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ASSESSMENT STUDIES ON PLUTONIUM RECYCLE IN CANDU REACTORS

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FOR DISCUSSION PURPOSES ONLY

ASSESSMENT STUDIES ON PLUTONIUM RECYCLE IN CANDU REACTORS

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ASSESSMENT STUDIES ON PLUTONIUM RECYCLE IN CANDU REACTORS

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ASSESSMENT STUDIES ON PLUTONIUM RECYCLE IN CANDU REACTORS

1. INTRODUCTION

Since the early 1950's, Atomic Energy of Canada Limited (AECL), in collaboration with many segments of Canadian industry, has evolved the CANDU heavy water moderated, natural uranium fuelled power reactor system to the point where it is now widely accepted as proven for utility service.

A major driving force underlying the development program was the concept of "neutron economy", that is, reducing non-fuel absorptions to a minimum. This was accomplished by using heavy water (deuterium oxide) as both coolant and moderator, low-absorption zirconium alloys as both core structural and fuel bundle materials and by adopting on-load, bi-directional refuelling. This has resulted in a capability to operate reactors using natural uranium oxide as fuel with average discharge burnups in the range 7.0 - 8.0 MWd/kgU and corresponding uranium requirements in the range 178 - 156 MgU/GWe.a*.

Despite this excellent fuel utilization, a weakness of all once-through uranium fuel cycles is the requirement for expanding supplies of uranium as the nuclear capacity grows. Consequently, for several years AECL has been examining the potential of the fissile values in the spent natural fuel to reduce dependence on long-term supplies of mined uranium. The topic has been examined from many aspects including,

(i) potential for improving mined uranium utilization in CANDU reactors,

(ii) potential for reducing the sensitivity of CANDU nuclear fuel cycle costs to the price of mined uranium,

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* GWe.a is used as a unit of energy equal to the electrical energy production of 1 GWe of installed capacity operating at full output for 1 year.

(iii) feasibility of recycling plutonium and uranium in the CANDU reactor.

While this document deals mainly with the above three topics, it is realized that other aspects are equally, if not more, important particularly non-proliferation aspects. However, at this time, criteria for evaluating non-proliferation risks are being discussed within the INFCE study framework. Consequently, no attempt has been made in this document to perform a rigorous examination.

2. REACTOR AND FUEL REFERENCE

2.1 General Considerations

Studies on plutonium recycle in CANDU have been performed for designs ranging from the 200 MWe Douglas Point design (Reference 1) to a conceptual 1200 MWe design (Reference 2). For the purpose of this paper, all calculations have been referenced to a 1000 MWe CANDU reactor. This reactor is an extrapolation of the current AECL standard natural-fuelled 600 MWe (nominal) unit (Reference 3). The extrapolation has been made purely on the basis of the number of fuel channels required to produce the reference net power output. It is anticipated that essentially the same reactor system and fuel design can be adapted to employ plutonium-uranium recycle. Consequently, only differences associated with the change in fuel cycle will be discussed.

Although reference fuel cycles are defined, it will be seen that their choice was somewhat nominal. The range of possible fuel cycles is quite broad and choice of a particular reference would depend critically on the economic conditions at the time of implementation together with the requirements and circumstances of the customer utility. Consequently, the reference fuel cycles have been chosen mainly to illustrate potential and not as a judgement on the conditions of future implementation.

2.2 Reference Reactor

Figure 2.2.1 is a simplified overall reactor system process flow sheet. The reactor proper consists of a large, horizontally oriented cylindrical tank, called the calandria, which contains the cold, low pressure heavy water moderator. This tank is penetrated by a number of horizontal tubes, called fuel channels, which contain the natural uranium fuel and the pressurized, high temperature heavy water coolant. This coolant is pumped through the fuel channels, removing heat from the fuel, and then through heat exchangers (termed boilers) where this heat is given up to produce steam which is fed to the unit turbine. The boilers and coolant pumps are located at each end of the reactor so that flow is in one direction through one half of the fuel channels and in the opposite direction through the other half. A pressurizer is provided in this coolant circuit to maintain the circuit pressure at a relatively high value. High circuit pressure permits high coolant temperatures which in turn permits the generation of steam at a high enough pressure to achieve reasonable turbine cycle efficiencies. It will be noted from Figure 2.2.1 that a circulation and cooling system is provided for the low temperature moderator. This is needed to dissipate heat generated in the heavy water through interaction with fission neutrons and gamma radiation.

General reactor performance specifications for the 1000 MWe reference design are given in Table 2.2.1.

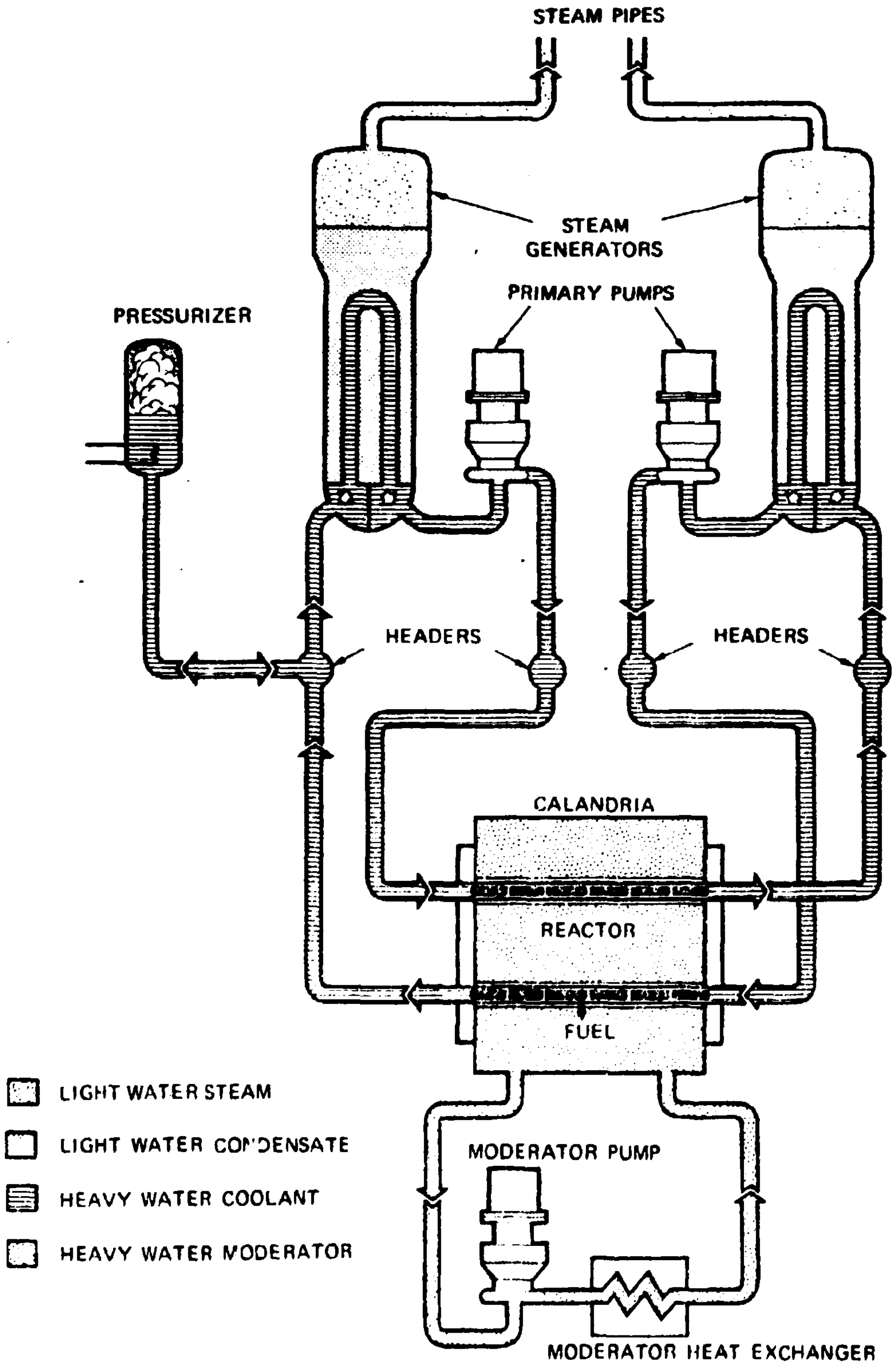

FIGURE 2.2.1 CANDU REACTOR SIMPLIFIED FLOW DIAGRAM

TABLE 2.2.1

GENERAL REACTOR PERFORMANCE SPECIFICATIONS

A. Power Plant Performance

Thermal Power : 3425 MW
Electrical Power, Gross : 1074 MW
Net : 1000 MW
Thermal Efficiency : 29.2%

B. Reactor Parameters

No. of Channels : 596
Core Radius : 3.871 m
Core Length : 5.944 m
Core Volume : 279.3 m^3 [2.798×10^5 ℓ]

[N.E. A 0.655 m D_2O reflector surrounds core on sides]

Core Power Density : 0.01224 MW/ℓ
Coolant Flow Rate : 11.7 Mg/s
Maximum Channel Flow : 24 kg/s
Reactor Inlet Temperature : 267°C
Reactor Outlet Temperature : 310°C
Reactor Outlet Facility : 4%
Reactor Outlet Pressure : 10.0 MPa

C. Fuel Parameters

Maximum Fuel Temperature : 2100°C
Maximum Cladding Surface Temp. : 326°C
Initial Core Fuel Loading
  - total heavy metal : 133.7 Mg
No. of Elements/Bundle : 37
No. of Bundles/Channel : 12
No. of Bundles/Reactor : 7152

Neutron absorbing systems, both liquid and solid, are provided to assist in controlling reactivity. Two fast-acting reactor shutdown systems are provided using vertical shut-off rods and horizontal liquid poison injection into the moderator. The primary method of controlling reactivity in the long-term is through the on-load refuelling capability. This eliminates the need for a reactor regulating system with large reactivity-worth capability. The required bulk reactivity and flux tilt control is provided by light water control absorbers.

The fuelling system is based on an on-power, bi-directional push-through method. Fuel bundles are pushed into the upstream end of a reactor channel by a remotely operated ram in one fuelling machine. Simultaneously spent fuel bundles are discharged at the down-stream end of the channel into another fuelling machine. Spent fuel is transferred to a water-filled storage bay located in a Service Building adjacent to the Reactor Building. It should be noted that only part-refuelling of a channel is normal practise e.g. for most current designs only eight new fuel bundles are charged, and eight irradiated bundles discharged, from a twelve bundle channel, with four irradiated bundles remaining.

2.3 Reference Fuel

The reference fuel is illustrated on Figure 2.3.1. The plutonium-uranium fuel is in the form of compacted and sintered cylindrical pellets of plutonium-uranium dioxide. Approximately 29 of these pellets, stacked end-to-end are sealed in a zirconium alloy sheath to form a fuel element approximately 50 cm long. A thin layer of graphite (CANLUB) is interposed between the inner surface of the fuel sheath and the pellet stack to recuce the severity of the pellet-sheath interaction. Thirty-seven of these elements are welded to two end-plates to

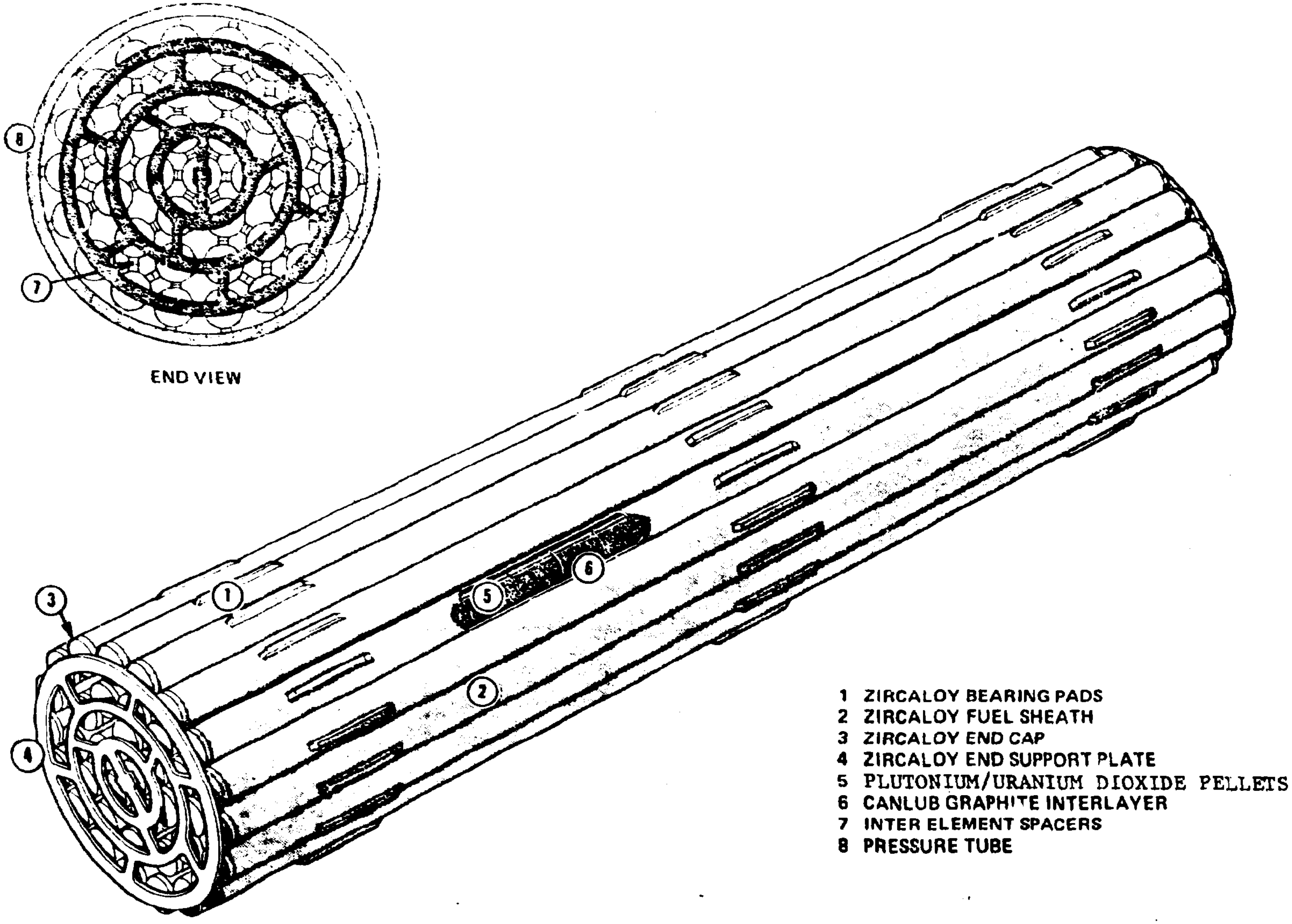

FIGURE 2.3.1 37-ELEMENT FUEL BUNDLE

form a cylindrical bundle. Twelve fuel bundles are loaded into each channel to form an active core length of approximately 6 M.

Fuel parameters are given in Table 2.1.1 for the reference 100 MWe design.

3 PLUTONIUM/URANIUM RECYCLE - SPENT NATURAL CANDU FUEL

3.1 Fuel Cycle Definition

The uranium and plutonium values in spent natural fuel, which has been discharged from a CANDU reactor with a burnup of 7.3 MWd/kgU, are given in Table 3.1.1. Two recycling schemes have been examined,

(i) fresh fuel is made from natural uranium with varying weight fractions of plutonium extracted from the spent CANDU fuel (the NUPU scheme),

(ii) fresh fuel is made from the depleted uranium with varying weight fractions of plutonium (the DUPU scheme).

The reactivity-limited average fuel discharge burnup is plotted on Figure 3.1.1 as a function of fissile content for the two schemes. The equivalent normalizing natural uranium burnup and that corresponding to the use of 1.2% U235-enriched uranium oxide fuel is also plotted.

Large increases in fuel discharge burnup can be obtained with modest increases in fissile content. The data also illustrate that fissile plutonium is equivalent to U235 on a gram-for-gram basis with respect to burnup increases. In an LWR, a gram of fissile plutonium is only equivalent to roughly 0.8 grams of U235. The major difference is that the majority of neutron thermalizations in a CANDU occur in the cold heavy-water moderator and so escape absorption in the low-lying Pu239 and Pu241 resonances in the 0.25 - 0.3 eV range.

TABLE 3.1.1

URANIUM AND PLUTONIUM VALUES IN SPENT FUEL

Fuel	Spent Natural CANDU Fuel	Spent "Standard" PWR Fuel
	Fissile Values (g/kgIHE)	
U235	2.349	8.200
U236	0.721	3.847
U238	986.0	978.9
Pu238	0.003	
Pu239	2.562	5.168
Pu240	1.016	2.168
Pu241	0.190	1.303
Pu242	0.006	0.462

DISCHARGE BURN-UP VERSUS FRESH FISSILE CONTENT

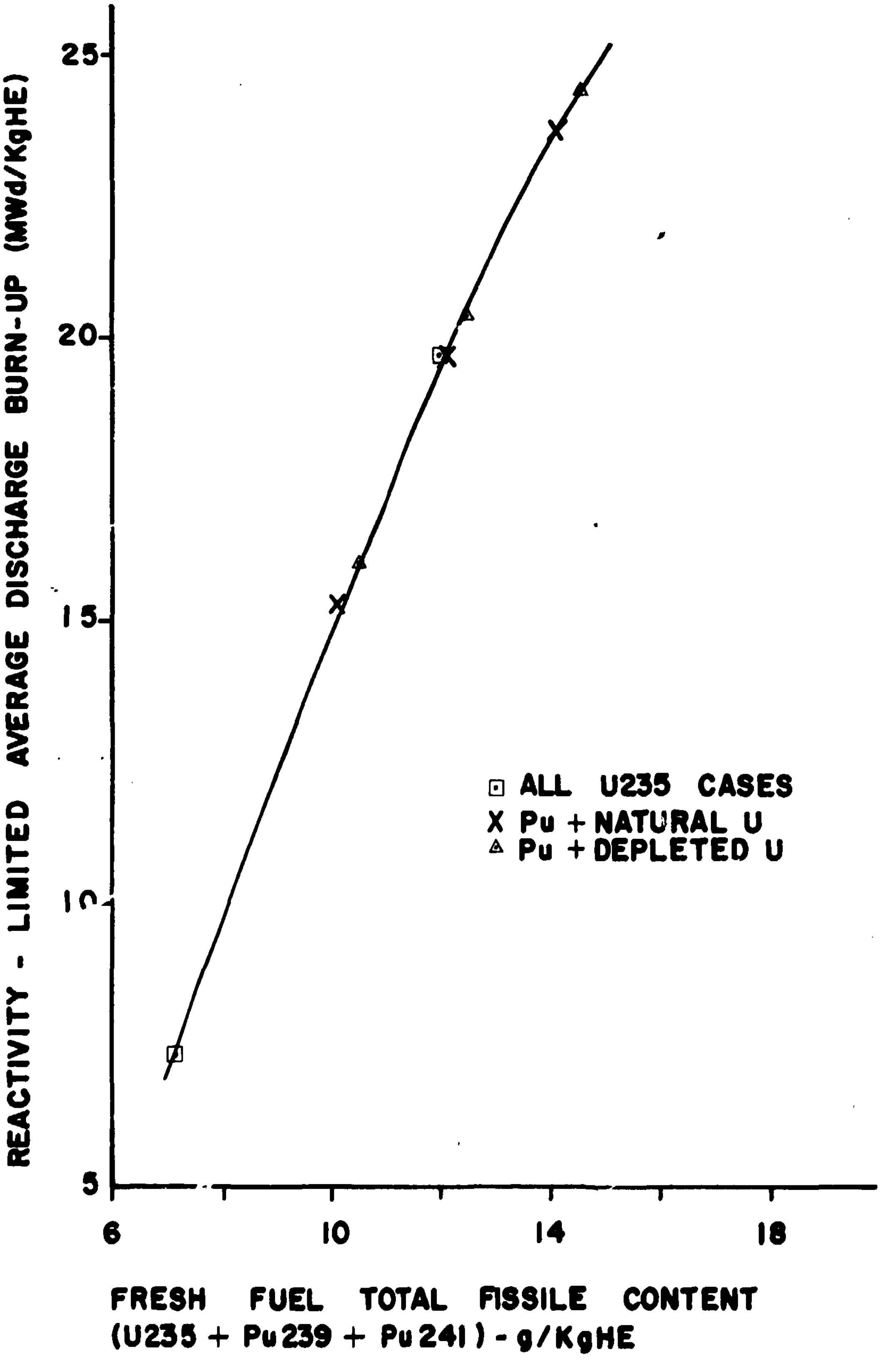

FIGURE 3.1.1

The interconnection between the natural- and recycle-fuelled CANDU's is shown on Figure 3.1.2. The major difference between the options i.e. use of either natural U or depleted U for the recycle fuel, is shown by the dotted lines on the figures. The mined uranium requirements for the combined reactor system (i.e. natural and recycle CANDU's) are plotted on Figure 3.1.3 as a function of recycle fuel average discharge burnup. On the same plot, the installed capacity of natural uranium CANDU's required to support 1000 MWe (1 GWe) of recycle-fuelled CANDU's is also shown. In both cases the requirements are for a system operating under equilibrium fuelling conditions.

Three observations follow,

(i) either scheme can reduce mined uranium requirements by 50-60%, relative to the natural-fuel CANDU requirements of 170.9 Mg/GWe.a.

(ii) the major difference between the schemes is the required capacity of natural uranium CANDU's to support the recycle CANDU's.

(iii) from (ii) it follows that the DUPU scheme will require significantly higher reprocessing capacity for natural fuel.

Essentially the DUPU scheme (i.e. recycle of Pu with some depleted uranium) is a Pu-burning scheme while the NUPU (i.e. Pu recycle with natural uranium feed) is a Pu-conserving scheme.

3.2 Reference Schemes

Major fuel cycle parameters for the reference recycle fuel are given in Table 3.2.1 for NUPU and DUPU schemes. As stated earlier the choice of recycle fuel reference burnup is somewhat arbitrary and is a balance between conflicting trends. Higher burnups would tend to reduce fuel cycle costs while lower burnups

SCHEMATIC SHOWING INTERCONNECTION OF NATURAL AND RECYCLE CANDU'S

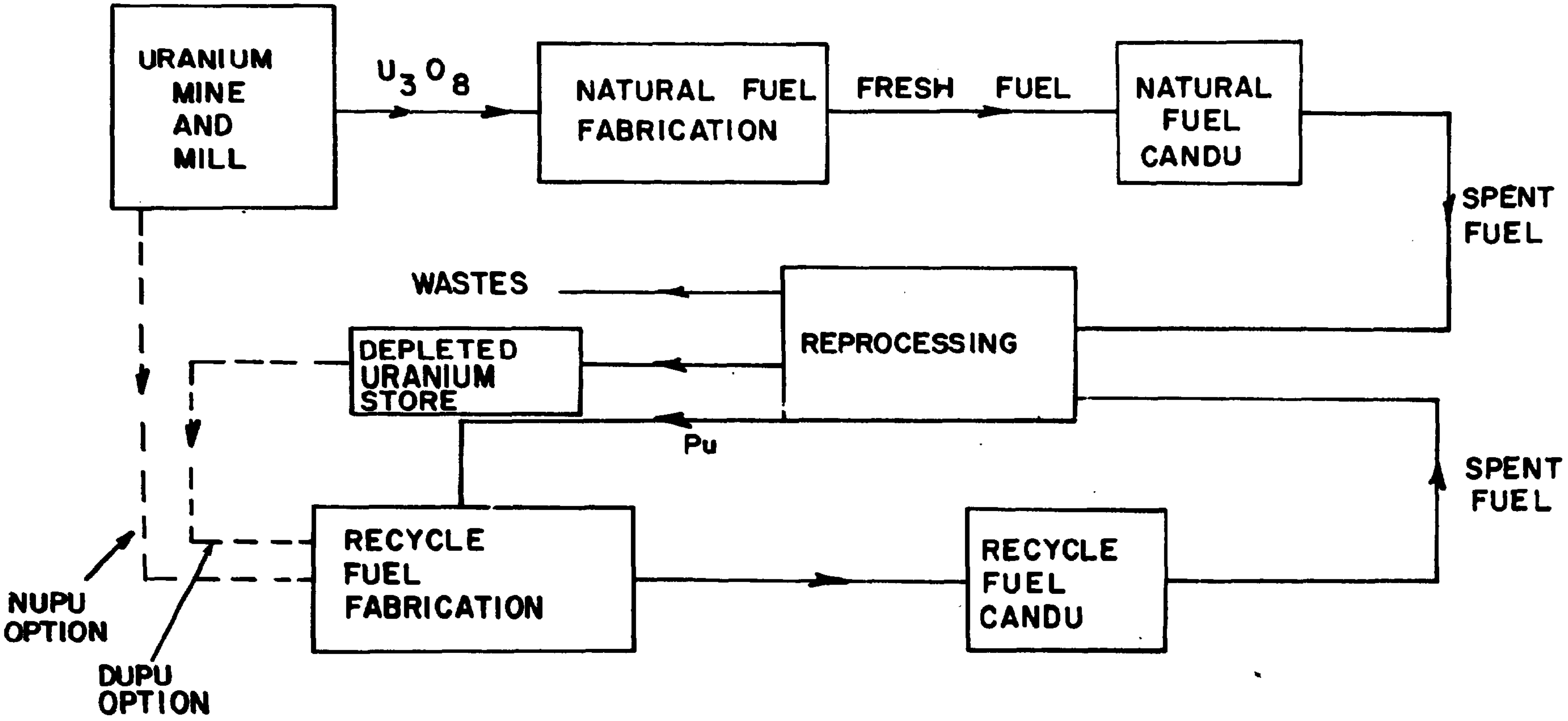

FIGURE 3.1.2

PARAMETER FOR COMBINED REACTOR SYSTEM VERSUS RECYCLE FUEL BURN-UP

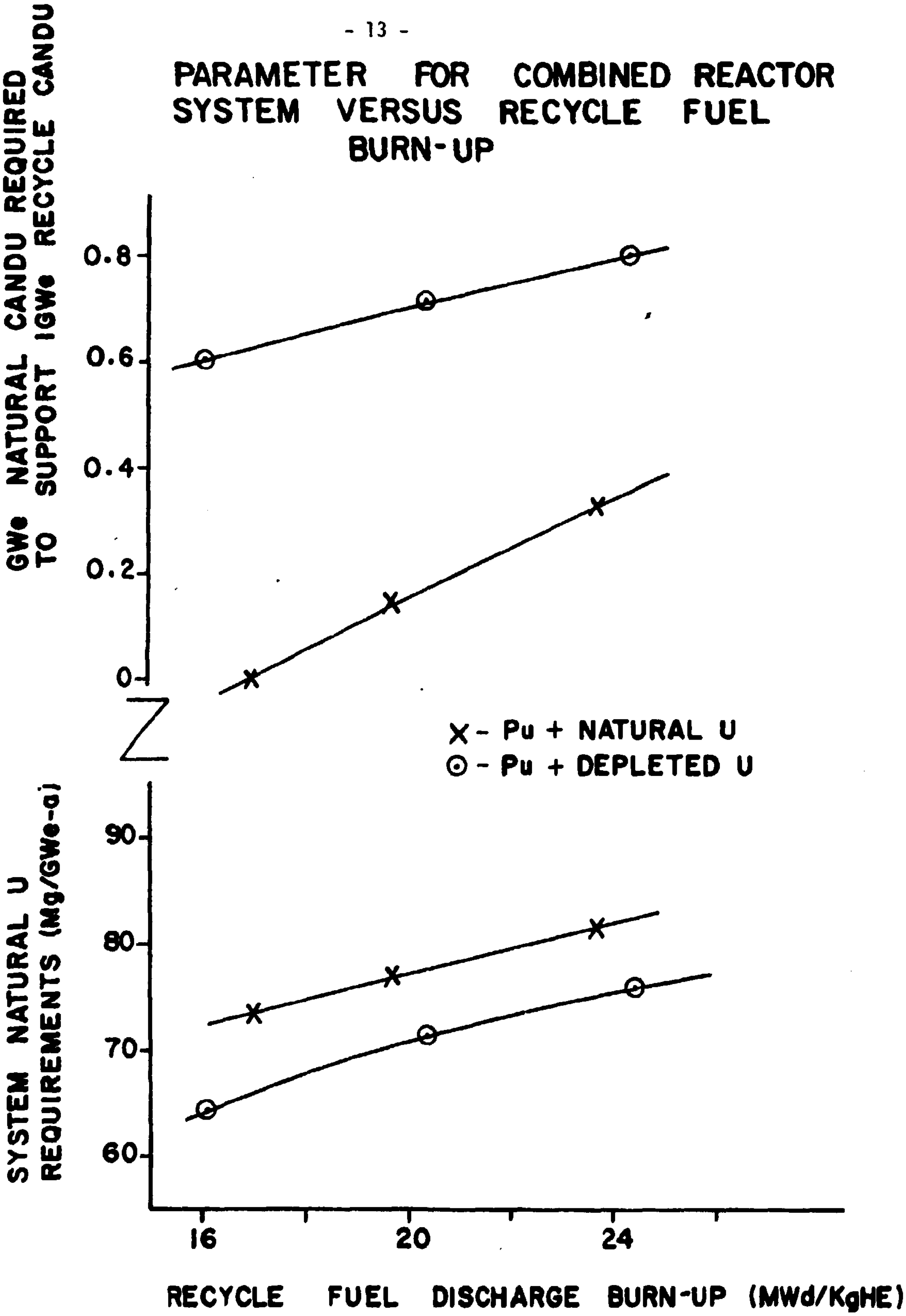

FIGURE 3.1.3

TABLE 3.2.1

REFERENCE RECYCLE FUEL PARAMETERS

Initial Core Loading = 133.7 Mg Heavy Elements

Spent Fuel Cycle	CANDU		"Standard" PWR	
	Pu + Nat U	Pu + Depl U	Pu + Nat U	Pu + Depl U
Fuel average discharge burnup (MWd/kgHE)	19.7	20.4	19.7	23.8
Average dwell time in core (full power years)	2.1	2.2	2.1	2.6
Fuel charge rate (Mg/GWe-a)	63.3	61.2	63.3	52.4
Fresh Fuel Enrichment*				
U235 (wt%)	0.71	0.25	0.71	0.82
Fissile Pu (wt%)†	0.50	1.00	0.50	0.65
Discharge Fuel Enrichment*				
U235 (wt%)	0.09	0.04	0.09	0.08
Fissile Pu (wt%)	0.39	0.46	0.39	0.04

* Note - composition of initial core and first generation fuel are the same.

† Note - isotopic composition of plutonium given in Table 3.1.1.

tend to reduce overall mined uranium requirements and limit the required extrapolation of fuel performance over current experience.

Parameters for the combined natural-recycle CANDU's are given on Table 3.2.2 and have been normalized to 1 GWe of installed reactor capacity, Cases 2 and 3. Data for a natural fuel CANDU (Case 1) have been included for comparison.

3.3 Multiple Recycling of Plutonium

Data presented so far have been for first-recycle fuel. The recovered Pu from this fuel will have a larger fraction of the higher plutonium isotopes. Subsequent recycles will continue this trend.

Table 3.3.1 compares the effect on system uranium requirements when the plutonium undergoes 1, 6 and 13 recycles. Although there has been large changes in the isotopic composition and ~7% reduction in discharge burnup, the natural uranium requirements are basically unchanged.

4. PLUTONIUM/URANIUM RECYCLE - SPENT PWR FUEL

4.1 Fuel Cycle Definition

The spent fuel from a uranium-fuelled PWR can also serve as feed material for a CANDU operating on plutonium recycle. Data for the PWR fuel cycle were taken from Reference 6 and the composition of the spent fuel is given in Table 3.1.1. This fuel contains significantly higher fissile values than CANDU spent fuel. Although there are small differences in plutonium isotopic composition between the two fuels, basically their behaviour in a CANDU recycle core is similar.

Although spent PWR fuel has been used in this analysis, BWR spent fuel could also be used with similar results.

TABLE 3.2.2

REQUIREMENTS FOR REACTOR SYSTEMS UNDER EQUILIBRIUM FUELLING CONDITIONS

System	1	2	3	4	5	6	7
Description	Natural-Fuel CANDU	Natural-Fuel CANDU + Recycle-Fuel CANDU (NUPU)	Natural-Fuel CANDU + Recycle-Fuel CANDU (DUPU)	Uranium-Fuel PWR(1)	Pu+U Recycle in PWR(4)(1)	Uranium-Recycle PWR(1) + Recycle-Fuel CANDU (NUPU)	Uranium-Fuel PWR(1) + Recycle-Fuel CANDU (TANDEM)
Installed Capacities (GWe)							
Natural-fuel CANDU	1.0	0.128	0.417	-	-	-	-
Recycle-fuel CANDU	-	0.872	0.583	-	-	0.754	0.317
PWR	-	-	-	1.0	1.0	0.246	0.683
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Service Requirements (Mg/GWe.a)							
Inactive fabrication(3)	170.9	21.9	71.2	35.1	24.9	8.6	24.0
Active fabrication(3)	-	55.2	35.7	-	10.2	47.8	23.3
Reprocessing	-	77.1	106.9	-	35.1	56.4	-
SWU(2)	-	-	-	133.8	93.8	31.8	91.4
Natural Uranium Requirements (Mg/GWe.a)	170.9	77.0	71.2	209.4	130.5	88.4	143.0

NOTES
1. Data on PWR fuel cycle taken from Reference 6.
2. Units for SWU requirements are t SWU/GWe.a.
3. Inactive fabrication is for U-bearing fuels only, Active is for U + Pu fuels.
4. PWR 5th Pu recycle.

TABLE 3.3.1

EFFECT OF MULTIPLE RECYCLING OF PLUTONIUM IN CANDU

Fuel Cycling Scheme is Plutonium Plus Natural Uranium

Recycle	1st	6th	13th
Isotopic Composition of Plutonium in Fresh Fuel		wt%	
Pu239	65.0	33.2	30.6
Pu240	25.9	36.1	33.7
Pu241	4.8	8.7	8.2
Pu242	1.3	22.0	27.5
Wt% Fissile Pu in Fresh Fuel	0.50	0.50	0.50
Average Discharge Burnup (Reactivity Limited) MWd/kgHE	19.7	18.6	18.3
Wt% Fissile Pu in Spent Fuel	0.39	0.43	0.43
Combined system* uranium requirements (Mg/GWe.a)	77.0	77.0	78.1

* The system consists of a mixture of natural and recycle fuel CANDU's.

4.2 Reference Cycles

The inter-connection between the PWR and CANDU recycle reactors can be basically the same as illustrated on Figure 3.1.2 i.e. a PWR operating on uranium fuelling replacing the natural fuel CANDU. One major difference is that the depleted uranium now has a fissile content greater than natural and can also be recycled for use in the PWR as well as being used in the recycle CANDU.

Data for two reference fuel cycles are given in Table 3.2.1. The Pu plus natural U cycle has effectively the same characteristics as that using CANDU Pu. The Pu plus depleted U cycle assumes no adjustment of the Pu/U ratio and has a relatively high burnup because of the fissile content.

Requirements for a system of PWR's and recycle CANDU's are shown as Case 6 on Table 3.2.2. Case 4 is a PWR operating on an enriched U, once-through cycle and Case 5 is a PWR operating on Pu and U recycle. Case 6 assumes the PWR operates on U recycle and the Pu is mixed with natural uranium and used for fuelling CANDU. The PWR-recycle CANDU system shows significant reductions in both SWU and U requirements, albeit at the expense of higher reprocessing and active fabrication requirements.

4.3 Other Options

A further option for use of spent LWR fuel is the tandem fuel cycle i.e. the refabrication and irradiation of spent LWR fuel in a CANDU without processing to separate transuranics and fission products.

Calculations were performed for a scheme where PWR fuel is stripped of cladding, crushed and mixed to ensure uniformity, then refabricated as CANDU fuel. It was assumed that all fission products, except noble gases, were retained within the fuel. After irradiation in CANDU the fuel is put into long-term storage.

The results of the calculations are given as Case 7 in Table 3.2.2. It can be seen that while an improvement in fuel utilization results, the reduction in uranium requirements is not as great as that resulting from the reference recycling scheme.

5. ECONOMICS

5.1 Base Data

Base data used for economic studies are given in Table 5.1.1. It will be noted that the two major components, reprocessing and refabrication, have been treated as variables rather than as fixed quantities. This reflects the situation that Canada has little or no experience of these industries and international costs quoted for these services show a wide variation.

Studies have been conducted within AECL on conceptual designs to assess reprocessing and fabrication costs for facilities dedicated to recycling CANDU fuel (e.g. Reference 5). Generally, these studies have indicated costs significantly lower than those for facilities dedicated to LWR fuel. The major reasons underlying the difference are,

(i) the lower enrichment levels and burnup ranges for the CANDU fuel,

(ii) the simplicity of the CANDU fuel design.

However, the present wide range of costs quoted for the services for the LWR system make choice of absolute values very difficult. Consequently these costs have been treated as variables and the economic studies have been directed towards defining those changes in economic conditions (particularly uranium price) which would be necessary before recycle fuelling becomes economically competitive with once-through natural uranium fuelling.

5.2 Fuel Costs - Base Economic Conditions

Fuel costs for the base economic conditions defined in Table 5.1.1 are plotted on Figure 5.2.1 as a function of the combined active fabrication and reprocessing costs. Costs are plotted for,

TABLE 5.1.1

BASE VALUES OF ECONOMIC PARAMETERS

All Costs are in 1978 Canadian Dollars

U_3O_8 Cost	99$/kg [117$/kg(U)]
Natural UO_2 Fuel Fabrication Cost	55$/kgU
Spent Natural Fuel Storage Cost	17$/kgU
Recycle Fuel Fabrication Cost	Variable - See Notes 1, 3
CANDU Spent Fuel Reprocessing	Variable - See Notes 2, 3
Ratio of LWR Spent Fuel/CANDU Spent Fuel Reprocessing Costs	1.25
Separative Work Cost	100$/kg SWU
Enrichment Plant Rails	0.2%
Reactor Capacity Factor	80%
Reactor Life	30 a
Escalation Rate	0%
Discount Rate	4%
Interest Rate	4%

NOTES:

1. Fabrication cost is assumed to include the cost of shipping fresh fuel to the reactor site.
2. Reprocessing cost is assumed to include the cost of shipping spent fuel and disposal of waste from the reprocessing plant.
3. The reprocessing and fabrication costs are assumed equal to each other.

TOTAL FUEL CYCLE COSTS (1978 CANADIAN DOLLARS) NATURAL UO_2 AND RECYCLE FUELLING IN CANDU ECONOMIC CONDITIONS AS IN TABLE 5.1.1

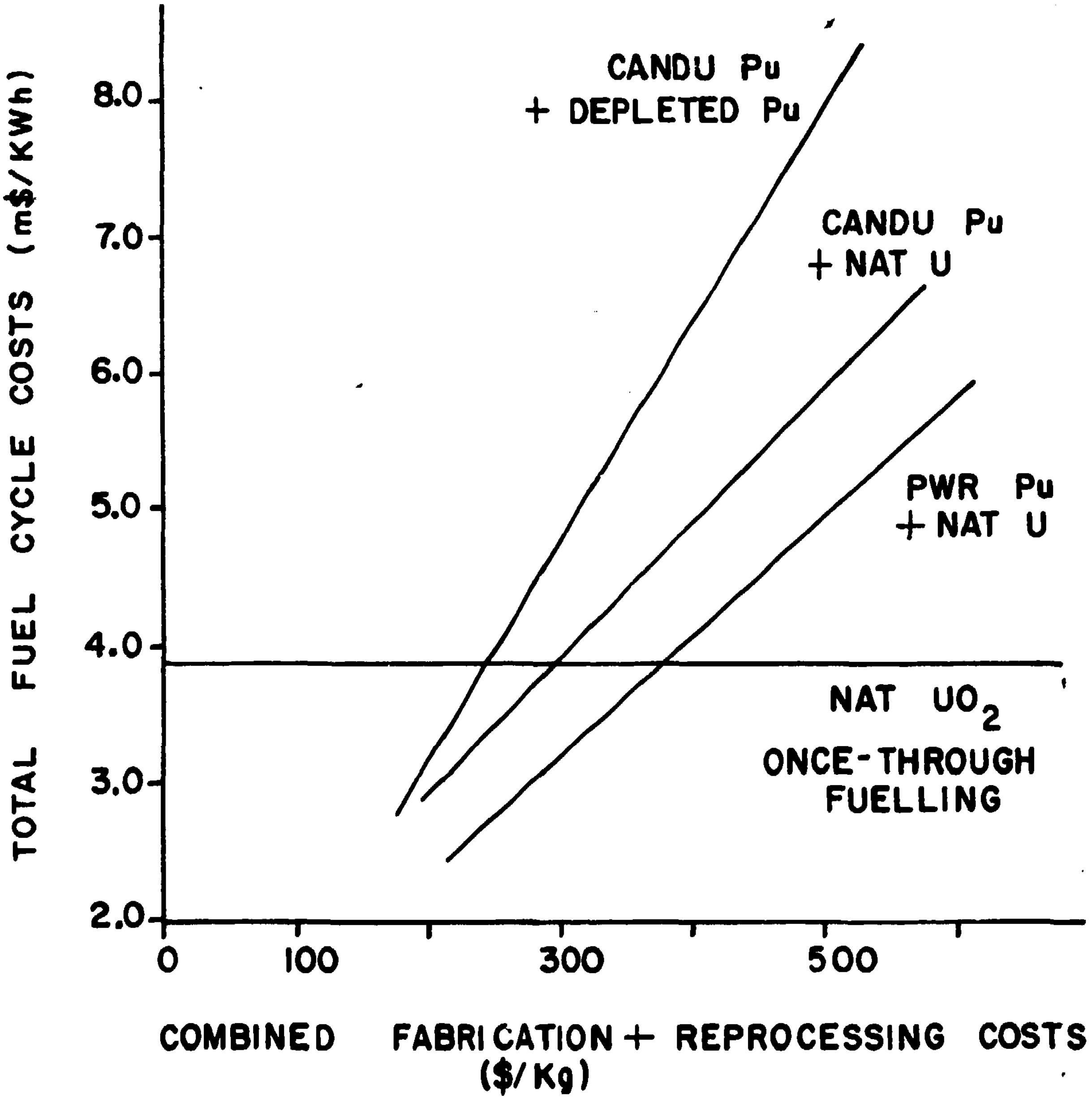

FIGURE 5.2.1

(i) natural UO_2, once-through fuelling,

(ii) recycle fuelling with Pu obtained from spent CANDU fuel mixed with natural uranium oxide,

(iii) recycle fuelling with Pu and depleted uranium oxide from spent CANDU fuel,

(iv) recycle fuelling with Pu obtained from spent PWR fuel mixed with natural uranium oxide,

Fuel cycle parameters for cases (ii) to (iv) are defined in Table 3.2.1.

For CANDU Pu, the price was determined assuming the spent fuel has no value and hence the price is the cost of recovery. For PWR Pu the situation is more complicated and the price of Pu was determined to be the cost of recovery less the credit for the recovered slightly enriched uranium. Generally, although assuming a higher reprocessing charge, the cost of the PWR Pu was less than that of the CANDU Pu.

For the base economic conditions, natural UO_2 once-through fuelling is cheaper unless the combined fabrication plus reprocessing costs can be held below \$375/kgU. Current information (Reference 7) indicates the range of equivalent costs for LWR fuel is 450 to 1000 \$(US)/kgHE. Even assuming some reduction in charges for facilities dedicated to CANDU technology, break-even costs would only occur at the lower end of the range.

Break-even uranium prices are shown on Figure 5.2.2 as a function of combined fabrication and reprocessing costs. For each particular cycle, the line represents the combinations of uranium and refabrication prices at which the fuel cycle cost equals that for natural uranium fuelling.

BREAK - EVEN URANIUM PRICES FOR NATURAL UO_2, ONCE-THROUGH AND Pu/U RECYCLE

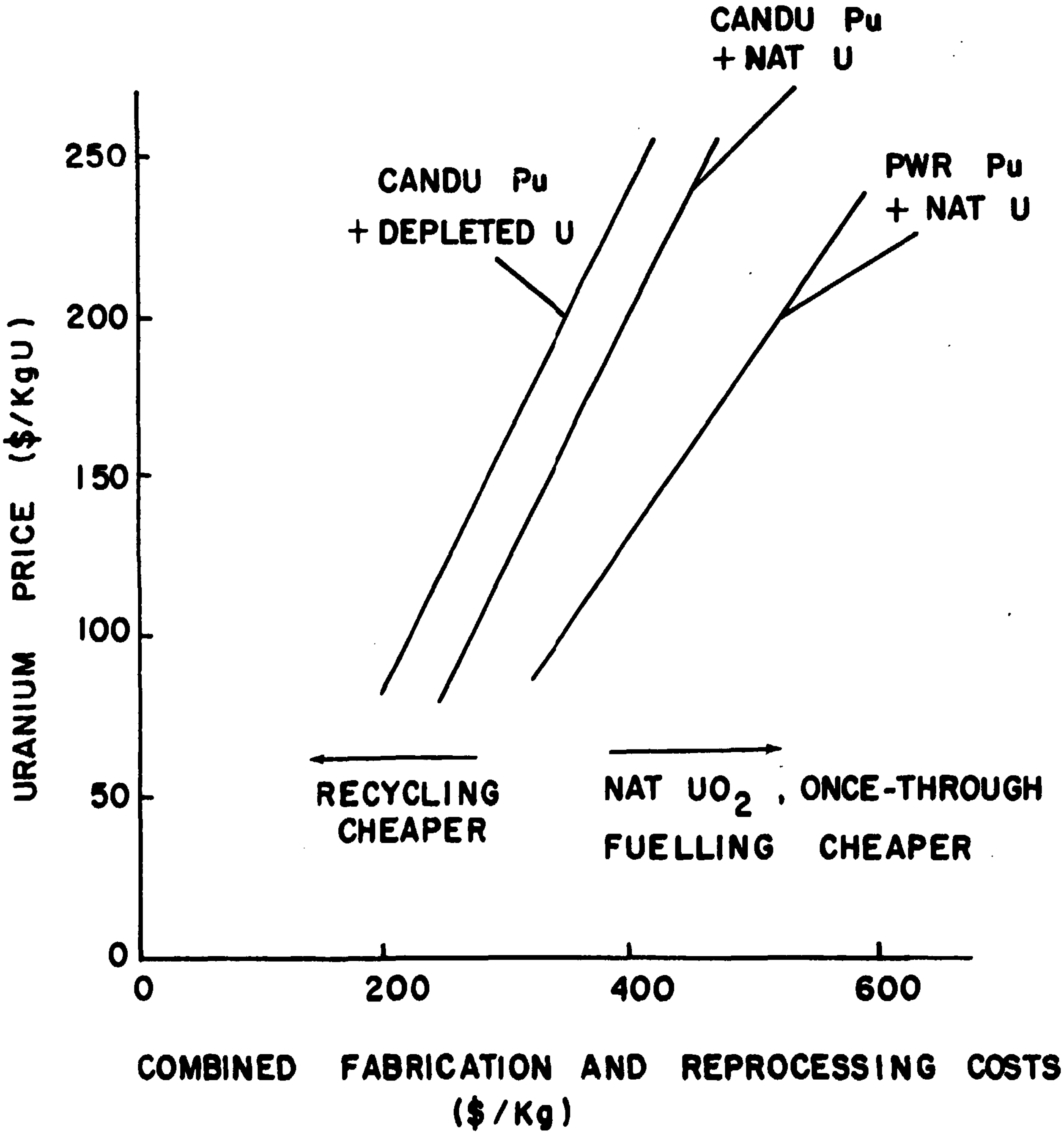

FIGURE 5.2.2

6. TECHNICAL STATUS

6.1 General

At this time, AECL has no committed program for the development of a recycle fuelling capability. Work has been confined to assessment studies and applied research in the laboratories. Brief summaries of the status in various key areas are given below.

6.2 Reactor System

The assumed reactor concept has been demonstrated in unit sizes up to 750 MWe. The extension to a unit size of 1000 MWe would be regarded as a normal commercial engineering development requiring no special fundamental research and development.

A few minor modifications might be required to adapt the design, developed for the natural uranium cycle, to operation on plutonium/uranium recycle. These would be in the areas of fresh fuel handling and storage, spent fuel handling, and in control and safety mechanisms. Any necessary modifications are expected to be relatively straightforward.

6.3 Safety and Accident Considerations

Characteristics of a CANDU-PHW operating on recycle fuel which are most relevant to safety have been investigated. No safety problems were identified which would pose a feasibility block to the use of recycle fuel in CANDU-PHW reactors. The same basic safety system as used for the natural uranium, once-through cycle should give similar performance.

6.4 Physics

There are uncertainties in the physics of plutonium recycle fuel cycles arising from uncertainties in nuclear data (including that for fission products), in the interaction effects among the various isotopes and in the approximations and methods used in calculations. Although experimental data exist from the FUGEN and SGHWR programs, integral experiments designed for CANDU lattices are required to attain satisfactory accuracy in physics estimates for final assessment and possible design. Three stages of such experiments are,

Stage 1: Clean lattice experiments for recycle fuels as a function of fuel assembly temperature.

Stage 2: Measurements of fuel bundle isotopic composition and reactivity as a function of irradiation for representative fuel bundles irradiated in a well-defined, well-controlled typical neutron spectrum.

Stage 3: Conversion of an existing reactor to recycle fuel and monitoring its behaviour.

Currently AECL is engaged in Stage 1 activities and is co-operating internationally with both Italy and Japan on related topics.

6.5 Fuel Management

Fuel management simulation for plutonium recycle is more complex than for natural uranium cycles because the fuel properties change with irradiation to a much greater extent. Work remains to be done in studying alternative strategies. However the flexibility afforded by the on-power fuelling system should ensure satisfactory control of the power distribution without significant reduction of power density below current levels.

6.6 Fuel Development

It is anticipated, on the basis of current estimates and limited tests and experience, that no major fuel design changes will be required. A fuel irradiation testing program is being initiated to verify this, including irradiations to relatively high burnups and measurements of the behaviour of fuel subjected to power ramps, as a function of fuel burnup.

6.7 Reprocessing and Fabrication

In several countries, reprocessing and refabrication facilities have been developed to the commercial stage. However, the facilities are mainly directed towards LWR technology and no facilities have been developed which are optimized for CANDU technology. There is little experience in Canada in this area beyond laboratory-scale activities.

7. COMMENTS ON NON-PROLIFERATION ASPECTS

7.1 Introduction

No detailed evaluation of the non-proliferation aspects of plutonium recycling in CANDU is reported here. This work is part of an on-going study which is not yet completed. However, as described below, the sensitivity of the cycle has been assessed against some suggested changes in the reference fuel cycle which may increase proliferation resistance.

The reference combined system (Figure 3.1.2) shows two major changes from the currently developed once-through natural uranium system,

(i) the requirement for reprocessing and recycle fuel fabrication facilities where plutonium is separated and purified before refabrication,

(ii) the requirement to ship freshly-fabricated mixed oxide fuel from the fabrication facility to the reactor site.

Two modifications to the above reference system have been proposed and their impact is partially assessed in the following sections.

7.2 Co-processing

Some reprocessing of the fuel is desirable to remove fission products and so improve neutron economy. However, the necessity of separating the plutonium from all the uranium has been queried (e.g. the CIVEX proposal, Reference 4) and several laboratories around the world are addressing this topic. The CIVEX process has been reviewed within AECL and the effects of a few process variables have been determined by use of a simulation code. Spent CANDU fuel could be reprocessed in a suitably designed CIVEX plant and the plutonium concentrations in the feed material are such that it is unlikely that a product could be prepared which contained much more than 10 - 15% plutonium in the U-Pu mixture.

A modified schematic for the reprocessing-fabrication part of the combined natural-recycle CANDU system (see Figure 3.1.2) would delete the Pu output line and replace it with a co-processed fuel output line. The plutonium from the reprocessing plant is now contained as a 10 - 15% component in a U-Pu mixture. However, it is again possible to blend with either natural or depleted uranium to obtain the required initial enrichment. The major difference is for the NUPU cycle where the U235 content is now reduced below natural concentration because of the depleted uranium in the reprocessing plant product. However studies indicate the effect on fuel cycle characteristics and system natural uranium requirements to be very small.

7.3 Fuel "Spiking"

To give some measure of "self-protection" to the plutonium and mixed oxide fuel, spiking with gamma-emitters has been proposed, either in the form of retained fission products (e.g. CIVEX) or by other additives (e.g. Cobalt-60). Two major adverse effects of spiking will be to increase handling and fabrication costs and to reduce the efficiency of uranium utilization because of parasitic neutron absorptions in the spiking material.

To understand the impact on uranium utilization, data are presented in Table 7.3.1 comparing the efficiency of use with and without a fuel reactivity burden of 33 mk (3.3%) of spiking material. The result is a significant increase in natural uranium requirements for the overall system. Work in this area will be pursued to try to define "neutron efficient" spiking materials.

TABLE 7.3.1

EFFECT OF SPIKING REACTIVITY BURDEN OF 33 MK ON CHARACTERITICS

Reactivity burden - mk (%)	0 (0)	33 (3.3%)
Fuel	Plutonium + Natural UO_2	
Fissile Plutonium Content in new fuel (wt%)	0.50	0.70
Average discharge burnup (MWd/kgHE)	19.7	19.7
Fissile Plutonium content in spent fuel (wt%)	0.39	0.43

System* natural uranium requirements (Mg/GWe-a)	77.0	92.5

* NOTE: - system consists of natural fuel CANDU's and recycle CANDU's operating on the NUPU cycle.

8. SUMMARY

For several years, AECL has been exploring the potential for using the CANDU reactor system with recycle fuelling to improve fuel utilization and meet the long-term challenge of assurance of economic supplies of nuclear fuel.

The results of the work indicate,

(i) that recycle fuelling of CANDU's should be feasible with little modification to the reactor design and no degradation of safety,

(ii) that relative to once-through natural uranium fuelling further significant improvements in uranium utilization could result (>50%) but that this could be influenced by the type of proliferation-resistant features deemed necessary,

(iii) that recycle fuel CANDU's could operate in a uranium-efficient manner with LWR reactors operating on uranium recycle,

(iv) that recycle fuelling costs do not appear competitive with natural uranium, once-through fuelling in CANDU under current economic conditions but that increases in uranium price and/or reductions in the cost of recycling services could change the relative balance.

It should also be noted, that the work reported here is only part of a much broader study of alternative fuelling options and other information, particularly on the use of thorium cycles, is being presented to INFCE Working Group 8.

9. REFERENCES

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