# Optimal Fuel Management of CANDU Reactors At Approach to Refuelling Equilibrium

C.P. Tingle and H.W. Bonin

Royal Military College of Canada - Collège militaire royal du Canada
Department of Chemistry and Chemical Engineering
P.O. Box 17000; Stn FORCES
Kingston, Ontario, Canada K7K 7B4

## ABSTRACT

Initially the CANDU Pressurised Heavy Water Reactor (PHWR) was designed to use natural uranium dioxide ($UO_2$) as its fuel, but its versatility was soon evidenced as early studies demonstrated that the reactor could accommodate several other types of nuclear fuels without the need for major re-design. These alternate fuels include low enriched uranium (LEU), thorium-containing oxide mixtures (MOX), plutonium-based MOX, and Pressurised Water Reactor (PWR) spent fuel recycled in CANDU reactors. CANDU reactor refuelling is carried out on-power in a quasi-continuous fashion by having a refuelling machine inserting a string of fresh fuel bundles into one end of a fuel channel and another similar machine unloading an equal amount of spent fuel bundles.

The quasi-continuous nature of the refuelling creates a so-called refuelling equilibrium state, which is reached about one year after initial reactor start-up and characterized by a constant rate of refuelling and a constant discharge burnup. The present work rather focuses on the "Approach to Refuelling Equilibrium" period which immediately follows the initial commissioning of the reactor. This period is indeed a sequence of two phases: the first one characterized by the absence of refuelling since the reactor has initially a high excess reactivity compensated by burnable poison present in its moderator, and the second one when refuelling is done at a higher rate which tapers out to the constant value of the equilibrium The in-core fuel management problem for this period is treated as an optimization problem in which the objective function is the refuelling frequency to be minimized by adjusting the following decision variables: the channel to be refuelled next, the time of the refuelling and the number of fresh fuel bundles to be inserted in the channel. The optimization problem also includes the following constraints: maximum channel power, maximum bundle power, maximum discharge burnup, minimum time span between successive visits by the refuelling machines, and, in some cases, a minimum channel separation for consecutive refuellings.

In this study, a simulation program was developed to investigate the optimum approach to refuelling equilibrium in a CANDU-6 reactor. Finite difference methods are used to solve the diffusion equations in two energy groups, using a $80 \times 80 \times 26$ mesh point grid yielding 18 mesh points per fuel bundle. The lattice parameters are determined from interpolating neutron flux and fluence within parameter tables calculated using the

transport code WIMS-AECL coupled with the ENDF/B-V data library. Refuelling is simulated by setting the fluence to zero for mesh points representing fresh fuel bundles. Since at this stage it is desired to investigate the effects of the refuelling optimization itself, the model does not include reactivity control devices for the moment. The model simulates individual refuellings and follows closely the evolution of the core throughout the whole "Approach to Refuelling Equilibrium" period.

Channel selection is optimized by first setting up a modest group of channels as candidates for the next refuelling, based on accumulated fluence and on exclusion criteria when a channel separation constraint is active. Perturbation Theory is used to simulate in turn the refuelling of these channels and to calculate for each of them, among other parameters, the cycle length (i.e. the time between this refuelling and the next). The channel for which refuelling yields the largest cycle length is then selected and its refuelling "implemented" in the full core model. This process is repeated until the whole "Approach to Refuelling Equilibrium" period is simulated and optimized. In this study, two methods of refuelling were investigated: a so-called "static" method in which the refuelling mode (i.e. number of fresh fuel bundles inserted) and the minimum channel separation constraint were initially selected and unchanged throughout the simulation, and a "dynamic" refuelling method in which the two parameters above were part of the decision variables. With this last method, "deshifting" was observed in some of the simulations as it permitted to resolve maximum power density constraints.

Four different fuels were investigated in this work: natural $UO_2$, the lower fissile content plutonium MOX option investigated at AECL for nuclear weapon's material disposal in a BRUCE A CANDU reactor, "Self-Sufficient-Equilibrium Thorium Cycle" (SSET) fuel as an ultimate case representative of thorium-containing fuels, and DUPIC ("Direct Use of Spent PWR Fuel in CANDU") fuel. Both the present 37-rod bundle design and the proposed CANFLEX bundle design are part of this study.

The results include the time to reach refuelling equilibrium from initial start-up of the reactor, the average discharge burnup, the average refuelling frequency and the average channel and bundle powers relative to natural $UO_2$. The model was initially tested and the average discharge burnup for natural $UO_2$ came within 2% of the industry accepted 199 MWh/kgHE. For this type of fuel, the optimization exercise predicted the savings of 43 bundles per full power year. The optimization yielded for the advanced fuels the following values for the average discharge burnup at refuelling equilibrium: PuMOX: 180-186 MWh/kgHE, SSET: 492-503 MWh/kgHE, and DUPIC: 635-638 MWh/kgHE. The calculations also evidenced some problem areas such as high power densities for fuels such as the DUPIC. In this case in particular, frequently, the optimization had to be set aside in order to refuel channels in which bundles had reached or exceeded the maximum allowable burnup. These problems would be resolved once the model includes a representation of the control elements. Perturbation Theory has proven itself to be an accurate and valuable optimization tool in predicting the time between successive channel refuelling operations.

## INTRODUCTION

Presently in use in six countries, the unique design of the CANDU nuclear reactor offers a broad versatility with the nature to the nuclear fuel that can be used with advantage. In addition to the natural uranium dioxide fuel for which the CANDU has been originally designed, alternate fuels have been used or are considered, such as thorium-based oxide mixtures, plutonium-containing MOX fuels, low enriched uranium (LEU) fuels, and Pressurised Water Reactor (PWR) spent fuels. More recently, a new initiative under study proposes the "burning" in a CANDU reactor of plutonium from discarded nuclear warheads as part of the bilateral disposal of plutonium from existing nuclear weapon's arsenals in Russia and the United States. The design of the CANDU reactor is such that the use of these alternate fuels is possible without major modifications to the present design of the reactor.

Refuelling of the CANDU reactor is conducted on-power using a pair of refuelling machines connected to opposite ends of the reactor core. Each one of the channels of the reactor is refuelled in turn, an operation in which all or part of the twelve (or thirteen) fuel bundles is replaced with fresh fuel bundles, with current practice for natural uranium CANDU reactors being eight bundles (1,2). For advanced fuels with higher fissile content, lower bundle shifts may be necessary to reduce power peaking, resulting in skewed flux profiles and thermal efficiency reductions, problems that may be addressed by the means of adjuster rod relocation and alternate (checkerboard) bundle shift schemes (3,4). The fuel management problem then consists in determining the order by which the channels are to be refuelled, the time of the refuelling, and the number of fuel bundles to be replaced with fresh fuel bundles at a given refuelling operation (axial mode of refuelling). Since the refuelling is carried out on-power and is a quasi-continuous process, an equilibrium state is eventually reached, characterized by a constant refuelling frequency and constant discharge fuel burnup (5). For a natural uranium-fuelled CANDU reactor, this equilibrium is reached after nearly a year of continuous operation after initial reactor start-up. This work focuses on this initial operation period called "Approach to Refuelling Equilibrium" and characterized by two distinct phases: first, a transient period during which the reactor excess reactivity is such that no refuelling is required to maintain criticality, and second, a period during which refuelling is initiated and maintained at a decreasing rate until equilibrium is attained.

## MATHEMATICAL MODEL

The CANDU-6 reactor is represented mathematically with a two-neutron energy group model for which the nuclear parameters are calculated using the transport code WIMS-AECL and the ENDF/B-V library (6,7). A finite difference method is used to solve in three dimensions the following coupled differential equations with a 80 × 80 × 26 mesh point grid in which each of the fuel bundles is represented by 18 mesh points:

$$\begin{aligned} \nabla^2 \phi - (A+\theta) + B\psi &= 0 \\ \nabla^2 \psi - C\psi + D\phi &= 0 \end{aligned} \quad (1)$$

where $\phi$ and $\psi$ represent the thermal and the fast neutron flux, respectively, and are normalized to the power of the reactor, $\theta$ is the eigenvalue (linked to the effective multiplication coefficient), and the coefficients $A$, $B$, $C$ and $D$ are material-dependent lattice parameters determined (by WIMS-AECL) as functions of the respective cross sections, diffusion coefficients and infinite multiplication factors and depend on both the neutron flux and the fluence. The solution is obtained iteratively by converging first on flux distributions, then on the eigenvalue, giving the thermal and fast neutron flux distributions and the reactor's effective multiplication factor, from which the core reactivity is calculated. Refuelling is represented in the model by setting the fluence to zero for all the mesh points representing just inserted fresh fuel bundles and calculating the nuclear parameters accordingly. The nuclear parameters for the mesh points representing the axially shifted fuel bundles in the refuelled channel are adjusted according to the fluence previously accumulated by these bundles.

## THE OPTIMIZATION PROBLEM

At present, the selection of the channel to be refuelled next is performed using AECL's Reactor Fuelling Simulation Program (RFSP) which is based on core neutron flux detector measurements and an integrated semi-empirical lattice code, POWDERPUFS-V. No optimisation is conducted in this approach and the code is limited to $^{235}U$ fuels (8,9). In the present work, the in-core fuel management problem is treated as an optimization problem in which the objective function is the refuelling frequency to be minimized (or, conversely, the average discharge fuel burnup to be maximized). Maximum channel power constraints are included in the model, as well as maximum bundle power and maximum bundle discharge burnup. The optimization problem also accounts for a minimum time between successive refuelling operations by the refuelling machines, and, in some cases, an optional constraint may be added in which there is a minimum channel separation between two channels to be refuelled consecutively.

Channel selection is optimized by first selecting a small group of potential channels for the next refuelling based on maximum accumulated burnup and utilizing Perturbation Theory (10, 11) to estimate the effects of refuelling each one of these channels in turn. The basis for the use of Perturbation Theory lies in the fact that the refuelling of a single channel (or part of it) represents indeed a small perturbation in the reactor core. In addition, the cycle length is so short that the accumulation of fluence within the fuel bundles during this time leads to very small variations of the lattice coefficients $A$, $B$, $C$, and $D$, representing yet another very small perturbation. The Perturbation Theory equation below uses the adjoint fluxes, $\Psi_1$ and $\Psi_2$, determined by solving the adjoint flux equations (a problem very similar to solving the diffusion equations, except that the parameters $B$ and $D$ are interchanged):

$$\int\left[\Psi_1\left(-\delta C_i^k-\delta C_f^k\right)\psi+\Psi_2\left(\delta B_i^k+\delta B_f^k\right)\psi+\Psi_1\left(\delta D_i^k+\delta D_f^k\right)\phi+\Psi_2\left(-\delta A_i^k-\delta A_f^k\right)\phi\right]dV=0 \quad (2)$$

The subscripts 1 and 2 in the equation refer to the fast and thermal neutron energy groups, respectively, and the subscripts $i$ and $f$ refer to the beginning and the end of cycle $k$, respectively. The beginning of a cycle is when a channel is refuelled, and the end of this same cycle is the moment when the excess reactivity of the core becomes exactly zero, i.e. immediately before the next refuelling. The Perturbation Equation is also an eigenvalue/eigenvector problem, the eigenvalue giving the cycle length, i.e. the time from the refuelling to the end of the cycle. Figure 1 illustrates the logic sequence of the optimization process for a given cycle "k".

## RESULTS

A refuelling computer code, CATER (CANDU APPROACH TO REFUELLING EQUILIBRIUM) has been developed to implement the optimization method described above (12). This work investigated two possible methods of refuelling: static and dynamic. In the static refuelling model, the axial mode of refuelling and the minimum channel separation are pre-selected and unchanged afterwards. In the dynamic model as the optimisation progresses, they may be adjusted by the user with the optimum bundle shift selected within a range of axial refuelling modes, and the channel separation may be adjusted as well. For a given cycle, the axial mode of refuelling is optimized in order to maximize the cycle length and the discharge burnup, while ensuring that the constraints, notably the maximum power densities, are all respected. Generally, the optimum axial mode of refuelling is nine or ten bundles. In some cases, during the dynamic simulation, *"deshifting"* has to be implemented within the specified range until power peaking constraints are met.

Four different types of fuel were investigated in this study: natural uranium dioxide (13), the lower fissile content plutonium MOX option presently investigated at AECL for nuclear weapon's material disposal in a Bruce A reactor (14,15,16,17), the so-called "Self-Sufficient Equilibrium Thorium" cycle fuel (SSET) (18,19,20,21) and the fuel mixture proposed for the Direct Use of Spent PWR Fuel in CANDU (DUPIC) application of a tandem coupling of a PWR and a CANDU reactor (22, 23, 24). Both the present 37-rod bundle design and the proposed CANFLEX bundle design are part of this study (25, 26, 27). For each fuel, static refuelling with at least one specific bundle shift and two channel separation exclusion zones were used. Additionally, natural $UO_2$ had two other bundle shifting schemes and the dynamic refuelling mode simulated.

The results include the time to reach refuelling equilibrium from initial start-up of the reactor, the average discharge burnup, the average refuelling frequency and the average channel and bundle powers. The model was initially tested and the average discharge burnup for natural $UO_2$ came within 2% of the industry accepted 199 MWh/kgHE. For this type of fuel, the optimization exercise predicted the savings of 43 bundles per full power year, when the results from the optimized simulation were compared with those from a non-optimal simulation where the channel selected for refuelling was merely the one with the highest fluence. The results are presented below by means of Table I and Figures 2 to 7.

In Figure 2, the "Approach to Refuelling Equilibrium" is shown, for a natural $UO_2$ fuelled CANDU-6 reactor, with an eight-bundle shift axial mode of refuelling and no channel separation constraint, as a typical example. The discharge burnup averaged among the bundles unloaded from the reactor at each visit by the refuelling machines is plotted against the exact time of the refuelling. Inception of refuelling occurs at 156.68 full power days (FPD). The oscillations are due to the location of the channels refuelled, the ones closest to the core center producing higher values for the average discharge burnup. In general, the determination of the exact point of inception of the refuelling equilibrium period remains a subjective question based on the user's judgement from examination of the curve, as it oscillates uniformly above and below the value of the equilibrium discharge burnup.

Figures 3 to 7 compare the various fuels studied in terms of several performance indicators. Figure 3 presents the time lengths of the "Approach to Refuelling Equilibrium" period for the various fuels and management schemes. This is an important parameter since this period is the least economic time in the life of the reactor, as there are monetary savings in reaching refuelling equilibrium as early as possible. For natural uranium fuel, the results of eight- and ten-bundle shift modes, with or without a channel separation constraint, are almost the same, but there is a nearly 40 days savings by implementing a seven-bundle shift mode. Implementing the dynamic optimization option yields another reduction of 25 full power days. Due to their high reactivity, the advanced fuels forced the use of axial refuelling modes of two- to four-bundle shifts. The time to refuelling equilibrium for the plutonium fuel was slightly less than the time for the natural uranium fuel, but the value was much higher for the SSET and the DUPIC fuels. For these, no significant effects from activating the channel separation constraint were observed.

Comparable results are observed at Figure 4 for these fuels for the average discharge burnup. As expected for natural uranium fuel, slightly higher average burnups are obtained for the eight- and the ten-bundle shift modes, since the channels are visited less often. The dynamic mode of optimization results in a 4% burnup penalty, and the plutonium fuel gives even less burnup than the natural uranium fuel. As for the other two fuels, the burnup is more than 150% higher. For the DUPIC fuel, (and, in rarer cases, for the SSET fuel), the maximum burnup constraint (450 MWd/kgHE) was exceeded, forcing the refuelling of the channels containing such fuel bundles. In the case of the DUPIC fuel, the optimization exercise could not be implemented to full extent.

Figures 5 and 6 present the results of the average channel and bundle power obtained as a result of the optimal fuel management for the various fuels investigated. It is important to remember here that the reactivity control devices are not included in the CANDU-6 reactor model in order to assess the effects of the fuel management in the control of the reactor. It was therefore expected that the present maximum license channel and bundle power levels would be exceeded in this model, and including the neutron flux adjuster devices in the model will reduce the average power densities below the acceptable levels. Activating a channel separation constraint of five channels separation provides some improvement for most of the fuels, notably for the average bundle power for the DUPIC fuel. Even with a two-bundle shift refuelling mode, the DUPIC fuel develops excessively high power densities while exceeding on many occasions the maximum discharge burnup constraint before reaching refuelling equilibrium. This problem was such that a majority of the refuelling operations for this particular fuel were devoted to removing fuel bundles having exceeded the maximum allowable burnup, at the expense of the optimal objective function and the power related constraints. On the other hand, the SSET fuel displayed excellent performance such as low power densities and refuelling frequency, this in spite of a few occurrences of maximum burnup exceeded.

In Figure 7, the reader may compare the average cycle length for the various fuels and axial refuelling modes/channel separation scenarios studied. It is interesting to consider that, even with axial refuelling modes as low as two- or three-bundle shifts, comparable cycle lengths are obtained for most of the natural uranium fuel scenarios and the SSET and the DUPIC fuels investigated. For these advanced fuels, no or little modifications would apparently be needed for the refuelling machine system. On the other hand, the refuelling frequency is more than doubled for the four-bundle shift refuelling mode for the plutonium-based MOX fuel, signaling the need for faster refuelling machines for a CANDU-6 reactor burning such fuel at the present power level.

## DISCUSSION

This study was aimed at determining the effects of applying a Perturbation Theory-based optimization method to the "Approach to Refuelling Equilibrium" phase of CANDU reactors fuelled with various traditional and advanced fuels. In a first step, the reactor model did not include the reactivity control and the adjuster devices, as their presence would have made the effects of the optimal fuel management on the power densities indiscernible. The optimization method worked out very well and nearly all the refuelling patterns obtained were salt-and-pepper arrangements with near perfect symmetry around the core center (12). In order to determine the pay-off from implementing optimal fuel management, a non-optimal refuelling simulation was performed for natural $UO_2$ fuel such that the channels having accumulated the most average burnup were the ones that were refuelled. In this case, the refuelling frequency obtained was 0.6895 FPD between refuellings, versus 0.6966 FPD for the optimized case. At first glance, the difference is minimal, but it translates to the savings of 43 fuel bundles for the approach to refuelling equilibrium period (about a year). At roughly $2,000 par $UO_2$ bundle, the savings are some $86,000 for the first year of operation of a natural uranium-fuelled CANDU-6. Implementing this optimization method to the refuelling equilibrium phase may well provide comparable savings, estimated at more than $2.5 million for a 30-year life span. In addition, the monetary savings would be significantly greater for the advanced fuels.

The study revealed interesting information on the use of the Pu MOX AECL Option 1 fuel in a CANDU-6 reactor. With a channel separation constraint active, the average channel power was reduced by 500 kW and the average bundle power by 28 kW, in addition to slightly increasing the average discharge burnup by 7 MWh/kgHE. The latest figure is well within the error bars of some 30 MWh/kgHE, however. The Pu MOX fuel gave high values for the power densities, a problem needing to be addressed. It is felt that even if the control devices were included in the model, the power densities would remain unacceptably high forcing a two-bundle refuelling mode. For the two channel separation options used in this work, the four-bundle shift refuelling mode gave a refuelling frequency of 0.39 FPD/cycle, which may be interpreted as an amount of 871 kg of plutonium transmuted per year. The annihilation objective for AECL is 1000 kg of plutonium per year per reactor, apparently quite possible in a Bruce A CANDU reactor, the reference reactor for the AECL studies (15), but hardly possible in the CANDU-6 reactor used in this work.

The investigation of the SSET fuel confirmed the effect of $^{233}Pa$ (a precursor to $^{233}U$ and a strong neutron absorber) on the flux history. The flux and power flattening effect was evidenced in the simulation, providing the SSET fuel with the best behavior in terms of channel and bundle powers. The average discharge burnups reported are higher in the present work than those traditionally associated with the SSET fuel in CANDU reactors (240-288 MWh/kgHE) (28). In most of these studies, the goal of the fuel management resided in the design of a fuel cycle achieving independence from external sources of fissile elements (near-breeding), at the expense of the burnup. In the present work however, the SSET fresh fuel composition was simply used as an ultimate case representative of thorium-based fuels, the fuel management aiming at maximizing the discharged fuel burnup, without consideration for achieving near-breeding.

The DUPIC fuel often required remedial refuelling of channels containing bundles having reached or exceeded the maximum allowable burnup, because the higher fissile content of the fresh fuel and the associated lower bundle shift mode permitted longer residence times. The optimization process was therefore often bypassed, leading to problems such as the large increases of reactivity making it difficult to accurately determine the inception of the refuelling equilibrium period. Also, as mentioned above, high power densities exceeding the allowable limits resulted. The presence of neutron flux adjuster devices would obviously help in solving these problems, but further solutions may be required, such as the addition of burnable poison in the fuel composition, improved fuel bundle designs, or even a revision of the primary heat transport system to increase the maximum license channel and bundle power levels.

The program CATER was validated for the natural uranium dioxide fuel against the published results from the industry with the equilibrium discharge burnup predicted by CATER as 201±9 MWh/kgHE versus a published value of 199 MWh/kgHE. With a large number of mesh points per bundle, CATER provides more accurate reactivity and neutron flux values than the model used currently in the industry. Perturbation Theory has proven itself to be an accurate optimization tool in predicting the time between successive channel refuelling operations. For larger axial refuelling modes (seven bundle shift or more), the time estimated by Perturbation Theory was found to be 7% accurate, with little effects, if any, observed in the optimization process. The Perturbation Theory accuracy fell to 37% for the lower bundle shift modes, causing some problems for the two-bundle shift mode used in this work for the DUPIC fuel, in particular. The precision of the lattice parameters in the reactor model is suspected as the main cause of these problems.

## CONCLUSIONS

A fuel management code, CATER, has been written to investigate the optimal "Approach to Refuelling Equilibrium" for a CANDU-6 reactor using four types of fuel: natural $UO_2$ , plutonium mixed oxide from weapon's fissile material disposal, self-sufficient equilibrium thorium (SSET) fuel, and DUPIC fuel from spent PWR fuel elements. The first three fuels were simulated using the standard 37-element fuel bundle design, while the DUPIC fuel simulation used the CANFLEX bundle design.

Each refuelling operation was explicitly simulated for all the "Approach to Refuelling Equilibrium" period, and the selection of the channel to be refuelled next was done through an optimization method using Perturbation Theory. The reactor model was based on a two-neutron energy group representation using lattice parameters calculated by WIMS-AECL coupled with the data library ENDF/B-V. The refuelling frequency, or conversely, the average discharge burnup, were the parameters to be optimized (objective function), and several constraints were included in the optimization problem.

The fuels with the higher initial fissile content yielded longer "Approach to Refuelling Equilibrium" periods and larger values for the average discharge burnup. Since the reactor model did not include reactivity control devices, the current maximum channel and bundle power limits were sometimes exceeded, and the results identify some problem areas for the Pu MOX and the DUPIC fuels for which solutions may reside in modifications to the bundle design or the reactor primary heat transport system.

Perturbation Theory has proven a reliable tool within the optimization method and, with the precision of the lattice parameters improved for fuels such as DUPIC, it is recommended that the optimization method be incorporated to the present CANDU refuelling simulator RFSP. The next step of this study would represent explicitly the reactivity control elements in the reactor model. Consultation should be initiated within the industry to establish more consistent findings regarding the DUPIC fuel.

## ACKNOWLEDGEMENTS

The authors would like to extend their thanks to the following persons for their generous assistance: from AECL: Dr Peter Laughton, Dr Jim Donnelly, Dr John Griffiths, Mr. Peter Boczar, Dr Peter Chan and Dr Ben Rouben; from Point Lepreau Generating Station: Mr Tim Whynacht and Mr. Rick Sancton.

## REFERENCES

(1) Thompson, P.D. and Young, E.G.; "CANDU-6 Reactor Core Physics and Site Physicist Role", Point Lepreau Generating Station, New Brunswick Power, undated.

(2) G.M. Frescura and A.L. Wight, "CANDU-PHW Fuel Management - A Lecture Course"; Report 80023, Ontario Hydro Nuclear Studies and Safety Department, May 1980.

(3) Boczar, P.G.; "Physics Characteristics of a CANDU-600 with Repositioned Adjuster Rods Fuelled with MOX or Natural Uranium", Atomic Energy of Canada Limited, Report AECL-8839, Chalk River Laboratories, January 1985.

(4) Boczar P.G. and VanDyk, M.T.; "Improved Location of Reactivity Devices in Future CANDU Reactors Fuelled with Natural Uranium or Enriched Fuels"; Atomic Energy of Canada Limited, Report AECL-9194, Chalk River Laboratories, February 1987.

(5) Dormuth, K.W. and Lidstone, R.F.; "A Study of the Running-in Period of CANDU-PHW Thorium Converter"; Atomic Energy of Canada Limited, Report AECL-5391, Whiteshell Nuclear Laboratories, Pinawa, Man., August 1977.

(6) Griffiths, J.; "WIMS-AECL Users' Manual, Revision 2", Report RC-1176, COG-94-2, Chalk River, Ontario, March 1996.

(7) Donnelly, J.V., "Application of WIMS-AECL to CANDU Lattice Cell Analysis, Revision 0", Atomic Energy of Canada Limited, August 1997.

(8) Rouben, B.; "Overview of Current RFSP-Code Capabilities for CANDU Core Analysis", Atomic Energy of Canada Limited, Report AECL-11407, Mississauga, Ontario, January 1996.

(9) Rouben, B.; "Description of the Lattice Code POWDERPUFS-V", Atomic Energy of Canada Limited, Report AECL-11357, Mississauga, Ontario, October 1995.

(10) Lamarsh, J.; "Introduction to Nuclear Reactor Theory", Addison-Wesley Publishing Co., Reading, MA, USA, 1972.

(11) Bonin, H.W., "Thorium-Fuelled CANDU Nuclear Reactor Optimal Fuel Management at Approach to Refuelling Equilibrium", 13th Annual Reactor Simulation Symposium, Chalk River, Ontario, 27-28 April 1987, pp 447-461.

(12) Tingle, C.P., "Optimal Fuel Management of CANDU Reactors at Approach to Refuelling Equilibrium"; Master's Degree Thesis, Royal Military College of Canada / Collège militaire royal du Canada, Kingston, Ontario, April 1998.

(13) International Nuclear Fuel Cycle Evaluation Working Group 8; "Data Base for a CANDU-PHW Operating on a Once-Through Natural Uranium Cycle", Atomic Energy of Canada Limited, Report AECL-6593, Chalk River Laboratories, Chalk River, Ontario, July 1979.

(14) Editorial Staff, Nuclear Engineering International, Vol. 42, No. 510, January 1997, p.2.

(15) Boczar, P.G., *et al.*; "Plutonium Dispositioning in CANDU", 4th International Conference on CANDU Fuel, Pembroke, Ontario, 1-4 October 1995, pp. 4A-1 - 4A-12.

(16) Krudiavtsev, E.G., *et al.*; "The Utilization of Russian Weapon's Plutonium in Canadian CANDU Reactors: A Feasibility Study"; 5th International Conference on CANDU Fuel, Toronto, Ontario, 21-25 September 1997, Vol. 1, pp. 267-278.

(17) FAX Dr. P. Chan (AECL) / LCdr C.P. Tingle (RMC/CMR) 29 September 1997: Chan, P.S.W. *et al.*; "CANDU - A Versatile Reactor For Plutonium Disposition or Actinide Burning"; GLOBAL '97 Conference, Japan, October 1997.

(18) Milgram, M.S.; "Thorium Fuel Cycles in CANDU Reactors: A Review"; Atomic Energy of Canada Limited, Report AECL-8326, Chalk River Laboratories, Chalk River, Ontario, January 1984.

(19) Critoph, E. *et al.*; "Prospects for Self-Sufficient Equilibrium Thorium Fuel Cycles in CANDU Reactors"; Atomic Energy of Canada Limited, Report AECL-5501, Chalk River Laboratories, Chalk River, Ontario, March 1976.

(20) Bonin, H.W. and Sesonske, A.; "Optimal Thorium-Fueled CANDU Nuclear Reactor Fuel Management", Nuclear Technology, Vol 68, March 1985, pp. 319-328.

(21) Das, M. et al.; "Fuel Development and Manufacturing Programme in India and Advanced Fuel Designs"; 4th International Conference on CANDU Fuel, Pembroke, Ontario, 1-4 October 1995, pp. 1-1 - 1-5.

(22) Choi, H., Rhee, B.W. and Park, H.; "Physics Study on Direct Use of Spent Pressurized Water Reactor Fuel in CANDU (DUPIC)"; Nuclear Science and Engineering, Vol. 126, 1997, pp. 80-93.

(23) Suk, H.C. *et al.*; "CANDU Advanced Fuel R and D Programs for 1997-2006 in Korea"; 5th International Conference on CANDU Fuel, Toronto, Ontario, 21-25 September 1997, Vol. 1, pp. 1-10.

(24) Sullivan, J.D., Ryz, M.A. and Lee, J.W.; "AECL's Progress in DUPIC Fuel Development"; 5th International Conference on CANDU Fuel, Toronto, Ontario, 21-25 September 1997, Vol. 1, pp. 300-306.

(25) Lane, A. D. *et al.*; "Bringing the CANFLEX Fuel Bundle to Market", 4th International Conference on CANDU Fuel, Pembroke, Ontario, 1-4 October 1995, pp. 5A-1 - 5A-9.

(26) Alavi, P. *et al.*; "Design Verification of the CANFLEX Fuel Bundle - Quality Assurance Requirements for Mechanical Flow Testing"; 5th International Conference on CANDU Fuel, Toronto, Ontario, 21-25 September 1997, Vol. 1, pp. 52-59.

(27) Sim, K.S. *et al.*; "Some Considerations in the CANFLEX-NU Fuel Design", 5th International Conference on CANDU Fuel, Toronto, Ontario, 21-25 September 1997, Vol. 2 ,pp. 46-61.

**Table I : Summary of Results**

| Fuel | Bundle Shift | Channel Separation Between Refuelling | Duration Of Approach to refuelling Equilibrium (FPD) | Average Discharge Burnup at Equilibrium (MWd/kgHE) | Average Refuelling frequency (FPD) | Average channel power (MW) | Average Bundle Power (kW) |
|---|---|---|---|---|---|---|---|
| Natural $UO_2$ | 7 | 0 | **305** | **196±19** | **0.61** | **10.6** | **1436** |
| | 8 | 0 | **341** | **201±9** | **0.70** | **10.8** | **1393** |
| | | 5 | **343** | **204±10** | **0.69** | **10.6** | **1372** |
| | 10 | 0 | **339** | **202±6** | **0.82** | **10.8** | **1239** |
| | 7-10 | 5 | **280 days** | **192±19** | **0.93 days** | **7.25** | **877** |
| Pu MOX 1 | 4 | 0 | **293** | **179±31** | **0.39** | **13.5** | **2128** |
| | | 5 | **302** | **186±28** | **0.39** | **13.0** | **2100** |
| SSET | 3 | 0 | **492** | **327±45** | **0.59** | **7.9** | **910** |
| | | 5 | **494** | **339±34** | **0.6** | **8.0** | **932** |
| DUPIC | 2 | 0 | **640** | **422±26** | **0.62** | **16.0** | **3080** |
| | | 5 | **640** | **405±32** | **0.61** | **16.0** | **2800** |

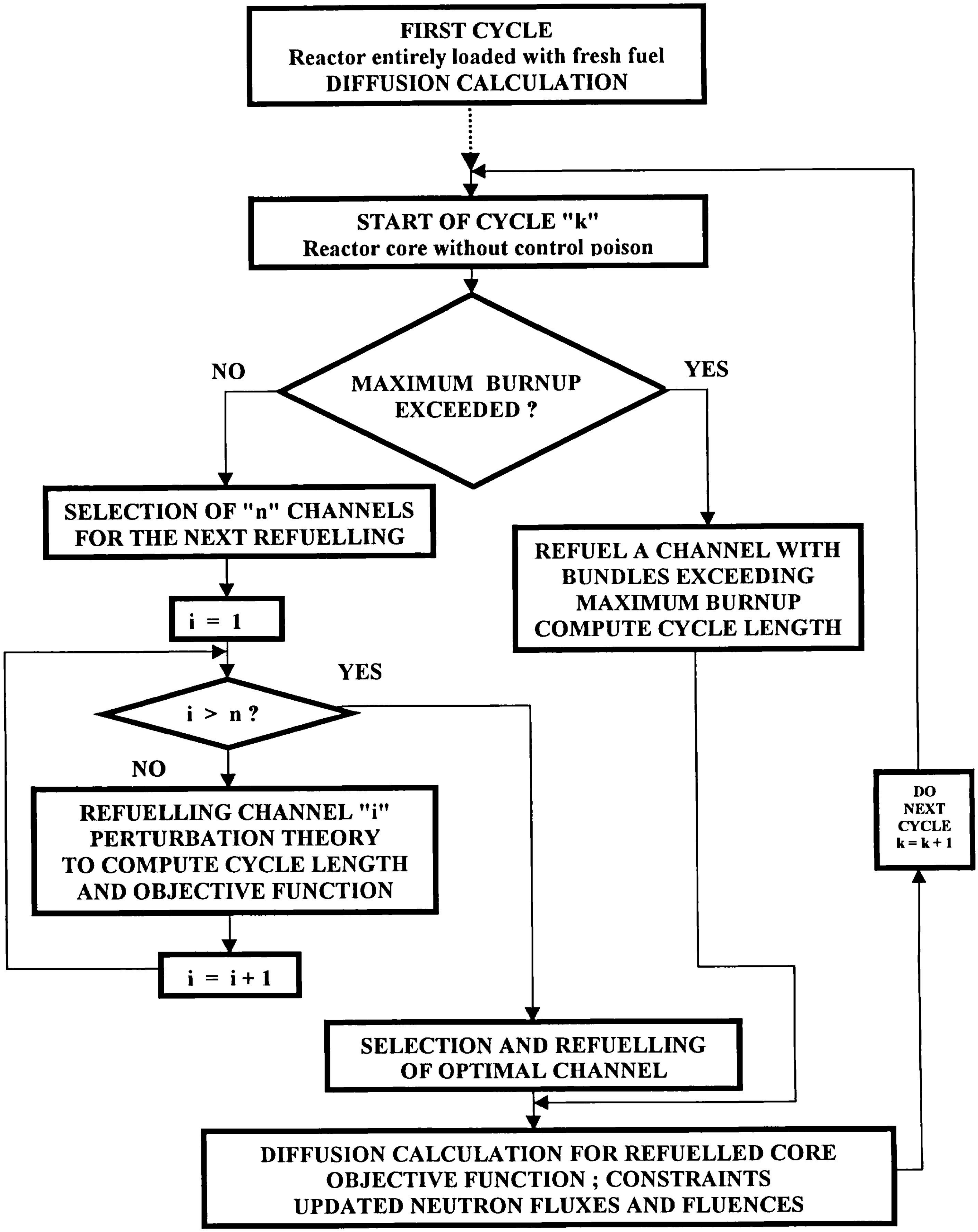


**Figure 1 : Refuelling Optimisation Flow Chart**

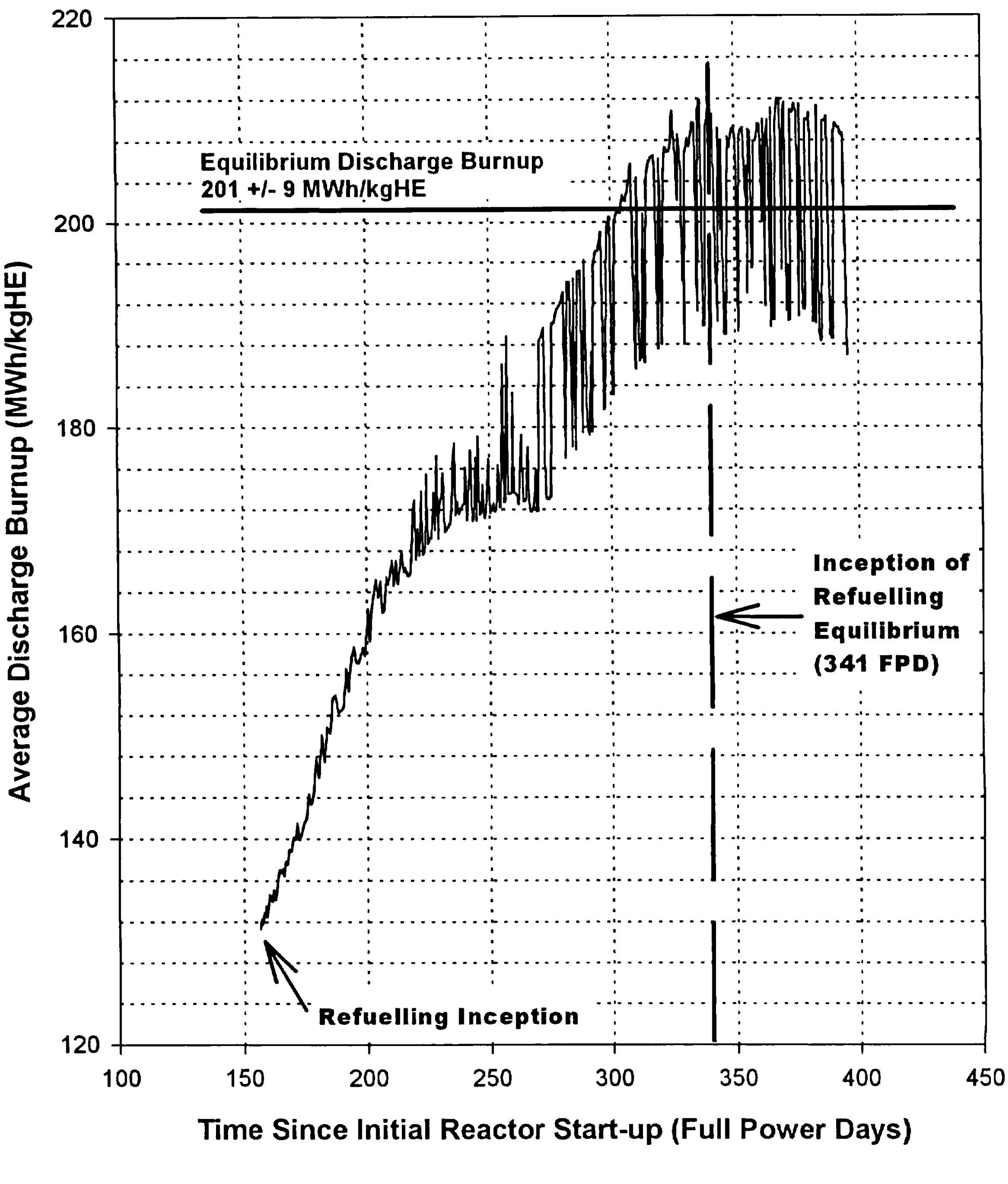


**Figure 2 : Time Evolution of the Average Discharge Burnup**

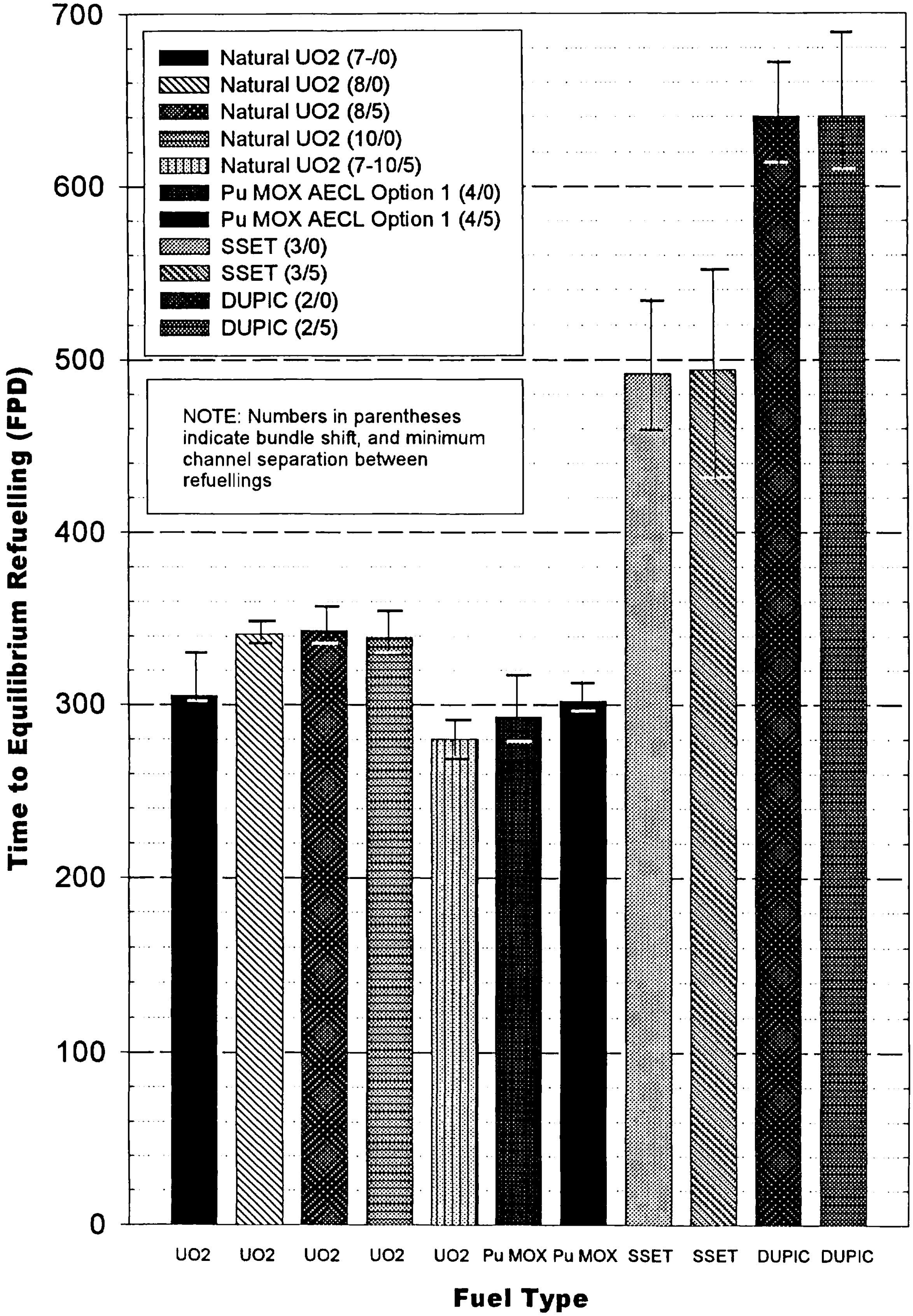


**Figure 3 : Comparison of Time to Refuelling Equilibrium**

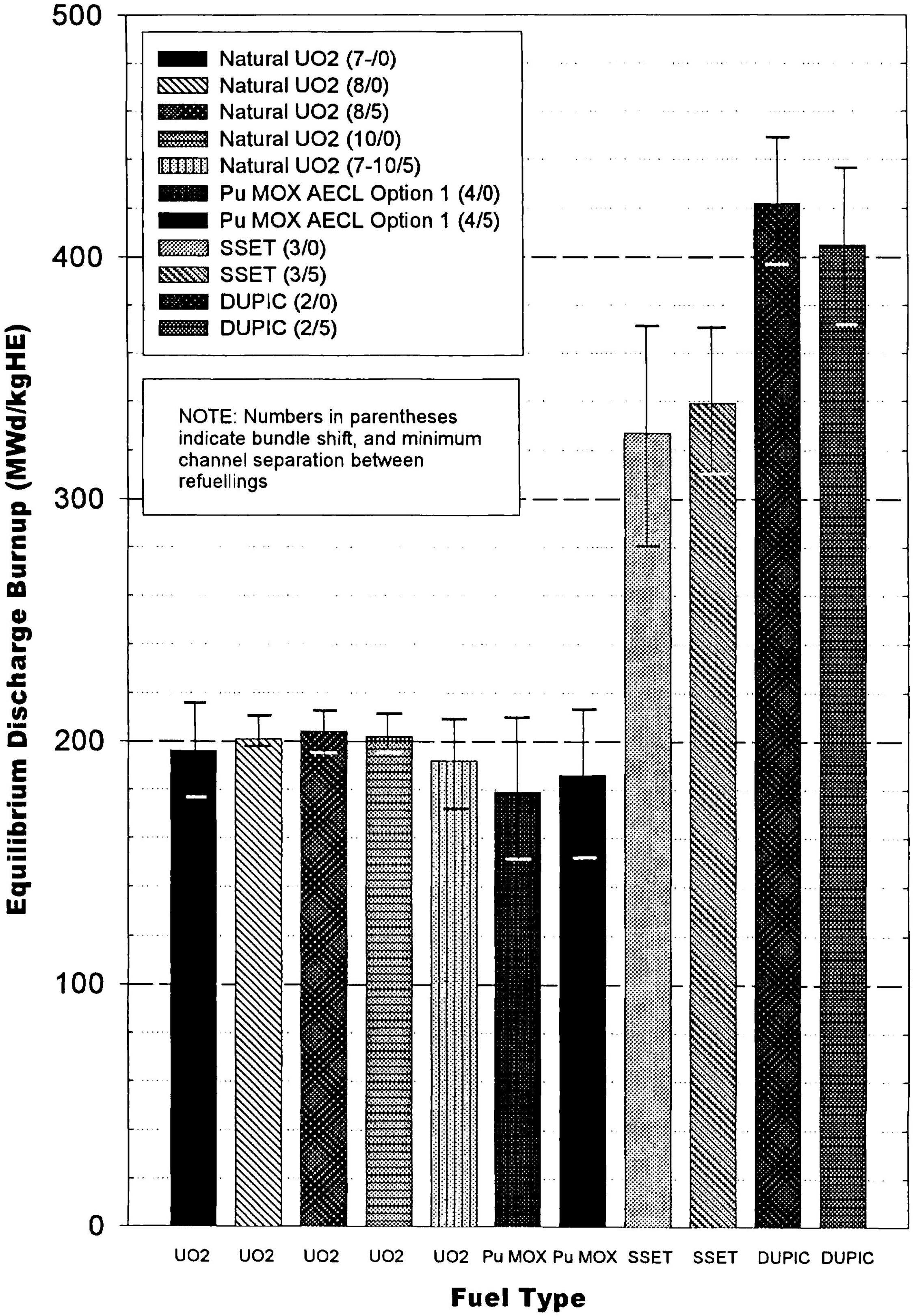


**Figure 4 : Comparison of Equilibrium Discharge Burnup**

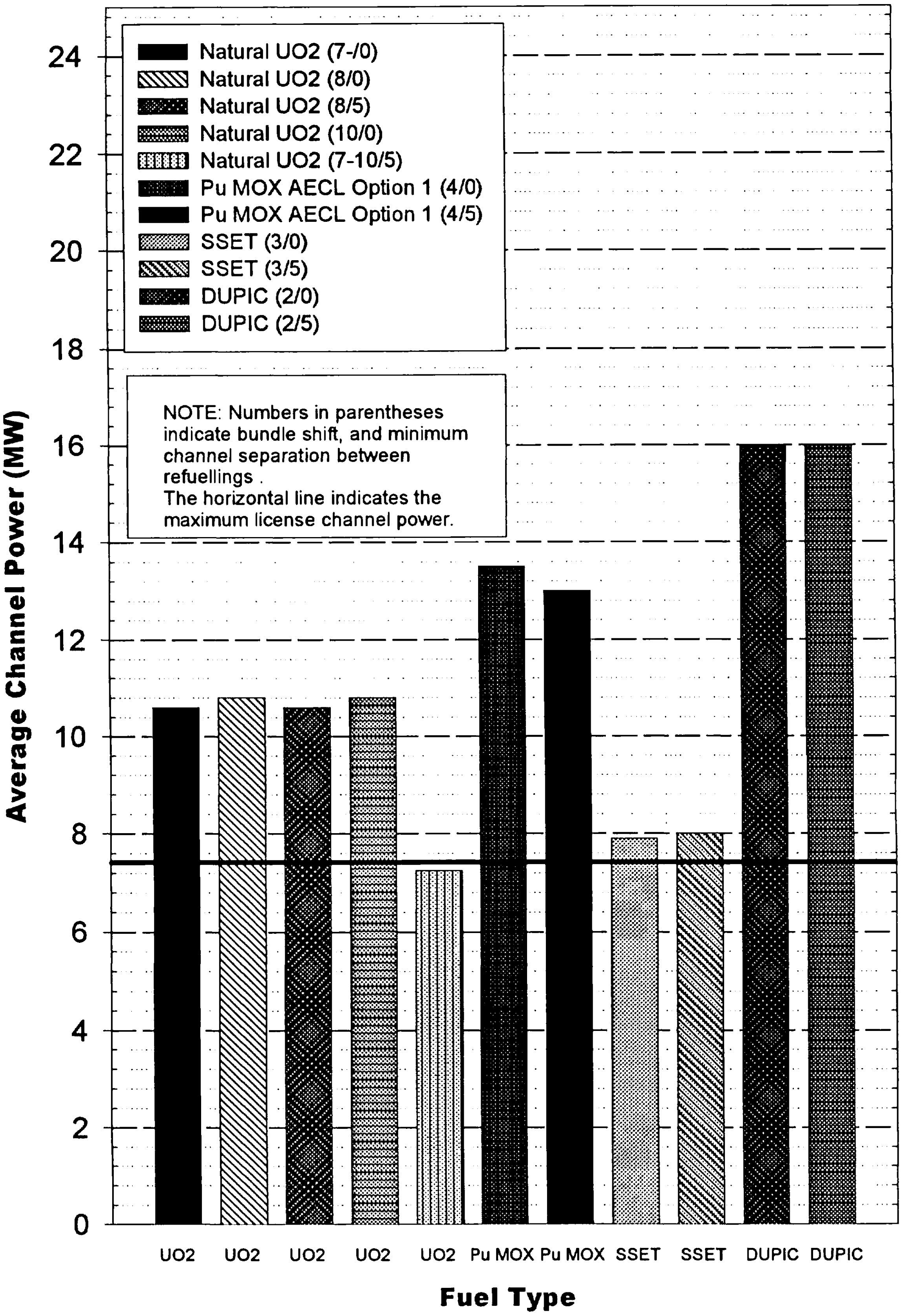


**Figure 5 : Comparison of Average Channel Power**

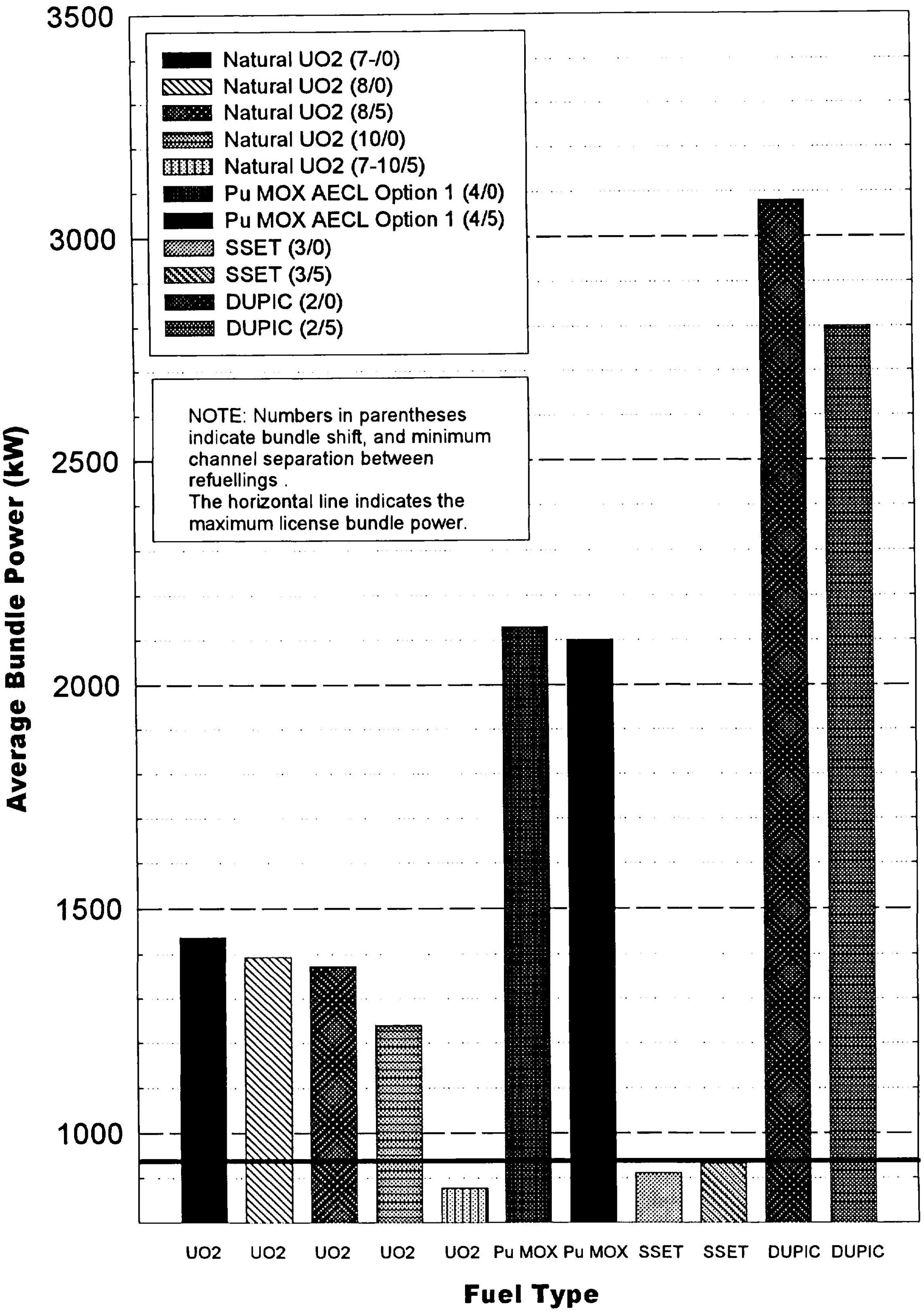


**Figure 6 : Comparison of Average Bundle Power**

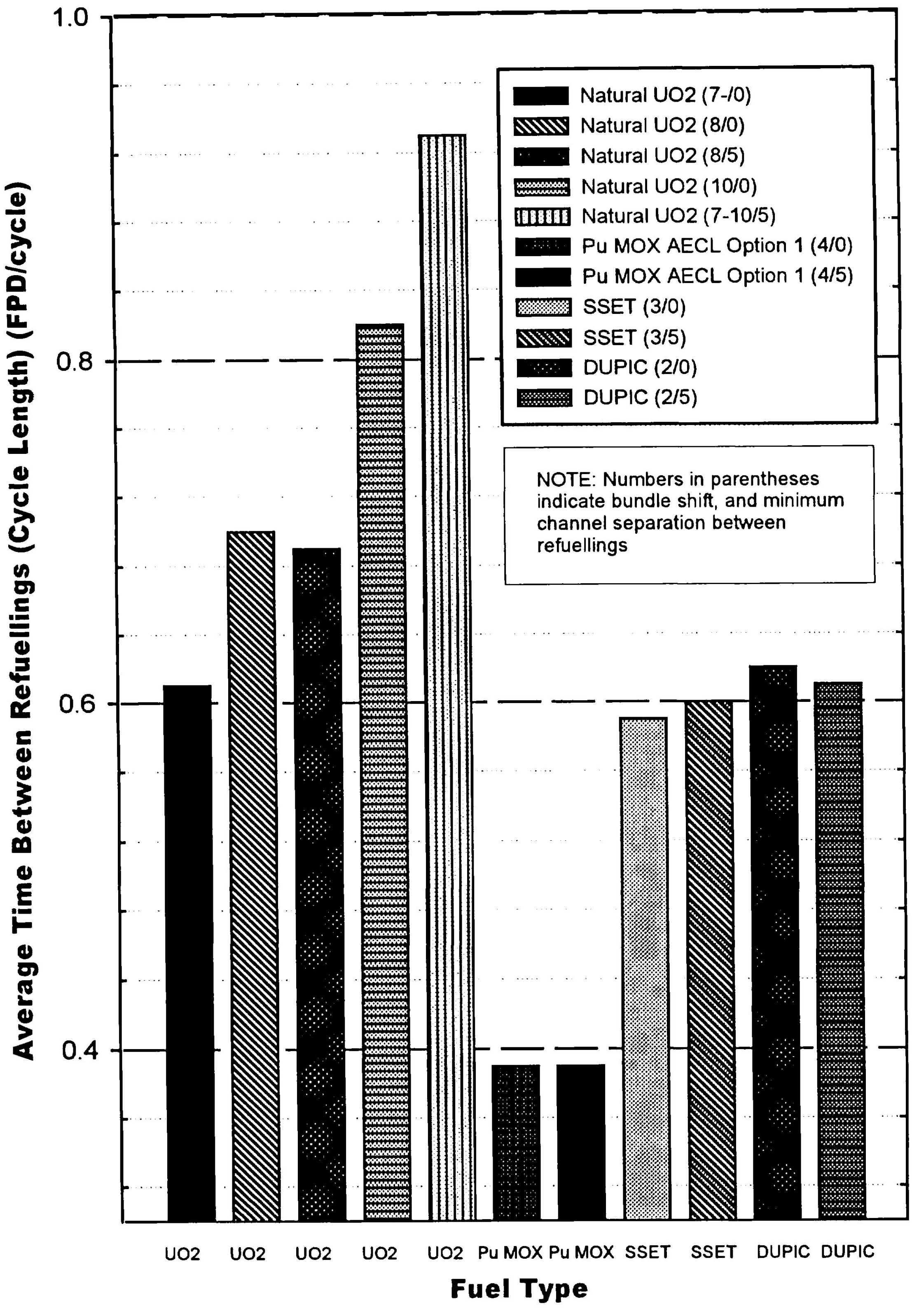


**Figure 7 : Comparison of Time Between Refuellings (Cycle Lengths)**