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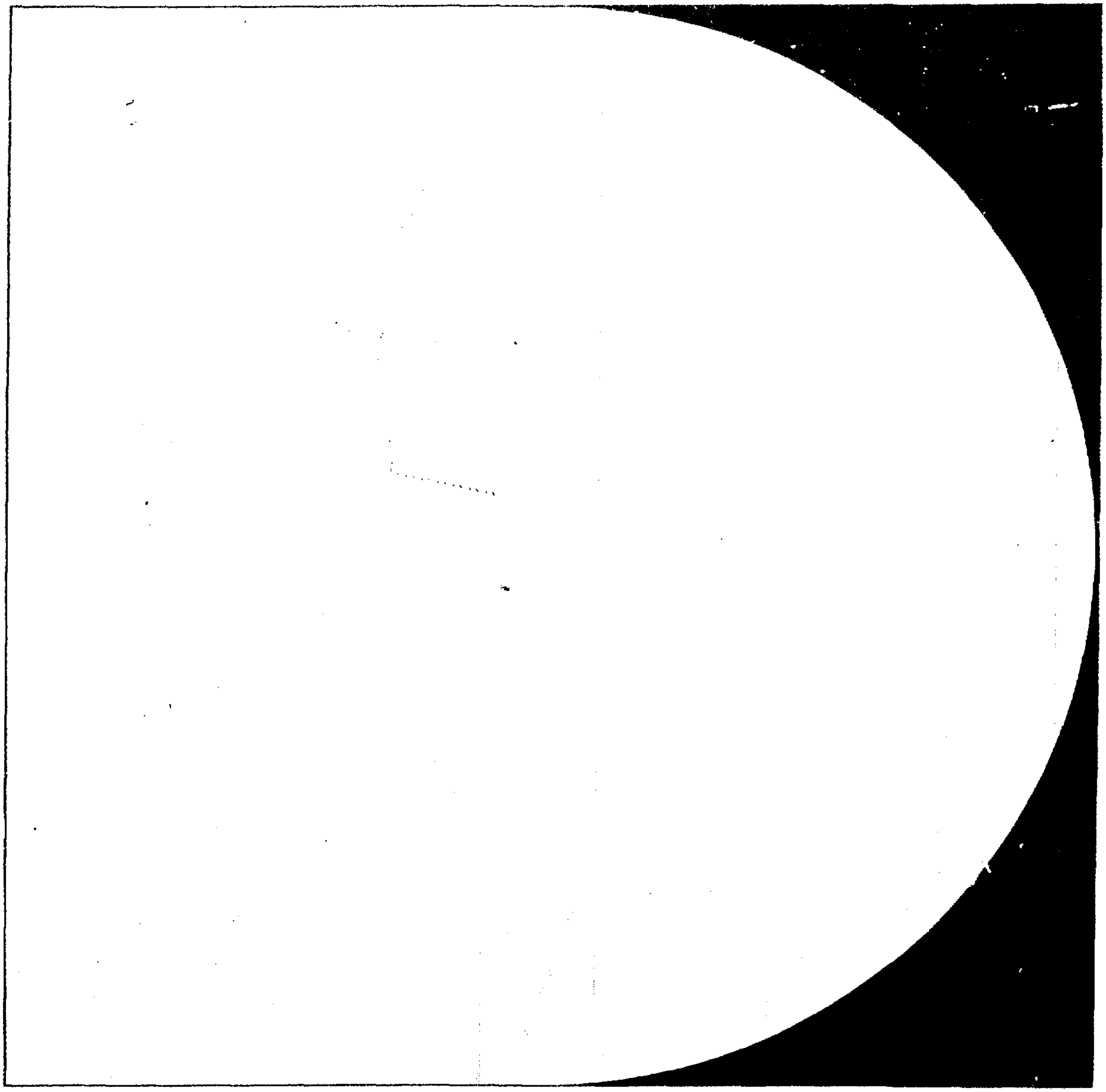

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FUEL CYCLE PARAMETERS FOR STRATEGY STUDIES

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Abstract

This report summarizes the fuel cycle parameters to be used in long-term strategy analyses of alternate nuclear fuel cycles.

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FUEL CYCLE PARAMETERS FOR STRATEGY STUDIES

1. Introduction

Any nuclear fuel cycle can be characterized by a few basic parameters. The values of these parameters strongly affect the perceived economic competitiveness of the fuel cycle under consideration. Hence, the choice of parameters is a critical one when comparing the economics of different fuel cycles and strategies.

For the purposes of long-term strategy analyses of alternate nuclear fuel cycles, the following parameters are sufficient to define each fuel cycle:

- Feed Fuel (ie. uranium or thorium)
- Burnup
- Fissile Content of Feed Fuel at Equilibrium
- Fissile Material Required to Reach Equilibrium
- Fissile Content of Irradiated Fuel
- Specific Power
- Station Efficiency

The decision to reprocess irradiated fuel, and the choice of topping material (ie. extra fissile material added to fresh fuel) are also important considerations. This document details the values of the above parameters for each fuel cycle considered and, where necessary, presents reasons for selecting a particular value.

2. Summary

Table 2.1 contains a summary of the important parameters for the fuel cycles considered. The following notes apply to the table.

(a) The specific power for all the CANDU fuel cycles is assumed to be the same as for the natural uranium (Nat. U) cycle. Although power peaking considerations may require a lower specific power for the advanced fuel cycles, preliminary studies indicate that a reduced bundle-shift refuelling scheme may alleviate the peaking problem (1). Detailed studies of potential power peaking problems for the low enriched uranium (LEU) fuel cycle are presently underway. They will confirm, or modify, the assumptions made here.

(b) Equilibrium net fissile feed is the quantity of fissile material, over and above that retrieved from irradiated fuel, which is contained in fresh fuel. For example, the net fissile feed for the Nat. U cycle is just 7.1 g U-235 per kg of uranium, which is the concentration of fissile uranium in natural uranium.

(c) Equilibrium net fissile surplus is the amount of fissile material remaining after the fissile material in irradiated fuel is recycled into fresh fuel. Where no reprocessing occurs, the net fissile production is simply the fissile material contained in irradiated fuel. As would be expected, there is a positive net fissile surplus for the LMFBR.

(d) The first charge fissile content includes all extra fissile material required to reach equilibrium. For the thorium cycles, a significant first charge is required because of the lack of any fissile material in natural thorium. It is assumed that all fissile material required to reach equilibrium is contained in the initial fuel loading. Equilibrium is normally reached after two or three fuel loads.

(e) The values for the LMFBR are for a weighted average of the core and blankets.

Table 2.1: Summary of Fuel Cycle Parameters

	Natural UO_2 (Nat. U)	Low Enriched Uranium (LEU)	Mixed Oxide (Pu Recycle)	Pu Topped Thorium (Th(Pu))	U Topped Thorium (Th(U))	Fast Breeder Oxide Cycle (LMFBR)
Efficiency (%)	30.5	30.5	30.5	30.5	30.5	38
Specific Power (kW(th)/kg HE) (a)	25	25	25	25	25	29 (e)
Burnup (MW.d/kg HE)	7.0	21.0	16.5	27.0	27.0	21.7 (e)
Equilibrium Net Fissile Feed (b) (g fissile/kg HE)	7.1 U-235	12.0 U-235	7.1 U-235 .27 Pu	3.5 Pu	3.2 U-235	0.0
Equilibrium Net Fissile Surplus (c) (g fissile/kg HE)	2.7 Pu	3.4 Pu	0.0	0.0	0.0	6.7 Pu (e)
First Charge Fissile Content (d) (g fissile/kg HE)	7.1 U-235	12.0 U-235	4.0 Pu 7.1 U-235	25.6 Pu	23.5 U-235	53.4 (e) Pu
Fuel Reprocessing	No	No	Yes	Yes	Yes	Yes

3. Uranium Based Fuel Cycles

3.1 Natural Uranium

The commercialization of a new technology usually requires the introduction of that technology in stages, with each successive stage being an improvement over the previous one. Such is the case with the nuclear generation of electricity in Ontario, with the result that successive generations of nuclear stations are based on larger reactor units. The operating characteristics of the reactors are dependent on the reactor size, and so no single set of characteristics describes all operating reactors.

The methodology used for strategy analysis requires a single set of values for the parameters in Table 2.1 for each fuel cycle. Thus, the value of efficiency, specific power and burnup for the Nat. U cycle must take into account the present mix of operating units, plus the projected generation expansion program. Since most future stations will probably consist of 850 MWe or 1250 MWe units, the values are weighted accordingly.

The expected station efficiency is 30.3% for Darlington, and 31.4% for 4 x 1250 MWe stations. Hence, a compromise value of 30.5% was chosen.

Specific power is expected to be 25.8 kW(th)/kg U for Darlington, and 25.0 kW(th)/kg U for 4 x 1250 MWe stations. However, the value for Pickering is only 18.7 kW(th)/kg U, so the value chosen for future use was 25.0 kW(th)/kg U.

Values of burnup range from 7.6 MW.d/kg U for Pickering, to 6.87 MW.d/kg U for Darlington, to 6.96 MW.d/kg U for 4 x 1250 MWe stations. A compromise value of 7.0 MW.d/kg U was chosen for use in strategy analyses.

3.2 Low Enriched Uranium

Static economic analyses have indicated that the optimum enrichment for the LEU fuel cycle is 1.0-1.2% for a wide range of uranium prices (2). Preliminary scenario studies were based on a 1.2%-enriched LEU cycle, and future studies will initially assume the same enrichment level. An enrichment level of 1.0% may also be considered.

The burnup for 1.2% enriched LEU fuel was previously assumed to be 21.0 MW.d/kgHE (3). Recent AECL studies have indicated that burnup would be 20.9 MW.d/kgHE for the same enrichment (4). Preliminary results of a detailed Ontario Hydro study show burnup to be about 22.0 MW.d/kgHE for Pickering B type stations (5). The latter value is for plenum fuel, which causes only a .05 MW.d/kgHE reduction in burnup. Pending results of a detailed fuel management simulation, burnup will be assumed to be 21.0 MW.d/kgHE.

The design of stations operating on the LEU cycle is not expected to differ greatly from the design of Nat. U stations. Hence, station efficiency and specific power are assumed to be the same as for the Nat. U cycle. Although power peaking may be a problem in LEU reactors, reducing the number of bundles shifted per channel visit when refuelling may alleviate the problem (1). Thus, a decrease in specific power may not be needed.

3.3 Plutonium Recycle

In the mixed oxide fuel cycle considered here, plutonium retrieved from irradiated fuel is added to natural uranium in order to extend the burnup of the fuel. Static economic analyses have shown that an enrichment level of 4 g fissile Pu per kg heavy element is near the economic optimum (2). With a burnup of 17.0 MW.d/kgHE, the fissile plutonium content of irradiated fuel is 3.73 g/kg HE. Hence, 0.27 g/kgHE of fissile plutonium must be added to that retrieved from reprocessing to make up the total 4.0 g/kgHE which is contained in fresh fuel. This extra fissile material, or topping, will probably be obtained by reprocessing irradiated Nat. U or LEU fuel.

Reference 2 indicates that successive recycling of plutonium will result in a changing fissile isotopic composition. Consequently, the average discharge burnup will decline with succeeding fuel generations. Based on data contained in Reference 2, the 30 year lifetime average burnup decreases to 16.5 MW.d/kgHE when this factor is included.

For reasons identical to those discussed in Section 3.2 for the LEU cycle, specific power and reactor efficiency are assumed to be the same as for the Nat. U fuel cycle.

In another variation of the mixed oxide cycle, both the plutonium and uranium contained in irradiated fuel are recycled. The proper fissile concentration is achieved by reducing the relative concentration of uranium. This fuel cycle has the advantage of being more proliferation resistant, and more uranium-conserving than would be achieved by recycling only the plutonium. Economic benefits may also be achieved as a result of a reduced requirement for mined uranium and a reduction in irradiated fuel disposal requirements. Parameters for CANDU reactors for the above fuel cycle are not yet available but are under investigation.

4. Thorium Based Fuel Cycles

4.1 Plutonium-Topped Cycle

Technical considerations and static economic analyses indicate that the optimum burnup for a thorium cycle is near 27.0 MW.d/kgHE (2). However, reactor design modifications necessary for the thorium cycle are uncertain, and theoretical physics studies have yet to be confirmed by experiments. Compounded with the uncertainty in the physics data, namely the η-value for U-233, these factors have led to considerable uncertainty in the quantity of fissile topping required to achieve a burnup of 27.0 MW.d/kgHE. The value recommended for use in future studies is 3.5 g fissile Pu per kg HE.

Depending on the assumptions for reactor operating conditions and processing losses, estimates of fissile Pu topping required to achieve a burnup of 27.0 MW.d/kgHE range from 2.3 to 3.5 g/kgHE (6). The latter figure is a conservative one, based on 1% processing losses and operating conditions similar to those of Nat. U CANDU's.

Reference 7 discusses factors which contribute to the uncertainty in the topping-burnup relationship for thorium cycles.

- uncertainty in U-233 η-value causes 15% burnup uncertainty
- uncertainty in fuel management schemes adds 2.5 MW.d/kgHE uncertainty
- 1 MW(th) decrease in maximum channel power causes 3.5 MW.d/kgHE burnup increase
- 1% processing loss of fissile material causes 1.7 MW.d/kgHE burnup penalty

Reference 7 estimates that for 1% processing losses, standard 37 element bundle fuel, a maximum channel power of 6.5 MWth and specific power of 29 kW(th)/kgHE, fissile topping for a burnup of 27.0 MW.d/kgHE is 3.2 g Pu/kgHE.

Reference 8 discusses possible increases in burnup which might be achieved as a result of lower Xe-override reactivity requirements. For the same decision and action time, thorium reactors would require about half the reactivity penalty associated with Nat. U reactors. This is due to the lower I-135 yield and lower flux density for thorium reactors. For 1% fissile losses, Reference 8 estimates that the fissile topping required for a burnup of 27.0 MW.d/kgHE is 2.8 g Pu/kgHE.

It is evident from the foregoing discussion that the selection of a fissile topping of 3.5 g Pu/kgHE is somewhat conservative.

However, the point of strategy studies is to determine if, and when, an alternate fuel cycle will become economically feasible. Hence, the use of conservative, but realistic values is prudent.

The pre-equilibrium fissile content associated with an equilibrium fissile topping of 3.5 g Pu/kgHE and a burnup of 27.0 MW.d/kgHE is 25.6 g Pu/kgHE (6). This is the total amount of pre-equilibrium fissile material required, and would normally be added in decreasing amounts over the first few generations of fuel. The methodology of strategy analysis assumes that all this extra material is added to the first generation of fuel, which imposes only a slight penalty in terms of the timing of the consumption of fissile material.

As they were for the LEU and mixed oxide fuel cycles, the operating characteristics of thorium reactors are assumed to be the same as for Nat. U reactors.

4.2 Uranium-Topped Cycle

As an alternative to using fissile Pu as topping material in the thorium fuel cycle, highly-enriched uranium can also be used. It is assumed that the topping will be 93% U-235. The fissile topping requirements for U-235 are estimated to be 92% of those for Pu to achieve the same burnup (7). The values in Table 2.1 reflect this difference.

The difference in topping material is not expected to affect the operating conditions of the reactor. Hence, the other parameters in Table 2.1 are identical to those for the plutonium-topped thorium cycle.

5. Liquid Metal Fast Breeder Reactor

The LMFBR parameters listed in Table 2.1 are based on a reference reactor design of current technology (9). The values have been averaged over the core and blankets to enable simulation of the LMFBR material flow rates (10).

The reference LMFBR is a pool-type, liquid-sodium-cooled reactor. The parameters used are based on those of an Argonne National Laboratories' design concept. It is likely that if widespread acceptance of breeder reactors occurs, these performance characteristics will improve. Hence, the parameters listed in Table 2.1 might be on the conservative side for a mature system of LMFBR's.

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