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SUBJECT: Fuel Cycle Cost for Aqueous Homogeneous Reactors

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ABSTRACT

By using a large central fuel and blanket reprocessing facility, slurry-fueled aqueous homogeneous reactors can attain an estimated minimum fuel cycle cost of 1.4-1.6 mills/kwh; with solution-fueled two-region reactors, a doubling time of 14 years may be obtained at a fuel cycle cost of 2.0 mills/kwh. On-site processing appears desirable only for large power stations made up of reactors designed for short doubling times. For instance, a solution-fueled two-region reactor can attain a 12-year doubling time at an estimated fuel cycle cost of 1.5 mills/kwh at a 2000 Mw electricity station with an on-site processing plant.

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1.0 SUMMARY

The fuel cycle cost, defined as the total cost of reactor fuel and D₂O inventory, chemical plant inventory, D₂O recovery, storage, shipping, chemical processing, losses, and reconstitution, has been estimated for two situations: (1) a reactor system designed to give a minimum fuel cycle cost based on present technology and prices, and (2) the added cost of obtaining a system doubling time of about 10 years.

A minimum fuel cycle cost of 1.4-1.6 mills/kwh was obtained with a one- and a two-region slurry-fueled reactor (Table 1). Processing was considered on the basis of a central 6-tons-of-thorium-per-day processing plant. At the optimum fuel cycle cost the two-region slurry-fueled reactor has a conversion ratio of 1.05; however, the doubling time is of the order of 50 years because of the large U-233 inventory.

To obtain a system doubling time of the order of 10 years, it is necessary to use a solution-fueled two-region reactor operating at 90-100 kw/liter average in the core. In such a reactor, a doubling time of 14 years may be obtained by processing to hold the blanket U-233 concentration at 3.5 g/liter. With a central processing plant, the fuel cycle cost for this reactor system was estimated to be 2.0 mills/kwh, a premium of 0.5 mill/kwh for a 14-year doubling time. For on-site processing of this reactor system, the fuel cycle cost is sensitive to the station size. For a 2000 Mwe station, a doubling time of 12 years can be obtained for a fuel cycle cost of 1.5 mills/kwh. The corresponding fuel cycle cost for a 500 Mwe station is 2.0 mills/kwh.

Table 1. Fuel Cycle Cost and Doubling Time for Aqueous Homogeneous Reactors

Reactor Type	Processing Location	Station Size, Mwe	Doubling Time, years	Fuel Cost, mills/kwh
One-region slurry fuel	6 tons of Th/day central plant	300	(nonbreeder)	1.4
Two-region slurry fuel	6 tons of Th/day central plant	300	50	1.6
Two-region solution fuel	6 tons of Th/day central plant	300	14	2.0
	On site	500	12	2.0
	On site	2000	12	1.5

2.0 INTRODUCTION

Fuel cycle costs for aqueous homogeneous reactors were reviewed for use in the Fluid Fuel Reactors Task Force study. Insufficient time was available for this review to permit new detailed estimates of the cost of chemical reprocessing facilities; instead, previous estimates published in ORNL-1764, MIT-5005, and IDO-14363 were corrected for the increased construction cost index and modified to cover the particular needs of aqueous homogeneous reactors where needed. Certain inconsistencies were introduced in the data since the work was done by several people and at different times. However, these inconsistencies do not significantly affect the conclusion reached in this review.

Many members of the ORNL staff contributed to this review. The Oracle calculations were made by P. Kasten and members of his section of the Reactor Experimental Engineering Division. C. E. Guthrie, J. W. Ullmann, W. G. Stockdale, J. C. Suddath, and H. O. Weeren made the processing cost review. W. D. Burch, R. A. McNees, and H. O. Weeren assembled the schematic flowsheets used. N. A. Krohn made the fuel cycle cost analysis for the solution-fueled reactor.

3.0 REACTORS STUDIED

Three basic reactors were studied: a solution-fueled slurry-blanketed two-region reactor; a slurry-fueled slurry-blanketed two-region reactor; and a slurry-fueled one-region reactor (Table 2). The solution fuel reactor was considered only as a short doubling-time reactor, while both minimum fuel cycle cost and doubling time were investigated for the slurry fuel reactors.

The solution-fueled slurry-blanketed reactor was considered at two power levels, 200 and 400 Mw. For the higher power level the core external volume was doubled. The doubling time of the reactor was varied by changing the blanket processing period and therefore the amount of mass-233 in the reactor system. The blanket thorium concentration was held constant and the changes in blanket power were neglected.

The slurry-fueled reactors were investigated using the Oracle. Two power levels, 1000 and 1200 Mw, were considered. The main variables studied were the neutron poison level and thorium concentration vs. fuel cycle cost. For the single-region reactor two diameters, 12 and 14 ft, were also considered. In general, the optimum fuel cycle cost was obtained with a total poison fraction of 0.12-0.14 and a thorium concentration in the fuel of 200-300 g/liter. Detailed results of the Oracle calculations are presented in Sec. 7.0.

Table 2. Aqueous Homogeneous Reactors Studied

Reactor Type	Two-region, Solution Fuel ThO ₂ Slurry Blanket		Two-region, Slurry Core ThO ₂ Slurry Blanket		One-region, Slurry
Core dimensions	4 ft dia x 12 ft cylinder		7 ft dia x 18 ft cylinder		12 ft sphere
U-233 + U-235 in core, g/liter	2	2	7.5	13.2	10.0
Th in core, g/liter	0	0	200	300	250
U-233 + U-235 in blanket, g/liter	varied	varied	6	6	-
Core power, Mw	170	340	1,122	1,138	1,200
Blanket power, Mw	30	60	78	62	-
Total power, Mw	200	400	1,200	1,200	1,200
Core volume, liters	4,260	4,260	19,300	19,300	25,000
U-233 + U-235 in core, g	8,520	8,520	145,000	255,000	250,000
Th in core, kg	0	0	3,200	4,800	6,250
Core external volume, liters	8,500	17,000	55,600	55,600	60,000
U-233 + U-235 in external vol., g	17,000	34,000	407,000	734,000	600,000
Th in external volume, kg	0	0	11,120	16,680	15,000
Blanket thickness, ft	2	2	2	2	-
Blanket volume, liters	18,500	18,500	44,600	44,600	-
U-233 + U-235 in blanket, g	varied	varied	267,600	267,600	-
Th in blanket, kg	18,500	18,500	44,600	44,600	-
Blanket external volume, liters	3,200	3,200	4,700	4,700	-
U-233 + U-235 in blanket ext., g	varied	varied	28,200	28,200	-
Th in blanket external vol., kg	3,200	3,200	4,700	4,700	-
Core cycle time, days	-	-	360	630	700
Blanket cycle time, days	varied	varied	720	770	-
Total fission and corrosion product poison fraction	0.06	0.06	0.12	0.12	0.15
Breeding ratio	1.09	1.09	1.05	1.08	0.92

4.0 CHEMICAL PROCESSING

Aqueous homogeneous reactor fuels are processed to remove fission and corrosion products, which absorb neutrons and cause solution fuel instabilities. For the blanket of a two-region reactor processing has the primary purpose of separating fissionable and fertile material, and removal of fission and corrosion products is of secondary importance. The Thorex process is readily adaptable for the recovery of decontaminated U-233 and thorium from both solution fuel and slurries for aqueous homogeneous reactors.

4.1 Solution Fuel Processing

Processing of a uranyl sulfate solution fuel consists in removing fission products and/or corrosion products from three places in the reactor system: the hydroclone underflow, the reactor dump tank, and vapor from the reactor low-pressure system (Fig. 1).

A system of hydroclones capable of processing one reactor volume per hour, 100 gpm, will concentrate insoluble fission and corrosion products into a small volume of fuel solution in the underflow tank. Slurry discharged from this tank at convenient intervals is the chief withdrawal of material from the fuel system. The use of hydroclones for this purpose was demonstrated on the HRT, where a single 0.5-in. hydroclone removed the insoluble materials that reached it, maintaining a clarified fuel in the reactor.

The fuel solution, after passing through the hydroclones, is let down to the low-pressure system, evaporating about 10% of the D_2O . This D_2O vapor effectively strips iodine, xenon, krypton, and dissolved oxygen from the fuel solution, as demonstrated with the HRT. These gases can be readily separated from the D_2O in a liquid-gas absorption tower. Under these conditions (pure water and lower temperature) iodine is relatively nonvolatile and is removed from the bottom of the tower dissolved in a small stream of D_2O . The bulk of the D_2O , sufficiently pure for re-use without further treatment, may be recovered by condensing the overhead from the tower, and the xenon, krypton, and oxygen will remain as noncondensables. The gases are passed through a charcoal bed sized to retain the krypton and xenon for a period sufficient to decay all radioactive isotopes except the 10-year Kr-85. The exit gas from the charcoal, oxygen containing low concentrations of stable xenon and krypton and Kr-85, can be discharged up a stack with adequate dilution, or the rare gases can be separated from the oxygen by low-temperature charcoal adsorption for additional storage.

With hydroclone processing and continuous removal of iodine and rare gases, soluble nickel, from corrosion of stainless steel, becomes the chief chemical and nuclear contaminant in the fuel solution. The concentration of this material is kept at 0.02 m, an acceptable level from the standpoint of neutron poisoning, by withdrawing fuel solution from the hydroclone underflow tank at a rate of 60 liters/day. However, since dissolved nickel

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Fig. 1. Reprocessing flowsheet for solution-fueled two-region reactor.

contributes so heavily to solution instability, it is advisable to remove nickel at a rate sufficient to hold the concentration to 0.005 m or less. An attractive method for this is to remove copper and nickel, from about 200 liters of fuel solution per day from the reactor dump tank, in an electrolytic cell. Such a cell works best with a mercury cathode. After the addition of fresh copper catalyst, the treated fuel solution can be returned directly to the reactor. The mercury can be purified for re-use by passing sulfuric acid solution through the electrolytic cell and reversing the electrode potential. The resulting nickel and copper sulfate solution becomes a radioactive waste. This method has been developed and successfully tested only in the laboratory.

Electrolytic removal of nickel is highly desirable for a reactor operated as a breeder, where the amount of fissionable material in the chemical plant becomes an important consideration in determining doubling time, because little decay time is required before electrolysis. However, if doubling time is not an over-riding consideration, sizing the hydroclone underflow withdrawal rate to control nickel is the simplest, most economical procedure.

The hydroclone underflow tank contents and the iodine-D₂O solution from the iodine removal system may be combined with slurry (Sec. 4.2) removed from the reactor blanket dump tanks for subsequent D₂O and U-233 recovery.

4.2 Slurry Blanket Processing

Slurry for processing is removed from the blanket dump tanks at convenient intervals. The amount of slurry processed varies from about 130 liters/day (130 kg Th/day) for a 400-Mw reactor operated to obtain a 10-year doubling time, to only about 60 liters/day (60 kg Th/day) for a 1200-Mw reactor operated to minimize fuel cycle cost. The slurry is combined with the underflow from the hydroclone, and the D₂O is recovered for immediate re-use by evaporating the slurry to dryness and heating the solids to about 300°C. Laboratory tests indicated that this will drive off 99.9% of the D₂O. Larger scale tests indicated that foaming during evaporation and entrainment of ThO₂ particles in the off-gas are the most serious problems associated with D₂O recovery.

The residual material is stored for about 150 days for decay of short-lived fission products, Pa-233 and Th-234, before solvent extraction processing. This time is sufficient to decrease the U-233 loss as Pa-233 and Th-234 to insignificant levels. If processing is done on the reactor site, the dried solids may be dissolved in nitric acid and stored as a solution for decay. If the material is to be shipped to a central chemical processing plant, both the drying for D₂O recovery and decay storage may be done in a suitably designed shipping container.

By using two full cycles of Thorex solvent extraction, the thorium and U-233 are recovered essentially free of fission product activity, but both contain isotopic contaminants that make them difficult handling problems. The uranium contains U-232, which adds to the alpha hazard and has daughters

that are energetic gamma emitters. The thorium contains appreciable Th-228 after several cycles through the reactor. This also contributes added alpha activity and energetic gamma-emitting daughters.

4.3 Slurry Fuel Processing

In the case of a slurry fuel essentially all the fission and corrosion products are adsorbed on the surface of the particles. There is a possibility that elemental iodine, xenon, and krypton can be stripped from the slurry in the reactor, but the technology for accomplishing this does not now exist. Therefore, at present, slurry fuel processing must be considered as essentially the same, in principle, as slurry blanket processing---for a 1200-Mw reactor the amount of slurry fuel processed per day would be about 120 liters or 30 kg of thorium.

Laboratory tests indicated that it may be possible to remove the bulk of the fission and corrosion products from the slurry with a nitric acid--hydrogen peroxide leach, without dissolving the slurry. However, more work is necessary to determine whether or not this represents an improvement over sending all the thorium through Thorex and reconstituting the slurry from decontaminated thorium and uranium.

4.4 Reconstitution of Fuel Solution

This has been satisfactorily accomplished in two ways, both equally attractive. In one, uranium from the Thorex product uranyl nitrate solution is sorbed on a cation exchange resin and eluted with sulfuric acid, and the uranyl sulfate is evaporated to dryness and redissolved in D₂O. In the other, the uranium is precipitated from the uranyl nitrate solution as UO₄, fired to anhydrous UO₃, and redissolved in D₂SO₄ solution. Both methods can be carried out rapidly enough to avoid serious radiation problems from U-233 daughters.

4.5 Reconstitution of Blanket Slurry

The preparation of pure ThO₂ for the blanket of a two-region reactor involves precipitating thorium oxalate from the Thorex thorium nitrate product solution and decomposing this material to the anhydrous oxide by firing (Fig. 2). Present indications are that a final firing temperature of 800-900°C is sufficient if care is taken to thoroughly digest the thorium oxalate after precipitation.

The particle size of the final oxide is controlled by the conditions under which the oxalate is precipitated, i.e., the concentration of the reagents, the rate of reagent addition, and temperature. Present practice consists in adding 0.7 M oxalic acid to 0.7 M Th(NO₃)₄ at 25°C and at a rate determined to produce a final average particle size of $2.2 \pm 0.2 \mu$. The oxalate precipitate is digested for 48 hr at 85°C, filtered, and fired to 800°C. The present scale of this operation is about 200 lb of ThO₂ per batch.

If subsequent work indicates that a firing temperature well above 1000°C is required, the procedure becomes more complicated. The oxide after being

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Fig. 2. Preparation of pure ThO_2 . Note: If a calcination temperature above 1000°C is required, the oxide is transferred to a gas-fired furnace and refired. In this case classification to remove oversize sinters is also required.

Fig. 3. Preparation of mixed thoria-urania. Note: If calcination as high as 1000°C is required, classification to remove oversize sinters is also required.

fired in the electric furnace must be transferred to a gas-fired furnace, fired to the desired temperature, discharged, slurried in water containing oxalic acid to disperse the oxide, classified to remove oversize sinters, centrifuged, and refired in an electric furnace to remove the oxalic acid.

4.6 Preparation of Fuel Slurry

The simplest, most satisfactory method of adding uranium to controlled-particle-size ThO_2 is the following (Fig. 3): The thorium oxalate is prepared as before to control the final particle size; however, the thorium oxalate is fired only to 650°C to produce a high-surface-area oxide. Urania is deposited on the preformed ThO_2 particles by slurrying the thorium in a solution of uranyl ammonium carbonate, which decomposes to UO_3 on heating to 100°C . The UO_3 precipitates on the ThO_2 particles, and the solids are recovered by centrifugation. The uranium diffuses into the ThO_2 to give a homogeneous mixed oxide when the particles are fired at 1050°C . This oxide has been routinely produced in 200-lb batches.

The decay products of U-232 and Th-228 will make fuel slurry reconstitution a highly radioactive operation. Shielding will be required, and all materials must be carefully contained to prevent spread of the alpha-active materials.

5.0 UNIT COST OF CHEMICAL PROCESSING

For solvent extraction plants of less than 1 ton per day capacity, the unit cost of chemical processing is quite sensitive to plant size. The unit cost increases rapidly as the plant size is decreased. On the other hand, a chemical plant built as an integral part of a reactor station can share many facilities with the reactors, such as, maintenance, utilities, analytical work, and waste disposal. For these reasons reactor stations with small chemical processing requirements will ship their fuel and blanket materials to a central chemical plant and large reactor stations will find it more economical to process on site. In the case of aqueous homogeneous reactors operating on the thorium cycle and using the Thorex process, the breakeven rate is at about 0.5 ton/day of thorium processed.

For two-region solution-fueled reactors processing at the rate required to maintain a doubling time of about 12 years, 500 kg/day corresponds to a 300 Mwe station; however, for slurry-fueled reactors operating under conditions set to minimize the fuel cost, 500 kg/day corresponds to 1500 and 5000 Mwe stations for two-region and single-region reactors, respectively. In the 500-2000 Mwe range, therefore, on-site plants are most economical for reactors striving to obtain short doubling times, and for reactors designed to minimize fuel cycle cost a central plant is more desirable.

5.1 On-site Chemical Processing

The estimated capital investment and operating cost for an on-site processing plant serving two-region solution-fueled reactors for various

plant sizes are given in Table 3 and plotted in Fig. 4. The estimate includes hydroclones, iodine removal, nickel removal, D₂O recovery, decay storage, solvent extraction, analytical facilities, gaseous and liquid waste disposal, and reconstitution of fuel and blanket media. The estimate is based on present day costs and technology and includes no allowance for profit or inventory of D₂O, uranium or thorium.

5.2 Central Chemical Processing Plant

Based on the detailed estimate of an 8-ton/day Purex plant given in MIT-5005, a 6-ton/day central chemical processing plant with facilities for receiving fuel and blanket media, storage, Thorex solvent extraction, and reconstitution of solution and slurry fuels is estimated to cost \$100,000,000. The annual operating cost for this plant is \$15,000,000 per year for a total annual cost of \$30,000,000.

5.3 On-site Investment for Reactors Using a Central Processing Plant

On-site facilities for reactors using a central reprocessing facility are estimated as follows, based on a 315 Mwe station (see Appendix for conceptual design):

Analytical laboratory (including 5 hot cells)	\$1,000,000
Off-gas system and stack (including rare gas bottling)	550,000
For slurry-fueled reactors:	
D ₂ O recovery, packaging slurry for shipment, carriers	800,000
Total for slurry-fueled reactors	\$2,350,000
For two-region solution-fueled reactors:	
Hydroclones, nickel removal, iodine removal, D ₂ O recovery packaging, carriers	1,800,000
Total for two-region solution-fueled reactors	\$3,350,000

The estimate for slurry packaging assumes that the slurry and/or hydroclone underflow are collected in a carrier designed to serve as a D₂O recovery and storage vessel. After the slurry has been evaporated to dryness, the carrier is disconnected from the utilities and stored under water until ready for shipment (see Appendix for detailed design).

Table 3. Cost of On-site Chemical Processing for Solution-fueled Two-region Aqueous Homogeneous Reactors

Plant Capacity, kg/day	Capital Investment	Annual Cost			Unit Cost, per kg Th
		Fixed Changes (15%)	Operating	Total	
200 ^a	\$11,800,000	1,620,000	1,620,000	3,240,000	54.00
1000 ^b	20,000,000	3,000,000	3,000,000	6,000,000	20.00
4000 ^c	46,400,000	6,960,000	8,000,000	15,000,000	12.50

^aTaken from MIT-5005 with minor modifications and correction for construction cost index change.

^bExtrapolated from footnote a.

^cTaken from IDO-14363, p. 833, with modifications.

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Fig. 4. Cost of on-site processing for two-region solution-fueled reactors.

5.4 Shipping Cost

The cost of shipping 150-day-decayed material from the reactor to the chemical plant and shipping the reconstituted fuel and/or thorium oxide back to the reactor is estimated to be \$9 and \$8 per kilogram of thorium for slurry and solution fuels, respectively. This estimate does not include amortization of carriers but does include cost of courier service.

6.0 DOUBLING TIME

Preliminary calculations indicated that only the two-region solution-fueled reactor could attain doubling times of 10 years or less, and only this concept was studied from the standpoint of cost of short doubling times. The system doubling time* for the two-region solution-fueled reactor is given in Fig. 5 as a function of blanket mass-233 concentration for 200- and 400-Mw reactors and for 180 and 60 day holdups for U-233 in the chemical plant cycle. From these curves it was concluded that only the 400-Mw reactor would yield doubling times near 10 years at reasonable processing rates for 180 days' holdup of U-233 in the chemical plant. Doubling times of the order of 10 years at reasonable processing rates can be obtained by holding the U-233 for only 60 days in the chemical plant.

Based on the estimated central processing plant unit cost of \$28 per kilogram of thorium, a doubling time of 14 years can be obtained with a fuel cycle cost of 2.0 mills/kwh (Fig. 6). This is on the same basis as the 1.4-1.6 mills/kwh optimum fuel cost for the slurry fuel reactors. Shortening the doubling time greatly increases the fuel cost for this case.

Based on the unit cost as a function of capacity for the on-site plant with a 2000-Mwe station (Fig. 4), the doubling time for 1.5 mills/kwh is 12 years if the U-233 holdup is 180 days and 10 years if the holdup is only 60 days. For the 180-day holdup, the fuel cost increases rapidly with lower doubling times; however, for 60 days' holdup a doubling time of 7.5 years can be obtained with a 2.0 mills/kwh fuel cost on the basis used. For a 500-Mwe station the fuel cycle cost is increased by a factor of about 1.3 over the 2000 Mwe station, and is approximately 1.4 times as great for a 330-Mwe station.

7.0 MINIMUM FUEL CYCLE COST FOR SLURRY FUEL REACTORS

The fuel cycle cost for both one- and two-region slurry-fueled reactors was optimized using the Oracle. Small inconsistencies were introduced into the data in calculating the fuel cycle cost from the results, and the data plots should be interpreted only to show trends. A detailed calculation of fuel cycle cost for reactors determined to be near optimum shows a total

*The doubling time for a large reactor system differs from that of a single reactor by a factor of $\ln 2$, or 0.69.

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Fig. 5. Doubling times for two-region solution-fueled reactor.

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Fig. 6. Fuel cycle cost for two-region solution-fueled 400 Mw per reactor, 2000 Mwe station; unit cost of processing as shown in Fig. 4.

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fuel cycle cost of 1.6 mills/kwh for the two-region reactor and 1.4 mills/kwh for the single-region reactor (Table 4). For the single-region reactor the optimum poison fraction was found to be 0.12 to 0.14 (Figs. 7 and 8, fission products, plus corrosion products at 0.5 mpy), for both 12- and 14-ft reactors operating in the optimum thorium concentration range of 200-300 g/liter (Fig. 9).

It is not practical to obtain a conversion ratio of 1.0 in the 12-ft single-region reactor (Fig. 10). Even with the 14-ft reactor operating with 300 g of thorium per liter, a breeding ratio of 1.0 can be obtained only by processing at a rate that will maintain the poison fraction at 0.09. This represents about 0.1 mill/kwh increase in fuel cycle cost over the optimum.

In the case of the two-region slurry-fueled reactor, the thorium concentration that gave minimum fuel cycle cost was in the 200-300 g/liter range with a U-233 concentration of 6 g/liter, or 6 g of U-233 per kilogram of thorium in the 1000 g Th/liter blanket. The optimum core poison fraction appeared to be 0.12-0.14, as with the single region reactor studied (Fig. 11). Breeding ratios at a poison fraction of 0.12 were 1.05 and 1.08 with core thorium concentrations of 200 and 300 g/liter, respectively. The doubling time at this poison fraction was 50 years.

8.0 APPENDIX

8.1 Preparation of ThO₂ for Shipping

It is proposed to carry out the operations of D₂O recovery, reslurrying with H₂O, and decay storage in the final shipping container (Fig. 12), thus obviating the need for transfer of the ThO₂ between vessels. The capacity of the carrier-evaporator is about 170 gal and the total weight is about 23 tons. The lead thickness is 9 in. Connections are provided on the top face for charging, discharging, and venting the carrier, for steam to the jacket, and for instruments. These nozzles are shielded while the carrier is in transit by a 2-in.-thick lead cap. Details of the loading and storage pits are shown in Figs. 13 and 14. The layout of the proposed slurry-handling equipment is shown in Fig. 15.

Prior to the discharge of slurry from the reactor, the plug will be removed from the loading pit and a carrier will be lowered into place on a small trolley similar to the one presently in use in the HRT-CP loading pit. As the carrier is lowered into place, the cap is caught by lugs and held above the carrier. The plug will be replaced and the trolley (with the carrier riding on it) will be cranked into place beneath the charging nozzles. Long-handled tools projecting through the lead roof will be used to connect the carrier to the charging nozzles and service lines. The ThO₂ slurry will be discharged to the carrier and evaporated to virtual dryness. The D₂O system will then be valved off and the almost dry ThO₂ will be reslurried in H₂O. The charging nozzles will then be disconnected, the carrier cranked back into position beneath the plug, the plug removed, and the carrier lifted out of the pit, the cap being automatically engaged as the carrier is lifted.

Fig. 7. Fuel cost vs neutron poison fraction in 14-ft-dia single-region reactors containing various thorium concentrations.

12 ft dia sphere

Neutron poison fraction contains

0.04 fixed poisons

— 1000 Mw

- - - 1200 Mw

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Fig. 8. Fuel cost vs neutron poison fraction for 12 ft dia, single-region reactors having various thorium concentrations.

Fig. 9. Fuel cost vs thorium concentration in single-region reactors for two power levels and reactor diameters.

1000 or 1200 Mw (thermal)

Doubling time given in parenthesis

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Fig. 10. Breeding ratio vs neutron poison fraction in single-region thorium breeder reactors for various thorium concentration and reactor diameter.

Fig. 11. Fuel cost, breeding ratio, and doubling time in two-region, cylindrical reactors having a 7 ft dia--18 ft length core, 2 ft blanket--6 g U/kg of Th--1000 g Th/liter, as a function of core poison fraction.

Fig. 12. Slurry carrier.

Fig. 13. Loading pit.

Fig. 14. Storage pit.

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Fig. 15. Layout of slurry-handling equipment.

Table 4. Fuel Cycle Cost

	<u>Two-region Slurry</u>		<u>Single-region Slurry</u>
	<u>200 g/liter</u>	<u>300 g/liter</u>	
Th processed, kg/day	109	97	30
U-233 processed, kg/day	1.94	1.95	1.20
D ₂ O processed, liters/day	276	183	121
Total Th in reactor, tons	63.6	70.8	21.2
Total U-233 in reactor, kg	848	1,285	850
Total D ₂ O in reactor, liters	124,000	124,000	85,000
Th inventory charge (\$22/kg at 14%/y), \$/day	670	750	230
U-233 inventory charge (\$18/g at 4%/y), \$/day	2,100	3,160	2,100
D ₂ O inventory charge (\$60/liter at 16.5%/y), \$/day	<u>4,200</u>	<u>4,200</u>	<u>2,880</u>
Subtotal, \$/day	7,000	8,100	5,200
Process cost (\$20 + \$8 = \$28/kg of Th), \$/day	3,060	2,760	840
Process inventories, \$/day	<u>1,310</u>	<u>1,200</u>	<u>690</u>
Subtotal, \$/day	4,400	4,000	1,500
On-site process \$2.35 x 10 ⁶ investment at 30%/y, \$/day	2,410	2,410	2,410
Value breeding gain, \$/day	<u>-1,190</u>	<u>-1,890</u>	<u>+1,890</u>
Total, \$/day	12,600	12,600	11,000
Mills/kwh at 330 Mwe	1.6	1.6	1.4

The carrier will be lowered into a shallow water-filled storage pit. The cap will be removed and one of the charging nozzles will be connected to a vent system by a flexible pipe. Connections will be made from above through the shielding water. The carrier will be allowed to remain in the storage pit until it is ready to be shipped. Then the connection to the vent system will be broken, the cap put on the carrier, and the carrier lifted out of the pit and put on a flatcar.

When the carrier is brought back from the processing plant it will be lowered into a shallow pit similar to the storage pit except for having room for only one carrier. Connections will be made under water, the roof plugs will be put on, and the shielding water drained. The H_2O will be evaporated and D_2O added to the dry ThO_2 , and the ThO_2 slurry will be charged to the reactor by being pumped from the carrier to a hydroclone, the underflow being discharged to an underflow pot and the overflow recirculated. When the ThO_2 has been transferred from the carrier, the pump will be shut off and the underflow pot dumped to the reactor.

8.2 Processing for a Two-region Reactor

The processing of a two-region reactor will be in all ways similar to that of a one-region except that the carrier will be larger and the core solution will be mixed with the blanket slurry prior to the D_2O evaporation step. The uranium will be returned from the processing plant separately as a concentrated solution.

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