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THE ECONOMICS OF PLUTONIUM RECYCLE

Nuclear Studies and Safety Department

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Abstract

This report discusses the individual cost components, and the total fuel cycle costs, for natural uranium and uranium-plutonium mixed oxide fuel cycles for CANDU-PHW reactors. A calculation is performed to establish the economic conditions under which plutonium recycle would be economically attractive.

The report provides 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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1. Introduction

In 1975 a brief, informal review of this subject was made (1). The last two years have seen some dramatic shifts in the costs of some components of the nuclear fuel cycle. This report, therefore, updates that review and provides a more comprehensive treatment of the issues involved.

The report discusses the individual cost components, and the total fuel cycle costs, for natural uranium and uranium-plutonium mixed oxide fuel cycles. A sensitivity study of the total fuel cycle cost to changes in the cost of various components of the cycle is provided. The economically optimum plutonium enrichment is found for a variety of conditions. Finally, the economic conditions under which plutonium recycle reaches 'break-even' with the natural uranium cycle are identified.

There are only passing references to resource utilization and technical feasibility problems within this report. Clearly, decisions regarding advanced fuel cycles can not 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 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 plutonium fuel cycle is shown in Figure 2.1. Each of the major components of the cycle are dealt with in the remainder of Section 2. In each case a brief description of the state of the industry is included. This provides a perspective for the present costs and immediate cost trends which, in so far 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.

2.2 Uranium

2.2.1 State of the Industry

There are many independent purchasers and suppliers of uranium operating in a world wide market. The market, however, is heavily influenced directly by Government participation or indirectly as a result of Government policy.

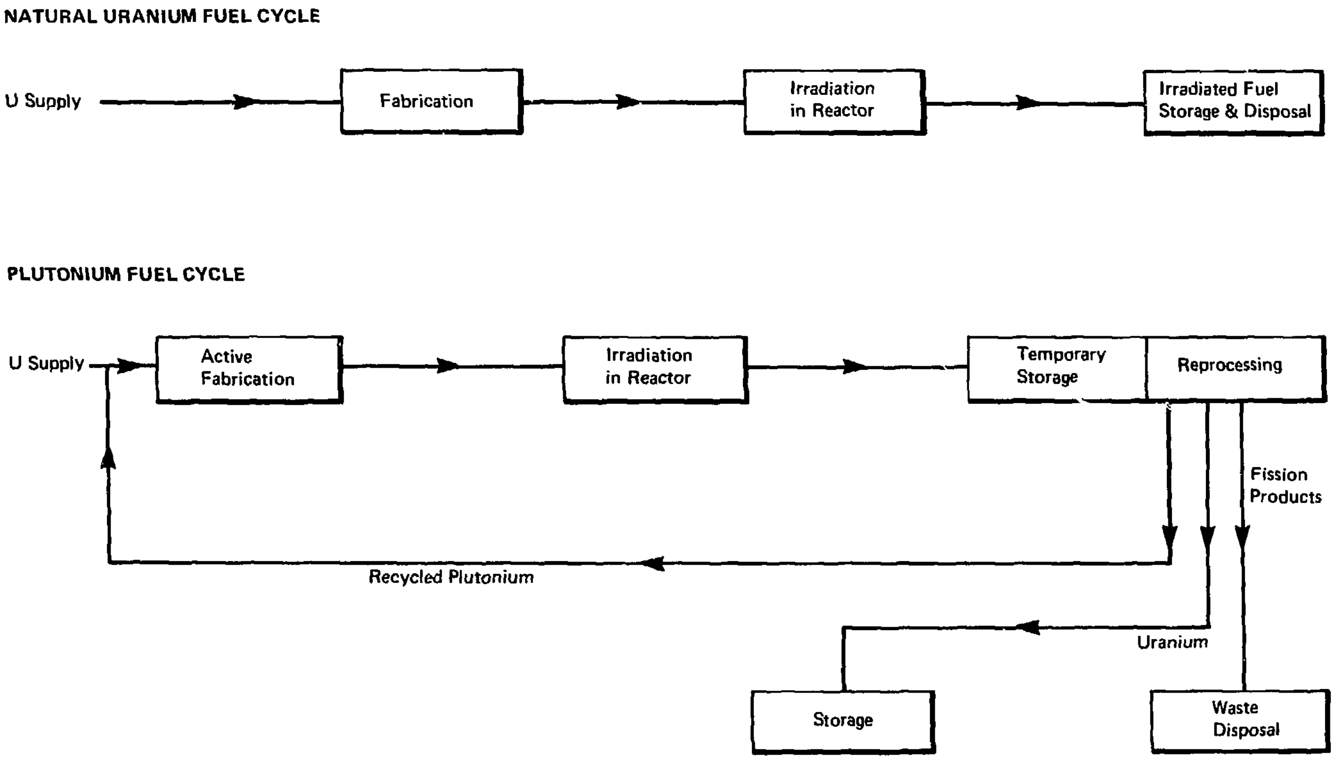

FIGURE 2.1

SCHEMATIC DIAGRAM OF NATURAL URANIUM AND PLUTONIUM FUEL CYCLES

The earliest need for major quantities of uranium was for a military weapons program. Hence the Canadian and U.S. Governments were involved from the earliest days of the uranium industry. Both Governments subsequently took action, by stockpiling and introducing import restrictions, to protect their domestic industries. Now the Governments of all major uranium producing countries are concerned about the strategic value of uranium from both an energy supply and military viewpoint.

Since uranium can command prices which are in some cases significantly higher than production costs, some Governments also see uranium as a large potential tax source (eg. State of New Mexico) or at least as a source of foreign currency.

The price of uranium is therefore essentially a 'free-market' price, but the market conditions are particularly vulnerable to Government policy decisions.

2.2.2 Uranium Costs

A comprehensive report on recent uranium price changes, and an analysis of the situations and events which caused these changes, has been prepared by Nuclear Exchange Corporation (2). No attempt to precis that report will be made but the following table was compiled by extracting values from the text of the report.

Table 2.1

Immediate Delivery Uranium Prices

Date		Immediate Delivery Uranium Price $/lb U_3O_8
January	1969	6.35
October	1972	5.95
June	1973	6.50
December	1973	7.00
January	1974	7.70
December	1974	15.00
January	1975	16.00
December	1975	35.00
January	1976	35.20
September	1976	41.00

In the above table "price" refers to the Nuexco Exchange Value for immediate delivery. That is, the price is a 'spot price' and it must be remembered that spot sales constitute perhaps only five percent of the uranium market. Further, some officials in the uranium industry question the accuracy of Nuexco's figures (3).

ERDA compiles figures on weighted average prices for uranium delivered and these are quoted in Reference 3 as follows:

Table 2.2

Weighted Average Uranium Prices from ERDA

Year	Weighted Average Price of Delivered Uranium $/lb U_3O_8
1973	7.10
1974	7.90
1975	10.50
1976	16.10

The above prices are for the U.S. but are fairly representative of the world-wide situation.

Most uranium is purchased by long term contract. The price stipulated in contracts has, in the past, generally reflected the prevailing price at the time the contract was signed. The average price of delivered uranium is the weighted average of old and new contracts. In a time of rising prices, it is therefore natural that the average delivered price should lag behind the current spot price. Tables 2.1 and 2.2 above, are therefore compatible. Recently, prices in contracts which were signed several years ago have become so out of line with present values that many have been re-negotiated.

In summary: present day average delivered prices to a utility will very much depend on its mix of existing contracts, and the date they were signed, but will likely be around 15 to 20 $/lb U_3O_8. New contracts are likely to be at a price of between 40 and 45 $/lb U_3O_8 (4).

2.2.3 Developments up to 1995

The future balance between supply and demand will largely determine uranium price.

As much of the world turns to nuclear power, the absolute demand for uranium is increasing rapidly. Yet a number of factors are indicating that the increase will not be as rapid as previously predicted. Recent estimates of world-wide nuclear capacity are lower than those of a few years ago.

In the U.S., contractual uranium enrichment supply schedules, primarily as a result of ERDA's long term, fixed commitment contracting policy, are much in excess of needs for approximately the next ten years. Demand for uranium feed, at least in this major market, has been artificially high and will result in large uranium inventories (5). Of course, there will be a corresponding softening in demand when inventories can be reduced.

ERDA's enrichment tails assay has remained at 0.2% so far, though a rise to 0.25% is likely. This increase is smaller than was being projected as little as a year ago. This will moderate the previously projected uranium demand. If centrifuge technology can reduce enrichment costs, other countries will likely operate on a 0.2% tails assay. They may even be able to lower the tails below that level and save still more uranium feed.

On the supply side we may also be experiencing a broad turning point. In early 1975, Nucleonics Week were reporting that exploration drilling in 1974, although higher than in 1973, was 7 million feet less than the industry had expected. The discovery rate fell from 1.8 lb/ft. in 1973 to 1.2 lb/ft. in 1974 (6). There seemed to be an air of pessimism that the required amount of uranium would be found.

In early 1977, Reference 5 reported that the uranium industry had responded to recent uranium price increases by launching exploration programs larger than any before, and, "although the results of these efforts are not yet in, industry rumors indicate that they are relatively successful." This quote referred to the U.S. industry but encouraging finds have also been made in Canada, Australia and other parts of the world.

In short, the supply looks more promising and the demand less awe inspiring than a couple of years ago. What effect will this have on uranium price? Most long term contracts now have more sophisticated provisions than a simple $/lb figure. Most contracts have a 'floor' price and are linked in some way to the prevailing market price at the time of delivery. The highest dollar range recently quoted appears to be 56 to 62 $/lb in the period 1980-82 (7). This is equivalent to about $45/lb in 1977 dollars with inflation of 7%/annum. So at the time of that contract, late 1976, prices still seemed to be rising in constant dollar terms, though quite slowly.

More recently B. Solomon has stated, "Spot prices for immediate delivery have increased only marginally over the $40 a pound figure reached early last year - which, in real dollars, means that the price actually has declined a bit ... for the next four to seven years, the dollar price for uranium will remain about the same, but the real price will fall." (3).

A study by the consulting firm of Pickard, Lowe and Garrick gives stronger indications of a uranium price decline. The study is reported to have concluded that uranium production can expand as fast as necessary given sufficient economic incentive. This incentive probably exists at prices (in today's dollars) of $30 to $40 per pound. "We believe", the authors of the study say, "that under a wide range of conditions, the market will be unstable and will tend to exhibit a downward movement (from today's level) through most of the 1980's".

Personal contact with R.D. Page of AECL indicates that he thinks that uranium prices will rise slowly in constant dollars; that is at a rate of between zero and 1.5%/annum.

Another trend, the increasing involvement of utilities in uranium exploration and production, may exert a downward push on uranium prices in the post-1985 period. Already a number of utilities are acquiring reserves or participating in production projects. By supplying exploration financing, sharing some of the risk, and providing an assured market for the uranium product, the utilities will acquire uranium at the lowest possible price.

This section has dealt with some qualitative arguments. Their consequences can only be quantified by making an informed guess. With this in mind it is suggested that the 1980's and early 1990's will see uranium prices in the range of 30 to 50 $/lb U_3O_8, in today's dollars.

2.2.4 Developments Beyond 1995

Nuclear stations not yet committed will be in-service by the early 1990's. Some of the uranium which will fuel these stations has probably not yet been discovered. Political parties and their energy policies will, in various parts of the world, have come and gone. In short, beyond 1995 any uranium price predictions become very speculative.

In such distant time periods predictions cannot be based on specific events or actions of individual organizations. Rationalizations of predictions can only be based on very general principles. Three broad types of reasoning come to mind. The first is that any existing trend will continue. This has little or no validity for uranium prices beyond 1990 because the price estimates for uranium prior to that time are based on the existence of atypical circumstances. Such circumstances include, for example, the depletion of unusually high inventories.

The second argument would have uranium prices stay constant in real terms. Such an assumption is generally valid for a commodity produced by a mature industry where no major technological break-throughs are to be expected. Such an argument, however, is not valid for a resource industry if the demand becomes sufficiently great to cause serious concern about the adequacy of the resource base.

This brings us to the third argument, which is most widely held and most valid, namely that uranium will become both scarce and considerably more expensive. The difficulty here is the wide range of opinion as to how expensive, how soon.

The scarcity will depend on the uranium demand which in turn hinges on the need for fission reactors and the efficiency of uranium use. The reactor growth rate will depend on electrical growth rates and the cost and availability of alternative power sources such as oil, coal, solar, geothermal and fusion. The efficiency of uranium utilization depends on the mix of reactor types (CANDU, LWR, LMFBR) and the choices of fuel cycle.

The uranium scarcity also, of course, depends on the favourability of the economic and socio-political climate for initiating uranium exploration; as well as the success rate of the exploratory efforts.

If a uranium scarcity becomes sufficiently severe, it is possible that means of recovery will be developed from very low grade sources such as granites or sea water. The Japanese are even now investigating the technology of uranium extraction from sea water. These potential low grade resources are so extensive that they could not be depleted. The cost of recovery from such sources would thus represent an ultimate limit on uranium price rises due to depletion of higher grade deposits.

It is doubtful if it is meaningful to attempt to estimate actual dollar values based on the considerations discussed in this section. A value of 100 \$/lb U_3O_8 (1977 \$'s) is the type of number which may be postulated for early in the next century. Analogy with events in the oil industry is almost irresistable and if such an analogy is valid the figure may be higher. It also suggests that price increases will occur in a highly non-uniform manner.

2.3 Fuel Reprocessing

2.3.1 State of the Industry

There is no commercial reprocessing presently being undertaken in North America. The Nuclear Fuel Services' West Valley plant and General Electric's Morris plant are essentially abandoned except as temporary fuel storage sites. The Barnwell plant of AGNS appeared to be approaching operation prior to President Carter's energy policy announcement. It now seems unlikely, even if it becomes an international cooperative venture as some recommend, that it will start operation for several years.

In Europe, the conglomerate known as United Reprocessors is becoming a viable commercial industry. United Reprocessors was formed by the merger of the reprocessing interests of British Nuclear Fuels Ltd. (BNFL) of the United Kingdom, the Commissariat a l'Energie Atomic (CEA) of France, and Kernbrennstoff-Wiederaufarbeitungs-Gesellschaft mbH (KEWA) of Germany.

BNFL is government owned, but is operating as a commercial enterprise. It presently operates a uranium metal reprocessing plant at Windscale and a new head-end which is under construction will allow the same plant to handle UO_2 fuels. The major overseas contracts which it is negotiating are, however, contingent on it receiving approval to proceed with two new 1000 Te/annum plants which are also planned for the Windscale site.

In France, early in 1976, Cogema (Compagnie Generale des Matieres Nucleaires) was formed. Cogema inherited the assets of CEA and will run the French reprocessing business. The French are in a similar position to the British. A new head-end facility in the final stages of installation will allow their La Hague plant to handle oxide fuels. New plants for oxide fuels are in the planning stages.

In Germany, KEWA are in the early planning stages for a plant but it will not be on line until the late 1980's. Swiss utilities have been invited to participate in this plant (8).

2.3.2 Reprocessing Costs (LWR fuel)

As indicated in the previous section, the reprocessing industry is not fully commercialized. However, some contracts have been signed with European reprocessors and the price of such contracts is 'de facto' today's market price. The terms of the contracts are not public knowledge and Ontario Hydro, not having been a party to them, does not have 'inside' knowledge. In private discussions held at the ANS conference on the 'Plutonium Fuel Cycle' some information was, however, made available. The indicated cost of reprocessing was close to $500/kg heavy element. *While this value is not subject to immediate verification, the* author received the information from two independent sources and believes it to be accurate.

This value is significantly higher than published values of reprocessing cost which generally fall in the range of $200 to $300/kg HE. For example, the value quoted in the United States GESMO study is $280/kg HE. Such published values are in present day dollars but are usually based on design studies of future plants (9). They are not, therefore, necessarily incompatible with a present day cost of $500/kg HE.

Whether or not such a reduction in real (constant dollar) costs will be achieved is debatable. A case can be made that future plants will benefit from previous experience, will show economies of scale and possible duplication, and will have the benefit of improved technology. A saving of 40% to 50% is not inconceivable. It is also possible, however, that the design studies are optimistic in failing to make adequate allowances for unforeseen delays and problems during the plants' construction. A large commercial reprocessing plant will cost of the order of a billion dollars. Accurate cost estimates of such major undertakings are notoriously difficult to make. The experiences of General Electric and Nuclear Fuel Services are perhaps attributable to special circumstances and should be considered atypical. Nevertheless they are a warning of the financial hazards of undertaking such a project. In short, there is no solid evidence that significant cost reductions over present experience will, in fact, be realized.

Cost data in the open literature is also difficult to interpret due to the lack of details regarding the contract terms associated with the published cost. Reprocessing waste would normally be the reprocessor's responsibility but contracts may require the customer to accept the waste along with the separated fissile material. The chemical form of the uranium and plutonium may vary from contract to contract.

The financial details are perhaps even more significant. Future contracts will almost invariably require large pre-payments by the customer to help finance the construction of the reprocessing plant. The contract will likely have cost escalation provisions and may even require the customer to share a proportion of the financial risk of the whole venture. Essentially the 'customer' may become an equity shareholder. Under these circumstances a statement of 'dollars per kilogram heavy element' can only be a gross simplification of the actual transaction involved.

2.3.3 Reprocessing Costs (CANDU fuel)

CANDU fuel is not reprocessed at this time and it is necessary to draw conclusions regarding the probable cost of such reprocessing from the international scene.

For the same irradiated fuel throughput, a CANDU fuel reprocessing plant would be cheaper than an LWR fuel reprocessing facility due to the lower fuel burn-up of CANDU fuel. The lower burn-up results in a lower fission product inventory and lower plutonium concentrations. The lower activity eases shielding requirements and waste disposal volumes. The irradiation degradation of process solutions will also be reduced. The lower plutonium concentration will ease criticality control, reduce the size of nitrate-oxide conversion facilities, and reduce plutonium storage requirements.

Financially, the major difference between CANDU and LWR reprocessing is the assumed rate of return on capital investment. Non-Canadian facilities, at least those with significant investor equity, are likely to be seeking a rate of return on the equity of about 25% before taxes, or about 12% after taxes. To the extent that the debt portion of the financing is considered to be 'high-risk', this too will be at a high interest rate. Any Canadian, CANDU reprocessing facility is expected to be government or utility owned, with essentially 100% debt, and the required rate of return is expected to be around 12%.

AECL have conducted a study of CANDU fuel reprocessing costs based on the AGNS plant but incorporating allowances for the factors discussed above. The derived reprocessing cost was 73$/kg U and this value was thought to be reconcilable with the values of about 140 $/kg U which were being quoted for the AGNS plant. The study was conducted in 1975 and must now be considered out of date. What modification to that cost estimate is appropriate in the light of more recent data?

Today's cost of reprocessing is perhaps an academic question on which it is not fruitful to speculate. There are no domestic facilities to perform such services and Ontario Hydro has no firm plans to seek commercial size reprocessing contracts from overseas suppliers. Insufficient development work on the use of plutonium in CANDU reactors has been performed and clearly present-day, overseas costs would make plutonium recycle far from economic.

The cost of CANDU reprocessing in the early 1990's and beyond is something we would very much like to know since it influences future advanced fuel cycle R&D policy.

Clearly, the current basis for an accurate cost estimate is not very adequate. As speculation one might reason as follows:

a) Reference 11 suggest CANDU reprocessing costs are about half those for LWR fuels.

b) Typical published reports for future LWR costs are in the range of 200 to 300 $/kg U. (Say 250 $/kg U in 1977 dollars).

c) Published values imply that future reprocessing costs will be about 50% lower (in constant dollars) than today's costs. It may be more realistic to assume only half that saving is realized.

On this basis:

CANDU Reprocessing cost = 0.5x250x1.5 = 187 $/kg HE. This is a future cost (say 1990) but in 1977 dollars. The author again stresses this is very speculative and has a subjective error band of at least ±25%. Confirmation of this figure requires final definition of the process cycle and detailed plant design.

2.3.4 Future Developments

What political, regulatory, social, or technological developments may occur which would have a serious impact on reprocessing availability or cost?

The most dramatic event would be an outright government ban on reprocessing. Less dramatic would be a reluctance to approve and/or adequately fund AECL's proposed advanced fuel cycle program. This would not necessarily prevent reprocessing in the long term but may postpone the date of any commercial exploitation.

There is no reason why regulatory action from organizations such as the AECB should prohibit reprocessing. Ever more strict regulatory requirements, however, appear to be a very widespread trend, apparently occurring in Europe and Japan as well as the U.S.A. The regulatory bodies would appear to be responding to political and/or public opinion (or perceived public opinion) and a similar trend may well occur in Canada. More stringent regulations almost inevitably increase costs.

Increased awareness amongst all sectors of the population about energy supply problems is occurring. In the U.S. this has manifest itself in a growing trend towards pro-nuclear public interest groups. So the pendulum could swing to a socio-political environment more conducive to nuclear development, thus reversing the trend described above.

Technological improvements in new reprocessing plants are likely as organizations benefit from past experience. The close cooperation amongst the European community enhances the probability of significant design improvements being made by them. Canada should benefit from both its own research and development effort and the general industry wide developments in reprocessing technology.

It is not possible to quantify the above considerations. In the absence of more specific information this report will, therefore, assume long term reprocessing costs will stay constant in real terms.

2.4 Active Fuel Fabrication

2.4.1 State of the Industry

Due to plutonium's chemical and radioactive toxicity, it is necessary to ensure that it is fully contained during the fuel fabrication process. For highly enriched fuel the radiation levels may necessitate heavily shielded cells with remote operation. For fuels bearing up to about 1% plutonium, glove box operation is considered adequate. This report therefore assumes that plutonium fuel for a CANDU reactor would be fabricated in a glove box line. Even the necessity for glove boxes does, of course, greatly increase the manufacturing costs.

Active fuel fabrication is a considerable way from being a developed, commercial industry. In Section 2.3 we saw that the reprocessing industry is in its infancy, and active fabrication depends on reprocessing for a supply of plutonium. Military reprocessing for bomb material has had some technological spin-off to the non-military reprocessing industry. No parallel exists for active fuel fabrication. Furthermore, much of the plutonium recovered for use by the power-industry is being stock-piled for future use in fast breeder reactor programs. Consequently, relatively small amounts of low concentration plutonium fuel have been fabricated.

Test quantities of fuel have been fabricated in at least twelve different industrial and Government-owned facilities in the United States, and similar experience has been gained in a dozen other facilities in different parts of the world (10). The European plants have demonstrated that mechanization of plutonium fuel processing lines is a practical goal and they are planning commerical size facilities. These facilities have, or will, produce LWR fuel. Details of the fabrication procedure are not directly applicable to the Canadian (CANDU) situation. Nevertheless many of the problems and techniques utilized will be the same and, lacking more directly relevent experience, we must learn what we can from the LWR experience.

AECL have built a pilot line at Chalk River to fabricate plutonium bearing CANDU fuel. This line is at present undergoing a 'shake-down' run with natural uranium fuel, and plutonium may be introduced by the end of 1977. Its maximum capacity when running smoothly is approximately one 19 element bundle per day. At this time, however, it is experiencing a considerable number of equipment problems.

2.4.2 Active Fabrication Costs

An estimate of the cost of producing plutonium bearing CANDU fuel in a commercial size plant has been made by AECL. The cost derived was 88 \$/kg HE (in 1975 \$'s) for a 400 Mg HE/annum facility. This estimate was made over two years ago and since then considerable escalation in the cost of nuclear facilities has taken place. Moreover, the cost was based on a design study without the benefit of operating experience. There is considerable concern that the problems of building and operating such a plant may have been under-estimated and that the resultant cost is very optimistic. While perhaps not directly relevant, the problems encountered in the CRNL pilot line do nothing to dispel such a concern.

The only other cost data available is that produced for LWR fuel. This is not directly relevant but is worth examining as a broad cross check on the AECL estimate. The Nuclear Regulatory Commission's GESMO study states that uranium fuel fabrication costs 94 \$/kg, and projects a differential of 105 \$/kg for mixed oxide fuels (11). This differential, however, is based on the contention that learning effects and technical advances will "eventually" reduce costs. During the early years of recycle the estimate is for mixed oxide fabrication costs to be \$350 to \$400/kg. The Edison Electric Institute suggest a differential of about \$260/kg which would be consistent with the higher GESMO figures (11). Private discussions with a representative of a European organization involved in active fabrication were held at a recent ANS conference on 'The Plutonium Fuel Cycle'. This source indicated that commercial mixed oxide fabrication would cost 400 \$/kg assuming that no unforeseen problems arose. That figure was, in other words, a fairly optimistic estimate. Other knowledgeable people indicated general agreement with this estimate.

The concensus would seem to be that mixed oxide fuel fabrication for LWR reactors will be at least 3.5 to 4.0 times as expensive as uranium fabrication costs. Whether or not such a ratio would be applicable to CANDU type fuel is not known. However, in this author's opinion, further doubt is cast on the validity of the 88 \$/kg estimate, a value which is only about double the present cost of fabricating CANDU uranium fuel. All things considered, a value of about 120 \$/kg (1977 dollars) would be the author's best guess for the first generation, commercial, active fabrication plants.

2.4.3 Future Developments

The same types of considerations which were discussed for reprocessing (Section 2.3.4) also apply to active fabrication. Clearly second generation commercial plants are likely to show cost reductions based on earlier experience. Such plants, however, will not be in operation until perhaps a decade or two into the next century. Speculation on economic costs in this industry, at such a distant time, is very difficult.

Lacking better data, the assumption will be made that active fabrication costs beyond 1990 will remain constant in real terms.

2.5 Irradiated Fuel Storage and Transportation

Irradiated fuel storage and transportation are important topics which are receiving detailed study within Ontario Hydro and AECL. However, the cost of these items is expected to be less than 0.1 m$/kWh, which is a relatively small fraction of the total fuel cycle cost (12). The cost will also be of a similar magnitude for the natural uranium and plutonium fuel cycles. Any cost difference is unlikely to alter the economic ranking of these fuel cycles. These topics will not, therefore, be dealt with in detail in this report; just a few qualitative observations will be made.

The irradiated fuel from a natural uranium fuelled core contains plutonium; it is not qualitatively different from irradiated fuel which contained plutonium when it went into the reactor. The fission product concentration will be higher in the originally enriched fuel. This will lead to greater shielding and cooling requirements for the irradiated enriched fuel during both storage and transportation. On a dollars per kilogram basis, the cost will be higher for the enriched fuel but, since the burn-up will be greater, the cost on a dollars per megawatt basis will be essentially the same for the two fuel types.

Note that while additional bays may be constructed to do this, the irradiated fuel bays at a station are not at present sized to take fuel for the full station's life. With a once-through cycle, the irradiated fuel may be shipped to a central storage facility. With plutonium recycle, ideally, the fuel would be shipped directly to the reprocessing plant, and the cost incurred would be similar. Prior to a mature reprocessing industry, it may be necessary to ship to a central storage facility first and subsequently to the reprocessing plant. The extra handling in this two stage process could result in some additional cost.

From a safeguards point of view it is highly desirable that a reprocessing plant and an active fabrication facility be as closely integrated as possible. At the least, they may be expected to be on the same site. The cost of shipping between these facilities will therefore be very small.

The cost of shipping plutonium enriched fuel to a reactor will be significantly higher than shipping natural uranium fuel. The additional cost will be largely attributable to safeguards' regulations. Since these regulations are not well defined, cost estimates cannot be made with precision. However, the additional cost on a weight for weight basis will, at least to some degree, be compensated for by the additional burn-up achievable with the enriched fuel.

2.6 Geological Disposal

The final stage of a fuel cycle is disposal of the wastes. In the case of a once-through natural uranium fuel cycle, the 'wastes' are the irradiated fuel bundles. For a plutonium fuel cycle, the 'wastes' are the fission products and irradiated process solutions from the fuel reprocessing plant.

The most likely method of final disposal of these wastes is in stable geological formations. It is not known at this time if irradiated fuel bundles can be placed in geological storage without first being canned to provide an additional barrier against radioactive leakage. Whether or not such encapsulation is required, the total disposal cost is not expected to exceed 0.1 m$/kWh (12).

The wastes from a reprocessing plant will probably be vitrified into a glass which exhibits very low leach rates. The glass will then be suitable for placement in a geological disposal site. The cost of waste vitrification is included in the reprocessing cost.

The density of packing in a geological site, or mine, will probably be determined by rates of heat generation. The heat rate is proportional to the fission product concentration which is proportional to the fission energy generated in the fuel. Hence a given energy generation will result in a similar heat load in the waste stream, regardless of the fuel cycle employed, if the fission product decay times are comparable. Since the size of the heat load will be an important cost parameter, it is likely the costs will also be of the same order of magnitude for the different fuel cycles. The precise costs will depend on the reprocessing technology and process solutions utilized, the vitrification procedure, and the regulatory requirements. Discussion of these is beyond the scope of this report. Since, for both cycles, the waste disposal costs are expected to be less than 0.1 m$/kWh, differences between these costs are unimportant.

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 plutonium recycle. 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 four major parameters: uranium cost, plutonium cost, fuel fabrication cost, and fuel burn-up. Some justification for ignoring irradiated fuel storage and transportation costs and waste disposal cost is provided in Sections 2.5 and 2.6 respectively.

Strictly speaking, a discounted cash flow analysis is required for accurate determination of fuel cycle cost. However, the calculations are performed in constant dollars (1977$'s) so the appropriate discount rate would be small (~3%/annum). Also, the costs to be considered occur over a relatively short space of time, so the discounting process may be safely ignored.

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 early 1990's. The costs are expressed in 1977 dollars. Anticipated future costs are used in preference to those existing today simply because plutonium recycle is not an option at this time. It may be an option in the 1990's.

Plutonium is assigned a value according to the cost of extracting it from the irradiated fuel. That is:

$$\text{Plutonium cost} = \frac{\text{Cost of Reprocessing Irradiated Fuel}}{\text{Plutonium content of Irradiated Fuel}}$$

It is assumed the reprocessing cost is constant (187$/kg HE) for all CANDU fuels considered. Hence the plutonium cost depends on its source. In calculating plutonium cost the following data was used (13).

Table 3.1

Plutonium Content of Irradiated Fuel

Initial Fuel Enrichment % fissile Pu	Average Discharge Fuel Burn-up MWd/MgHE	Plutonium Content of Discharged Fuel g fissile Pu/kg HE
Natural	7,500	2.60
0.1	10,750	3.10
0.2	13,450	3.33
0.3	15,800	3.56
0.4	17,900	3.73
0.5	19,875	3.87
0.6	21,730	3.95

The uranium and fuel fabrication prices are taken directly from Sections 2.2.3 and 2.3.3 respectively. The fuel fabrication price includes the cost of zirconium and all other necessary fabrication materials except uranium and plutonium. It also includes the cost of conversion from yellow cake (U_3O_8) to uranium oxide (UO_2).

Table 3.2

Base Case Cost Data

Uranium	40	$/lb U_3O_8
	91	$/kg UO_2
Plutonium	72	$/g fissile from natural U fuel
	60	$/g fissile from 0.1% Pu fuel
	56	$/g fissile from 0.2% Pu fuel
	53	$/g fissile from 0.3% Pu fuel
	50	$/g fissile from 0.4% Pu fuel
	48	$/g fissile from 0.5% Pu fuel
	47	$/g fissile from 0.6% Pu fuel
Fuel Fabrication	44	$/kg HE for natural U fuel
	120	$/kg HE for plutonium fuel

3.1.3 Range of Plutonium Enrichments

The range of fuel enrichment considered is from zero to 0.6% fissile plutonium. A study has indicated that there is a likelihood of some power peaking problems if fuel of 0.3% Pu concentration is utilized in the present CANDU designs (13). The consideration of fuel costs for still higher plutonium concentrations should not be construed as implying such fuel compositions are technically feasible.

To achieve technical feasibility it may be necessary to reduce the average power density of the fuel. This would require a larger core for a given power output and hence a capital cost penalty. Alternatively, the power peaking may be overcome by changes to the fuel design or the fuel management scheme.

Such changes are likely to have some detrimental effect on either fuel burn-up or fuel fabricaiton costs. Either way there would be a corresponding increase in fuel cost. It is not the purpose of this report to explore technical feasibility; no fuel cost penalty is assigned to the power peaking phenomenon which occurs to an increasing extent with increasing plutonium enrichment.

3.1.4 Fuel Burn-up

The fuel burn-up as a function of initial enrichment is assumed to be as follows (13):

Table 3.3

Fuel burn-up for various Initial Enrichments

Initial Enrichment % fissile Pu	Fuel Burn-up MWd/Mg HE
Natural	7,500
0.1	10,750
0.2	13,450
0.3	15,800
0.4	17,900
0.5	19,875
0.6	21,730

In the calculation of the above, no allowance was made for any loss of burn-up which may result from changes designed to overcome potential power peaking problems (Section 3.1.3).

The calculation also assumed that the plutonium in the fresh fuel was obtained from natural uranium bundles which had an average discharge burn-up of 7,500 MWd/MgHE. Plutonium obtained by reprocessing the enriched fuel which has achieved a greater burn-up will have a higher plutonium-240 content. Fuel fabricated using this plutonium will achieve a significantly lower average discharge burn-up for a given fissile plutonium enrichment. Subsequent recycles will result in plutonium of increasingly unfavourable isotopic composition and corresponding decreases in achievable burn-up.

Hence the assumption that is made in the calculation, namely that Table 3.3 is applicable for each recycle, is one that has a significant bias in favour of plutonium recycle.

3.1.5 Recycling Enriched Fuel

When irradiated enriched fuel becomes available it will be reprocessed in preference to irradiated natural uranium fuel. This will take advantage of the higher plutonium concentration in the irradiated enriched fuel and hence lower the plutonium price (Table 3.2).

A study of the Pickering GS A reactor lattice conditions shows that fuel cycles utilizing initial plutonium concentrations of up to 0.36% fissile plutonium are net producers of plutonium (13). Hence these cycles can provide their own plutonium feed. The cycles employing higher initial enrichments are net consumers of plutonium and will require, in addition to plutonium recovered from their own irradiated fuel, some higher priced plutonium from irradiated natural uranium fuel.

For example (using Tables 3.1 and 3.2):

If the fuel cycle employed utilizes an initial enrichment of 6 g Pu/kg HE, 3.95 grams of the plutonium will be obtained at a cost of 47 $/g by reprocessing the enriched fuel, and the remaining 2.05 grams will be obtained at 72 $/g by reprocessing natural uranium fuel.

Hence the average cost of plutonium feed to such a fuel cycle is given by:

$$\text{Average cost} = \frac{(3.95 \times 47) + (2.05 \times 72)}{6} = 56\ \$/\text{g}$$

Repeating this calculation allows the compilation of the following table.

Table 3.4

Average Cost of Plutonium Feed at Equilibrium

Initial Enrichment % fissile Pu	Average Cost of Fissile Plutonium $/g
0.1	60
0.2	56
0.3	53
0.4	51
0.5	53
0.6	56

The above table assumes that all reactors committed to an enriched fuel cycle would utilize the same degree of enrichment. This may not be an optimum strategy but it is an adequate assumption for present purposes.

The table also assumes all fissile plutonium is equally valuable. The degradation due to the increasing plutonium-240 concentration with multiple recycle is ignored. This is an assumption favourable to plutonium recycle.

3.2 Results of Fuel Cycle Cost Calculations

The first cost calculations were performed assuming the plutonium was obtained from irradiated natural uranium fuel. This would be the situation for the first load of plutonium fuel in each reactor. It would also apply to the first few years of refuelling following the conversion of the reactor to the use of plutonium fuel. These calculations are summarized in Table 3.5.

The second set of cost calculations assume the enriched fuel cycle is at equilibrium.* The calculations are therefore based on the plutonium feed costs given in Table 3.4. These calculations are summarized in Table 3.6.

A sensitivity study was performed and the results are summarized in Tables 3.7 and 3.8 and Figures 3.1 and 3.2.

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* The word 'equilibrium' is henceforth used to refer to all but the first fuel recycle. As discussed in Section 3.1.4, equilibrium is not truly established due to the changing isotopic composition of the plutonium. This effect has been ignored.

Table 3.5

Fuel Cycle Costs for First Recycle, Base Case

Fuel Cycle Component	Fuel Cycle Costs for Various Fuel Enrichments $/kg HE							
	Natural	0.05% Pu	0.1% Pu	0.2% Pu	0.3% Pu	0.4% Pu	0.5% Pu	0.6% Pu
Fuel Fabrication	44	120	120	120	120	120	120	120
Uranium	91	91	91	91	91	91	91	91
Plutonium	-	36	72	144	216	288	360	432
Total Cost	135	247	283	355	427	499	571	643
Burn-up MWd/Mg HE	7,500	9,125	10,750	13,450	15,800	17,900	19,875	21,730
Fuel Cost m$/kWh	2.46	3.70	3.60	3.61	3.69	3.80	3.92	4.04

Note: Burn-up in thermal units.
Fuel cost in electrical units.
Assumed efficiency of 0.305.

Table 3.6

Fuel Cycle Costs for Equilibrium Recycle, Base Case

Fuel Cycle Component	Fuel Cycle Costs for Various Fuel Enrichments $/kg HE							
	Natural	0.05% Pu	0.1% Pu	0.2% Pu	0.3% Pu	0.4% Pu	0.5% Pu	0.6% Pu
Fuel Fabrication	44	120	120	120	120	120	120	120
Uranium	91	91	91	91	91	91	91	91
Plutonium	-	30	60	112	159	204	265	336
Total Cost	135	241	271	323	370	415	476	547
Burn-up MWd/Mg HE	7,500	9,125	10,750	13,450	15,800	17,900	19,875	21,730
Fuel Cost m$/kWh	2.46	3.61	3.44	3.28	3.20	3.17	3.27	3.44

Note: Burn-up in thermal units.
Fuel cost in electrical units.
Assumed efficiency of 0.305.

Table 3.7

Summary of Fuel Cycle Cost Sensitivity Analysis (First Recycle)

Assumptions		Fuel Cycle Cost for Various Fuel Enrichments m$/kWh							
		Natural	0.05% Pu	0.1% Pu	0.2% Pu	0.3% Pu	0.4% Pu	0.5% Pu	0.6% Pu
Base Case		2.46	3.70	3.60	3.61	3.69	3.80	3.92	4.04
Fabrication cost	-25%	2.26	3.25	3.22	3.30	3.43	3.58	3.72	3.85
	+25%	2.66	4.15	3.98	3.92	3.95	4.02	4.12	4.23
Uranium cost	70 $/lb	3.72	4.73	4.47	4.31	4.29	4.34	4.40	4.48
	100 $/lb	4.97	5.76	5.35	5.01	4.89	4.86	4.87	4.91
Plutonium cost	-25%	2.46	3.56	3.37	3.24	3.23	3.26	3.31	3.36
	+25%	2.46	3.84	3.83	3.98	4.15	4.34	4.53	4.72
Fab. and Pu cost	-25%	2.26	3.11	2.99	2.94	2.97	3.03	3.10	3.17

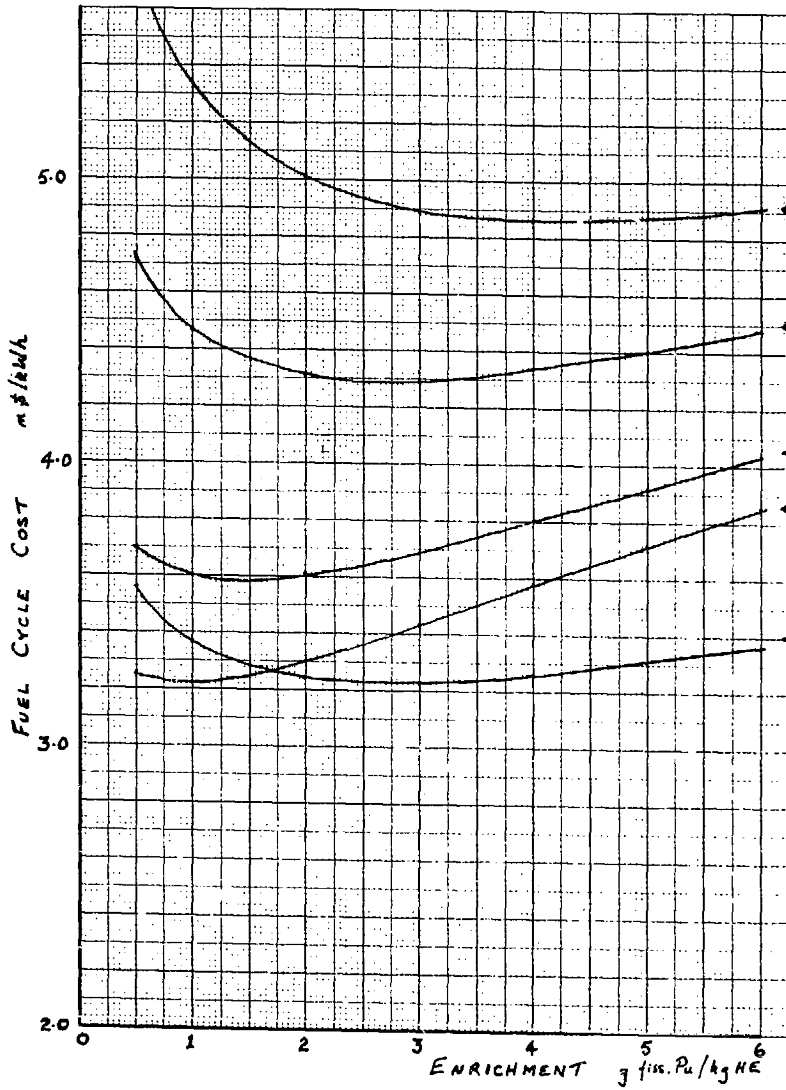
Table 3.8

Summary of Fuel Cycle Cost Sensitivity Analysis (Equilibrium Recycle)

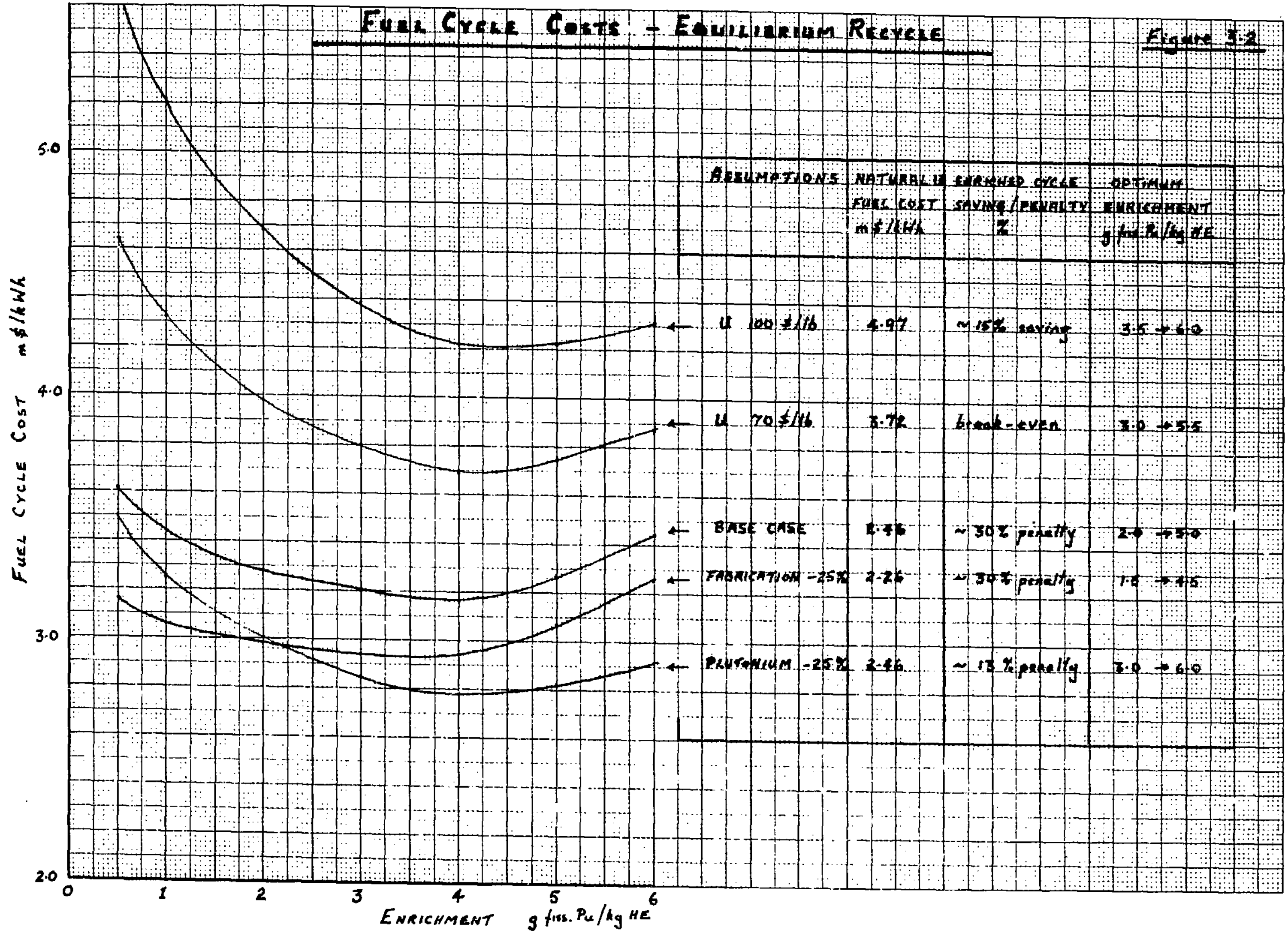
Assumptions		Fuel Cycle Cost for Various Fuel Enrichments m$/kWh							
		Natural	0.05% Pu	0.1% Pu	0.2% Pu	0.3% Pu	0.4% Pu	0.5% Pu	0.6% Pu
Base Case		2.46	3.61	3.44	3.28	3.20	3.17	3.27	3.44
Fabrication cost	-25%	2.26	3.16	3.06	2.98	2.94	2.94	3.07	3.25
	+25%	2.66	4.06	3.83	3.59	3.46	3.40	3.48	3.63
Uranium ore	70 $/lb	3.72	4.64	4.32	3.98	3.80	3.69	3.75	3.87
	100 $/lb	4.97	5.67	5.20	4.68	4.39	4.22	4.22	4.31
Plutonium cost	-25%	2.46	3.50	3.25	3.00	2.85	2.78	2.82	2.91
	+25%	2.46	3.73	3.63	3.57	3.55	3.56	3.73	3.97
Fab. and Pu cost	-25%	2.26	3.05	2.87	2.69	2.59	2.55	2.61	2.72

FUEL CYCLE COSTS - FIRST RECYCLE

Figure 3·1



ASSUMPTIONS	NATURAL U FUEL COST m$/kWh	ENRICHED CYCLE SAVING/PENALTY %	OPTIMUM ENRICHMENT g fiss. Pu/kg HE
← U 100$/lb	4·97	~ 2% saving	2·5 → 6·0
← U 70$/lb	3·72	~ 15% penalty	1·5 → 4·5
← BASE CASE	2·46	~ 45% penalty	0·5 → 3·0
← FABRICATION -25%	2·26	~ 42% penalty	0·5 → 2·0
← PLUTONIUM -25%	2·46	~ 31% penalty	1·5 → 5·5



FUEL CYCLE COSTS - EQUILIBRIUM RECYCLE
Figure 3.2
ASSUMPTIONS
NATURAL U FUEL COST m$/kWh
ENRICHED CYCLE SAVING/PENALTY %
OPTIMUM ENRICHMENT g fiss. Pu/kg HE
U 100 $/lb 4.97 ~15% saving 3.5 → 6.0
U 70 $/lb 3.72 break-even 3.0 → 5.5
BASE CASE 2.46 ~30% penalty 2.0 → 5.0
FABRICATION -25% 2.26 ~30% penalty 1.5 → 4.5
PLUTONIUM -25% 2.46 ~15% penalty 3.0 → 6.0
FUEL CYCLE COST m$/kWh
2.0
3.0
4.0
5.0
0
1
2
3
4
5
6
ENRICHMENT g fiss. Pu/kg HE

3.3 Discussion of Results

The first thing to be noted about the results is that, with the 'base case' assumptions, plutonium recycle is not economically attractive by the early 1990's. With the base case assumptions, the natural uranium fuel cost is 2.5 m$/kWh compared to 3.6 and 3.2 m$/kWh for first recycle and equilibrium recycle respectively. Only a few years ago 'break-even' was expected to occur at uranium prices of 40 to 50 $/lb. The recent rapid escalation in uranium price has been widely reported and has created an impression that plutonium recycle is already competitive, or that it will be in the very near future. The calculations in this report indicate this will probably not be the case. Higher, more realistic, cost data for other components of the fuel cycle are responsible for this conclusion.

A reduction of 25% in reprocessing, and hence plutonium, cost combined with similar sized reduction in active fabrication cost still leaves the natural uranium fuel cycle with a marginal cost advantage. The author believes reductions of this magnitude from the base case, which already allows for some cost reductions from present experience, to be quite unlikely.

A more probable path to plutonium recycle competitiveness is via uranium price increases. At a uranium price of 70 $/lb the equilibrium plutonium cycle is at break-even; only at 100 $/lb does the first recycle show a marginal cost advantage.

During first recycle conditions the curve of fuel cycle cost versus plutonium enrichment is fairly flat. At base case conditions the optimum enrichment is only 0.1% fissile plutonium. Hence, if recycle is initiated to gain experience prior to it reaching commercial competitiveness, the enrichment may be small without incurring an economic penalty. This should reduce fuel production difficulties and minimize in-reactor power peaking problems although the experience gained would not be totally the same as that required for higher enrichments. In that regard, it should be noted that as the uranium price rises the optimum enrichment increases. By the time enriched fuel is being recycled (i.e. equilibrium conditions) there is a definite economic incentive to increase the enrichment to 0.4% fissile plutonium. Power peaking may result in an inability to operate the reactor at such enrichments without reducing the specific power. This would cause a delay in the date at which plutonium recycle will be economically attractive.

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 recycling fuel from CANDU reactors. This need has already been recognized and an appropriate work program developed within the Advanced Nuclear Concepts Section of the Nuclear Studies and Safety Department.

4.2 Technical Feasibility

This report does not address questions of technical feasibility, but it has implications for that part of the work program in so far as it indicates the economically optimum fuel enrichment for various stipulated conditions. Hence it provides a target for the technological program, namely, to devise fuels and fuel management schemes which will allow the use of those optimum enrichments.

The data contained in this report will also assist in the economic assessment of technological changes. For example, if the solution to the power peaking problem involves some reduction in fuel burn-up, the corresponding change in fuel cost can readily be found. The relative merits of the solution as compared to, say, reducing the initial fuel enrichment will then be known.

4.3 Resource Utilization

This report highlights the fact that the major incentive for developing a plutonium recycle fuel industry is 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. A scenario computer code such as FISS is valuable for resource studies and the development and use of FISS, or a similar code, is recommended.

4.4 Economic Studies

This report provides some guidance as to the most appropriate type of economic analysis which should be performed in the future. In particular, the value of scenario codes will be examined, and possible alternate approaches will be discussed.

There are a number of computer codes, such as FISS, which are being developed for the analysis of future nuclear expansion scenarios (14,15,16,17,18). As mentioned in Section 4.3, these are valuable tools for the study of resource utilization. A number of these codes also have the capability to perform cost calculations and they are sometimes used to compare the economics of alternative fuel cycles.

The economic input data for such calculations can be estimated with some confidence up to the early 1990's, although even in this time frame an error band of ±25% is necessary for many parameters. Beyond 1995, the best that can be assumed for the majority of costs is that they will stay relatively constant in real terms. (Expressed another way, their price will rise at roughly the same rate as the general rate of inflation.) Uranium is an exception to this general rule; its price will almost certainly eventually rise substantially in constant dollars as a result of its scarcity, and the general scarcity of other energy sources. What is not known, and by the nature of the problem cannot be known, is the timing of the scarcity and the precise way the price will react to the scarcity. Uranium prices may first exceed 100 $/lb (1977$'s) anytime from about 1995 to 2020.

The need for research and development prior to implementing any advanced fuel cycle on a commercial scale will prohibit significant throughput of any enriched fuel before the mid 1990's. The problem faced is, therefore, that differences in nuclear scenarios only start to become significant in the time period characterized by very uncertain cost data. Further, this report has indicated that plutonium recycle is unlikely to become economic before the mid 1990's. Since by then we are in a period of considerable cost uncertainty, the year at which a break-even cost situation will occur is also very uncertain.

The major advantage of a dynamic type of analysis inherent in a scenario code is that long term benefits can be assessed. A dynamic analysis may show that an advanced fuel cycle should be implemented prior to the break-even date in order to be in a position to take advantage of savings which will start to accrue at a later date. The type of analysis which only looks at costs at a discrete moment in time, as did the calculations in this report, does not factor future benefits directly into the calculation. This inherent advantage of the dynamic calculation is largely lost if, as here, the actual break-even date of an advanced fuel cycle is not known.

The dynamic analysis, when incorporated into a computer code, requires data input specific to each year of the scenario simulation. To specify data to this accuracy over large time periods is a very uncertain art. The computer code does provide the facility for rapidly performing a sensitivity analysis, but such an analysis may still be difficult to interpret. The consequence of having to specify many variables, each as a function of time, makes it difficult to retain an understanding of the major economic causes and effects. In summary, the sophistication of the calculation requires a substantial analytical effort which may not be warranted by the accuracy of the input data. Further, the results may be difficult to interpret because of the nature of the calculation.

The calculations in this report are not, in themselves, an adequate alternative to the dynamic type of analysis performed by the FISS code. The calculations, however, may be readily extended to show the annual costs of fuelling a reactor with natural uranium and plutonium enriched fuels for various uranium prices. The annual benefit or penalty of an advanced fuel cycle can then be quoted as a simple function of uranium price. Information in this form would likely be useful to a manager considering the implementation of a demonstration loading of a plutonium fuel. The Advanced Nuclear Concepts Section's work program entails developing calculational techniques and methods of presentation which illustrate the measure of risk and benefit various nuclear policies entail. This report does not provide that methodology, but it does give some guidance as to what approaches may be fruitfully explored.

5. Concluding Remarks

This report has reviewed the major economic components of the natural uranium and mixed oxide fuel cycles. An estimate has been made of the most probable cost of each of these components, and the total fuel cycle costs have been derived. A detailed rationale for the chosen values is included and a sensitivity study was made to show the consequences of choosing alternative values.

Quoted sources of cost data have not been selected to justify a particular point of view. Where published data covers a wide range of values, or is at variance with the author's data, these discrepancies have been identified. The resolution of such discrepancies is then discussed. This approach has, it is hoped, provided a comprehensive analysis of the economics of advanced nuclear fuel cycles.

Calculations were made to define the economic circumstances under which plutonium recycle will be cheaper than the once-through, natural uranium cycle. It is suggested that these economic conditions will probably exist around the turn of the century, but not significantly before that time. Since full commercialization of an advanced fuel cycle will take about twenty years, this conclusion supports the need to actively pursue an advanced fuel cycle research and development program at this time. However, complete justification for such a program also entails resource utilization and security of supply considerations which are beyond the scope of this report.

The optimum plutonium enrichments for various economic conditions have been calculated. The economic penalty associated with other enrichments, which may have to be chosen for technological reasons such as power peaking problems, is also illustrated.

In summary: this report has shown that plutonium recycle will probably be economic around the turn of the century. It has provided a framework for the technical feasibility studies, and resource utilization studies, which are necessary to ensure that recycle will be a viable option at that time. Finally, and most importantly, it constitutes a comprehensive review of the economics of uranium-plutonium mixed oxide fuel cycles.

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