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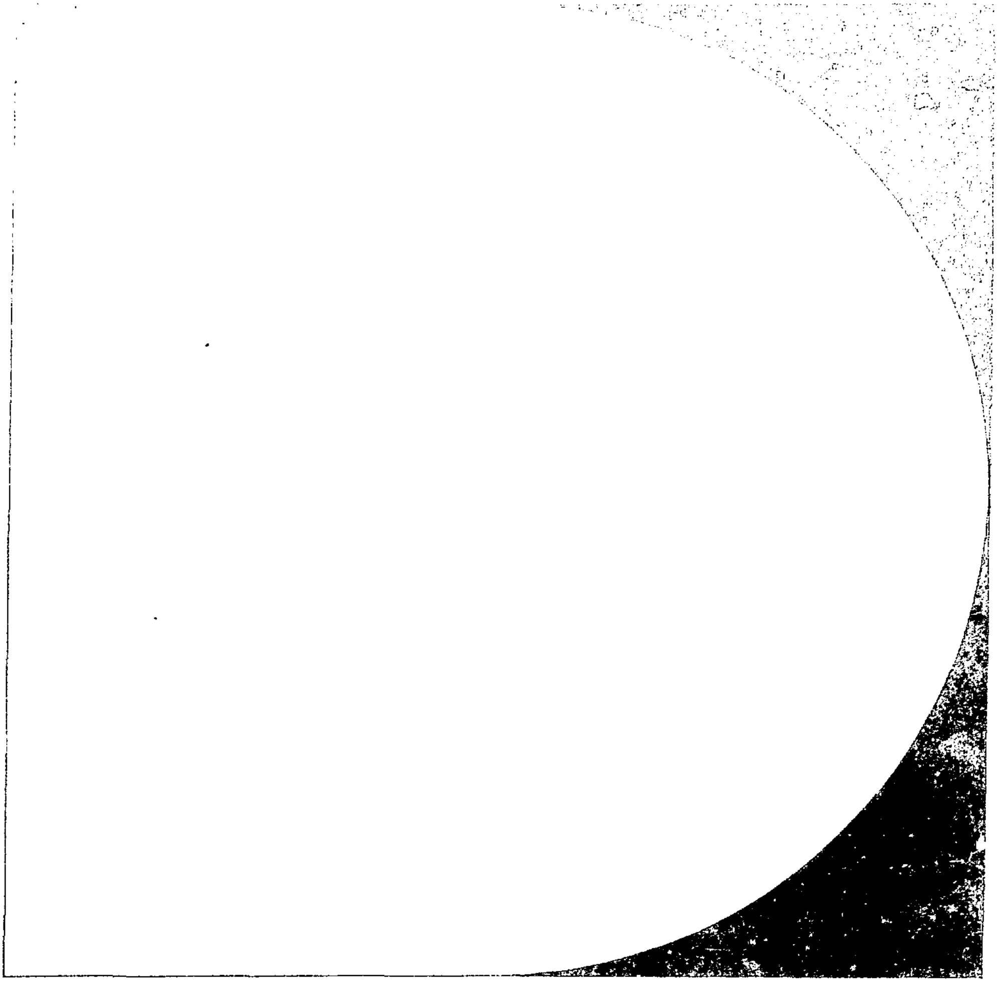

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THE ECONOMICS OF THORIUM FUEL CYCLES

Nuclear Studies & Safety Department

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Abstract

This report discusses the individual cost components, and the total fuel cycle costs, for natural uranium and thorium fuel cycles. The thorium cycles are initiated by using either enriched uranium or plutonium. Subsequent thorium cycles utilize recycled uranium-233 and, where necessary, either uranium-235 or plutonium as topping. A calculation is performed to establish the economic conditions under which thorium cycles are economically attractive.

This is a companion report to one entitled, "The Economics of Plutonium Recycle". The two reports together provide a framework for further advanced fuel cycle studies which will be conducted by the Advanced Nuclear Concepts Section of the Nuclear Studies and Safety Department.

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THE ECONOMICS OF THORIUM FUEL CYCLES

1. INTRODUCTION

A review of the economics of using plutonium in the form of a uranium-plutonium mixed oxide has been made (1). The analysis of that report is now extended to cover thorium fuel cycles. Irradiated thorium is reprocessed to yield uranium-233 and this material is recycled in new thorium fuel. It is necessary to have an external fissile source of material to enrich the initial thorium and, usually, to enhance the enrichment provided by the uranium-233. Two such fissile sources are examined, namely uranium-235 and plutonium.

This report discusses the individual cost components, and the total fuel cycle costs, for natural uranium and thorium fuel cycles. A sensitivity study of the total fuel cycle cost to changes in the cost of various components of the cycle is provided. Finally the economic conditions under which each of the cycles is the most competitive are identified.

There are only passing references to resource utilization and technical feasibility problems within this report. Clearly, decisions regarding advanced fuel cycles cannot be made on economic calculations alone. Data in this report must be considered along with the results of further studies of the resource and technical feasibility questions.

This review is primarily intended for staff within the Design and Development Division who have a broad understanding of the subject. No attempt is made to explain concepts with which this readership is likely to be familiar. Further, this document is intended to provoke thought and discussion. Hence ideas and some subjective opinions are included.

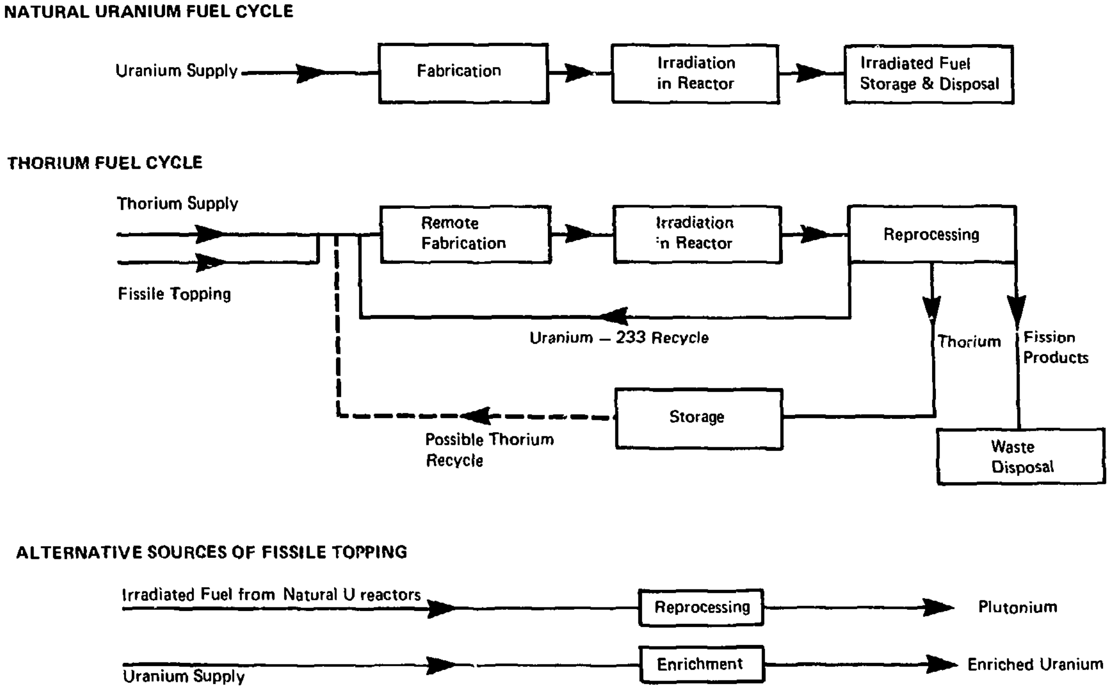
The report does, in conjunction with Reference 1, provide a framework for further advanced fuel cycle studies which will be conducted by the Advanced Nuclear Concepts Section of the Nuclear Studies and Safety Department.

2. COMPONENTS OF THE FUEL CYCLE

2.1 General

A schematic diagram of the fuel cycles under consideration is shown in Figure 2.1. Each of the major components of the cycle are dealt with in the remainder of Section 2. A brief description of the state of the industries are included. This provides a perspective for the present costs and immediate cost trends which, insofar as they are known, are provided. Finally there is an enumeration of some of the possible political and commercial developments which may have major impacts on the economics of the fuel cycle component under discussion.

FIGURE 2.1
SCHEMATIC DIAGRAM OF NATURAL URANIUM & THORIUM FUEL CYCLES



2.2 Uranium

The state of the industry, the factors influencing supply and demand, and the possible uranium price trends were all discussed in depth in Section 2.2 of the companion report on plutonium recycle (1). The prediction in Reference 1 was that the uranium price in the late 1980's and early 1990's would be in the range of 30 to 50 \$/lb U_3O_8(1977 \$'s). It was further suggested that by early in the next century, prices may be of the order of 100 \$/lb U_3O_8(1977 \$'s). Beyond that time, the price is likely to continue to rise if energy sources become increasingly scarce.

2.3 Thorium

Thorium is not, at present, a commodity in very high demand. The total world consumption is believed to be between two and three hundred tons per year (2). Until such time as a major market is identified, an active exploration program is unlikely to be undertaken and information as to total thorium resources will be uncertain.

The abundance of thorium in the earth's crust is generally thought to be about three times that of uranium. Matheson has made estimates of thorium resources which have already been delineated(2). These estimates are given in the following table.

Table 2.1

Estimates of Thorium Resources

Country	Reserves Short Tons Th	Estimated Additional Resources Short Tons Th
United States	65,000	330,000
Australia	50,000	-
Brazil	72,000	4,000
Canada	100,000	100,000
India	375,000	-
Others	45,000	396,000
Total	707,000	830,000

Matheson pointed out that these totals represent only what has already been delineated or is considered probable on the basis of those delineations, and that actual resources are much greater.

TABLE 2.2

Production and Reserves of Rare Earths and Associated Thorium for 1973 (Excerpt From Mining Annual Review 1974)

	Production in Tons		Ratio	Reserves in Tons		Ratio
Country	Rare Earth Oxides	Thorium Oxide*	RE/Th	Rare Earth Oxides	Thorium Oxide	RE/Th
India	2700	420	6.5/1	1,000,000	150,000	7/1
Australia	3200	400	8.0/1	400,000	40,000	10/1
Brazil	1400	170	8.0/1	350,000	20,000	18/1
Malaysia	1100	170	6.5/1	30,000	10,000	3/1
U.S.	N.A.	N.A.	-	5,000,000	10,500	48/1
Canada	None	None	-	250,000	60,000	4/1
TOTAL	8400	1160		7,030,000	290,500	

*Only a percentage is actually processed and sold.

TABLE 2.3

Expected Uranium Production and Associated Thorium Potential At Rio Algom and Denison

Year	Annual Yellowcake Production Tons U_3O_8	Annual Possible ThO_2 Production Tons ThO_2	Cumulative Possible ThO_2 Production Tons ThO_2	Ratio U/Th
1975	4500	630	630	3.5/1
1980	7000	690	3300	5/1
1985	9000	890	7250*	5/1

*Does not include the tailings pond stockpile estimated at over 2000 Tons ThO_2.

Many of the major thorium reserves so far identified are associated with the production of rare earth oxides and these may be the first to be commercially exploited. Table 2.2, obtained from Reference 3, shows the potential production capacity as well as the reserves associated with the rare earth oxides.

Apart from expansion and discovery of new monazite sand deposits, a promising potential source of thorium is the waste streams of uranium mining and milling operations. In Canada these waste streams are limited to the Blind River and Bancroft areas. The extent of this potential was obtained from Reference 3 and is shown in Table 2.3.

The origin of the thorium used is important. Since thorium-230 is a daughter of uranium-238 α-decay, it can only be found mixed with thorium-232 coming from ores containing uranium. Thorium from beach sand deposits does not co-exist with uranium and, therefore, contains little thorum-230. However, Canada does not have known sources of this mineral deposit. The known Canadian thorium deposits are associated with uranium bearing minerals and consequently the concentration of thorium-230 in total thorium may be as high as 200 ppm. In the reactor, the thorium-230 is a major source of the production of uranium-232. This uranium isotope has a decay chain which includes daughter products which are hard γ-emitters. These increase the shielding requirements (and costs) at the reprocessing and active fabrication stages of the fuel cycle. If Ontario Hydro is to use thorium containing thorium-230, this problem must receive further investigation.

Many people expect the cost of thorium to be low due to the fact it can be obtained as a by-product of the mining and milling of other commodities. While demand for thorium remains low, uranium (or rare earth) mining companies may indeed view any sales of thorium as a bonus which is incidental to their main business. However, as thorium demand expands, the thorium sales will presumably be treated as an integral part of the whole operation. A proportion of the exploration, mining and overhead expenses may then be attributed to the thorium recovery operation: the thorium would have co-product rather than by-product status, and would be priced accordingly.

If the thorium is required to be very low in thorium-230, it may be necessary to mine thorium from non-uranium bearing areas. The thorium would then probably be the sole product of the operation. Such a situation would doubtless result in significantly higher thorium prices.

The price of reactor grade thorium in 1975 is quoted in Reference 3 as being:

From Thorium Limited of the U.K. - \$12.06/lb
From Tennessee Nuclear Specialities - \$11.52/lb (plus freight)

The extent of price rises between 1975 and the 1990's cannot be estimated with great precision. This report will, in view of the foregoing considerations, assume a moderately large increase to \$20/lb (1977 \$'s) for reactor grade thorium oxide.

Prices beyond the 1990's become still more difficult to predict; this report will assume that they will remain constant in real terms.

It is worthwhile noting that an effective upper limit on thorium price occurs at the point at which thorium recycle becomes economic. This report will not discuss the technical problems associated with thorium recycle; it is suffice to say that the thorium price at which recycle will become economic is not known.

An examination of the results of the fuel-cycle cost calculations will show that uncertainties in thorium price are not critical. The thorium constitutes a small part of the total fuel cycle cost and the relative economics of the various cycles are not sensitive to changes in its price.

2.4 Uranium Enrichment

There are, at present, no uranium enrichment facilities in Canada, but it is possible that Ontario Hydro could purchase enrichment services from foreign sources.

In the U.S., the Energy Research and Development Agency (ERDA) is the sole supplier of enrichment services. The present price of this service is about 75 \$/SWU, and is apparently based on government financing conditions. The proposed adoption of commercial ground rules will almost certainly be implemented by 1980. This is expected to raise the price to between 90 and 100 \$/SWU. Thereafter, ERDA prices are expected to keep pace with costs. Since the present enriching capacity utilizes the energy intensive diffusion process, the cost increases are likely to be equal to, or somewhat in excess of, the general rate of inflation.

The additional capacity which ERDA has been authorized to install will be based on centrifuge technology. Sufficient research and development has been performed to have considerable confidence in the centrifuge process, and it is expected to show savings in energy requirements and in total cost as compared to diffusion technology. The energy consumption of the process may, in fact, be of the order of one tenth of that required by the diffusion process for a comparable number of separative work units. However, until firmer economic data is available, it is not possible to say just how large the dollar savings may be.

It would, therefore, be imprudent to assume that the commissioning of centrifuge plants will be able to prevent the cost of enrichment services rising to close to \$100/SWU. They may, however, avoid price increases beyond that level in real terms.

Europe is a possible alternative source of supply of enriching services to Ontario Hydro. Eurodif, Coredif, and Urenco are the three major organizations building enrichment plants and by 1990 they are expected to have a total capacity of approximately 30×10^6 SWU/annum. As their names suggest Eurodif and Coredif facilities will be based on the diffusion process. Their corporate structure and expansion plans are detailed in References 4 and 5. Urenco's plans are based on using centrifuge technology. The price of enrichment services from these companies is likely to be competitive with, but not significantly less than, that of the U.S. ERDA. It should also be noted that the major customers of the European plants are providing financing for the construction of the facilities and are, in effect, virtually becoming equity shareholders. The expansion plans of the facilities are being geared to firm enrichment contracts. Therefore, while it is possible that Ontario Hydro could utilize these facilities, it should not be assumed that this could be done without long lead times.

A survey of the status of new enrichment facilities planned throughout the world is available from Reference 6. In addition this reference discusses the range of possible new processes which may be used for enriching uranium. Of these, a laser-based process would appear to offer the best chance of a major break-through in technology. A detailed discussion of the scientific basis of the process is provided by Reference 7. The commercialization of this process is not sufficiently assured for it to receive more detailed consideration in this report.

2.5 Fuel Reprocessing

Reprocessing of uranium fuels is discussed in Reference 1 and a repetition of the same information will be avoided. The best estimate of the cost of reprocessing natural uranium CANDU fuel in the early 1990's is 187 $/kg HE (1977 $'s). This reprocessing cost is equivalent to a charge of 72 $/g of fissile plutonium recovered.

The experience gained with both uranium metal and uranium oxide fuels is relatively large compared to that gained with thorium fuels. To date, only laboratory and pilot plant reprocessing of thorium oxide fuel has been performed. This work, however, has identified one additional problem with thorium fuels that does not exist with uranium fuels. This problem occurs in the head end of the process and arises due to the difficulty in dissolving the thorium oxide. It can be solved by the addition of fluorides, although this leads to corrosion problems in the front end of the process. Suitable materials for circumventing the corrosion problems do exist (8).

The extent of the accumulated experience does not provide a very firm basis for estimating the cost of reprocessing thorium fuels. However, in view of the relative lack of experience and the already identified problems, it would seem reasonable to assume the cost will be somewhat higher than for uranium fuels. On the basis of a fairly modest 10% penalty, the first generation, commercial size plants, will reprocess thorium fuels at a cost of 206 $/kg HE (1977 $'s).

Possibly, second generation commercial plants will show cost reductions based on earlier experience. Such plants, however, will not be in operation until a decade or two into the next century. In view of the uncertainty of cost projections that far into the future, this report will assume the reprocessing cost stays constant in real terms.

2.6 Fuel Fabrication

The discussion of uranium and uranium-plutonium fuel fabrication in Section 2.4 of Reference 1 is relevant to this topic. Only the cost data from that reference will be reiterated here. The significance of the differences between uranium and thorium fuels will then be explored.

The costs of fabricating natural uranium fuel and uranium-plutonium fuel were estimated to be 44 $/kg HE and 120 $/kg HE (1977 $'s) respectively. Both these costs were for the early 1990's. The costs beyond that date were assumed to remain constant in real terms.

The basic cost of fabricating thorium fuel in an uncontained environment, as can be done for natural uranium fuel, is 50 $/kg HE, that is, 6 $/kg HE higher than was assumed for uranium fuel (8).

Fabricating plutonium fuel is an order of magnitude more difficult than fabricating uranium fuel. The plutonium introduces problems due to the need for criticality control and the need for safeguards. A major increase in cost also occurs due to the high toxicity of plutonium which necessitates a glove box type of operation to ensure that plutonium is contained at all times.

The fissile product recovered from the reprocessing of thorium fuel is uranium-233. Unfortunately the uranium-233 is inevitably contaminated by the hard γ -emitting daughter products of uranium-232 decay. The presence of uranium-232 creates even more difficulties than are encountered in fabricating low concentration plutonium fuels. A fully remote, heavily shielded, fabrication line is necessary.

This remote type of facility will be more expensive to build and operate than a glove box line. Reference 8 states that the fabrication penalties, that is the costs over and above the cost of fabricating natural uranium fuel, will be as follows:

For uranium-233 bearing fuels	65 \$/kg HE
For plutonium bearing fuels	37 \$/kg HE
Additional penalty for U-233	28 \$/kg HE

Reference 9, by one of the same authors as Reference 8, is in essential agreement with the above values. Reference 10 quotes the fabrication penalty for uranium-233 fuel as 61 \$/kg HE. Unfortunately, however, none of the above mentioned references provide any indication of how these fabrication penalties were derived. It was suggested in Reference 1 that there may be considerable optimism in the AECL estimates of the penalty associated with plutonium fuels. A similar line of reasoning would suggest that their estimate of the uranium-233 penalty is also low.

The above values do suggest the additional penalty of fabricating uranium-233 rather than plutonium is at least 28 \$/kg HE. The values at the beginning of this section also show the basic cost of thorium fabrication to be higher than for uranium by 6 \$/kg HE. Using a value of 120 \$/kg HE for uranium-plutonium fabrication (from Reference 1) gives:

Minimum Cost of Th-U^{233} fabrication = 120 + 28 + 6 \$/kg HE
Minimum Cost of Th-U^{233} fabrication = 154 \$/kg HE

Since the differential, as well as the absolute values of the uranium-233 and plutonium penalties, is likely to be low; this report will assume a thorium-uranium-233 fabrication cost of 160 \$/kg HE (1977 \$'s).

The above value was derived on the basis that it would be applicable to the first generation of commercial fabrication plants. Second generation plants may well show cost reductions based on the experience gained with the first plants. The second generation plants will not be in-service before about the second decade of the next century. This report will, therefore, assume for the purposes of economic calculation, that thorium-uranium-233 fabrication will be available at a constant cost of 160 \$/kg HE (1977 \$'s).

2.7 Irradiated Fuel Storage and Transportation

The costs of irradiated fuel storage and transportation are expected to be similar, and less than 0.1 m\$/kWh, for any fuel cycle (Section 2.5, Reference 1). These costs will not, therefore, be discussed in this report.

2.8 Geological Disposal

The geological disposal of uranium and uranium-plutonium fuel cycle wastes was briefly discussed in Section 2.6 of Reference 1. Similar considerations apply to the waste disposal of thorium reprocessing wastes and the discussion will not be repeated here. The waste disposal cost for any of the cycles is expected to be below 0.1 m$/kWh, and differences between the costs are likely to be insignificant in any economic comparison of the fuel cycles. The geological disposal cost will not, therefore, be included in this report.

3. FUEL CYCLE COST CALCULATIONS

3.1 Calculational Method and Assumptions

3.1.1 General

The calculations compare the cost of the once-through natural uranium fuel cycle with that of the thorium cycle. The calculations also show the costs of the major components of the fuel cycles at which "break-even" occurs; that is, at the point of equal cost for the two cycles.

There is considerable uncertainty as to what future costs will be and only a broad understanding of the cost relationships is being sought. The calculation performed is accordingly a simple one which considers only the major cost parameters: uranium, thorium, plutonium and fuel fabrication. Some justification for ignoring irradiated fuel storage and transportation costs and waste disposal cost is provided in Sections 2.7 and 2.8 respectively.

3.1.2 Cost Data

The data which is used for the "base case" is the author's best estimate of prices which will exist in the 1990's. The costs are expressed in 1977 dollars. Anticipated future costs are used in preference to those existing today simply because a thorium cycle is not an option at this time. It may be an option by the late 1990's.

TABLE 3.1

Base Case Cost Data

Uranium	40	$/lb U_3O_8
	91	$/kg UO_2
Thorium	20	$/lb ThO_2
	44	$/kg ThO_2
Uranium Enrichment	100	$/S.W.U.
Reprocessing	187	$/kg HE for natural U fuel
	206	$/kg HE for enriched Th fuel
Plutonium	72	$/g fissile from natural U fuel
Fuel Fabrication	44	$/kg HE for natural U fuel
	120	$/kg HE for Pu-U fuel
	160	$/kg HE for U^{233}-Th fuel

The fuel fabrication prices include the cost of zirconium and all other fabrication materials except the fissile and fertile isotopes. It also includes the cost of conversion from yellow cake (U_3O_8) to uranium oxide (UO_2).

3.1.3 Value of Uranium-235

The value of uranium-235 is calculated using the economic data in Section 3.1.2 and assuming:

Enrichment Level	90% U-235
Tails Level	0.2% U-235

Let F = amount of feed (kg)
W = amount of tails (kg)
Xp = weight fraction U-235 in product
Xf = weight fraction U-235 in feed
Xw = weight fraction U-235 in tails

For 1 kg of 90 weight % U-235:

$$\text{Feed Requirements} = \frac{Xp-Xw}{Xf-Xw} = 176.078 \text{ kg}$$

$$\text{Tails} = \frac{Xp-Xf}{Xf-Xw} = 175.078 \text{ kg}$$

$$\text{S.W.U.} = (2Xp-1) \ln \frac{Xp}{1-Xp} + W(2Xw-1) \ln \frac{Xw}{1-Xw} - F(2Xf-1) \ln \frac{Xt}{1-Xt}$$

S.W.U. = 227.53

For U_3O_8@ 40 \$/lb (91.5 \$/kg UO_2)

$$\text{Cost of U-235} = \frac{(91.5 \times 176.078) + (100 \times 227.53)}{(0.90 \times 1 \times 1000)} \text{ \$/g}$$

Cost of U-235 = 43.2 \$/g

A similar calculation for other uranium costs gives:

TABLE 3.2

Cost of Uranium-235

Cost of Uranium \$/lb U_3O_8	Cost of U-235 \$/g
40	43
55	50
100	70

3.1.4 Enrichment and Fuel Burn-up

The first thorium cycle must be initiated by adding to the thorium an external source of fissile material, either plutonium or uranium-235. This report will examine both options.

The plutonium to initiate the advanced fuel cycles is assumed to be obtained by reprocessing natural uranium CANDU fuel. This point is mentioned because the value of the plutonium is dependent on its isotopic composition. This composition varies somewhat depending on the characteristics of the irradiated fuel from which the plutonium was obtained. The uranium-235 must, of course, be obtained by enriching natural uranium and the enrichment level is assumed to be 90%.

The burn-up obtainable from uranium-235 enriched thorium fuel is derived from an internal CRNL report, and is as follows:

TABLE 3.3

Burn-up for Various Uranium Enrichments

Enrichment % U-235 in Th	Burn-up MWd/Mg HE
2.00	18,800
2.25	31,500
2.50	42,750

Data for burn-up as a function of plutonium enrichment of thorium fuels is not as readily available. Reference 10, however, suggests that 1 gram of fissile plutonium may be taken as equivalent to 1 gram of uranium-235. This assumption will be used in this report and confirmed when detailed LATREP and WIMS lattice calculations are performed in the near future.

As soon as irradiated thorium fuel has been reprocessed there will be a source of uranium-233. This fissile material will be used to enrich further thorium fuel. If a low burn-up cycle is adopted, the uranium-233 recovered from the irradiated fuel is sufficient to enrich an equal amount of new fuel. Hence, no further external feed of fissile material is required and the cycle is referred to as "self-sufficient".

If economic considerations suggest that a higher burn-up cycle is desirable, the fissile concentration in the new fuel must be higher than that in the discharged fuel. The fissile uranium-233 must then be supplemented by an external supply of either plutonium or uranium-235. The sources of such a supply would be, as previously mentioned, reprocessed natural uranium fuel or an enrichment plant. This additional fissile enrichment is commonly known as "topping".

In order to perform an economic analysis a correlation between fissile topping and fuel burn-up is required. To obtain an accurate correlation, considerable reactor physics analysis of enriched thorium cores is required. Actual irradiations are also required to reduce the uncertainties in lattice parameters. The high breeding efficiency of uranium-233 and the relatively low capture cross-sections of the non-saturating uranium-233 fission products will give a fairly slowly decreasing reactivity with increasing irradiation. This implies a fairly high sensitivity of discharge burn-up to reactivity uncertainties. The data available is, therefore, less accurate than data for plutonium-uranium cores. The most reliable data published is probably that of Reference 10. Figure 3 of this reference contains a plot of burn-up versus topping for particular lattice conditions, namely:

Maximum channel power	6.5 MW (th)
Average fuel specific power	29 kW/kg HE
Lattice pitch	286 mm

The values in Table II of the same reference suggest somewhat lower burn-ups for the same conditions. One of the authors of the paper suggested the higher burn-ups were somewhat optimistic, while the lower were conservative. The author of this report has, therefore, assumed approximately mid values, as follows:

TABLE 3.4

Burn-up for Various Topping Enrichments

Topping Enrichment g fissile/kg HE	Burn-up MWd/kg HE
0	13.5
1	19.0
2	23.8
3	27.7
6	36.5
9	43.0
12	48.0

Lacking better data, it is again necessary to assume the above table is equally valid for both plutonium and uranium-235 fissile topping.

3.1.5 Technical Feasibility

This report does not consider technical feasibility: it deals only with economics. This does not imply that technical problems will not arise. The use of plutonium-thorium fuels may lead to more difficulty, as compared to natural uranium fuel, in such areas as:

a) Power peaking
b) Reactor control and Instrumentation
c) Fuel integrity at very high burn-up
d) Fuel handling at the generating station

Design modifications in these areas may involve additional capital and/or operating expense. This report does not assign any economic penalty to thorium cycles due to potential technological difficulties of this nature.

3.2 Fuel Cycle Cost Calculations Excluding Carrying Charges

The cost calculations were performed for the first thorium cycle on the assumption that no uranium-233 was available. The initial enrichment was assumed to be uranium-235 or plutonium. The results for uranium-235 enrichment are shown for two different prices of U_3O_8 in Tables 3.5 and 3.6. The plutonium enrichment results are shown in Table 3.7.

The fuel cycles costs for "equilibrium" cycles are shown in Tables 3.8-3.11. Note that "equilibrium" is here being used rather loosely to refer to all cycles beyond the first. That is, where cycles involve the recycle of uranium-233. Since all uranium-233 is assumed to be recycled in the same reactor (i.e. no net flow of uranium-233 to or from the system and no losses during reprocessing or refabrication) it is unnecessary to assign a dollar value to it. Its cost of extraction from the discharged fuel is accounted for by the reprocessing cost. In Table 3.11, the cost shown against reprocessing is the cost of reprocessing the thorium fuel only. The cost of reprocessing natural uranium fuel is recovered by assigning a suitable value to the plutonium which provides a fissile topping to the thorium cycle.

Note that in all the following tables the fuel cycle cost has been calculated for a thorium cycle as a separate entity. This contrasts with the alternative technique of quoting an average fuel cost for the thorium and natural uranium fuel cycles which have a symbiotic relationship. The technique used in this report highlights the economic circumstances for breakeven, i.e. the time when thorium cycles have the same cost as uranium cycles. The disadvantage of this method is that the incentive for lower burn-up cycles with plutonium recycle, when the uranium cost is high, is not evident. This is because the cost of the thorium cycle is independent of uranium cost. The incentive lies in reducing the required plutonium topping and hence increasing the possible ratio of thorium to uranium fuelled reactors.

TABLE 3.5

First Thorium Cycle with Uranium-235 (U_3O_8@ 40 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE Natural U Cycle	Thorium With Various U-235 Enrichments 2.00%	 2.25%	 2.50%
Fuel Fabrication	44	50	50	50
Natural Uranium	91	-	-	-
Enriched Uranium	-	864	972	1080
Thorium	-	44	44	44
Total Cost $/kg HE	135	958	1066	1174
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	2.46	6.96	4.62	3.75

TABLE 3.6

First Thorium Cycle with Uranium-235 (U_3O_8@ 100 $/lb)

	Fuel Cycle Costs $/kg HE			
Fuel Cycle Component	Natural U Cycle	Thorium With Various U-235 Enrichments		
		2.00%	2.25%	2.50%
Fuel Fabrication	44	50	50	50
Natural Uranium	227	-	-	-
Enriched Uranium	-	1400	1575	1750
Thorium	-	44	44	44
Total Cost $/kg HE	271	1494	1669	1844
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	4.94	10.86	7.24	5.90

TABLE 3.7

First Thorium Cycle with Plutonium

Fuel Cycle Component	Fuel Cycle Costs $/kg HE				
	Natural U Cycle		Thorium With Various Fissile Pu Enrichments		
	$40*	$100*	2.00%	2.25%	2.50%
Fuel Fabrication	44	44	50	50	50
Natural Uranium	91	227	-	-	-
Plutonium	-	-	1440	1620	1800
Thorium	-	-	44	44	44
Total Cost $/kg HE	135	271	1534	1714	1894
Burn-up MWd/kg HE	7.5	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	2.46	4.94	11.15	7.43	6.06

*Based on U_3O_8 @ $40 and $100/lb respectively.

TABLE 3.8

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8@ 40 \$/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	44	160	160	160	160	160	160	160
Uranium	91	-	-	-	-	-	-	-
Thorium	-	44	44	44	44	44	44	44
U-235 Topping	-	-	43	86	129	258	387	516
Reprocessing		206	206	206	206	206	206	206
Total Cost $/kg HE	135	410	453	496	539	668	797	926
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	2.46	4.15	3.26	2.85	2.66	2.50	2.53	2.64

TABLE 3.9

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 55 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	44	160	160	160	160	160	160	160
Uranium	125	-	-	-	-	-	-	-
Thorium	-	44	44	44	44	44	44	44
U-235 Topping	-	-	50	100	150	300	450	600
Reprocessing	-	206	206	206	206	206	206	206
Total Cost $/kg HE	169	410	460	510	560	710	860	1010
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	3.08	4.15	3.31	2.93	2.76	2.66	2.73	2.87

TABLE 3.10

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 100 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	44	160	160	160	160	160	160	160
Uranium	227	-	-	-	-	-	-	-
Thorium	-	44	44	44	44	44	44	44
U-235 Topping	-	-	70	140	210	420	630	840
Reprocessing	-	206	206	206	206	206	206	206
Total Cost $/kg HE	271	410	480	550	620	830	1040	1250
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	4.94	4.15	3.45	3.16	3.06	3.11	3.30	3.56

TABLE 3.11

Fuel Cycle Costs at Equilibrium with Plutonium Topping

Fuel Cycle Component	Fuel Cycle Costs $/kg HE									
	Natural U Cycle			Thorium Cycles with Various Plutonium Topping Enrichments g fissile/kg HE						
	$40*	$55*	$100*	0	1	2	3	6	9	12
Fuel Fabrication	44	44	44	160	160	160	160	160	160	160
Uranium	91	125	227	-	-	-	-	-	-	-
Thorium	-	-	-	44	44	44	44	44	44	44
Plutonium	-	-	-	-	72	144	216	432	648	864
Reprocessing	-	-	-	206	206	206	206	206	206	206
Total Cost $/kg HE	135	169	271	410	482	554	626	842	1058	1274
Burn-up MWd/kg HE	7.5	7.5	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	2.46	3.08	4.94	4.15	3.47	3.18	3.09	3.15	3.36	3.63

*Based on U_3O_8 @ $40, $55, and $100/lb respectively.

3.3 Fuel Cycle Cost Calculations Including Carrying Charges

3.3.1 General

The basic component costs were established in Section 3.2. Having obtained these costs, the calculations can be extended to include the effect of carrying (or inventory) charges.

The carrying charges arise because the fuel cycle costs are incurred before the fuel reaches the reactor. The benefit, in the form of the energy output from the fuel, occurs during the residence time of the fuel in the reactor. The interest on the investment in the fuel cycle, from the time the expense is incurred until the time the energy is generated, is a cost attributable to the fuel cycle.

3.3.2 Payment Schedule

Payment for various components of the fuel cycle is assumed to occur on the following schedule.

TABLE 3.12

Payment Schedule for Various Components of the Fuel Cycle

Cost Component	Payment Date Years Prior to Fuel Entering Reactor
Enriched Uranium	1.5
Natural Uranium	1.0
Thorium	1.0
Reprocessing (Plutonium)	1.0
Fuel Fabrication	0.5

The rationale for the above values is as follows:

(a) The time for the uranium to go from minehead to in-reactor (with enrichment) is shown in Reference 10 as being 1.70 years. The 1.5 years value shown in the table may be considered a weighted average of the time of payment for the uranium and the time of payment for the enrichment services.

(b) The time for the uranium to go from minehead to in-reactor (with no enrichment) is shown in Reference 10 as being 1.15 years. This was rounded to 1.0 years.

(c) The time for thorium to go from minehead to in-reactor was set equal to the comparable time for uranium.

(d) The timing of the reprocessing was set so that plutonium became available a few months prior to the fuel fabrication.

(e) The timing of the fuel fabrication was taken from Reference 10.

It would seem as if some of the above values may be a little optimistic; that is insufficient allowance may have been made for in-process time. However, lacking any other firm data, reliance was placed on the reference quoted.

The above table also implies that the customer (Ontario Hydro) will pay for the various goods and services at the time they are provided. In fact, prepayments before that time may sometimes be necessary. For example, Ontario Hydro may assist in the financing of a uranium mine. However, such prepayments would presumably result in a more favourable purchase price for the uranium. The investigation of the details of such commercial arrangements is beyond the scope of this report. For our purposes the implicit assumption that payment is made on delivery of the goods or service is quite adequate.

It will be seen from the next section that an error of a year in estimating the payment date results in an error in the cost of the component of only 3%.

3.3.3 Interest Rate

Historically, the interest rate has been very close to 3%/annum greater than the rate of inflation. Allowance for the rate of inflation is automatically made by performing the calculations in constant dollars. Hence, the appropriate interest rate for the calculations contained herein is the real rate of return of 3%/annum.

3.3.4 Fuel Cost Calculations

Knowing the actual dollar cost which must be paid, the payment date, and the interest rate, it becomes a simple matter to calculate the interest charges which occur up to the time the fuel enters the reactor. This was done and the interest was added to the actual basic cost of each component. The results are documented in Tables 3.13 to 3.22. In these tables, the row entitled, "Total Cost", is the arithmetic sum of the cost components. It represents the total cost present worthed to the date the fuel enters the reactor.

It remains to make an allowance for the time from fuel insertion to the time the energy is generated. This time may be considered to be, on average, half the residence time of the fuel in the reactor.

This residence time was calculated by assuming a specific power of 29 kW/kg HE. For example, for natural uranium fuel, the residence time is given by:

$$\text{Residence Time} = \frac{7500}{29\text{x}365}\ \frac{\text{MWd}}{\text{MgHE}} \cdot \frac{\text{kg HE}}{\text{kW}} \cdot \frac{\text{a}}{\text{d}}$$

$$\text{Residence Time} = 0.70 \text{ years}$$

Note: the effect of capacity factor has been ignored

Interest for half the residence time is given by:

$$\text{Interest} = 0.5\text{x}0.70 \text{ years x } 3\%/\text{annum}$$
$$\underline{\text{Interest} = 1.05\%}$$

The interest is, of course, correspondingly higher for the higher burn-up fuel cycles. The "Adjusted Total Cost" in Tables 3.13 to 3.22 is the "Total Cost" with the above interest added. The "Fuel Cost" is obtained from the "Adjusted Total Cost" and the "Burn-up". Hence the "Fuel Cost" represents the total cost of fuel including the inventory or carrying charges. Note that the "Burn-up" is given in thermal units while the "Fuel Cost" is in electrical units; the assumed efficiency of conversion is 30.5%.

3.3.5 Levelized Fuel Cost

The cost of the thorium fuel cycle is higher during the first recycle stage than at equilibrium. It is, therefore, convenient to find a levelized fuel cost over a reactor life which is economically equivalent to the actual costs incurred. The levelized value is, in effect, a weighted average of the first recycle and equilibrium costs. The weighting factor allows for both the number of years and the time during which the costs will be incurred. That is, the time value of money is taken into account by using a 3%/annum discount rate. An example will illustrate the technique used.

Consider a reactor fuelling scheme as follows:

Period 1	'First Recyle'	2.25% U-235 enrichment
Period 2	'Equilibrium'	0.6 % U-235 topping and U-233 recycle

Period 1 will last from reactor start-up to the time uranium-233 becomes available for insertion in the reactor. This is assumed to be approximately the residence time of the first fuel charge plus 1.5 years to allow for cooling of irradiated fuel, reprocessing, active fabrication, and fuel delivery to the reactor.

To obtain length of Period 1, we use:

Burn-up	31,500 MWd/Mg HE
Specific Power	29 kW/kg HE
Capacity Factor	80 %

$$\text{Residence time} = \frac{31{,}500}{29\text{x}365\text{x}0.80} = 3.7 \text{ years}$$

Period 1 = (3.7 + 1.5) years
Period 1 = 5.2 years

Period 2, the time of equilibrium recycle, lasts from the end of Period 1 to the end of the reactor life which, for economic purposes, is assumed to be 30 years.

The weighting factors for these two periods are then obtained as follows:

$$\text{Period 1 Weighting Factor} = \sum_{n=1}^{n=5} \frac{1}{1.03^{(n-1)}} + 0.2\,\frac{1}{1.03^{(6-1)}}$$

Period 1 Weighting Factor = 4.89

$$\text{Period 2 Weighting Factor} = \sum_{n=7}^{n=30} \frac{1}{1.03^{(n-1)}} + 0.8\,\frac{1}{1.03^{(6-1)}}$$

Period 2 Weighting Factor = 15.30

Assuming U_3O_8 is 40$/lb, we obtain from Tables 3.13 and 3.18:

First recycle cost	5.04 m$/kWh
Equilibrium cost	2.71 m$/kWh

Then, using the weighting factors, we have:

$$\text{Levelized fuel cost} = \frac{(5.04\text{x}4.89) + (2.71\text{x}15.30)}{(4.89 + 15.30)}$$

Levelized Fuel Cost = 3.27 m$/kWh

It is obvious from Table 3.13 that increasing the initial fuel enrichment to 2.50% uranium-235 significantly decreases the fuel cost during the first recycle period. However, the resultant increase in fuel burn-up delays the time of irradiated fuel discharge and the subsequent availability of uranium-233. Hence, 'Period 1' is longer and has a higher weighting factor. The new values are as follows:

First Recycle cost	4.16 m$/kWh, Weighting factor 6.00
Equilibrium cost	2.71 m$/kWh, Weighting factor 14.19

Levelized Fuel Cost = 3.14 m$/kWh

TABLE 3.13

First Thorium Cycle with Uranium-235 (U_3O_8 @ 40 $/lb)

	Fuel Cycle Costs $/kg HE			
Fuel Cycle Component	Natural U Cycle	Thorium With Various U-235 Enrichments		
		2.00%	2.25%	2.50%
Fuel Fabrication	45	51	51	51
Natural Uranium	94	-	-	-
Enriched Uranium	-	903	1016	1129
Thorium	-	45	45	45
Total Cost	139	999	1112	1225
Adjusted Total Cost $/kg HE	140	1026	1161	1299
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	2.55	7.45	5.04	4.16

TABLE 3.14

First Thorium Cycle with Uranium-235 (U_3O_8 @ 55 \$/lb)

Fuel Cycle Component	Fuel Cycle Costs \$/kg HE			
	Natural U Cycle	Thorium With Various U-235 Enrichments 2.00%	2.25%	2.50%
Fuel Fabrication	45	51	51	51
Natural Uranium	129	-	-	-
Enriched Uranium	-	1050	1181	1313
Thorium	-	45	45	45
Total Cost	174	1146	1277	1409
Adjusted Total Cost \$/kg HE	176	1177	1333	1494
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m\$/kWh	3.20	8.55	5.78	4.78

TABLE 3.15

First Thorium Cycle with Uranium-235 (U_3O_8 @ 75 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE			
	Natural U Cycle	Thorium With Various U-235 Enrichments		
		2.00%	2.25%	2.50%
Fuel Fabrication	45	51	51	51
Natural Uranium	176	-	-	-
Enriched Uranium	-	1239	1394	1549
Thorium	-	45	45	45
Total Cost	221	1335	1490	1645
Adjusted Total Cost $/kg HE	223	1371	1555	1744
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	4.07	9.96	6.75	5.58

TABLE 3.16

First Thorium Cycle with Uranium-235 (U_3O_8 @ 100 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE Natural U Cycle	Thorium With Various U-235 Enrichments 2.00%	2.25%	2.50%
Fuel Fabrication	45	51	51	51
Natural Uranium	234	-	-	-
Enriched Uranium	-	1463	1645	1829
Thorium	-	45	45	45
Total Cost	279	1559	1742	1925
Adjusted Total Cost $/kg HE	282	1600	1819	2041
Burn-up MWd/kg HE	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	5.13	11.63	7.89	6.53

TABLE 3.17

First Thorium Cycle with Plutonium

Fuel Cycle Component	Fuel Cycle Costs $/kg HE Natural U Cycle $40*	 $100*	 Thorium With Various Fissile Pu Enrichments 2.00%	 2.25%	 2.50%
Fuel Fabrication	45	45	51	51	51
Natural Uranium	94	234	-	-	-
Plutonium	-	-	1483	1668	1854
Thorium	-	-	45	45	45
Total Cost	139	279	1579	1764	1950
Adjusted Total Cost $/kg HE	140	282	1621	1843	2067
Burn-up MWd/kg HE	7.5	7.5	18.8	31.5	42.7
Fuel Cost m$/kWh	2.55	5.13	11.78	7.99	6.61

*Based on U_3O_8 @ $40 and $100 /lb respectively.

TABLE 3.18

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 40 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	45	162	162	162	162	162	162	162
Uranium	94	-	-	-	-	-	-	-
Thorium	-	45	45	45	45	45	45	45
U-235 Topping	-	-	45	90	135	270	404	539
Reprocessing	-	212	212	212	212	212	212	212
Total Cost	139	419	464	509	554	689	823	958
Adjusted Total Cost $/kg HE	140	427	476	526	576	725	873	1023
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	2.55	4.32	3.43	3.02	2.84	2.71	2.77	2.91

TABLE 3.19

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 55 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	45	162	162	162	162	162	162	162
Uranium	129	-	-	-	-	-	-	-
Thorium	-	45	45	45	45	45	45	45
U-235 Topping	-	-	52	105	157	314	470	627
Reprocessing	-	212	212	212	212	212	212	212
Total Cost	174	419	471	524	576	733	889	1046
Adjusted Total Cost $/kg HE	176	427	484	542	599	771	943	1117
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	3.20	4.32	3.48	3.11	2.95	2.89	3.00	3.18

TABLE 3.20

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 75 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	45	162	162	162	162	162	162	162
Uranium	176	-	-	-	-	-	-	-
Thorium	-	45	45	45	45	45	45	45
U-235 Topping	-	-	61	123	184	369	553	737
Reprocessing	-	212	212	212	212	212	212	212
Total Cost	221	419	480	542	603	788	972	1156
Adjusted Total Cost $/kg HE	223	427	493	561	627	829	1031	1234
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	4.07	4.32	3.55	3.22	3.09	3.10	3.28	3.51

TABLE 3.21

Fuel Cycle Costs at Equilibrium with U-235 Topping (U_3O_8 @ 100 $/lb)

Fuel Cycle Component	Fuel Cycle Costs $/kg HE							
	Natural U Cycle	Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
		0	1	2	3	6	9	12
Fuel Fabrication	45	162	162	162	162	162	162	162
Uranium	234	-	-	-	-	-	-	-
Thorium	-	45	45	45	45	45	45	45
U-235 Topping	-	-	73	146	219	439	658	878
Reprocessing	-	212	212	212	212	212	212	212
Total Cost	279	419	492	565	638	858	1077	1297
Adjusted Total Cost $/kg HE	282	427	505	584	663	902	1143	1385
Burn-up MWd/kg HE	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	5.13	4.32	3.63	3.35	3.27	3.38	3.63	3.94

TABLE 3.22

Fuel Cycle Costs at Equilibrium with Plutonium Topping

Fuel Cycle Component	Fuel Cycle Costs $/kg HE									
	Natural U Cycle			Thorium Cycles with Various U-235 Topping Enrichments g/kg HE						
	$40*	$55*	$100*	0	1	2	3	6	9	12
Fuel Fabrication	45	45	45	162	162	162	162	162	162	162
Uranium	94	129	234	-	-	-	-	-	-	-
Thorium	-	-	-	45	45	45	45	45	45	45
Plutonium	-	-	-	-	74	148	222	445	667	890
Reprocessing	-	-	-	212	212	212	212	212	212	212
Total Cost	139	174	279	419	493	567	641	864	1086	1309
Adjusted Total Cost $/kg HE	140	176	282	427	506	586	666	909	1152	1398
Burn-up MWd/kg HE	7.5	7.5	7.5	13.5	19.0	23.8	27.7	36.5	43.0	48.0
Fuel Cost m$/kWh	2.55	3.20	5.13	4.32	3.64	3.36	3.29	3.40	3.66	3.98

*Based on U_3O_8 @ $40, $55, and $100/lb respectively.

TABLE 2.23

Summary of Fuel Cycle Cost Calculations

Uranium Price $/lb U_3O_8	Fuel Cycles				Levelized Fuel Cost m$/kWh
	'First Recycle'		'Equilibrium'		
	Enrichment %	Cost m$/kWh	Topping %	Cost m$/kWh	
40	2.25 U-235	5.04	0.3 U-235	2.84	3.37
40	2.25 U-235	5.04	0.6 U-235	2.71	3.27
40	2.50 U-235	4.16	0.6 U-235	2.71	3.14
40	Natural U	2.55	-	-	2.55
55	2.25 U-235	5.78	0.3 U-235	2.95	3.64
55	2.25 U-235	5.78	0.6 U-235	2.89	3.59
55	2.50 U-235	4.78	0.6 U-235	2.89	3.45
55	Natural U	3.20	-	-	3.20
75	2.25 U-235	6.75	0.3 U-235	3.09	3.98
75	2.25 U-235	6.75	0.6 U-235	3.10	3.98
75	2.50 U-235	5.58	0.6 U-235	3.10	3.84
75	Natural U	4.07	-	-	4.07
100	2.25 U-235	7.89	0.3 U-235	3.27	4.39
100	2.50 U-235	6.53	0.3 U-235	3.27	4.24
100	Natural U	5.13	-	-	5.13
-	2.25 Pu*	7.99	0.3 Pu*	3.29	4.43
-	2.50 Pu*	6.61	0.3 Pu*	3.29	4.28
40	Natural U	2.55	-	-	2.55
55	Natural U	3.20	-	-	3.20
75	Natural U	4.07	-	-	4.07
100	Natural U	5.13	-	-	5.13

*fissile plutonium

It can be seen that the higher enrichment results in a relatively small economic gain.

Repeating the above calculation for a number of other fuel cycles leads to the compilation of Table 3.23.

Using the data in Table 3.23, the fuelling cost for the various possible fuel cycles was plotted in Figures 3.1 and 3.2. The data in Figure 3.1 assumes the use of the economically optimum fuel enrichment for the thorium cycles. Figure 3.2 is based on the assumption that the maximum initial enrichment is 2.25% U-235 (or fissile Pu) and that the maximum equilibrium topping is 0.3% U-235 (or fissile Pu). These enrichments restrict the burn-up to 31.5 MWd/kgHE which may be approaching the fuel bundle performance limitations. The economically optimum fuel cycles assume that burn-ups as high as 42.7 MWd/kgHE are physically achievable.

3.3.6 Uranium Break-Even Prices

The price of uranium at which the fuel cycles have equal cost (referred to as 'break-even') are obtained from Figures 3.1 and 3.2. These break-even prices are summarized in Table 3.24.

TABLE 3.24

Break-Even Uranium Price For Thorium Fuel Cycles

Preferred Fuel Cycle While Uranium Price is:		Break-Even Uranium Price*	
Lower Than Break-Even	Higher Than Break-Even	Optimum Burn-Up \$/lb U_3O_8	Burn-up 31.5 MWd/kgHe \$/lb U_3O_8
Natural U	Th, U-235	66	72
Natural U	Th, Pu	80	83
Th, U-235	Th, Pu	103	102

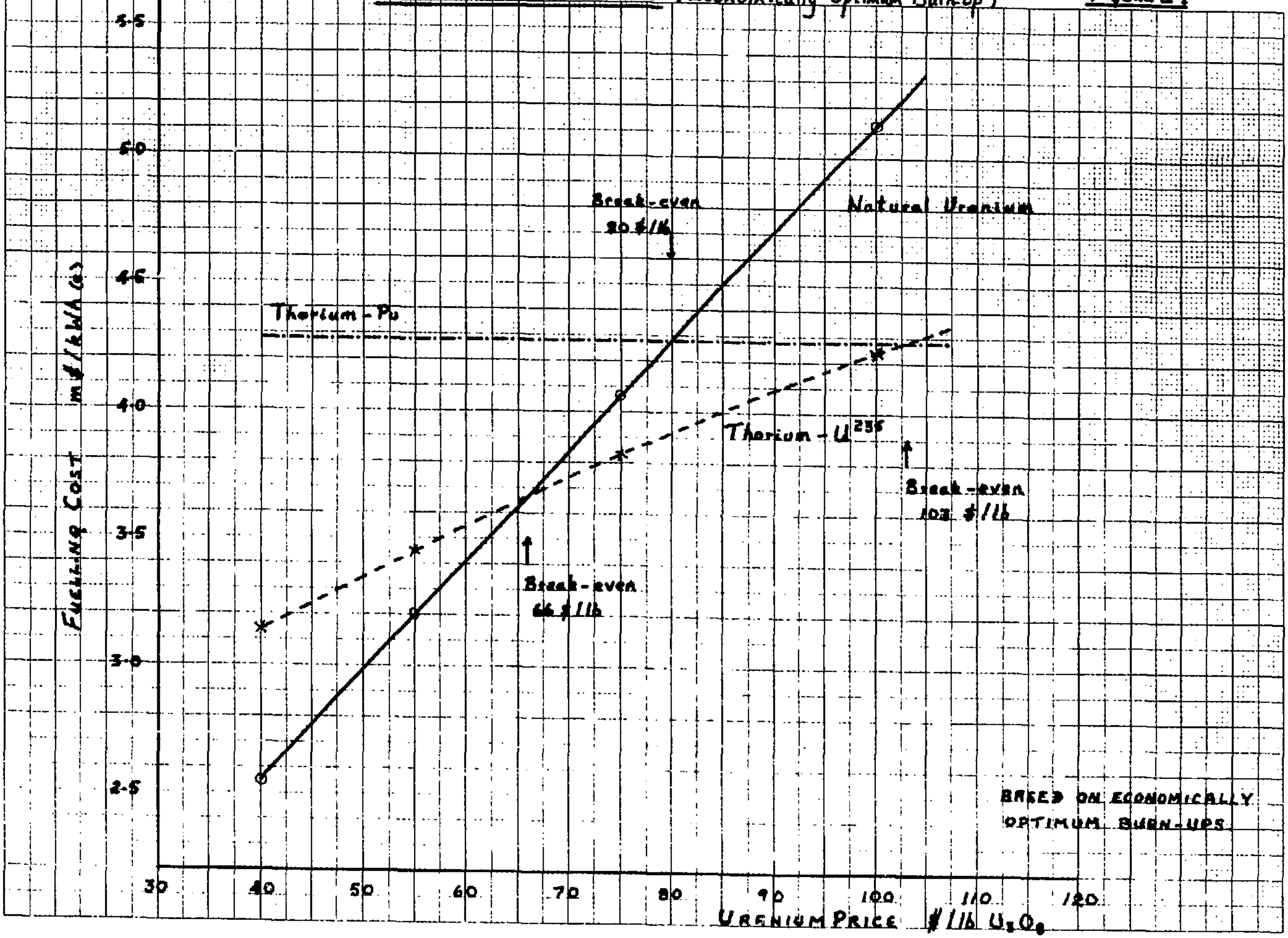
*Note that the prices quoted are in 1977 dollars.

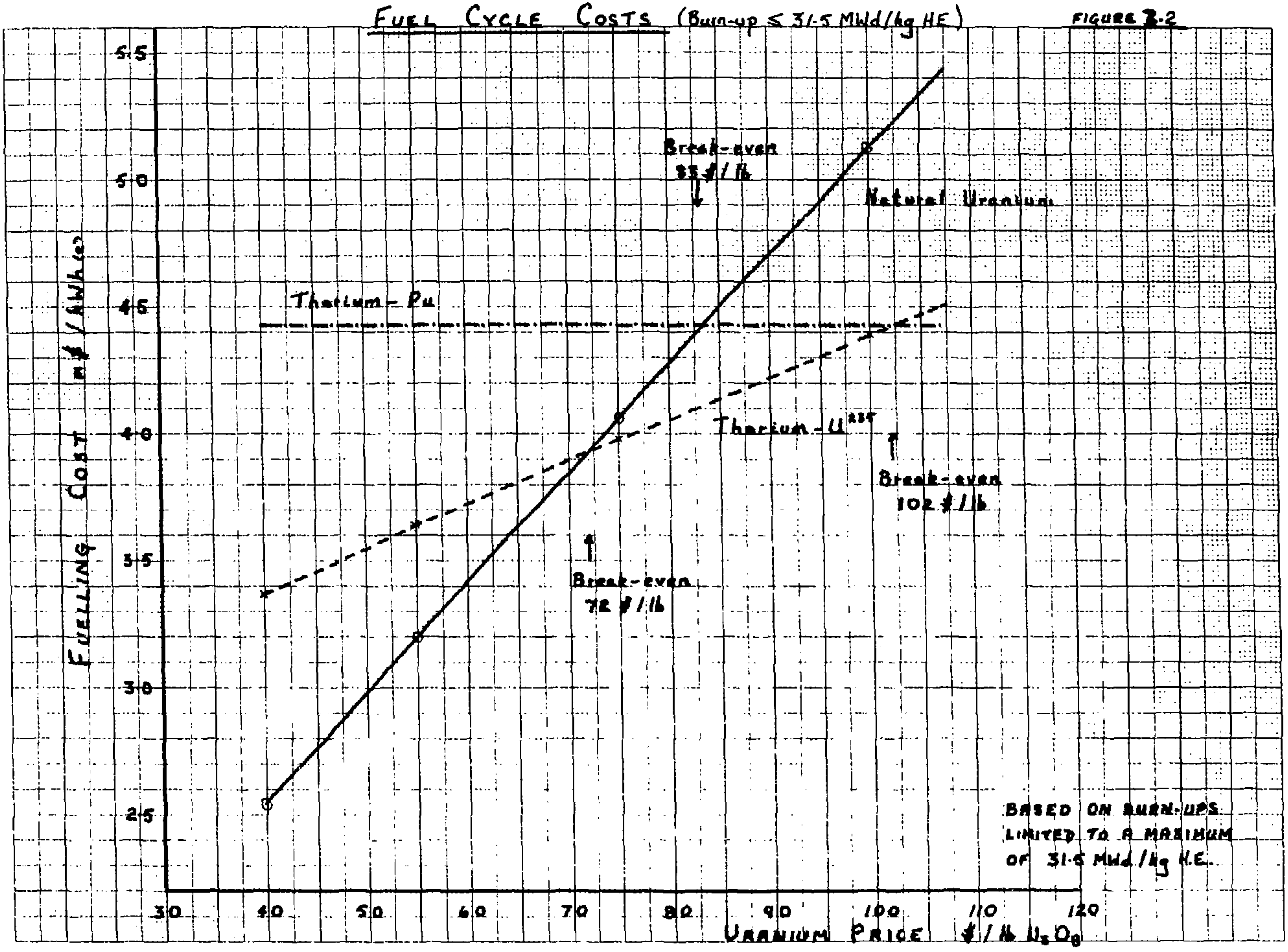
3.4 Discussion of Results

An examination of Table 3.24 shows that the economically most attractive uranium-235 enriched thorium cycle will be competitive with the natural uranium fuel cycle when the price of U_3O_8 reaches 66 \$/lb (1977 \$'s). This thorium cycle does, however, require burn-ups of 42.7 MWd/kg HE and such high

FUEL CYCLE COSTS. (Economically Optimum Burn-up)

FIGURE 3.1





FUEL CYCLE COSTS (Burn-up ≤ 31·5 MWd/kg HE)

FIGURE 3·2

burn-ups may require significant design improvements to the conventional 37-element, collapsible clad, CANDU fuel bundle. If the bundle design limits burn-up to 31.5 MWd/kg HE, the break-even U_3O_8 price is slightly higher at 72 $/lb.

The comparable break-even U_3O_8 prices for natural uranium and plutonium enriched thorium cycles are 80 $/lb and 83 $/lb, again depending on the burn-up which can be achieved before fuel sheath integrity becomes a problem. However, uranium-235 (rather than plutonium) is the more economic source of fissile enrichment for a thorium cycle until the U_3O_8 price is about 103 $/lb. Beyond that price, plutonium becomes the preferred enriching material.

4. IMPLICATIONS FOR FUTURE WORK PROGRAM

4.1 General

There is a need to continue to investigate the technical feasibility, the resource utilization, and the economics, of utilizing a thorium fuel cycle in CANDU-PHW reactors. This need has already been recognized and an appropriate work program developed within the Advanced Concepts Section of the Nuclear Studies and Safety Department. The remainder of Section 4 of this report will discuss some specific tasks identified during the economic analysis which can be incorporated into that work program.

4.2 Physics Studies

The analysis indicated that from an economic viewpoint high enrichments are desirable, particularly for the first thorium cycle. Earlier studies of uranium-plutonium fuels have indicated the use of enriched fuels is likely to result in power peaking problems. Some preliminary fuel management studies are therefore necessary to investigate the extent to which enriched thorium fuels will encounter this problem. Estimates should be made of the maximum enrichment level for plutonium, uranium-235, and uranium-233 at which operating margins to reactor trip during maximum peaking are acceptable.

The economic viability of the thorium cycles is dependent on the achievable burn-up. The flat reactivity versus irradiation curve indicates relatively small uncertainties in reactivity could lead to significant errors in the estimated burn-up. Considerable work is therefore required to provide more confidence in the burn-up estimates for various enrichments.

4.3 Capital Costs

This report has only addressed fuel costs. Uranium-233 enriched thorium fuel inevitably contains high energy γ-emitters. This will impose restraints on the way in which new fuel can be handled. The irradiated fuel will contain higher concentrations of fission products and fissile isotopes than irradiated natural uranium fuel. This may increase the required shielding and cooling demands on the irradiated fuel handling and storage systems. Criticality control may also become important. The problems in handling fuel throughout the generating station therefore requires study, and the extent of possible additional capital expenditures due to such problems should be identified.

There may also be additional capital costs associated with the reactor. For example, the power peaking problem may require the installation of more extensive power mapping instrumentation and a more elaborate zone control system. The reactivity increase during reactor shut-down, due to the decay of Pa-233 to U-233, may also result in a capital cost increase.

4.4 Resource Utilization

The economic calculations in this report indicate that the major incentive for developing thorium fuel cycles is to provide protection against very high uranium prices. Inadequate reserves and/or production capacity is the most likely cause of such high prices. The need for estimates of resource requirements for different expansion scenarios is therefore evident.

5. CONCLUSIONS

The time required to develop the necessary technology will delay the commercial introduction of thorium fuel cycles until beyond the end of this century. By that time, there is a fairly high probability that the price of uranium will be above the break-even price. That is, there will be an economic incentive, as well as a resource conservation incentive to adopt thorium cycles rather than continue utilizing the once-through natural-uranium cycle. Delays in undertaking the necessary research and development for thorium cycles will delay the commercialization date and have an adverse effect on the economics of nuclear power.

From a strictly economic viewpoint, the first thorium cycle should be uranium-235 enriched, and should be introduced when U_3O_8 reaches about 70$/lb (1977 $'s). This should be superceeded by a plutonium enriched thorium cycle when U_3O_8 exceeds about 100$/lb (1977 $'s). Resource conservation would favour a somewhat earlier replacement of uranium-235 with plutonium. If, in addition, U_3O_8 prices exceed 70$/lb by the end of the century, and are continuing to rise fairly rapidly, the time period when uranium-235 enriched thorium cycles are optimum may be relatively limited.

The U_3O_8 price at which thorium cycles become economically attractive is comparable to the price at which plutonium-uranium (mixed oxide) fuel cycles become attractive. It is, therefore, intended to refine the cost calculations performed for mixed oxide fuel cycles in Reference 1. The cost calculations for all the advanced fuel cycles will then be compared in detail. This will highlight the cycles which show the greatest economic potential. Ultimately this will lead to the development of a strategy for utilizing several cycles in a logical sequence to minimize long-term nuclear generation costs.

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