTION

The high-temperature gas-cooled reactors presently being developed by Gulf General Atomic are initially to be fueled with ^{235}U and thorium. The conversion of the thorium to ^{233}U will provide a major portion of the fissionable material needed subsequent to the first few years of operation. To benefit from the production of ^{233}U, an industrial capability must be developed to recover the ^{233}U from spent fuel and to fabricate ^{233}U-bearing fuel elements.

Such recycle operations can provide considerable cost savings in refueling reactors.[1] If only one reactor exists, obviously the cost of construction and operation of complex facilities necessary for recycle would not be justified. This background introduces the purpose of this paper — to describe the most economically favorable time to start recycle operations in an HTGR industry, the economic penalty for start of recycle operations at less favorable times, and briefly, the calculational techniques used to determine this information.

METHOD OF CALCULATION

This section describes the methods used in this study. First, a detailed description of the fuel cycle operations is presented. Next, the technique used to calculate the economically optimum time for the start of recycle operations is discussed. Finally, the input used in this calculation is described.

Fuel Cycle Description

In order to calculate the economically optimum time for recycle operation startup, the complete fuel cycle for both nonrecycle and recycle mode of reactor operation must be well understood. Figure 1 presents, in schematic form, a description of steps in both modes of operation.

HTGR's operating without the benefit of recycle facilities must be refueled using ^{235}U as the fissionable material. This material is purchased from gaseous diffusion plants[2] as uranium hexafluoride (UF_6). The UF_6 is then converted to uranyl nitrate, the form required for the sol-gel operation, the principal method considered.[3] In the sol-gel

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[1] M. W. Rosenthal et al., A Comparative Evaluation of Advanced Converters, ORNL-3686 (August 1964).

[2] AEC Gaseous Diffusion Plant Operations, ORO-658 (February 1968).

[3] R. G. Wymer, Laboratory and Engineering Studies of Sol-Gel Processes at Oak Ridge National Laboratory, ORNL-TM-2205 (October 1968).

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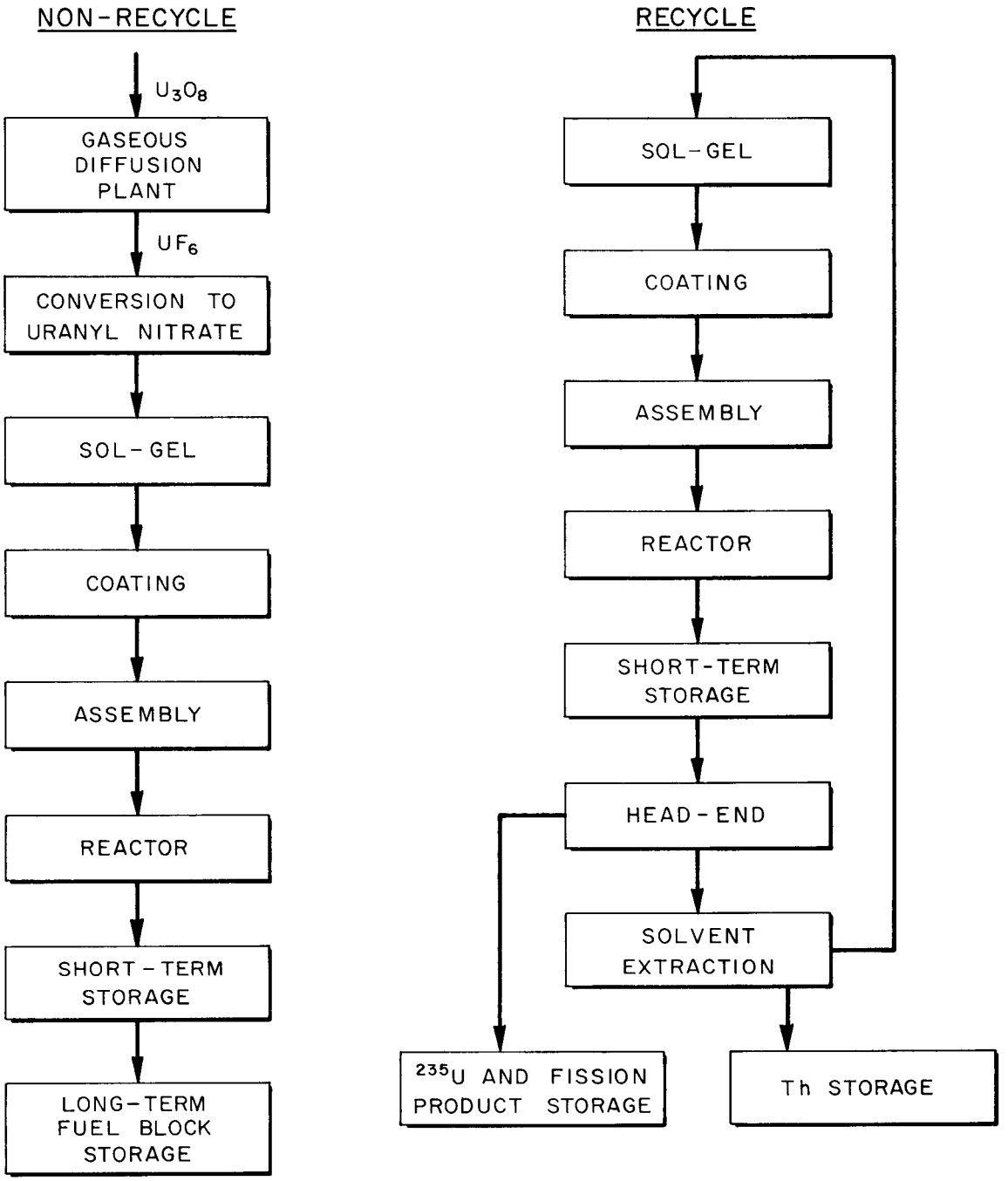

Fig. 1. Nonrecycle and Recycle Fuel Cycle Processes for the HTGR.

operation, fuel material containing either uranium, thorium, or both is formed. Next, microspheres are formed which are dried and fired to form hard, dense oxide or carbide particles.[4]

The microspheres are coated with layers of pyrocarbon and silicon carbide to retain fission products.[5–7] A typical 500-μm outside diameter coated microsphere is shown in Fig. 2. The outer coating layer is

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[4]P. A. Haas, W. D. Bond, M. H. Lloyd, and J. P. McBride, "Sol-Gel Process Development and Microsphere Preparation," pp. 391–415 in Thorium Fuel Cycle (Proceedings of Second International Thorium Fuel Cycle Symposium May 3–6, 1966) R. G. Wymer, Coordinator, U.S. Atomic Energy Commission/ Division of Technical Information, Oak Ridge, Tennessee, February 1968.

[5]R. B. Pratt, J. D. Sease, and A. L. Lotts, Pilot-Scale Equipment Development for Pyrolytic-Carbon Coating, ORNL-4302 (December 1968).

[6]R. B. Pratt, J. D. Sease, W. H. Pechin, and A. L. Lotts, "Pyrolytic-Carbon Coating in an Engineering-Scale System," Nucl. Appl. 6, 241–255 (March 1969).

[7]R. L. Beatty and C. F. Sanders, "Deposition of SiC Coatings for Fuel Reprocessing Studies," GCR Program Semiann. Progr. Rept. March 31, 1968, ORNL-4266, pp. 3–5.

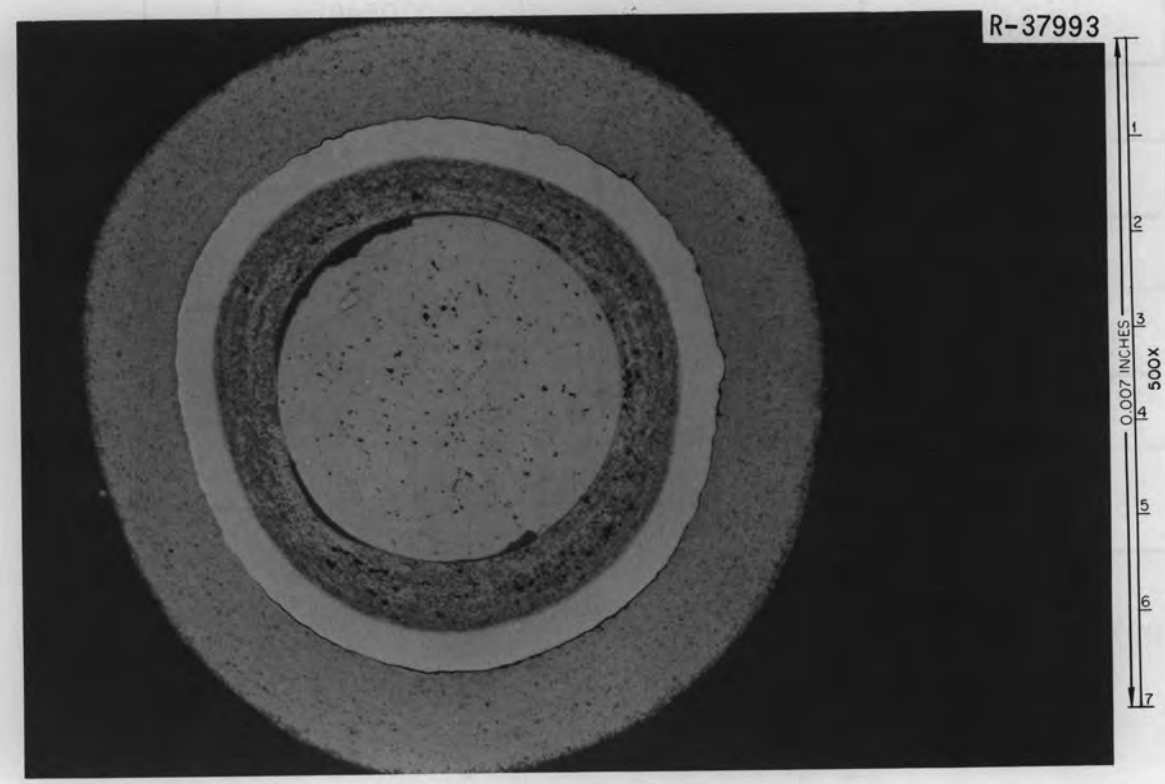

Fig. 2. Particle Coated With Pyrolytic Carbon and Silicon Carbide.

high-density pyrocarbon, the next layer is silicon carbide, and the inner layer is low-density pyrocarbon. The coated microspheres are formed into fuel sticks by mixing the particles with resin and filler and polymerizing the resin.[8] The resulting fuel sticks are loaded into carbon blocks approximately 30 in. long and the block is baked to remove volatiles. A cross section of a conceptual fuel block is shown in Fig. 3. The agglomeration of the microspheres into sticks and their sealing into carbon blocks prevents spread of the microspheres should the carbon block be cracked by some accident.

After final assembly the fuel block is shipped to the reactor. After exposure, the fuel block is placed in short-term storage until

[8] J M Robbins, R. L. Hamner, and H. Beutler, Status and Progress Report for Thorium Fuel Cycle Development for 1967 and 1968, ORNL-4429, pp. 85–86.

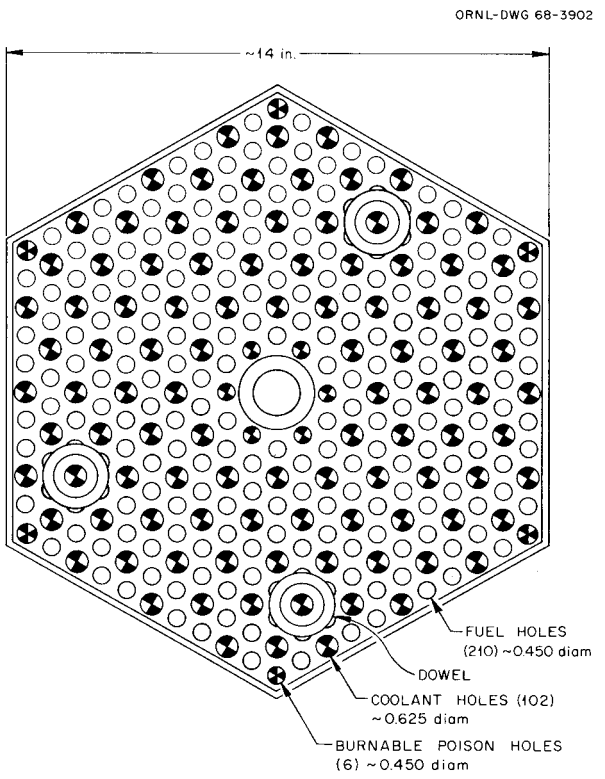

Fig. 3. HTGR Fuel Element Cross Section.

it has cooled sufficiently for transfer to long-term storage. Transfer to long-term storage completes the nonrecycle fuel cycle.

If the reactor fuel is to be recycled, the spent fuel block is removed from the reactor and placed in short-term storage until it has cooled sufficiently for transfer to head-end processing. Head-end processing is the crushing and burning of the fuel block, the separating of the ^{235}U particles which contain the undesirable ^{236}U from the ^{233}U and thorium particles, and the crushing and dissolving of the ^{233}U and thorium.[9] The ^{235}U particles are stored, and the solution of ^{233}U and thorium is sent to solvent extraction.

The solvent extraction process separates the uranium from the thorium and remaining fission products.[10] The thorium and remaining fission products are placed in long-term storage. The uranium is then used in the sol-gel process, where uranium or mixed thorium-uranium microspheres are formed. Next, the microspheres are coated and assembled with additional thorium-containing microspheres into fuel sticks which are then loaded into fuel blocks and shipped to the reactor. All preceding operations involving ^{233}U are performed using remotely operated equipment due to the high level of radiation associated with the recycled uranium.[11–13] After exposure of the fuel block in the reactor, the fuel cycle is complete.

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[9]E. L. Nicholson, L. M. Ferris, and J. T. Roberts, Burn-Leach Processes for Graphite Base Reactor Fuels Containing Carbon-Coated Carbide on Oxide Particles, ORNL-TM-1096 (April 1965).

[10]F. R. Bruce, "The Thorex Process," pp. 180–222 in Symposium on Reprocessing of Irradiated Fuels, Brussels, Belgium, May 20–25, 1957, Book 1, TID-7534.

[11]J. D. Sease, R. B. Pratt, and A. L. Lotts, Remote Fabrication of Thorium Fuels, ORNL-TM-1501 (April 1966).

[12]A. L. Lotts and D. A. Douglas, Jr., Refabrication Technology for the Thorium-Uranium-233 Fuel Cycle, ORNL-TM-1141 (June 1965).

[13]E. D. Arnold, "Radiation Hazards of Recycle ^{233}U-Thorium Fuels," pp. 253–284 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650 (July 1963).

Calculation Technique

We can arrive at the economically optimum time to start recycle operations by calculating the difference, in cost to the total economy, of various delays in recycle operations compared with the startup of recycle operations when the first 1000-Mw HTGR is refueled. This approach was used because certain items which are difficult to estimate accurately cancel and, therefore, do not have to be considered. One such item is shipping. Whether the reactor is being recycled or not, the used fuel blocks must be shipped, either to long-term storage or reprocessing. Another item which can be canceled is the cost of thorium. This cost would be extremely difficult to predict for a long-range study. The assumption is made that the cost of recycling thorium, which would probably require additional remote facilities or storage of about 15 years, would be comparable to purchasing fresh thorium. Any error in this assumption is minimized when the costs are considered as present worth. Hence, the thorium costs vary an insignificant amount when the recycle startup date is varied, and thus can be neglected in the calculation.

Other items, such as coating, cannot be neglected in the calculations. Although the coatings required for nonrecycle and recycle operations are very similar, the radioactivity of the materials being coated is sufficiently different to require hooded operation in the nonrecycle case and remote operation in the recycle case.

To simplify calculations, all operations are grouped into four categories:

1. ^{235}U fuel block fabrication,
2. ^{233}U reprocessing and refabrication,
3. fuel block storage,
4. reprocessing byproducts storage.

The first category, ^{235}U fuel block fabrication, includes all operations from the purchasing of ^{235}U from the gaseous diffusion plant to the final assembly of the ^{235}U-Th fuel block. This series of processes is used for all the fuel for nonrecycle operations and is also used for makeup fuel in recycle operations. The second category, ^{233}U reprocessing

and refabrication, is concerned with the steps in recovering ^{233}U from the spent fuel blocks and refabricating this material into new ^{233}U-Th fuel blocks for recycle operations. The third category, fuel block storage, consists only of storing spent fuel blocks which are not processed in a recycle facility, as would be the case when the reactor industry is operating before recycle facilities are completed. The fourth category, reprocessing byproducts storage, is a combination of all storage connected with the reprocessing industry. The main items in the storage are the ^{235}U which is contaminated with ^{236}U and fission products, and thorium which is also contaminated, to a lesser degree, with fission products.

Each of the four categories is considered as a plant, and capital, operating, and hardware costs are obtained for different plant sizes. This data is used with the mass balances for nonrecycle operation and recycle operation of a 1000-Mw(e) HTGR and an assumed growth rate of the HTGR industry to calculate the economically optimum time for startup of recycle operations.[14]

A simplified outline of the calculational procedures is shown in Fig. 4 (ref. 15). The mass balances, industry growth, and assumed start of recycle operations are combined to give the total mass balance for the HTGR industry. From this mass balance, demand curves based on material throughput for the HTGR fuel plants are calculated. Next, optimized plant construction schedules are selected and plant sizes and costs are calculated.[16]

To select the optimum plant construction schedule, plants are constructed based on the demand for a selected number of years in the future, called the look-ahead period. For instance, if the look-ahead period is five years, the demand curve is inspected and the next plant sized

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[14]P. R. Vondy and T. B. Fowler, Computer Code TONG for Zero-Dimensional Reactor Depletion Calculations, ORNL-TM-1633 (June 1967).

[15]F. J. Furman, R. B. Pratt, F. J. Homan, and A. L. Lotts, "DELAY — Computer Program for Predicting the Economically Optimum Time to Initiate Recycle in a Growing Reactor Industry," to be published as an ORNL-TM.

[16]F. J. Homan, Plant Size Optimization in a Growing Nuclear Fuel Fabrication Industry, ORNL-TM-2346 (December 1968).

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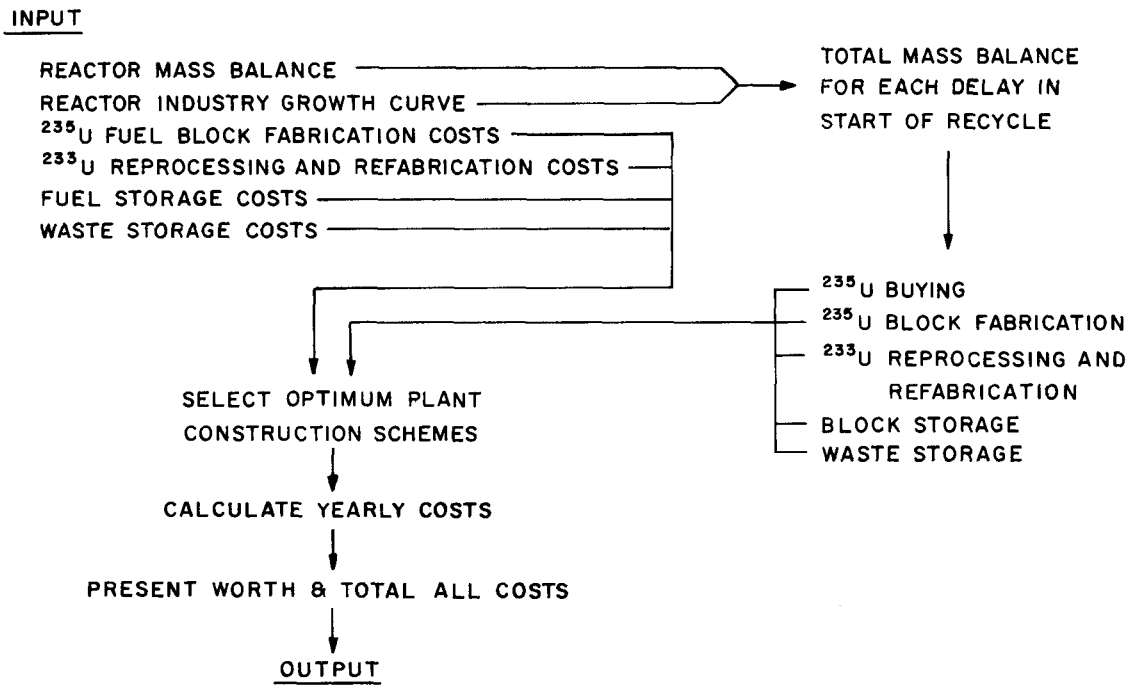

Fig. 4. HTGR Recycle Cost Calculation Method.

for the needs of five years in the future. This approach is continued until all plants are selected and then the present worthed cost for construction and operation of all the plants is calculated. Using the same look-ahead period, the calculation is redone, but now the plants are sized 10% larger. The calculation is repeated until the total present worthed cost begins to increase. At this point, another look-ahead period is selected, and the entire calculation repeated. When all look-ahead periods from 1 to 15 years have been tried, the plant schedule giving the lowest present worthed cost is selected.

This method of plant selection balances the economy of large plants with underproduction to produce a system which is most economic when considered in its entirety. In both the plant size optimization and the final calculation of costs, the yearly costs consist of fixed and variable costs. One portion of the fixed cost is the annual fixed

charge rate (24.04%) on capital. This covers the cost of money, depreciation, federal, state, and local taxes, replacement costs, and property insurance charged on a yearly basis for the 15-year life of the plant. Also considered fixed is 50% of the operating costs of the fully loaded plant. The variable costs include the remaining operating cost and the hardware cost prorated according to the ratio of actual production to plant capacity. In the plant size optimization, the economically optimum construction schedule is selected using a 12.7% discount rate for present worth calculations, reflecting the weighted cost of money based on 70% equity and 30% bonds. Since the correct interest rate for the calculation of total costs is somewhat debatable, the interest rate was varied from 0 to 15%, as described in the section on results of the parameter studies. For the base case, 7% was used to emphasize the long-range effects of varying the recycle start date.

Demand curves are combined to give yearly costs for ^{235}U purchases, ^{235}U fuel block fabrication, ^{233}U reprocessing and refabrication, fuel block storage, and reprocessing byproducts storage. These yearly costs are then converted to present worth and added to give the cost of all the items considered for a particular time of recycle startup. The entire calculation is repeated for other times of recycle startup, and the optimum time can be selected and the additional costs of other startup dates can be found.

Base Case Input

Input to the calculation consists principally of the reactor industry growth curve, and the cost as a function of throughput curves for the processes of recycle. Mass balances for operation of a 1000-Mw HTGR, both as a burner reactor (nonrecycle) and as recycle reactor, are used.

The initial Th-U loading is 40,700 kg with 1764 kg of ^{235}U. The thermal efficiency is 44%. After 1.4 years, annual refueling of one-fourth of the core is begun. Average burnup is 66,000 Mwd/ton with an 85% load factor. At equilibrium conditions, nonrecycle operation requires 569 kg fresh ^{235}U annually and recycle operation requires 210 kg fresh ^{235}U annually.

The particles which were used in estimating equipment needs were 400-μm-diam thorium carbide particles mixed with 200-μm-diam thorium-uranium oxide particles. These 200-μm-diam particles had a thorium-to-uranium ratio of 4.25:1. The particles were coated with layers of low-density pyrocarbon, silicon carbide, and high-density isotropic pyrocarbon.

A HTGR industry growth curve, Fig. 5, is assumed. The cost curves are calculated based on the best available data, as discussed in the following paragraphs.

Costs, as a function of plant size, for each operation are required. To simplify calculations, we assume that the fresh ^{235}U and the recovered ^{233}U were fabricated in separate fuel blocks. All ^{233}U operations, from

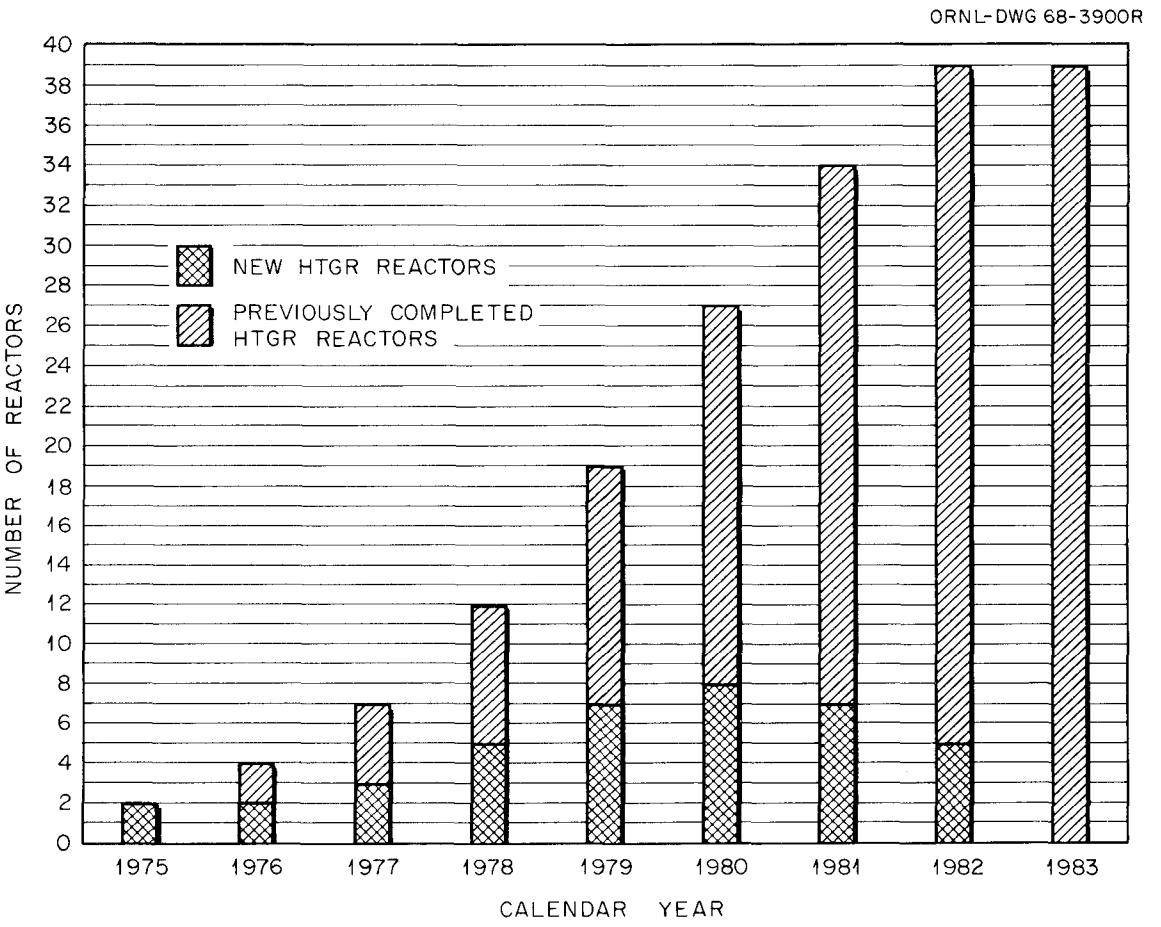

Fig. 5. Reference Growth Curve for 1000-Mw HTGR Reactors.

processing to fuel block final inspection, are done in remotely operated facilities. All operations with only ^{235}U or thorium are done in hooded facilities. The costs which must be calculated are (1) converting ^{235}U from the as-received state (hexafluoride) to the final fuel block, (2) converting ^{233}U from the as-received state (spent fuel blocks) to the final fuel block, (3) storage of ^{233}U as spent fuel blocks, and (4) storage of high-level (^{235}U) and low-level (Th) byproducts of the fuel block processing operations.

The costs for fabrication of the ^{235}U-containing fuel blocks were calculated as a combination of capital, operating, and hardware

$$\text{COST } (^{235}\text{U Blocks}) = C + O + H ,$$

where

C = capital costs,

O = operating costs, and

H = hardware costs.

The cost was calculated for plant sizes of 10, 50, 100, 500, 1000, and 3000 kg of heavy metal/day. All cost figures are in $/kg of heavy metal unless otherwise noted.

The capital costs were calculated by the following equation:

$$C = P_{MC} + P_{ThC} + A_C ,$$

where

P_{MC} = capital costs for processing mixed ^{235}U + Th particles (hooded operation),

P_{ThC} = capital costs for processing thorium particles (hooded operation), and

A_C = capital costs for assembly.[17]

The capital costs for processing were further broken down as follows:

$$P_{MC} = \text{wt } \%_M \ (CV_{CH} + SG_{CHM} + CT_{CH}) ,$$

$$P_{ThC} = \text{wt } \%_{Th} \ (SG_{CHTh} + CT_{CH}) ,$$

[17]A. L. Lotts, D. A. Douglas, Jr., and R. L. Pilloton, Refabrication Technology and Costs for High-Temperature Gas-Cooled Reactor Fuels, ORNL-TM-1115 (May 1965).

where

$wt\ \%_M$ = weight percent of mixed particles in fuel,

$wt\ \%_{Th}$ = weight percent of thorium particles in fuel,

CV_{CH} = capital cost for conversion,[18]

SG_{CHM} = capital cost for sol-gel uranium-bearing particle process,[19]

SG_{CHTh} = capital cost for sol-gel thorium particle process,[20] and

CT_{CH} = capital cost for coating.[17]

The same series of calculations were done to obtain the corresponding operating and hardware costs, with all data for hardware from reference.[17]

Fabrication of ^{233}U-bearing fuel blocks was calculated using a similar approach.

$$\text{COST } (^{233}\text{U Blocks}) = C + O + H ,$$

where

C = capital costs,

O = operating costs, and

H = hardware costs.

Costs were again calculated for plant sizes of 10, 50, 100, 500, 1000, and 3000 kg of heavy metal/day.

In this case:

$$C = HS_{MC} + P_{MC} + P_{ThC} + A_C ,$$

where

HS_{MC} = capital cost for head-end and solvent-extraction operations[21] (remote operation),

P_{MC} = capital cost for processing mixed ^{233}U + Th particles (remote operation),

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[18] J. M. Chandler and F. E. Harrington, A Study of Sol-Gel Fuel Preparation Cost for SSCR and HTGR Reactors, ORNL-TM-1109 (April 1965).

[19] T. N. Washburn, A. L. Lotts and F. E. Harrington, Comparative Evaluation of Sol-Gel Fuel Preparation Costs, ORNL-TM-1979 (September 1967).

[20] F. E. Harrington, personal communications.

[21] J. T. Roberts, personal communications.

P_{ThC} = capital cost for processing thorium particles (hooded operation), and

A_C = capital cost for assembly[17] (remote operation).

The capital costs for processing were further broken down as follows:

$$P_{MC} = \text{wt } \%_M \ (SG_{CR} + CT_{CR}) \ ,$$

$$P_{ThC} = \text{wt } \%_{Th} \ (SG_{CH} + CT_{CH}) \ ,$$

where

wt $\%_M$ = weight percent mixed particles in fuel,

wt $\%_{Th}$ = weight percent thorium particles in fuel,

SG_{CR} = capital cost for sol-gel uranium-bearing particle process,[17,19]

SG_{CH} = capital cost for sol-gel process for thorium particle process,[20]

CT_{CR} = capital cost for remote coating,[17] and

CT_{CH} = capital cost for hooded coating.[17]

Operations and hardware costs are calculated by the same method, with the exception that all hardware costs were obtained from reference.[17]

The costs for storage of used fuel blocks are based on unpublished work of Gulf General Atomic in which costs were calculated for fuel storage of one 1000-Mw HTGR. Those costs have been extrapolated to large-scale plants by using an 0.7 scale factor. The total costs have been divided into capital and operating costs by assuming that capital costs are 92.5% of total costs.

High-level waste and thorium storage costs were obtained from work done at ORNL.[22] These costs assume a single charge when material is stored.

All cost data is written in the form of the following equation:

$$\text{COST} = A(\text{PLANT SIZE})^B + C \ .$$

The parameters A, B, and C are obtained using a least-squares technique.

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[22]AEC, An Evaluation of HTGR, WASH-1085, to be published.

The cost curves for fully loaded plants, with capital, operating, and hardware costs combined, are presented in Figs. 6 and 7. Figure 6 shows the costs associated with the nonrecycle (^{235}U and thorium only) operation of the HTGR industry. The material preparation cost includes all costs from conversion of the uranium hexafluoride through sol-gel microsphere formation. The fabrication cost includes the coating operations through fuel element assembly. Spent fuel block storage cost is the cost incurred by storage of the used fuel elements until recycle facilities are available. No uranium, thorium, or shipping costs are included. Figure 7 shows the costs associated with the recycle of ^{233}U (i.e., the reprocessing of the spent fuel and refabrication into fuel blocks containing ^{233}U and thorium only). Again, capital, operating, and hardware costs are combined in each curve. Chemical processing cost includes head-end and solvent extraction costs. The waste

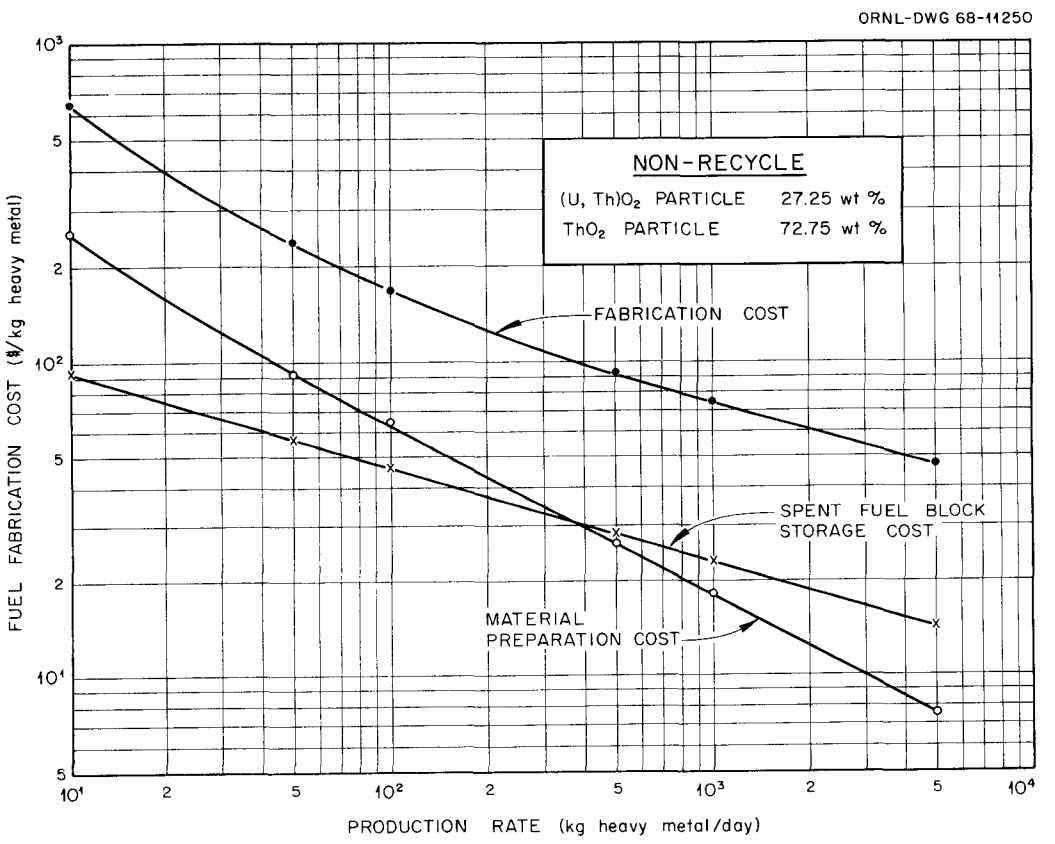

Fig. 6. Costs of Steps in Nonrecycle Process.

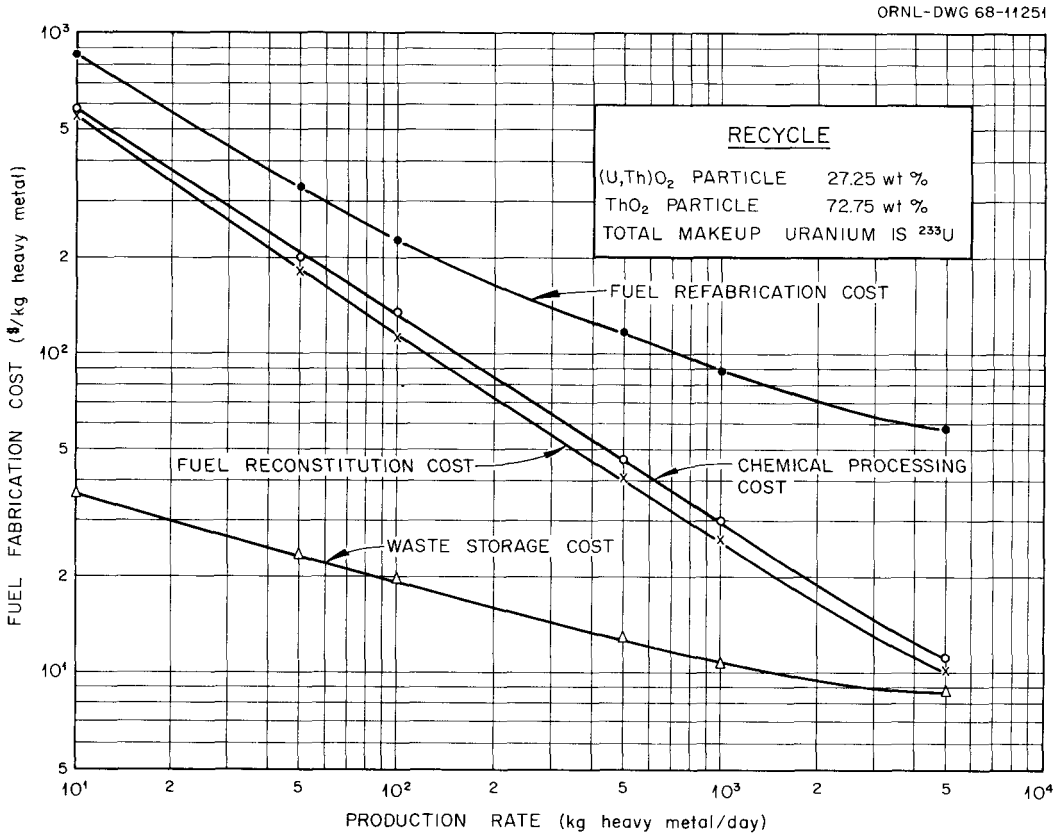

Fig. 7. Costs of Steps in the Recycle Process.

storage costs include both the high-level (fissile particle waste) and low-level (fertile particle waste including reusable thorium) waste storage costs from the head-end and solvent extraction processes. The fuel reconstitution cost includes sol formation, microsphere formation, drying, and firing. The fuel refabrication cost includes coating, stick making, and fuel element assembly. All operations involving ^{233}U are assumed to be remote for this calculation. For comparative purposes, Fig. 8 shows the total preparation costs for both the nonrecycle fuel (^{235}U + Th) and the recycle fuel (^{235}U and ^{233}U bred in the fertile particle + Th). The lower curve is the ^{235}U + Th fuel preparation starting from the hexafluoride conversion and ending in fuel element assembly. The upper curve is the ^{235}U + Th fuel preparation cost (the lower curve) plus the enriched uranium hexafluoride cost (93.4 enrichment, \$11.175/g of ^{235}U, based on a \$8/lb cost for U_3O_8 and \$26/kg U separative work cost). The middle curve is the preparation costs for bred

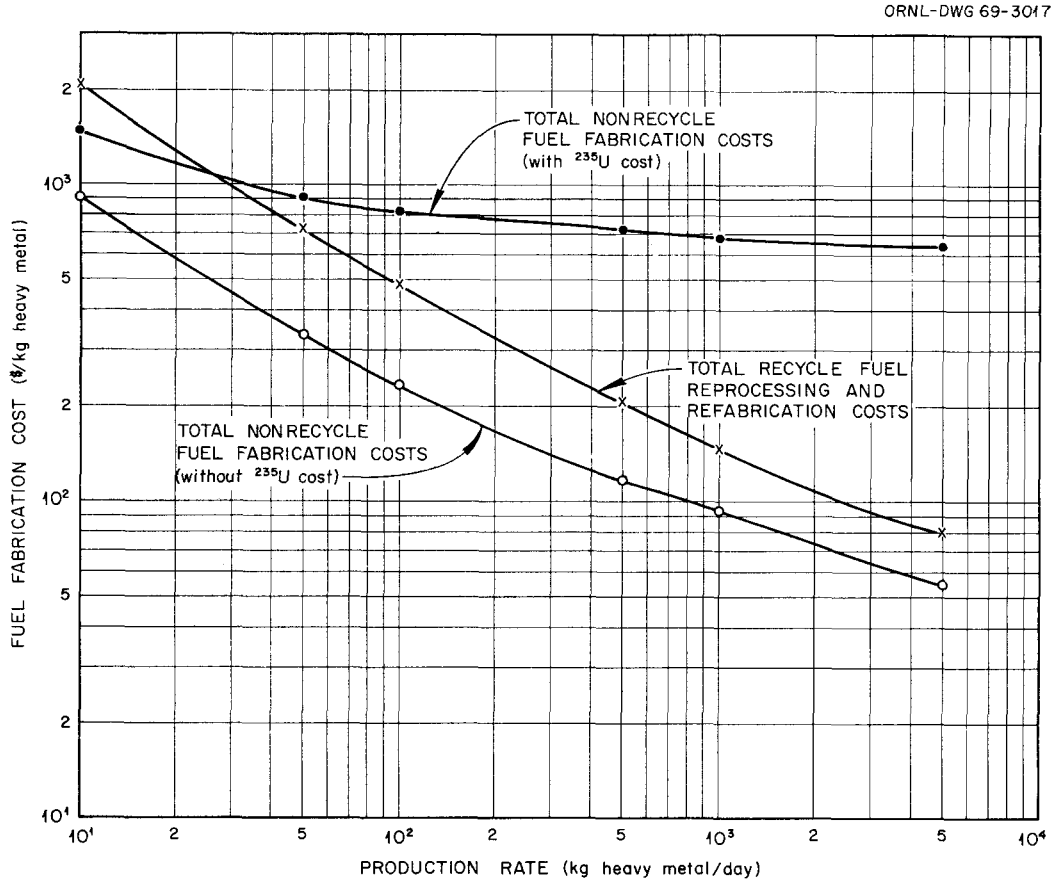

Fig. 8. Comparison of Nonrecycle and Recycle Processing Costs.

U + Th fuel, including head-end reprocessing, solvent extraction, microsphere formation, particle coating, fuel stick making, and element assembly. These are all remote operations except the preparation of particles containing only thorium. Since one 1000-Mw(e) HTGR requires a processing rate of approximately 39 kg heavy metal/day, the break-even point (not counting spent fuel or waste storage costs) for fueling with both recycle and fresh fuel as compared with just fresh fuel is between two and three 1000-Mw(e) HTGR's. Although recycle at the three HTGR level appears more economic than not recycling the fuel, it is certainly not the most economic scheme, as our following calculations will show.

In calculating total cost, the fresh fuel and recycle fuel plants were assumed to have 15-year lifetimes. The fuel block storage facility was considered to have an indefinite lifetime. The waste storage cost

was calculated as a cost incurred for disposal and perpetual maintenance. That is, one charge was made on each kilogram input to waste. The total charge was based on the total input for the year. Plant sizes for waste storage were not calculated.

The pricing of ^{233}U was circumvented by assuming that all ^{233}U produced was used in the HTGR industry. When processed ^{233}U was available, it was recycled in the reactor system, replacing ^{235}U on a 1:1.2 ratio; a ratio which was based on a worth calculated by comparing the nonrecycle and recycle mass balances at equilibrium. The price of ^{235}U was assumed to be \$11.175/g; this price was based on a \$8/lb price for U_3O_8 and separative cost of \$26/kg U for 93.4% enriched fuel. Rather than charging an arbitrary inventory charge, the necessary ^{235}U fuel was purchased outright. A delay of one year was allowed between the time fuel was released from the reactor and the time it was returned to the reactor as recycle fuel.

RESULTS

The results of this study are presented in two sections, the first section covers the results of what we believe to be the most realistic case. The following sections present the results of a parametric study in which we varied the input to cover the range of uncertainty of our data.

Base Case

The optimum plant sizes, starting dates, capital costs, total present worthed expenditures, and the levelized costs for various dates for initiating recycle operations are presented in Tables 1, 2, and 3. Table 1 shows the ^{235}U fuel block production plant data. Both the total present worthed cost and the levelized cost show the effect of long delays in starting recycle operations. Up through the recycle operations starting in 1980, the costs are stable. When recycle operations start in 1981 or later, additional capacity in ^{235}U fuel production is needed to keep the reactors fueled. As the recycle operations are delayed even further,

Table 1. Parameters Concerning ^{235}U Fuel Block Production as a Function of Recycle Start Dates

Year Recycle Start	Plant Start	Plant Size (kg/day)	Capital Cost (millions)	Total pw[a] Cost (millions)	Levelized Cost ($/kg HM)
1977	1975 1990 2005	1260 600 350	44.6 28.8 21.2	281.6	130.2
1978	1975 1990 2005	1260 600 350	44.6 28.8 21.2	281.6	130.2
1979	1975 1990 2005	1260 600 350	44.6 28.8 21.2	281.7	130.0
1980	1975 1990 2005	1220 600 350	43.8 28.8 21.2	279.8	128.5
1981	1975 1990 2005	1500 600 350	49.4 28.8 21.2	295.0	135.9
1982	1975 1990 2005	1650 600 350	52.3 28.8 21.2	303.8	138.8
1983	1975 1990 2005	1730 650 380	53.8 30.3 22.3	311.2	138.0
1984	1975 1990 2005	1725 600 350	53.7 28.8 21.2	310.2	136.5
1985	1975 1990 2005	1725 600 350	53.7 28.8 21.2	312.4	133.0
1986	1975 1990 2007	1725 590 165	53.7 28.7 14.1	305.4	126.9
1987	1975 1994	1725 590	53.7 28.7	298.8	121.6
1988	1975 1997	1725 590	53.7 28.7	296.1	117.0
1989	1975 1999	1725 590	53.7 28.7	295.7	113.6
1990	1975 2002	1725 590	53.7 28.7	294.8	110.5

[a]Present worth.

Table 2. Parameters Concerning ^{233}U Reprocessing and Fuel Block Production Plants as a Function of Recycle Start Dates

Year Recycle Start	Plant Start	Plant Size (kg/day)	Capital Cost (millions)	Total pw[a] Cost (millions)	Levelized Cost ($/kg HM)
1977	1977	1005	88.3	425.0	249.7
	1992	1200	96.1		
	2007	1180	95.1		
1978	1978	1015	88.6	402.3	227.5
	1993	1200	96.1		
	2008	1130	93.3		
1979	1979	1020	88.8	378.6	207.3
	1994	1200	96.1		
	2009	840	80.9		
1980	1980	1020	88.8	355.7	189.5
	1995	1200	96.1		
	2010	500	63.7		
1981	1981	1020	88.8	334.3	173.8
	1996	1200	96.1		
	2011	210	42.6		
1982	1982	1020	88.8	312.3	160.9
	1997	1200	96.1		
1983	1983	1040	89.5	297.1	153.6
	1998	1200	96.1		
1984	1984	1600	110.2	308.4	156.9
	1999	1200	96.1		
1985	1985	1600	110.2	291.5	150.0
	2000	1200	96.1		
1986	1986	1600	110.2	275.0	144.9
	2001	1200	96.1		
1987	1987	1610	110.5	259.4	141.3
	2002	1200	96.1		
1988	1988	1610	110.5	244.0	138.3
	2003	1200	96.1		
1989	1989	1615	110.6	227.7	135.9
	2004	1200	96.1		
1990	1990	1625	111.0	212.4	134.2
	2005	1200	96.1		

[a]Present worth.

Table 3. Parameters Concerning Spent Fuel Block Storage Facilities as a Function of Recycle Start Dates

Year Recycle Start	Plant Start	Plant Size (1000 kg)	Capital Cost (millions)	Total pw[a] Cost (millions)	Levelized Cost ($/kg HM)
1977	2008	525	9.1	3.5	7
	2011	510	8.9		
1978	1977	20	1.0	6.6	25
	2008	510	8.9		
	2011	510	8.9		
1979	1977	70	2.2	10.4	34
	2009	1060	14.9		
1980	1977	135	3.6	14.8	31
	2009	670	10.8		
	2012	225	5.0		
1981	1977	265	5.6	21.0	31
	2010	775	11.9		
1982	1977	70	2.2	31.1	23
	1979	395	7.5		
	2010	570	9.6		
1983	1977	135	3.6	41.2	14
	1980	615	10.2		
	2011	285	5.9		
1984	1977	265	5.6	51.6	16
	1981	845	12.7		
1985	1977	135	3.6	66.6	13
	1980	615	10.2		
	1983	775	11.9		
1986	1977	470	8.4	74.4	11
	1982	1515	19.1		
1987	1977	150	3.8	87.3	10
	1980	745	11.6		
	1983	1485	18.9		
1988	1977	290	6.0	98.6	9
	1981	1360	17.7		
	1985	1230	16.5		
1989	1977	470	8.4	102.8	8
	1982	2685	28.5		
	1988	115	3.1		
1990	1977	510	8.9	114.7	8
	1982	2025	23.4		
	1987	1165	15.9		

[a]Present worth.

the larger capacities become more economical as they are used with better efficiency. Note the continuous decline in later years for the levelized cost. The levelized cost is computed using the 12.7% present worth factor used in optimizing the plant sizes; otherwise the rate of change in present worthed cost and levelized cost would be the same.

Table 2 shows the size, cost, and startup dates for the ^{233}U reprocessing and fuel block production plants. As would be expected, the plants for reprocessing and refabricating ^{233}U fuel become larger and more economic with longer delays before starting the reprocessing operations. These delays serve to build up a large stockpile of ^{233}U-containing spent fuel blocks plus a ready market for fresh fuel. However, a large stockpile of spent fuel blocks necessarily requires a large storage facility.

Table 3 presents storage facility parameters for spent fuel blocks. Note the continuous rise in cost as the start of recycle operations are delayed. The plants built near the end of the study are not realistic since rather than store the spent fuel indefinitely, as is assumed in the calculation, the fuel would be reprocessed and sold to other reactor industries. Since these plants are only partially depreciated (i.e., the computer does not calculate costs after the 43rd year, and the present worthed cost of operations 30 years in the future is small) this inaccuracy is not significant for calculation of fuel block costs.

The value of stored fuel at the end of the calculation, after subtracting the cost for reprocessing, amounts to approximately $330 million. On a present worth basis (1974), this amount is $20 million or 1% of the total present worth cost of recycle for HTGR's. Therefore, in this study the discharged fuel value is not significant, but one can predict that as HTGR's go off-line the value of the discharged fuel will give economic impetus to the construction of reactors designed to use ^{233}U fuel. Hence, either more HTGR's will be built, meaning the growth curve used in this study is not realistic for the long term, or other reactor systems which can economically use ^{233}U, such as the molten salt reactors, will be built.

Table 4 presents the costs, present worthed at 7% for each item of recycle considered here. Also presented is the total cost of these items

Table 4. Summary of Costs for Various Start Dates
(In Millions Present Worthed to 1974, Except as Noted)

Year Recycle Start	^{235}U Production	^{233}U Fuel Reprocessing and Fabrication	Fuel Block Storage	Waste Storage	^{235}U Purchases	Total Cost	mills/kwhr
1977	281.6	425.0	3.5	27.0	1277.6	2014.8	0.788
1978	281.6	402.3	6.6	27.0	1277.8	1995.3	0.781
1979	281.7	378.6	10.4	26.8	1279.2	1976.8	0.773
1980	279.8	355.7	14.8	26.6	1282.4	1959.3	0.767
1981	295.0	334.3	21.0	26.2	1287.4	1964.1	0.768
1982	303.8	312.3	31.1	25.8	1298.9	1971.8	0.771
1983	311.2	297.1	41.2	24.9	1326.7	2001.1	0.783
1984	310.2	308.4	51.6	24.4	1337.1	2031.6	0.795
1985	312.4	291.5	66.6	23.5	1372.7	2066.8	0.809
1986	305.4	275.0	74.4	22.5	1415.8	2093.2	0.819
1987	298.8	259.4	87.3	21.5	1463.0	2130.1	0.833
1988	296.1	244.0	98.6	20.4	1512.5	2171.7	0.850
1989	295.7	227.7	102.8	19.3	1564.0	2209.6	0.864
1990	294.8	212.4	114.7	18.3	1616.0	2256.2	0.883

and this cost in mills per kilowatt-hour. Waste storage amounts to approximately 1% of the total cost and is essentially constant regardless of the start of recycle. The purchase of ^{235}U gets increasingly more costly the longer recycle is delayed since more ^{235}U must be purchased earlier in the life of the industry, plus the reactors fueled with ^{235}U do not produce as much ^{233}U as a reactor fueled with both ^{235}U and ^{233}U fuel. The total costs show a minimum in 1980. The mills per kilowatt-hour cost, as expected, shows the same minimum.

Although these calculations were intended to give cost differences of various startup dates for recycle operations, it is interesting to note the absolute costs in mills per kilowatt-hour. Using a 7% present worth factor, the minimum cost for the items calculated was 0.767 mills/kwhr. A 10% present worth factor, which would give values more comparable to studies in which a 10% inventory charge was used, gives a minimum cost of 0.825 mills/kwhr. By including 0.03 mills/kwhr for shipping and 0.04 mills/kwhr for thorium, a total fuel cycle cost of 0.84 to 0.89 mills/kwhr, depending on the present worth factor used, is obtained. This cost is optimistically low since no effort was made to include the effect of conservatism by the industrial community to minimize risk.

Parameter Studies

Some of the parameters used in this calculation that greatly affect overall costs are not known accurately. Since the date found to be economically optimum for starting recycle operations might be affected by the accuracy of these parameter estimates, an analysis was made to determine how much the optimum recycle start date would change when the questionable parameters were changed from our best estimates to extreme estimates. Parameters which were varied are the interest rate, scale factor for fuel block storage, scale factor for ^{233}U fuel block fabrication, and industry growth rate.

The interest rate was varied from 0 to 15%. Total present worthed cost curves for 0, 7, and 15% interest rates are shown in Fig. 9, normalized to the same scale for comparative purposes. (For absolute values, multiply the scale by the appropriate scale factor for the interest rate being considered.) The minimum remained in 1980 for all cases,

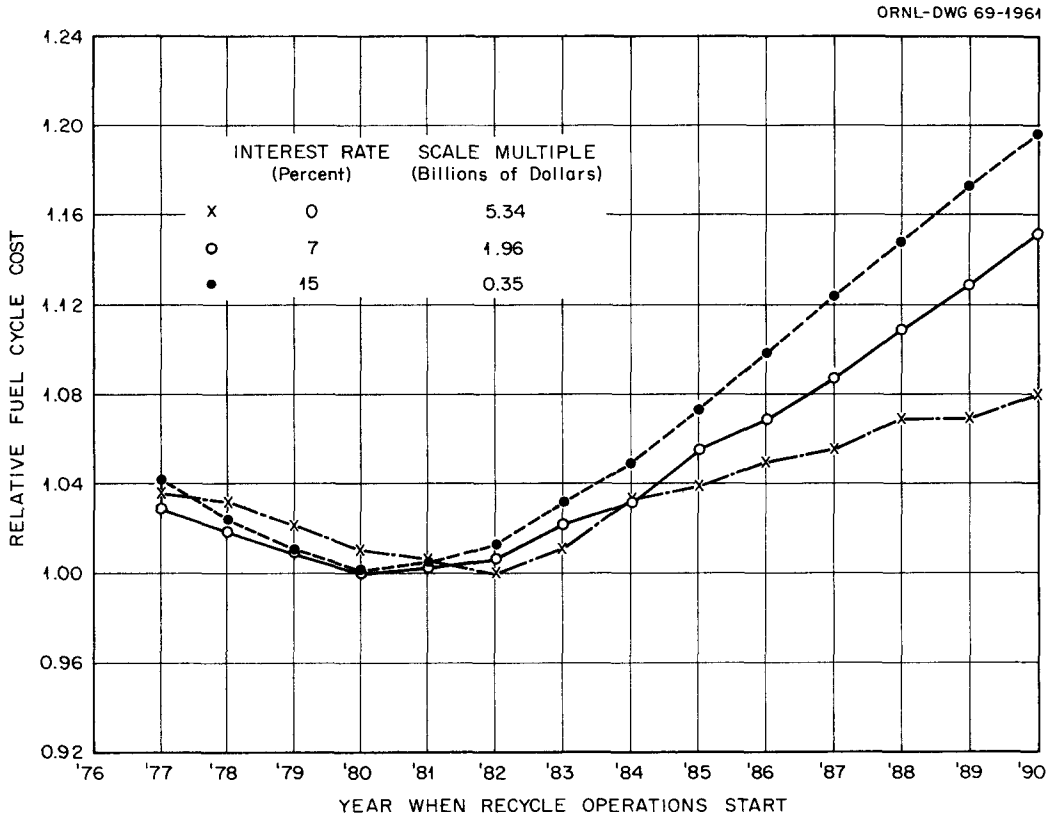

Fig. 9. Total Cost (at 1974 Worth by Various Interest Rates) Versus Time for Recycle Startup.

except for extremely low interest rates (0 through 3%) where the minimum shifted to 1982. Hence, the interest rates did not significantly affect the minimum in the total present worth cost curves.

The scale factor for fuel block storage was changed from 0.7 to 0.8. This change had very little effect on the present worthed cost when recycle operations were started early as shown in Fig. 10. When recycle operations start in 1981, the total cost is increased 0.5%. As the recycle operations are delayed further, the effect is more pronounced. In 1986, the total cost increase is 2%. However, this increase in cost for later recycle startup dates is not sufficient to shift the economically optimum time for recycle start.

The scale factors for ^{233}U reprocessing and block fabrication plants were low compared to other scale factors, 0.501 for capital and 0.605 for operating expenses. To test their significance, these factors were arbitrarily shifted to high values, 0.75 for capital and 0.9 for operating

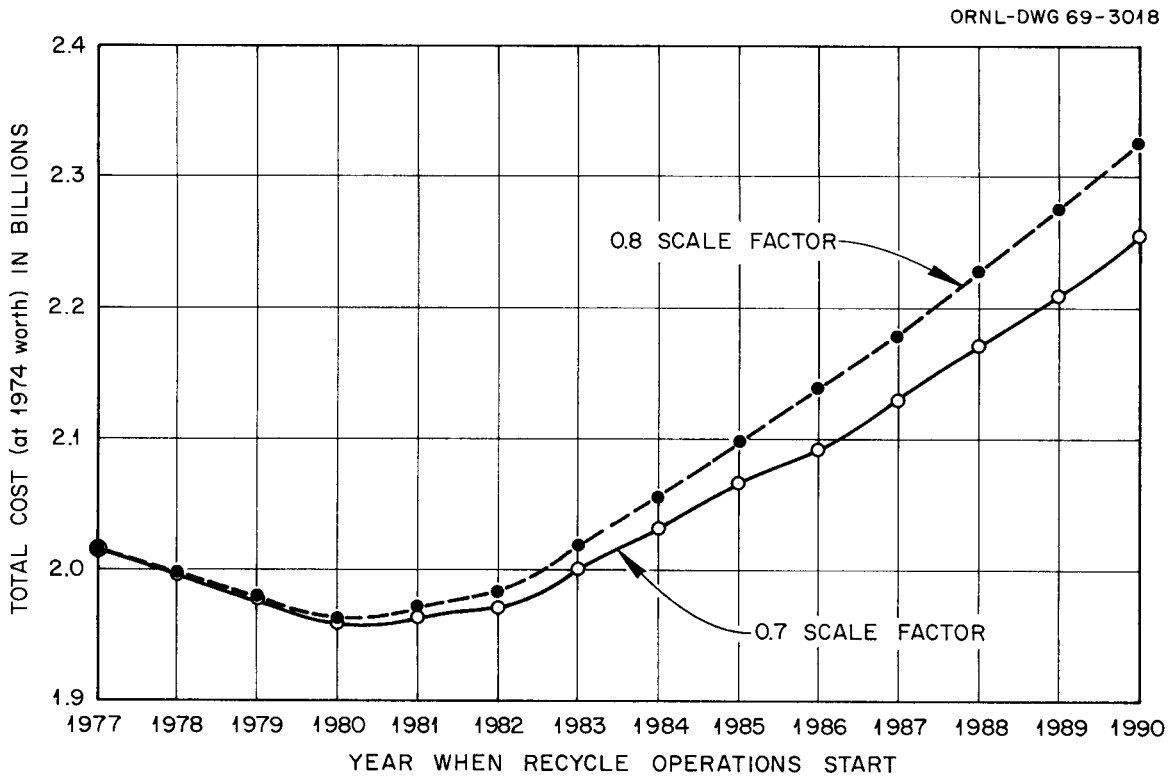

Fig. 10. Effect of a Change in the Spent Fuel Block Storage Scale Factor.

expenses. To normalize costs, coefficients in the cost equations were adjusted so that a plant with a capacity of 1515 kg/day (supplies approximately 5 reactors) in the modified case costs the same as a like sized plant in the base case calculations. The resulting cost curves for the base case and the modified case are shown as a function of production rate in Fig. 11. The base case total present worth costs, shown as a function of recycle start date, are compared to the modified ^{233}U reprocessing and fabrication plant scale factor case in Fig. 12. The minimum is shifted to 1982 with 1981 in second place and 1980 in third place. The cost curve rises quite steeply after this minimum indicating that additional minor adjustments would not shift the curve to a later date.

The assumption which should most affect the optimum time for recycle start is the growth curve. Although the growth curve used is plausible, at this stage in the development of HTGR's other growth curves are equally plausible. For that reason, the results using the original

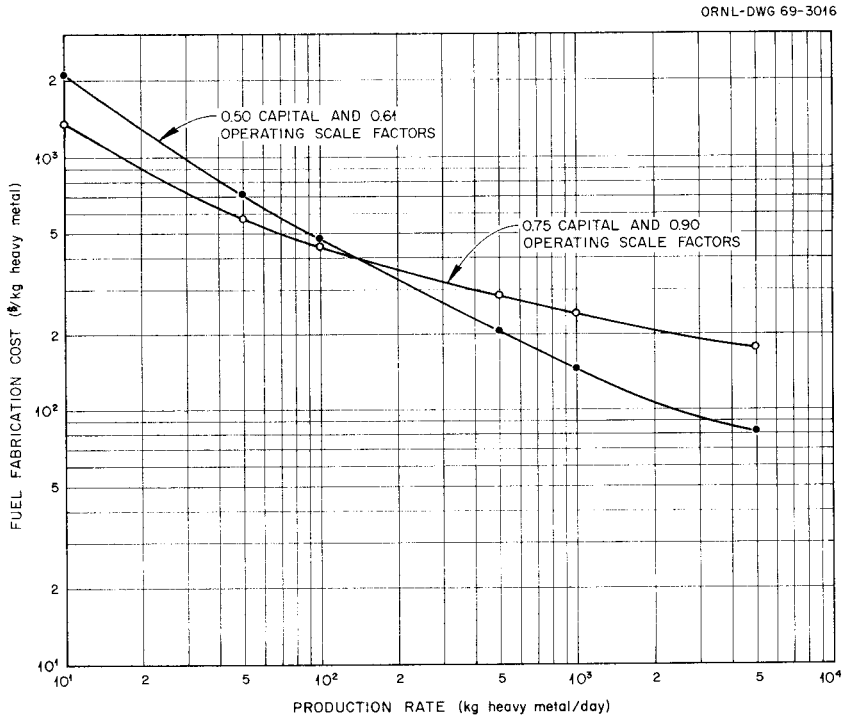

Fig. 11. Recycle Processing Costs With Different Scale Factors.

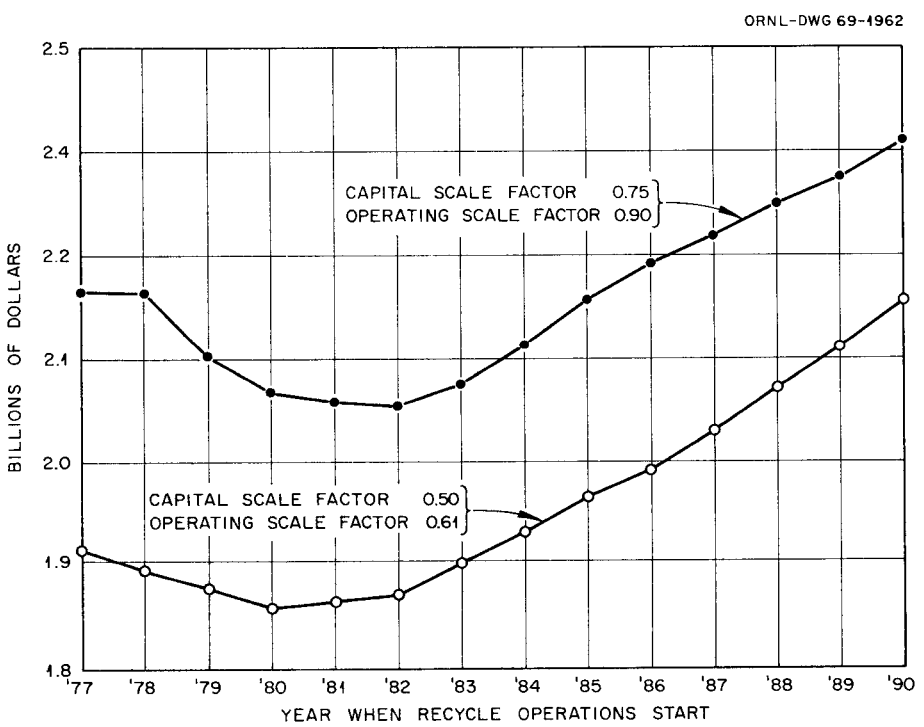

Fig. 12. Effect of Increased ^{233}U Fuel Production Scale Factor on Total Cost.

growth curve, which showed 39 reactors built over an 8-year period, were compared with results from a 32-reactor 9-year growth curve, a 105-reactor 12-year growth curve, and a growth curve which increased at the same rate as the 105-reactor growth curve, but then stayed constant at 20 reactors built per year for the remainder of the calculation period. The total present worthed costs for these cases are compared with the total present worthed cost for the base case. All are shown as a function of the time when recycle operations start in Fig. 13. The minimum for the 32-reactor case occurs in 1982, two years after the minimum exhibited by the base case of 39 reactors. The 105-reactor case also shows a minimum in 1982. The extended case shows a minimum in 1983. As would be expected, the growth rate is the parameter which causes the most change in the economically optimum time for start of recycle operations.

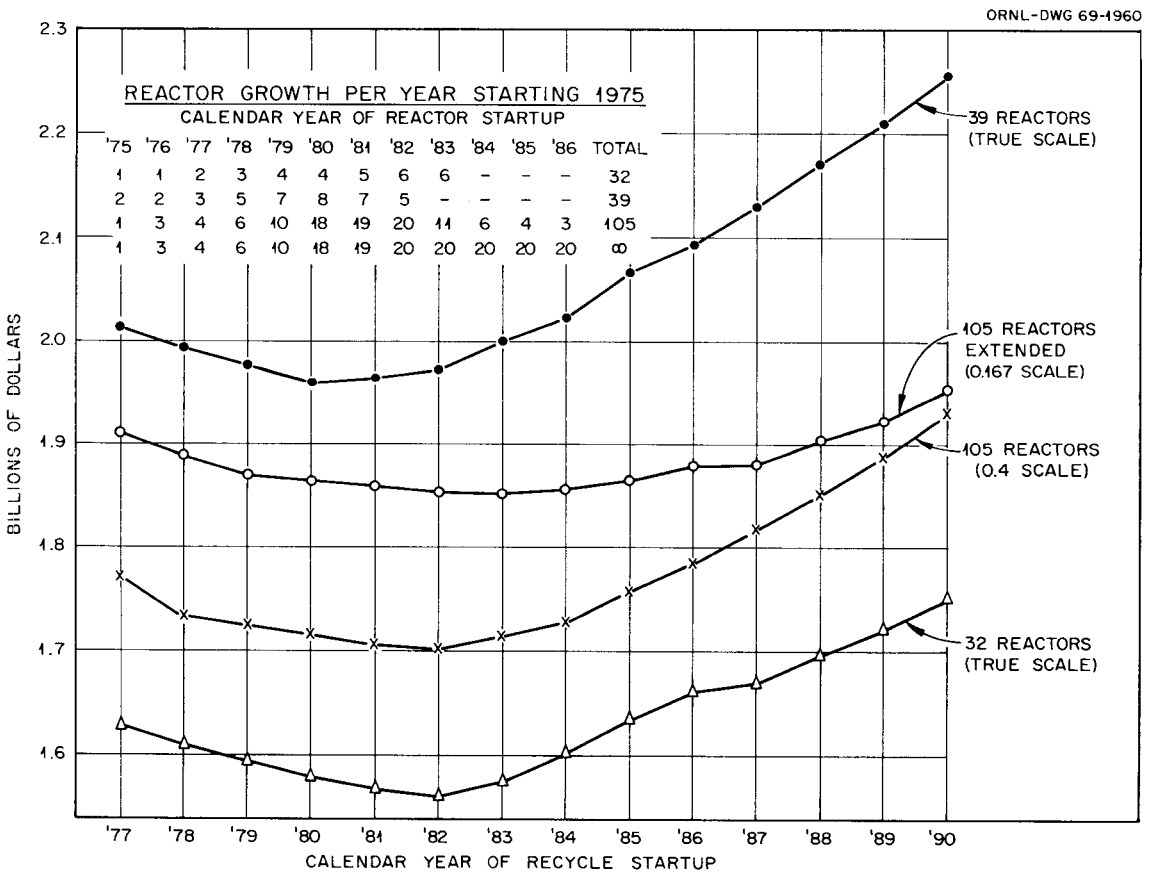

Fig. 13. Total Cost for 43 Years (at 1974 Worth) Versus Time of Recycle Startup for Various Growth Rates.

The results of varying parameters show that the economically optimum time for recycle operations to start is 1980 to 1983. Or, in terms relative to the start of the growth curve, the economically optimum time for recycle operations to start is 5 to 8 years after start-up of the first 1000-Mw(e) HTGR. The spread in the optimum recycle start date can be narrowed as the parameters used in the calculation are known more accurately.

The additional expenditures that will have to be made if recycle operations are not begun at the economically optimum time can be estimated from the base case as shown in Fig. 14. The units at the left represent the difference in the total present worth cost (1974 value) for the case where the recycle operation start is delayed and the case where recycle operation start is at the economically optimum time. The units at the right represent this difference expressed in mills per kilowatt-hour.

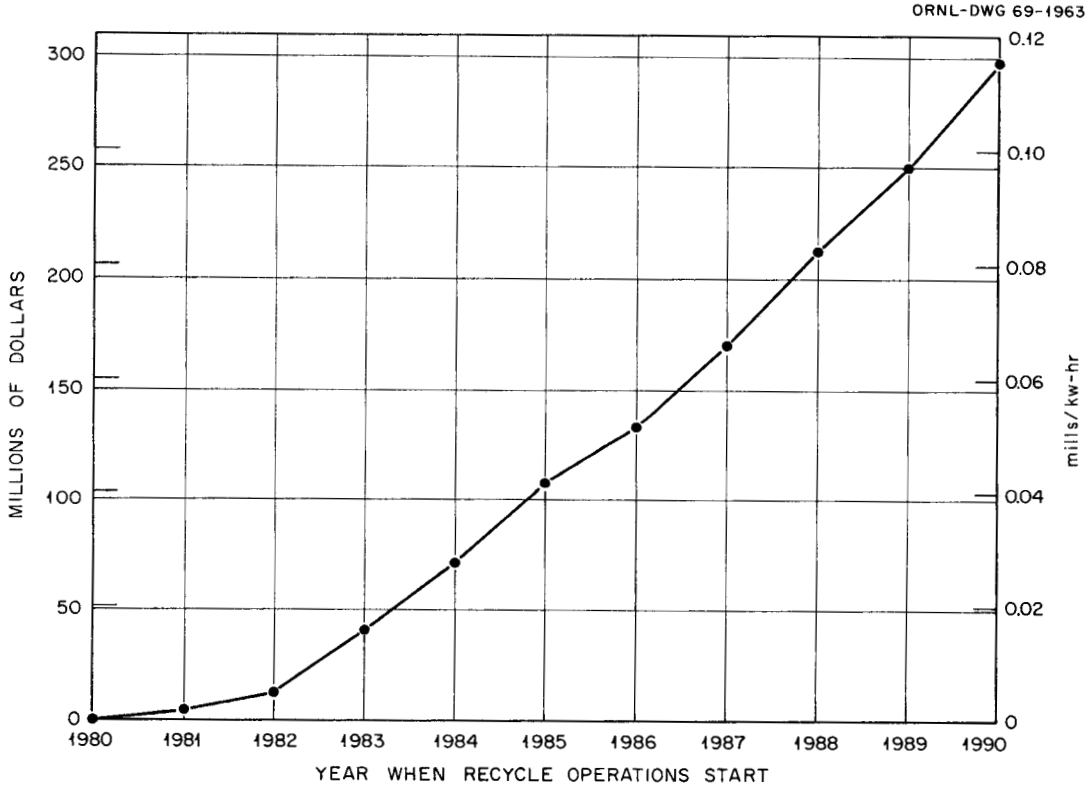

Fig. 14. Cost Penalty for Starting Recycle Operations at Economically Unfavorable Times.

Notice the steeper slope after a 2-year delay (1982). The low slope between 0 and 2 years and the higher slope after a 2-year delay partially explains why varying the parameters in the 39-reactor growth case could, in some circumstances shift the economically optimum date for recycle start from 1980 to 1982, but no farther. That is, starting recycle operations after 1982 would be grossly uneconomic for the 39-reactor case. In fact, as previously shown in Fig. 12, all cases considered, except the extended 105-reactor growth curve, show large economic penalities to be paid if recycle startup is delayed past 1982, or 7 years after the start up of the initial 1000-Mw(e) HTGR.

The power cost penalty, in mills per kilowatt-hour, seems insignificant in terms of the accuracy with which fuel cycle costs are presently known for HTGR's. However, one must remember that the mills per kilowatt hour costs shown here are differences of costs which are known accurately with respect to each other. Thus, the differences are real; for the size of the HTGR industry which may exist in a very few years, they add up to a significant dollar value. For the 39-reactor case, a 0.01 mill/kwhr difference in the industry amounts to a present worth cost of $20 million.

CONCLUSIONS

1. The economically optimum time to start recycle of HTGR fuels is 5 to 8 years after the completion of the first 1000-Mw(e) HTGR.

2. The fuel cycle cost for an ideally organized system of 39 reactors of the 1000-Mw(e) HTGR type is estimated to be 0.89 mills/kwhr.

3. Economic information useful for the scheduling of fuel recycle development programs can be obtained.

The first conclusions concerning the economically optimum time for fuel recycle operation start reflects uncertainty in the best estimates for costs of fabrication, processing and storage as well as the growth rate of the reactor industry. As better estimates of these factors are available, this variation can be narrowed.

The second conclusion on the fuel cycle cost must be considered with some circumspection since the study was performed to indicate differences in the cost of various recycle operation start dates, and

not for absolute cost values. Some of the costs included are not as accurate as one would desire, but represent the best information currently available. No consideration was given to technical advancements which might occur because of competition between firms or the likely case where smaller than economically ideal plants are constructed in an effort to minimize the risk of overconstruction. Hence, as in most estimates, the cost could be either low or high. In view of the conservative nature of most industries, the principal author considers the total fuel cycle cost arrived at by this study as slightly low.

The third conclusion is derived from the success of this study in finding a valid minimum in the curve of total present worth cost as a function of the time when recycle operations are started for an HTGR industry. In only a few new industries are the costs and future growth known with the accuracy needed for such estimates. Since the power industry has a reasonably predictable growth rate and since light-water reactors are well established, it is reasonable, at least in the early years, to predict the costs and time behavior for new systems. This study demonstrates a calculation method and its application to the HTGR industry.

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