J. A. Dougan

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DCPM 20/Dragon 3
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FUEL CYCLE ECONOMICS OF HTR'S

by

U. HANSEN

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1. INTRODUCTION

The economics of the fuel cycle depends on the economic conditions in which it operates. Changes in the conditions may increase or decrease the competitiveness of one reactor type or one particular fuel cycle. This simple truism is all too often overlooked.

The fuel cycle is characterised by certain data such as the amount of fuel required, the form in which it is required, how well it is utilised in the reactor, and the fate awaiting it once discharged. For these commodities and services certain prices have to be paid, so, according to individual requirements, the relative weights attached to each part of the fuel cycle differ for the various reactor types.

Given the commodities and services needed for different systems and sets of various economic scenarios it is possible to conceive reactor strategies intended to minimise overall costs. Numerous models have been developed and every organisation of some standing has presented its view on optimal strategies stretching well into the next millenium.

The construction time and operating life of a nuclear power plant are so long that a utility committed to a particular station may well view the problem from a different angle. The reactor is there and as the economic environment changes it will have to make the best of it.

This paper sets out to explore how a particular High Temperature Reactor, the GA 1160 MW(e), would react and adapt itself to the vagaries of the economic world. We have chosen two alternative fuel cycles, the reference thorium/high enriched uranium and the low enriched uranium cycle, and in addition the switch-over from uranium to thorium operation. The core design and fuel management have been described in papers DCPM 20/Dragon 1 and DCPM 20/Dragon 2.

The reference thorium cycle is a so called segregated cycle which distinguishes between feed and breed fuel particles. The concept leads to complications in the fabrication and reprocessing stages. The simpler one-particle-system with mixed feed and breed material is investigated and discussed as an alternative option.

The fuel cycle data produced by VSOP are contained on an interface for the following economic evaluation, which has been carried out with the latest version of the KPD code. The economic model is based on present-worth accounting with fuel financing calculated with the "buy-back" method. The history of individual fuel batches is followed separately through the different stages from pre-irradiation procurement, through irradiation in various core positions, to out-of-pile storage and reprocessing.

The investigation of a variety of cost input data has been supplemented by a dynamic cost calculation with time dependant, escalating cost data. The model allows to account for changes in the various prices for commodities and services contributing to the fuel cycle over the lifetime of the power plant.

Table 1

Cost Analysis Assumptions

Basic Costing Assumptions		
Annual Load Factor		0.8
Total Reactor Life		25 years
Interest Rate		10% p.a.
Discount Rate for Levelisation		10% p.a.
Lead Time for Ore Procurement	(Initial Core (Reload	730 days 548 days
Lead Time for Payment of Conversion and Enrichment Costs	(Initial Core (Reload	365 days 365 days
Lead Time for Fuel Fabrication Expenditures	(Initial Core (Reload	365 days 183 days
Lead Time for Fuel Re-Fabrication		125 days
Lag Time for Shipping + Reprocessing Expenditures		240 days
Lag Time for Credit for Discharged Fuel		240 days

Fuel Service Costs		Cost Set 1	Cost Set 2
Fabrication of Fresh Fuel (Including Block, Coated Particles Assembly)	(Th (U	1800 $/FE 1115 $/FE	2450 $/FE 1550 $/FE
Fabrication of Recycle Fuel	Th	2700 $/FE	3800 $/FE
Shipping Cost Spent Fuel		800 $/FE	800 $/FE
Reprocessing Cost (Including Head-End, Chemical Separation, Waste Store)	(Th (U	1300 $/FE 1200 $/FE	1800 $/FE 1600 $/FE

Fixed Materials Costs	
Conversion Cost U_3O_8-UF6	2.34 $/kg U
Tail Enrichment	0.25%
Thorium	10.00 $/kg
Pu-Parity	0.5
U233 Parity	1.25

Cost Parameter Variation		
Uranium Ore	10	100 $/lb U_3O_8
Separative Work	60	120 $/SWU

2. COST ASSUMPTIONS AND STRATEGY OF ANALYSIS

The outcome of a cost analysis is obviously sensitive to the cost input parameters, so the fuel cycle cost evaluation include a cost sensitivity and trends analysis. Two basic sets of cost assumptions for fuel service, i.e. fuel fabrication, shipping, reprocessing and refabrication, have been used, one reflecting a more optimistic view, Cost Set 1, and one a more cautious one, Cost Set 2, Table 1. The timing of payments and revenues are shown in Fig. 1.

Important parameters are the cost of uranium ore and separative work. It is not more than a year ago that one could assume uranium for delivery in the early eighties to cost 10\$/lb U_3O_8, now it is more likely that it will cost 30\$/lb U_3O_8. Separative work at this time is estimated to amount to 60\$/SWU when interest during the nine years commitment period is added. We have used these values in some base cost reference points and have then shown how fuel cycle costs would vary with increasing ore price and separative work costs. For the utilities engaged in the forward planning in a rapidly changing market, these results constitute a first set of guidelines.

A cost escalation study was made for an HTR that would come on line in the middle 1980's. Linear cost escalations were assumed for fuel to be loaded into the reactor from 1985 over 25 y reactor life to the year 2010. On the basis of present expectancies the ore price would go up from 30 to 100 \$/lb U_3O_8 and the separative work from 60 to 120 \$/SWU. It was further assumed that fabrication and reprocessing would escalate with half of the costs fixed and the other half increasing by 3% per annum, Fig. 5.

All costs are given in 1975 \$, i.e., no inflation was taken into account.

3. COMPARISON OF THE LOW ENRICHED URANIUM AND THE REFERENCE THORIUM FUEL CYCLE

The basic underlying factor of the nuclear fuel cycle economy is the neutron economy. A comparison of the equilibrium cycle neutron balances, Table 2, at mid cycle between two annual reloads shows that for the case of the low enriched cycle around 40% of all neutrons are produced in fissions of plutonium isotopes while for the thorium cycle 60% of all neutrons are contributed by U-233 fissions. The fractional absorption in all plutonium isotopes is roughly equal to the one in U-233, namely 26%. This demonstrates the better breeding potential of the thorium cycle and explains why 28% of its neutrons can be used for conversion as compared to only 18% in the case of the low enriched cycle. The conversion ratio (breeding ratio) for the low enriched cycle is therefore only 0.50 as compared to 0.63 for the thorium cycle.

This, together with the different enrichment requirements for the low enriched cycle and the thorium/high enriched cycle, leads to the natural uranium and separative work requirements given in Table 3. No ore and separative work credit has been accounted for the plutonium discharge in the low enriched fuel cycle, neither for the U-233 of the last core in the thorium cycle.

On the basis of a 25 y reactor lifetime, the average natural uranium requirement for the low enriched cycle is 65% higher. Also its separative work requirement is higher, namely by 42%. Consequently price rises in these two areas will penalise the low enriched cycle more than the thorium cycle. This is shown in Figs. 2 and 3 for ore price and separative work cost rising from a base point at 10\$/lb U_3O_8 and 60\$/SWU.

Table 2

Neutron Balance (at Mid Cycle Between Reloads)

	Thorium-Recycle		LE-Uranium	
	Losses (%)	Production (%)	Losses (%)	Production (%)
Th-232	27.79	0.17		
Pa-233	0.95			
U-233	25.89	57.41		
U-234	2.68			
U-235	20.89	40.84	29.81	58.47
U-236 + Np-237	1.83		1.35	
U-238	0.65		18.49	0.39
Pu-239	0.65	1.17	17.90	32.37
Pu-240	0.20		5.11	
Pu-241	0.17	0.33	4.19	8.74
Pu-242	0.02		0.32	
HM Total	81.71	99.94	77.22	99.97
Fission Products	9.34		9.18	
Graphite	1.65		1.91	
Control	3.88		8.18	
Leakage	3.42		3.51	
Total	100.00		100.00	
Conversion Ratio	0.63		0.50	

Table 3 Uranium and Separative Work Requirement			
Fuel Cycle		Thorium-U233 Reference (Segregation)	Low Enriched Uranium
Nat. Uranium Equilibrium	(kg U/MW(e)-y)	90	166
Sep. Work Equilibrium	(SWU/MW(e)-y)	97	157
Nat. Uranium 25 y Avg	(kg U/MW(e)-y)	102	166
Sep. Work 25 y Avg	(SWU/MW(e)-y)	110	156

At the base point a comparison of thorium and low enriched fuel cycle costs was made which shows the thorium cycle to be roughly 12% cheaper than the uranium cycle for a 25 y plant lifetime. See Table 4:

Table 4 Fuel Cycle Costs (10$/lb U_3O_8, 60$/SWU)			
		Thorium	Low-Enriched
Equilibrium	Fuel Service Cost Set 1	2.10 mills/kWh	2.47 mills/kWh
	Fuel Service Cost Set 2	2.27 mills/kWh	2.61 mills/kWh
25 y Lifetime Average	Fuel Service Cost Set 1	2.16 mills/kWh	2.47 mills/kWh
	Fuel Service Cost Set 2	2.35 mills/kWh	2.63 mills/kWh

In contrast to the base point frequently used in previous studies, uranium for delivery in the early eighties is at present assumed to cost 30$ /lb U_3O_8 and separative work amounts to 60$ per unit when interest during the nine years commitment period is added. The future ore price is expected to increase to 50$/lb U_3O_8 around 1990 and reach 80$/lb U_3O_8 at the turn of the century. Likewise, the cost of separative work will rise, although the rate and pace are more difficult to prognosticate, as new techniques may emerge and influence present trends. It is assumed that a more modest price evolution will prevail and that today's price of 60$/SWU will increase to 75$ and 100$/SWU, respectively.

The future economic environment clearly favours the thorium cycle. The two sets of fuel service costs assumptions do not change the relative merits of the thorium and the low enriched fuel cycle. It is found that the fuel service cost per fuel element unit is a third cheaper for the low enriched reactor, but the annual fuel service bill is roughly the same for both cycles as the low enriched reactor refuels a third more per year than the thorium reactor.

Cost breakdowns for the base point of 30\$/lb U_3O_8 and 60\$/SWU are given in Table 5. The results show that the thorium fuel cycle is 0.70 mills/kWh cheaper than the low enriched one in spite of a total fabrication cost penalty of 0.11 mills/kWh. Reprocessing and shipping costs are mainly affected by the number of fuel elements discharged per year.

Table 5

Equilibrium Fuel Cycle Cost Breakdown (mills/kWh) for 30 \$/lb U_3O_8, 60 \$/SWU and Service Cost Set 2

	Thorium	LE-Uranium
Fissile Cost (Including U-233 Buy-Back)	3.56	3.43
Fertile Cost	0.02	0.00
Pu-Credit	0.00	0.09
U-233 + U-235 Credit	1.06	0.09
Net Fuel Cost	2.51	3.25
Fabrication Cost (Including Refabrication)	0.39	0.28
Reprocessing and Shipping Cost	0.28	0.36
Total Fuel Cycle Cost	3.19	3.89

It is demonstrated in Fig. 4 how increases in reprocessing and refabrication costs would influence the thorium reference cycle. It should be noted that the refabrication costs of both fuel service cost sets, Table 1, already include a refabrication penalty of 50% compared with fresh fuel.

Because of its low uranium and separative work requirements, the reference thorium cycle is able to cope with multiple cost increases before loosing its cost advantage over the low enriched cycle. As uranium and separative work costs rise, the thorium cycle can absorb even higher penalties.

Inherent in the above comparison is the fact that mere storing of discharged fuel will hit the thorium cycle more than the low enriched one because of the greater value of its discharged fissile material; compare fissile credits in Table 5. Closing the thorium fuel cycle is of the greatest importance.

It is hereby tacitly assumed that the storage costs per low enriched fuel element would be equal to the costs of the annual reprocessing and selling of fissile material. Certainly, if the storage costs per fuel element were to increase dramatically, the LE cycle would be penalised considerably because of its higher annual discharge rate of fuel elements. If no further optimisation was undertaken it may even increase the chances for a once-through thorium cycle for which the early closing of the fuel cycle is not imperative.

All the comparisons so far are based on a load factor of 0.8, Table 1. The average load factor actually recorded in nuclear power stations is, however, closer to 0.6. It was investigated how a change to the lower load factor would effect the comparison between the two cycles. The results are given in Table 6 and show that the thorium cost advantage is reduced, though this effect will be small as uranium prices (and separative work costs) increase.

Table 6

Influence of Annual Load Factor on LE and Thorium Fuel Cycle Cost Comparison

Cost Set 2, 60 $/SWU

		Thorium Reference (mills/kWh)	Low Enriched (mills/kWh)	Thorium Advantage 100*(Th-LE)/LE
10 $/lb U_3O_8				
Load Factor	0.8	2.34	2.63	-11.2%
	0.6	2.50	2.71	- 7.7%
30 $/lb U_3O_8				
Load Factor	0.8	3.25	3.89	-16.5%
	0.6	3.49	4.01	-13.0%

4. THE URANIUM FUELLED HTR AND THE SWITCH OVER TO THE THORIUM CYCLE

As long as the fuel cycle for the thorium cycle is not closed the low enriched fuel cycle will offer an attractive alternative in spite of higher fuel cycle costs. The estimates are, that the thorium fuel cycle can be closed in the US in the late 1980s. It is quite clear that Europe would need its own fuel recycling facility. Hopefully this will be established in a few years after the start of successful recycling operation on the other side of the Atlantic.

Our studies, [1 and 2] have shown the feasibility of operating the GA 1160 MW reactor on a low enriched cycle. The flexibility of the HTR is furthermore such, that it can be switched over from the low enriched to the thorium cycle under normal operating conditions.

The initial low enriched core starts with a higher heavy metal loading, N_C/N_{HM} = 316, than in the low enriched replacement batches to avoid an excessive initial reactivity and to faciliate the running in of the reactor. During the first 10 y the reactor is fuelled with 10.65% enriched uranium with annual replacement of a third of the core. Then follows a gradual conversion to thorium fuel. The reload batches in the switch-over phase contain both uranium and thorium elements. After 5 y all uranium elements have been removed and the reactor is now on the thorium cycle with annual replacement of a quarter of the core.

The total fissile content of the core is much higher in the thorium cycle, and it is interesting to note that the bred U-233 stabilises at a level five times higher than the fissile plutonium in the low enriched cycle. The financing costs of the U-233 inventory constitutes an important item in the fuel cycle cost for a thorium system.

There is a clear cost incentive to switch to the thorium cycle, and this is already noticeable during the transition phase. The equilibrium cycle costs for the LE are 3.89 mills/kWh, whereas the thorium cycle levels out at 3.19 mills/kWh when U-233 recycle has been established (Table 5).

The HTR was considered to go on line in 1985 and operate for a period of 25 y until 2010. As mentioned above the switch over is supposed to start ten years after commissioning, i.e., in the year 1995. The economic implications have been calculated for various scenarios of natural uranium and separative work costs. In all cases the incentive to adopt the thorium cycle when recycle facilities became available was clearly displayed.

We shall now attempt to illuminate the utilities option at the time of decision making by evaluating the present worth value of the last 15 years of operation, from year 1995 to 2010, at time point 1995. The results are given in Table 7. The savings constitute the difference between continuing the low enriched cycle and the 5 y switch over period with subsequent thorium/U-233 recycle operation. The expected realistic saving will amount to more than 50 Mio $ in present worth terms. It must again be stressed that all costs and prices are in 1975 $ as no inflation has been accounted for.

Table 7

Savings as Cost Incentives for Switch Over to Thorium Fuel Cycle After 10 y of Operation on Low Enriched Fuel

For Fuel Service Cost Set 2 and 60 $/SWU	
10 $/lb U_3O_8	15.8 Mio $
30 "	33.1 "
50 "	50.4 "
100 "	93.7 "

Total present worth in 1995 but accounted in 1975 $ (no inflation).

Estimated 15 y of further reactor operation (1995-2010) for reactor assumed to have gone on power in 1985.

In all the cost studies reported in the preceding paragraphs, the cost input data were kept constant over the lifetime of the power plant. With certainty, however, the prices will change as new market situations develop. The dynamic cost model in KPD allows to simulate these future developments and the attempt has been made to investigate the relative competitiveness of alternative HTR fuel cycles as the market changes.

The study was made for the reactor to start up in 1985 and reach its full lifetime in 2010. The costs were assumed to escalate linearly from 30$/lb U_3O_8 and 60$/SWU and reach 100$/lb U_3O_8 and 120$/SWU, respectively. The fuel service costs are based on Cost Set 2, see Section 2 and Fig. 5. Against this economic back-cloth the fuel cycle costs for the thorium and the low enriched cycle are shown in Fig. 6. In the 10th year of operation when the cycles have reached their equilibrium, i.e., around 1995, the thorium cycle would be 22% cheaper. This cost advantage could increase to 30% in the last year of operation.

The incentive to switch over from low enriched to thorium also comes out clearly in the dynamic model. With the same accounting procedure as used for Table 7, i.e., for the last 15 y of operation, the estimated saving amounts to 67 Mio $ in present worth money in time point 1995.

On a whole the switch over requires a carefully planned fuel management strategy, but no alterations were found necessary to the existing design of the reactor or the power plant. This mode of operations appears a viable option for the introductory phase of the HTR and may possess particular appeal to utilities interested in HTRs.

5. COMPARISON OF THE THORIUM REFERENCE WITH THE THORIUM ONE-COATED-PARTICLE CYCLE

One of the advantages of the low enriched cycle compared to the thorium reference cycle is the use of only one type of coated particle. The thorium reference case is a segregated cycle with particles of different size which will be separated in the head-end stage of reprocessing to remove the main bulk of U-236, a neutron poison, from the system. Consequently the head-end for the reference thorium cycle is more complicated and more costly than the one for the low enriched cycle whereas otherwise they share the same head-end technology. It will therefore be easier to close the fuel cycle for a non-segregation system than for the segregated one.

We have investigated a thorium fuel cycle with one coated particle type only. Some data and results are given in Tables 8 and 9. The particle itself may either be of BISO or TRISO type. It is not likely that all particles would contain the mixed oxide fuel, for fabrication reasons some may be pure ThO_2 particles. The important point, however, is that in the reprocessing and refabrication stages no distinction is made between the pure thorium and mixed oxide particles. The reference cycle requires the fabrication of 630 fresh and 365 recycle fuel elements per year. Due to the larger amount of recycled material the one-coated-particle system would require 444 elements to be handled in the hot facilities, whereas only 542 elements would be cold fabricated. This means that the latter cycle will have to carry an increased refabrication penalty.

The uranium isotope 236 is a strong neutron absorber with pronounced captures in the resonance region. The cross section is similar to U-238, but due to its relatively small concentration the resonance self-shielding has been neglected in the VSOP calculations. Neptunium 237 is a daughter nuclide of the capture process in U-236. Also this nuclide is a noticeable neutron absorber. It has been assumed that Np-237 is completely removed in the fuel reprocessing stage, but still the Np-237 level in the core is much higher in the one-particle system than in the segregated one. This is caused by the larger concentration of U-236 and in consequence the greater rate of production of Np-237. The total absorption in the two nuclides exceeds 5.7% at the end of the lifetime compared to roughly 2% in the case of segregation (Table 9). The build-up of parasitic absorbers leaves less neutrons for the breeding process in thorium. It is also evident from the Table that U-233 contributes less to the production of neutrons, the fraction has fallen from roughly 65% to just over 56%.

Table 8

Thorium Fuel Cycle With and Without Total U-236 Recycle

Item	Reference (Segregation) Th-Cycle	1-Coated Particle (U-236 Recycle) Th-Cycle
Fuel	Feed/Breed	Mixed
Type of Coated Particle	TRISO/BISO	BISO or TRISO
Kernel Diameter (μm)	200/500	500
No. of Fresh FE per year	630	542
No. of Recycle FE per year	356	444
Amount of U-236 Recycle per year		
5th Cycle	57 kg	57 kg
15th Cycle	58 kg	156 kg
25th Cycle	58 kg	214 kg
Conversion Ratio Equilibrium year 25	0.631	0.566
Fissile Inventory Equilibrium year 25	1,269 kg	1,536 kg
Uranium Ore Requirement	102 kg Unat/MW(e)y	112 kg Unat/MW(e)y
Separative Work Requirement	110 SWU/MW(e)y	120 SWU/MW(e)y
FCC 25 y (10 $/lb, 60 $/SWU)	2.34 mills/kWh	2.37 mills/kWh
FCC 25 y (30 $/lb, 60 $/SWU)	3.25 mills/kWh	3.33 mills/kWh

Table 9

Absorption Rates [%] With and Without U-236 Recycle

	Segregation End of Cycle		U-236 Recycle End of Cycle	
	5	25	5	25
U-236 Absorption	1.26	1.20	1.63	3.48
Np-237 Absorption	0.80	0.76	1.03	2.25
Th-232 Absorption	29.45	28.85	28.85	24.96
Productions from U-233	63.79	64.95	62.34	56.28
Productions from U-235	34.76	33.81	35.84	40.45

The conversion ratio for the one-coated-particle cycle falls constantly as the neutron economy deteriorates and is down to 0.57 at the end of the reactor lifetime. To maintain criticality the fissile inventory steadily rises and ultimately reaches a level some 20% higher than in the reference cycle with fuel segregation. As a consequence the total natural uranium and separative work requirements averaged over the 25 y operating time have increased by some 10%.

The production costs of the large mixed oxide coated particles are assumed to be similar to the cost of low enriched particles. The reprocessing and shipping costs are taken to be the same as for LE fuel. The refabrication costs, however, are adopted unaltered from the thorium reference cycle. All fuel service costs are based on cost Set 2.

The fuel cycle cost calculated for 30$/lb U_3O_8 increases by 0.08 mills/kWh, corresponding to 2.5% of the fuel cycle cost, or approximately 0.5% of the total generating costs. This is a small penalty against the advantage of simplified fuel handling operations and the possible earlier closing of the fuel cycle.

6. SUMMARY

The High Temperature Reactor commands a unique fuel cycle flexibility and alternative options are open to the utilities.

The reference thorium reactor operating in the U-233 recycle mode is 10 to 20% cheaper than the low-enriched reactor; however, the thorium cycle depends on the supply of 93% enriched uranium and the availability of reprocessing and refabrication facilities to utilise its bred fissile material.

The economic landscape towards the end of the century will presumably be dominated by pronounced increases in the costs of natural resources. In the case of nuclear energy, resource considerations are reflected in the price of uranium, which is expected to have reached 50 $/lb U_3O_8 in the early 1990s and even 100 $/lb U_3O_8 around 2010. In this economic environment the fuel cycle advantage of the thorium system amounts to some 30% and is capable of absorbing substantial expenses in bringing about the closing of the out-of-pile cycle.

A most attractive aspect of the HTR fuel cycle flexibility is for the utility to start operating the reactor on the low enriched uranium cycle and at a later date switch over to the thorium cycle as this becomes economically more and more attractive. The incentive amounts to some 50 Mio$ in terms of present worth money at the time of decision making, assumed to take place 10 y after start-up.

The closing of the thorium cycle is of paramount importance and a step to realise this objective lies in simplifying the head-end reprocessing technology by abandoning the segregation concept of feed and breed coated particles in the reference cycle. A one-coated-particle scheme in which all discharged uranium isotopes are recycled in mixed oxide particles is feasible and suffers a very minor economic penalty only.

7. REFERENCES

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[2] H. Gutmann, U. Hansen, H. Larsen and H. J. Neef, "The High Temperature Reactor in the Future Fuel Market", ENC, Paris 1975.

[3] U. Hansen, "The VSOP System Present Worth Fuel Cycle Cost Calculations Methods and Codes KPD", D.P. Report 915, February 1975.

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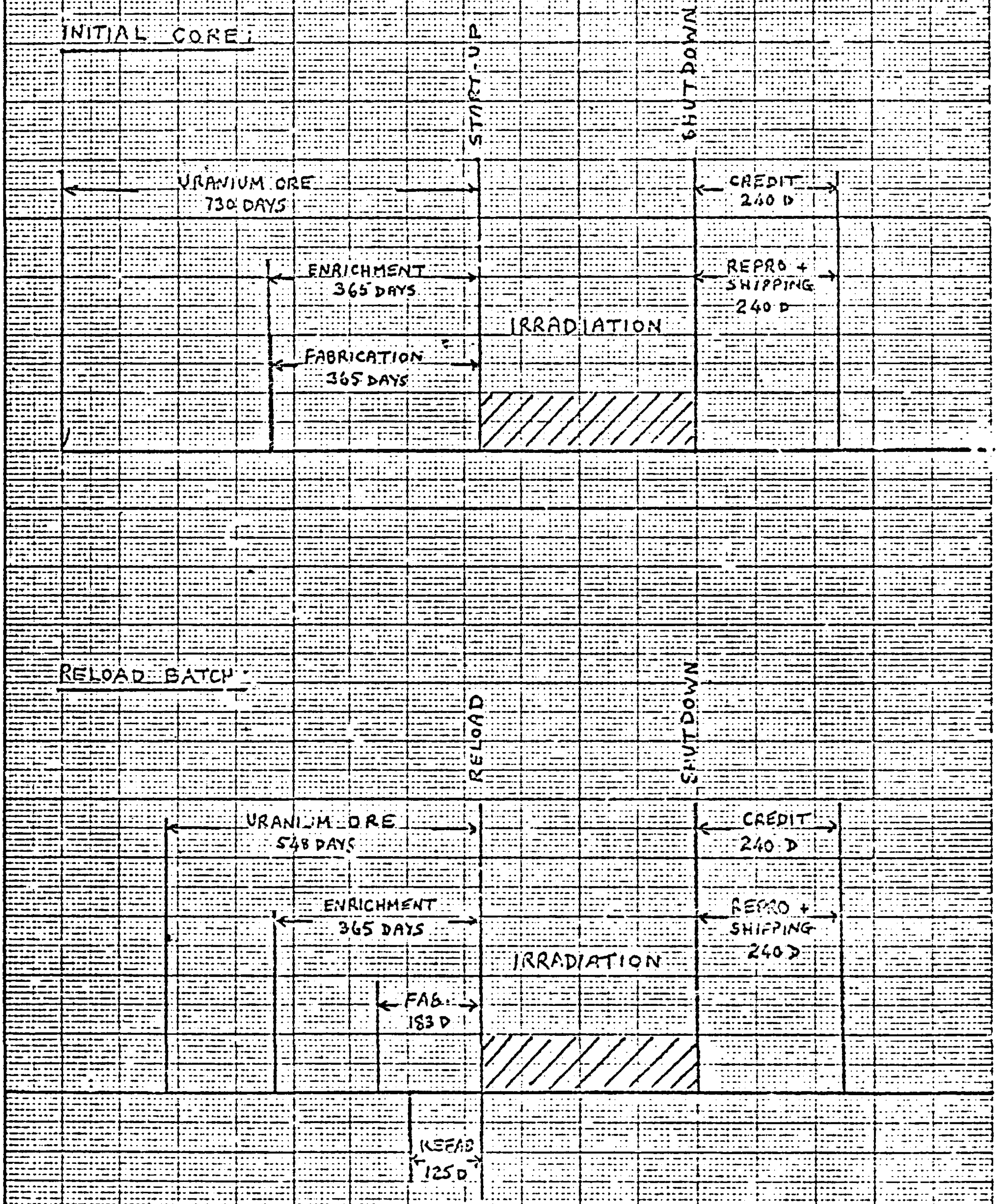

FIG 1 LEAD AND LAG TIMES FOR PAYMENTS AND REVENUES.

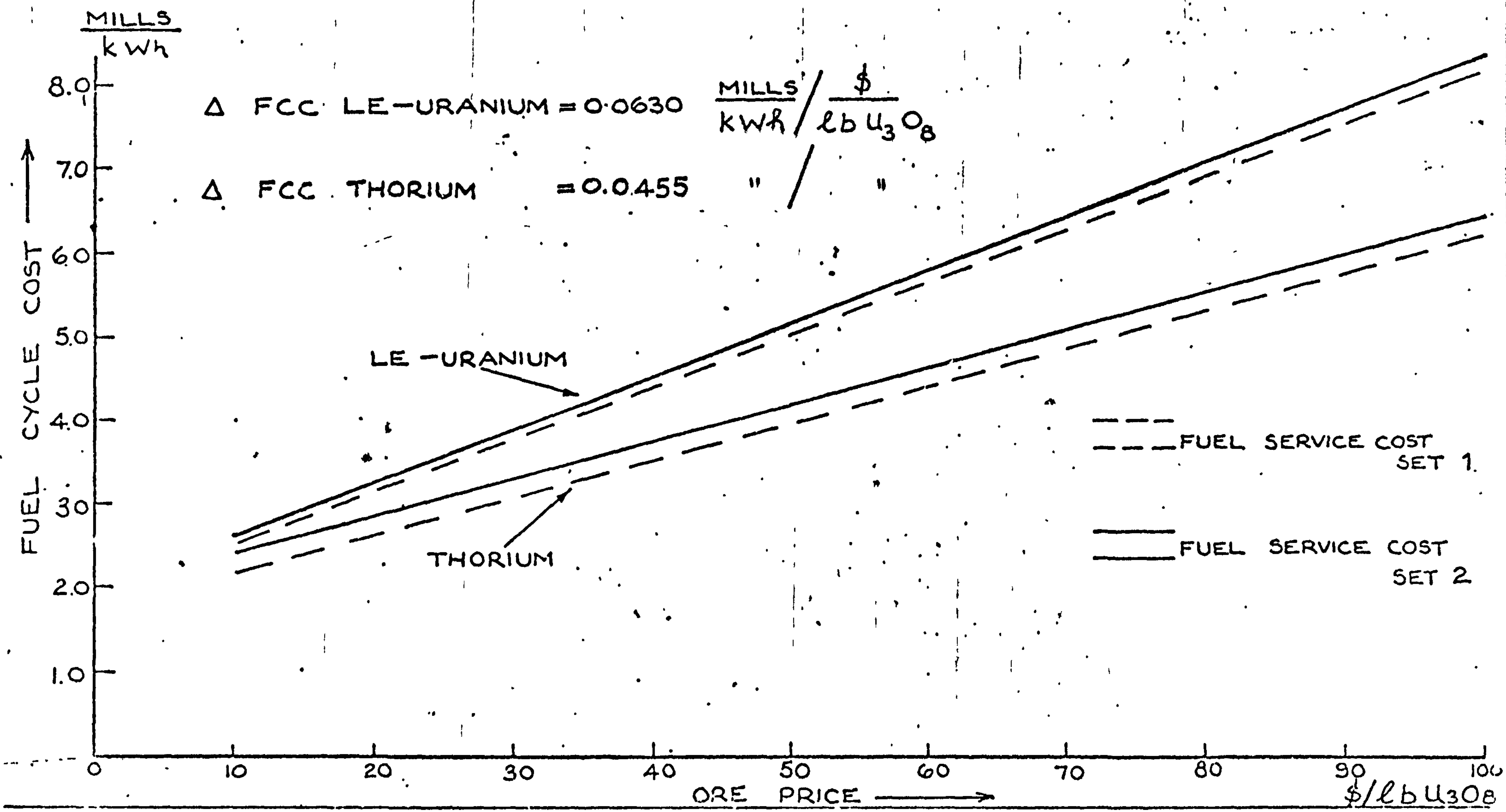

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FIG. 2 LE AND THORIUM FUEL CYCLE COSTS FOR 60 $/SWU VS ORE PRICE

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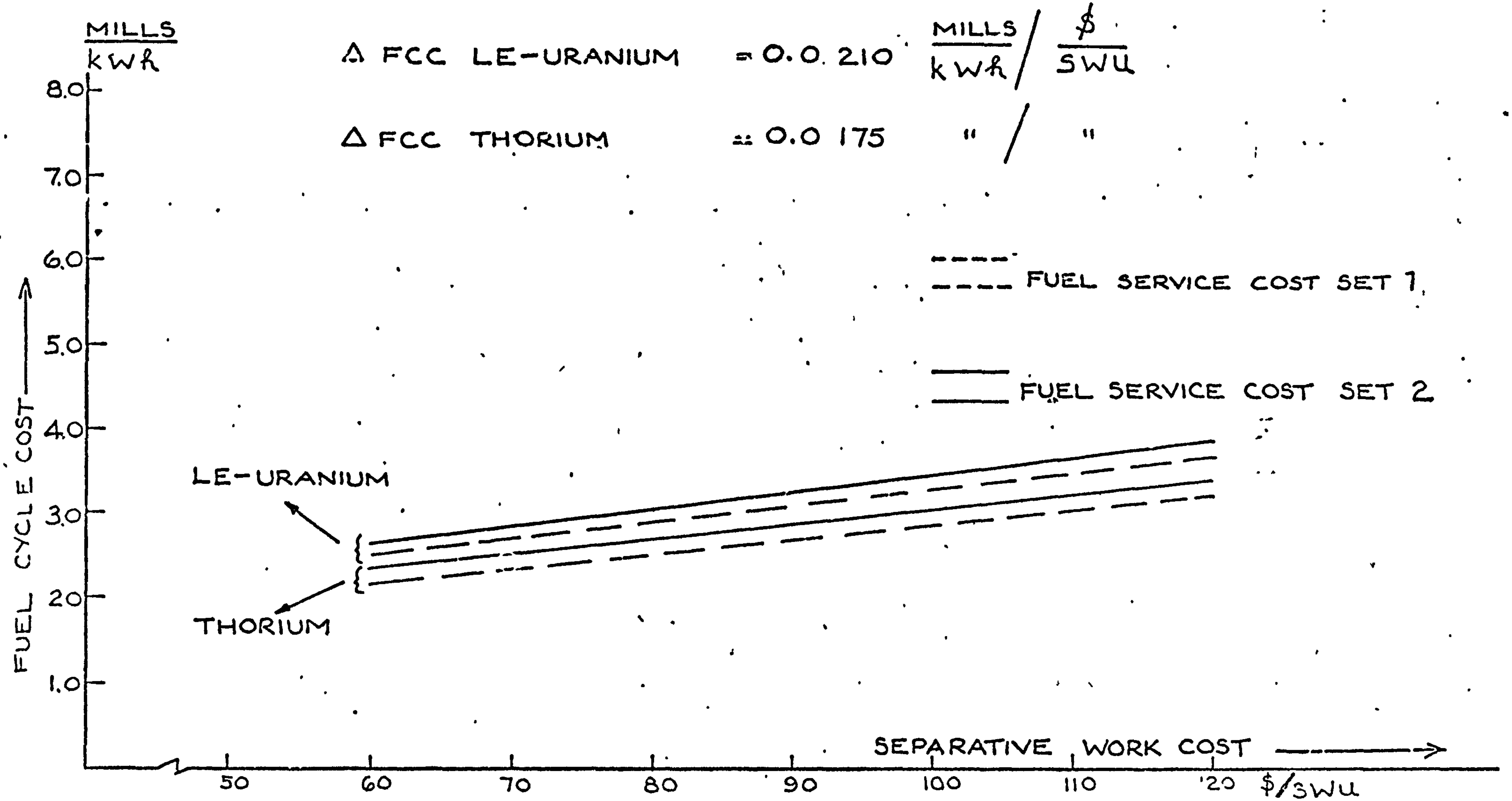

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FIG. 3 LE AND THORIUM FUEL CYCLE COSTS FOR 10 $/lb U_3O_8 VS SEPARATIVE WORK COSTS.

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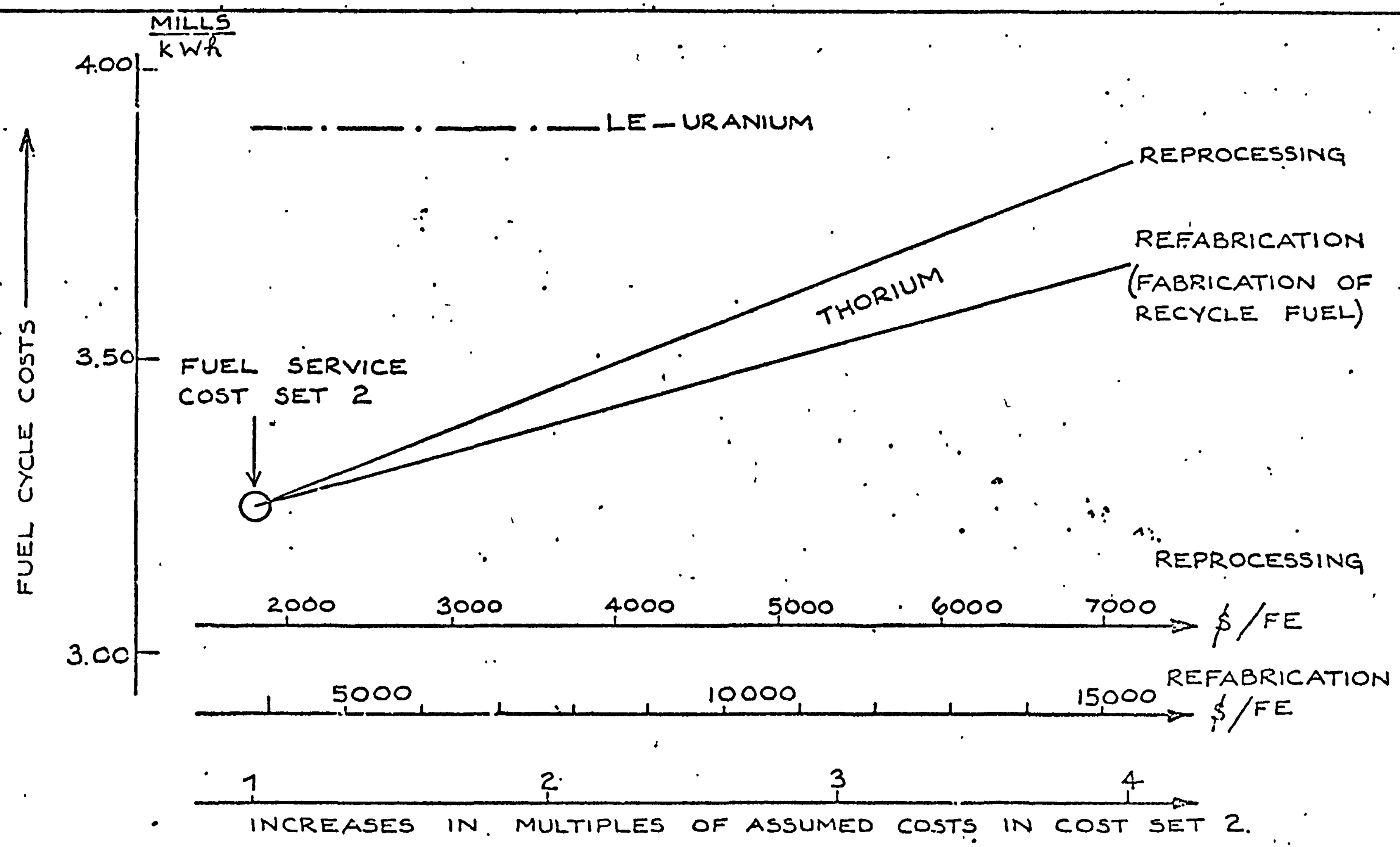

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FIG. 4 THE EFFECTS OF INCREASES IN REPROCESSING AND REFABRICATION COSTS ON THE THORIUM FUEL CYCLE COSTS (URANIUM ORE 30 $/lb U_3O_8, ENRICHMENT 60 $/SWU, FABRICATION AND SHIPPING COSTS AS IN COST SET 2.)

UAF 1702/73

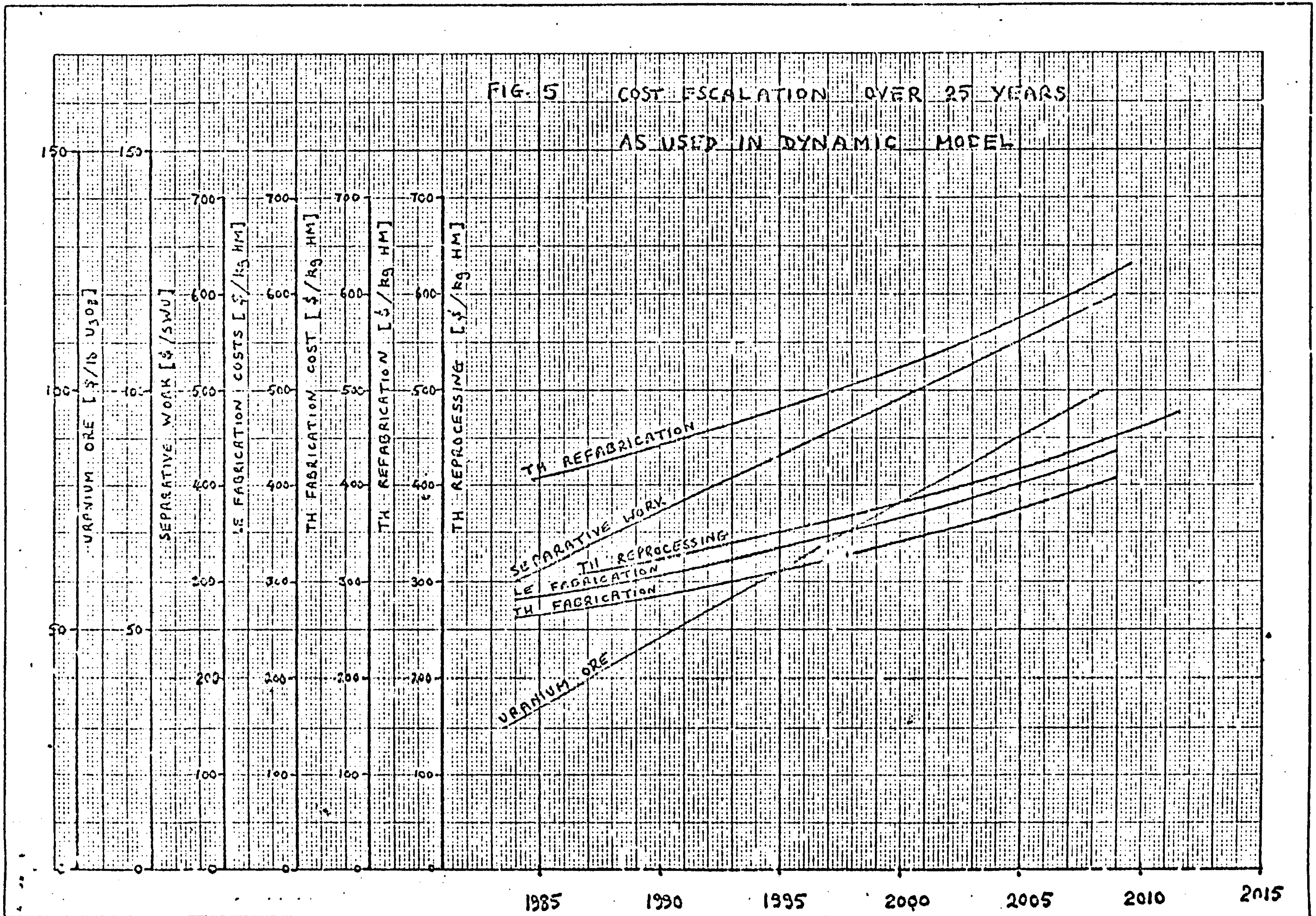

FIG. 5 COST ESCALATION OVER 25 YEARS AS USED IN DYNAMIC MODEL

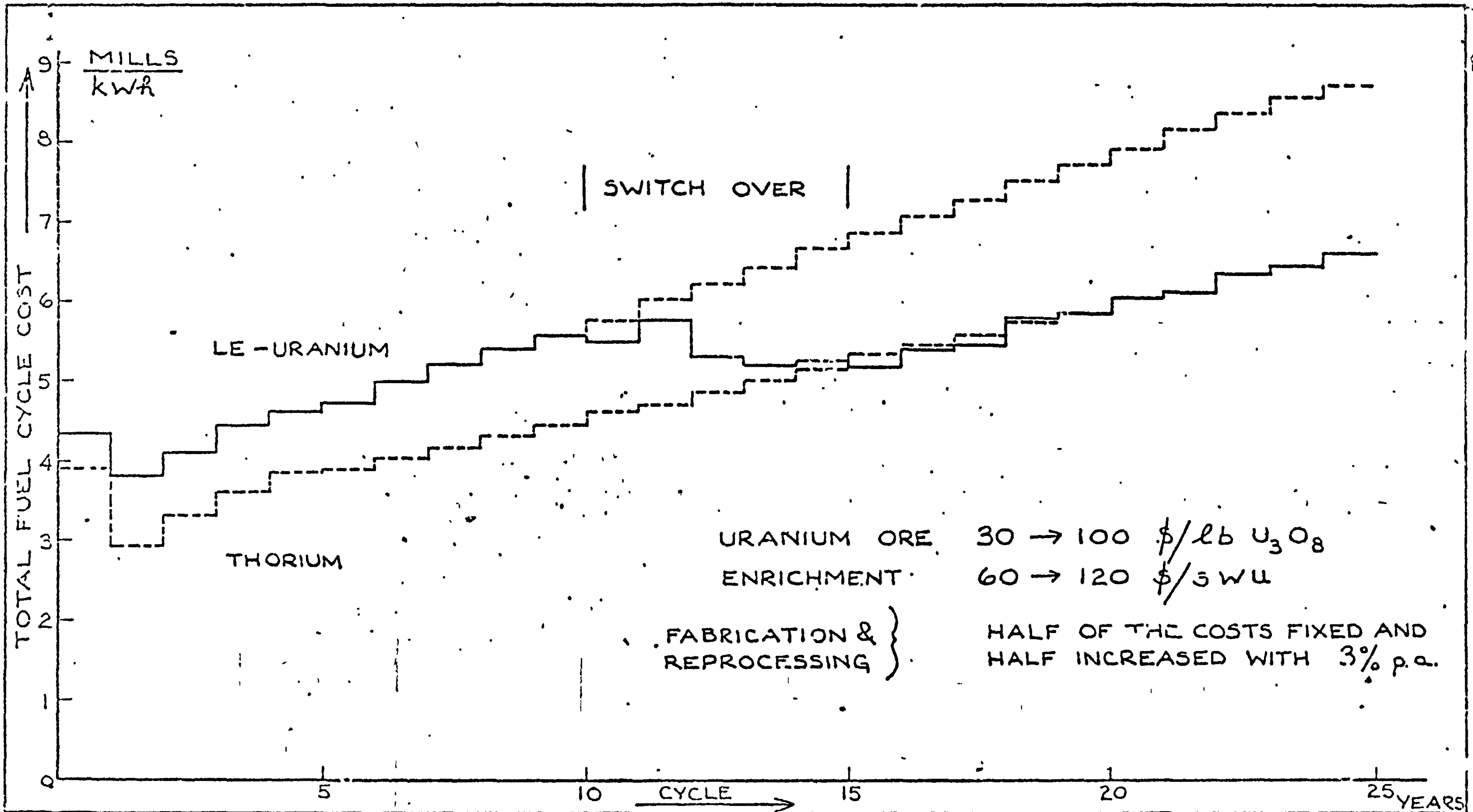

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FIG. 6 TOTAL FUEL CYCLE COSTS WITH COST ESCALATION OVER 25 YEARS (1985 TO 2010)

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