A Reactor Physics Study of the Economic Penalty associated with LVRF and Increased Pressure Tube Thickness

Daniel Rozon and Wei Shen
Institut de Génie Nucléaire
Ecole Polytechnique de Montreal
C.P. 6079, Succ. Centre-ville
Montreal (Quebec), Canada H3C, 3A7

ABSTRACT

Both the pressure tube (P/T) life and coolant void reactivity are essential factors in the design of CANDU reactors. In this paper, we report on a reactor physics study of the economic penalty associated with solutions related to these factors, i.e. increased pressure tube thickness and the use of burnable poisons. Natural uranium (NU), 0.9% and 1.2% slightly enriched uranium (SEU), and mixed-oxide (MOX) fuels were compared for an advanced 43-element CANFLEX geometry bundle design. Our calculations show that the burnup penalty associated with a 25% increase in P/T thickness for NU is of the order of 14%, which represents well over one million dollars every year in a CANDU 6 reactor. On the other hand, the same increase in tube thickness for a CANDU 6 fuelled with 1.2 w/o SEU fuel (using a 2 bundle-shift) yields a penalty of only 3.1%, or a few 100k$'s per year. This very large reduction in the burnup penalty for the same pressure tube thickness increase illustrates the fact that slightly enriched fuel in CANDU is superior to natural uranium in terms of neutron economy.

Another significant advantage of using enriched fuel in CANDU is the possible development of Low Void-Reactivity Fuel (LVRF). Previous studies have shown that void reactivity in a CANDU reactor can be reduced or even eliminated by adding an appropriate amount of neutron poisons mixed with depleted uranium in the inner elements of the CANDU fuel bundles. However, this can <u>only</u> be achieved with enriched fuel. In order to estimate the cost associated with the introduction of LVRF in CANDU, we compared the effect on void reactivity and discharge burnup of various quantities of a burnable poison (Gd) and a of a more permanent poison (Dy). The burnup penalty was defined relative to the performance of unpoisoned fuel with the same fissile content. We found a burnup penalty of approximately 1000 MWD/t(U) for each mk reduction in core void reactivity, regardless of the type of poison used in the design. All the calculations in this study were carried out by the DRAGON/DONJON chain of codes with Winfrith 69 groups library.

I. INTRODUCTION

In current CANDU designs, pressure tube (P/T) thickness is limited to minimise the parasitic absorption of neutrons so as to achieve a higher fuel burnup with natural uranium fuel. We shall see that advanced fuel cycles, such as SEU fuel [1], MOX fuel [2], DUPIC fuel [3-4] and others, offer a much greater flexibility with regards to the P/T thickness (assuming that a thicker pressure tube would offer possibilities for a longer life-time in the reactor). For the purposes of our study, natural uranium (NU), 0.9% and 1.2% slightly enriched uranium (SEU), and mixed-oxide (MOX) fuels were considered with advanced 43-element CANFLEX geometry design.

Previous studies have shown that the use of SEU fuel can offer many benefits such as lowering fuelling costs, improving uranium utilisation and reducing the volume of spent fuel. Another significant advantage of advanced fuel cycles is the possible development of Low Void-Reactivity Fuel (LVRF) [5]. Coolant void reactivity (CVR) refers to the change in core reactivity due to an increase in the coolant void fraction from 0% (cooled) to 100% (voided) in all pressure tubes in the reactor, which can be expressed as:

$$\Delta\rho_{CVR} = \rho(voided) - \rho(cooled) = \frac{1}{k_{eff}(voided)} - \frac{1}{k_{eff}(cooled)} \quad (1)$$

For current CANDU reactors using natural uranium fuel, $\Delta\rho_{CVR}$ is positive and is a key factor in CANDU safety analysis. In several loss-of-coolant accident (LOCA) scenarios, CVR values have a major influence on the size of the power pulse following the loss of coolant. Positive CVR has also come under focus in CANDU marketing because of specific requirements on passive safety. Previous studies have shown that coolant void reactivity in CANDU reactor can be reduced or even eliminated by adding an appropriate amount of burnable poison (BP) and using depleted uranium in the inner elements of CANDU fuel bundles. [5-9] This, however, can only be achieved with enriched fuel. In this paper, we will consider two different burnable poisons (Gd and Dy) for LVRF design. The cost associated with void reactivity reduction in CANDU will be expressed in terms of the burnup penalty relative to unpoisoned fuel with the same fissile content.

The advanced 43-element CANLEX fuel bundle design is used in this study. The unit cell calculations were carried out with the multi-group transport code DRAGON [10] using the Winfrith WIMS 69-group microscopic cross section library. From these, we obtain the (infinite) lattice void reactivity and the 2-group homogenized cross sections to be used in whole core reactor calculations. The latter are carried out with the 3D diffusion code DONJON [11] to generate the core-average discharge burnup at equilibrium refuelling. Using the local parameter feedback model, 3D system void reactivity can also be calculated directly by DONJON to verify the lattice reactivity obtained in 2D with DRAGON.

II. INCREASED P/T THICKNESS DESIGN

Increasing P/T thickness is quite attractive as it can lead to extended tube life, and possibly avoid the costly shutdown for retubing. Aside from NU fuel, the following two reference slightly enriched (SEU) fuels and two reference MOX fuels were used to study the burnup penalty associated with a 25% increase in P/T thickness: SEU09, slightly enriched uranium fuel with an initial U235 content of 0.9%, and SEU12, fuel with a U235 content of 1.2%. The two reference MOX fuels were defined by mixing 0.2% depleted uranium with different amounts of weapons grade plutonium [2] to match the initial lattice reactivities of SEU09 and SEU12 fuels. Although the total amount of fissile material (uranium plus plutonium) in fresh SEU fuel and in corresponding MOX fuels are initially equivalent, different operating characteristics are observed because the depletion characteristics depend strongly on the initial U/Pu ratios.[12]

The unit cell in a CANDU reactor contains a single fuel bundle surrounded by the heavy water moderator over one lattice pitch. For a given fuel type, the reactor physics calculations carried out for this study involve the following steps:

1. the DRAGON unit cell calculations provide the lattice properties (homogenized neutron cross sections) as a function of the instantaneous fuel burnup in the bundle;

2. these properties are then used in 3D diffusion calculations in DONJON to obtain flux and power distributions corresponding to a given fuel burnup distribution;
3. fuel burnup distributions in the reactor are determined by the postulated fuel management strategy, involving the axial shuffling scheme (bundle shift) in radial zones. By varying the refuelling frequency between inner and outer core, radial flattening of the power distribution can be achieved to satisfy limits on channel power;
4. at equilibrium refuelling, the average discharge burnup is then determined in DONJON by adjusting the fuelling rate in the reactor until the reactor is critical on a time-average basis.

Burnup Penalty associated with P/T thickness increase

Table 1 shows the burnup penalty associated with a 25% increase in P/T thickness for NU, SEU and MOX fuels. The burnup penalty for NU fuel is of the order of 14%, which represents well over one million dollars every year in operating costs in a CANDU 6.[a] We note that the burnup penalty reduced to 3.2%, or a few 100k$'s per year, for the same increase in tube thickness in a CANDU 6 fuelled with SEU12 fuel (using a 2-bundle shift, as opposed to an 8-bundle shift for NU). Bundle and channel power distributions are essentially unaffected by the P/T thickness increase. This reduction by a factor 4 in the burnup penalty for the same pressure tube thickness increase illustrates the fact that the current fuel lattice design with natural uranium is not optimal from a reactor-physics point of view. This behaviour can be explained by simple analogy with the behaviour of a function of a single variable $f(x)$ near or far from the maximum observed at x_0: the same Δx has a much smaller effect on f near x_0.

Effect of P/T thickness increase on coolant void reactivity

Removing the coolant in the 2D lattice transport calculations in DRAGON at each burnup step provides the burnup-dependent lattice coolant void reactivity ($\Delta\rho$, eq. 1) for the various fuel types in this study. As can be seen in figure 1, $\Delta\rho$ generally decreases with increasing fuel burnup. Taking an average of the lattice reactivity over the burnup range (between 0 and the discharge burnup) provides only an estimate of the actual system (core) void reactivity. Values obtained for the different fuel types are shown in table 1.

To evaluate the accuracy of these average values, 3D full core calculations with local parameter feedback[13] were carried out in DONJON to calculate the actual system reactivity change upon voiding all channels. Results are given in Table 2. It was concluded that the prediction of lattice void reactivity by the 2D DRAGON calculations agrees with full-core system reactivities within 3%, and is therefore a good approximation.

Coming back to Table 1, we observe that void reactivity is similar for all fuel types (slightly smaller for MOX fuel), and that it generally tends to increase (by about 5%) when the pressure tube thickness is increased by 25%. This is shown in Figure 2. The increase in void reactivity is probably due to the thermal neutron flux redistribution upon voiding.[b] *Variations in void reactivity when increasing P/T thickness are therefore not very significant.*

---

[a] Fuelling costs in a CANDU 6 are estimated at approximately 10M$/y, with natural uranium at 50$/kg and fabrication costs at $1500. /bundle for 37-element fuel.

[b] When coolant is removed, the thermal flux tends to increase in the center of the bundle and to decrease in the P/T. With a thicker P/T, this would lead to less parasitic absorption, and a (somewhat) larger void coefficient.

III. LOW VOID REACTIVITY FUEL

Since the thermal neutron flux rises at a higher rate in the inner region than in the outer region of the bundle upon uniform coolant voiding, the positive reactivity insertion can be reduced by locating less reactive fuel (depleted uranium) in the inner region of the fuel bundle. The innovation of using a burnable poison (BP) in the fuel is to provide additional negative reactivity in case of coolant voiding. Extra reduction is possible by adding absorber materials to the inner pins of the fuel bundle only. Because pure neutron absorber material would deteriorate fuel burnup too much, burnable poisons such as dysprosium, boron, gadolinium, erbium or europium should be used. Dysprosium was studied before[7-9] as a burnable poison material for advanced CANDU fuel cycles such as SEU and DUPIC, mainly because it is available, it controls void reactivity uniformly throughout the fuel burnup, and it is compatible with UO2 fuel.

In this paper, gadolinium (Gd) was also considered and compared with Dy for LVRF design. Adding neutron poisons to the fuel will obviously decrease the discharge burnup. With natural uranium, it is not possible to introduce burnable poisons and still have a critical reactor. Therefore, all LVRF designs imply the use of enriched fuel. To illustrate the importance of the burnup penalty associated with void reactivity reduction, our calculations were done with SEU fuel enriched to 1.2%. In all cases, the initial fissile content in the bundle was kept constant. The burnup penalty was determined by comparison to the discharge burnup achieved with SEU12 with no poison.

Compared to the standard 37-element CANDU fuel bundle, the CANFLEX fuel bundle is composed of 43 fuel rods, in which the size of the 8 fuel pins in the inner two rings is larger than the remaining 35 pins in the outer two rings. The CANFLEX fuel bundle design is expected to perform better than the standard 37-element design because it can accommodate more BP and depleted uranium in the inner fuel pins where the void reduction effect (increase in thermal neutron flux) is maximum. All our calculations were based on the CANFLEX bundle geometry.

LVRV design with dysprosium (Dy)

Two diferent Dy designs were considered: one is to mix natural Dy with depleted uranium (0.2% U235) in the inner 8 pins, another is to mix natural Dy with depleted uranium in the center pin only.

Design 1 : Dy + Depleted U in inner 8 pins

In this design, Dysprosium and depleted uranium were used in the inner two rings, i.e., the innermost 8 fuel pins of the CANFLEX bundle. The variation of k-infinity for SEU12 fuel with/without Dy is shown in Figure 3. As we can seen, Dy provides a uniform negative reactivity throughout fuel burnup (because neutron capture in ^{163}Dy produces a strong absorber ^{164}Dy with σ_c = 2700 b). At discharge burnup, a significant fraction of the initial ^{164}Dy inventory was produced from neutron capture in ^{163}Dy. Therefore, ^{164}Dy remains in the fuel for a long time and this type of burnable poison controls void reactivity effectively.

Table 3 gives the fuel discharge burnup and the burnup-averaged lattice void reactivity (CVR) for both 100% and 125% P/T thicknesses, for different Dy content. The instantaneous lattice CVR as a function of burnup is also illustrated in figure 4, while Figure 5 shows the variation of burnup-averaged (or equilibrium) lattice CVR with Dy. It can be seen *that void reactivity can be reduced to any desired value, even below zero*. We note that zero CVR could be reached by mixing about 13.5% Dy with depleted uranium in the inner 8 pins. *However, the discharge burnup is reduced by 70% compared to the case without the poison.*

Design 2 : Dy + Depleted U in central pin only

As a comparison, Dysprosium and depleted uranium were used in the central fuel pin in this design. Table 4 summarizes the fuel discharge burnup and burnup-averaged lattice CVR for 100% P/T thickness with different Dy content. The instantaneous burnup-dependent lattice CVR with various Dy contents is shown in Figure 6. Again, we note that Dy produces relatively uniform control of CVR throughout the fuel burnup. For this design, the reduction in the CVR by Dy was found to be effective only up to 15% content and then saturates asymptotically as shown in Figure 7. This behaviour can be attributed to a *self-shielding* phenomenon, whereby increasing the poison concentration inside the pin does not significantly increase neutron absorption, since most neutrons are absorbed at the surface of the pin. Nevertheless, zero CVR could be acheived with almost 90% Dy content in the central pin. The corresponding *discharge burnup is then reduced by 50%* compared to the case without the poison. Although it is unlikely that such a high concentration could be achieved in practice, the reduction in burnup penalty with a single poisoned pin suggests the use of an alternative poison, such as gadolinium.

LVRF design with gadolinium (Gd)

Gadolinium is widely used as an effective burnable poison in PWR fuel design. When Gd was used instead of Dy in the central pin, we found that gadolinium controls the CVR for low-burnup fuel only and cannot reduce the CVR uniformly thoughout the fuel burnup because the poison "burns" much faster. This is due to the much larger thermal neutron capture cross sections of Gd-155 and Gd-157 (σ_C=61000b and 255000b respectively). On the other hand, mixing Gd in the innermost 8 pins will make the fresh fuel subcritical, and therefore use of Gd is restricted to the central pin only for reducing void reactivity.

The variation of k-infinity for SEU12 fuel with different Gd content in the central pin is shown in Figure 8. The effect of self-shielding is quite evident. Compared with Dy, Gd has a much higher burnout rate especially when a lower amount of Gd is used in the central pin. When the initial Gd content is increased, the Gd burnout rate decreases and most of the Gd is still present in the central pin at the discharge burnup because of the strong self-shielding effect.[c] As a consequence, Gd will provide a uniform negative reactivity throughout fuel burnup and only a small difference in discharge burnup will be observed when the Gd content exceeds 15%, as shown in Table 4.

We also note that for different Gd content in the central pin, large variations in the instantaneous void reactivity will occur with fuel burnup, as shown in Figure 9. *Thus, reduction in void reactivity by adding Gd in the central pin is found to be effective only up to 15% Gd content, and then saturates at a level of about 2mk.* Zero CVR will never be reached with such a design because of strong self-shielding effect when more than 15% Gd is used in the central pin. This is illustrated in Figure 7, where Dy and Gd are compared.

---

[c] We note that in order to model the self-shielding effect correctly, very fine annuli and a large number of tracking lines were required in the DRAGON calculations.

Burnup penalty vs void reactivity

Although Dy and Gd were found to effectively control CVR up to 15%, the amount of Gd required to reduce CVR is generally higher than that of Dy. Also, large variations in the instantaneous CVR with fuel burnup were observed when Gd is used in the central pin, while the Dy shows a relatively uniform control of CVR throughout the fuel burnup. It would therefore seem that Dy is a more effective poison for the of coolant void reactivity. However, the burnup penalty with Gd is expected to be smaller for a given CVR because it burns faster.

The fuelling costs in CANDU reactors using LVRF depends on the achieved fuel discharge burnup, which in turn depends on the targeted void reactivity. We have plotted all our results in Figure 10, showing the discharge burnup achieved as a function of void reactivity. It is interesting to note that all cases nearly follow a straight line, suggesting the following relationship for discharge burnup *B* (in MWd/t) as a function of void reactivity (in mk), for SEU fuel enriched to 1.2%:

$$B = 8950 + 980 \cdot \Delta\rho_{CVR} \qquad (2)$$

Thus, we conclude that reduction in void reactivity can be achieved with SEU 1.2% at the cost of approximately *1000 MWd/t(U) in burnup penalty per mk decrease in coolant void reactivity*, regardless of the type of burnable poison used in the fuel.

IV. ECONOMIC STUDY

Fuelling costs are not simply a function of discharge burnup, although burnup is the dominating factor that determines the fuelling rate. We must also take into consideration the cost of an individual fuel bundle, which will also vary with enrichment (fabrication costs, enrichment services, natural uranium requirements,...). In order to estimate the economic impact of the above burnup penalty, we have made a number of simplifying assumptions:

- the current price of natural uranium is low, assumed at roughly 50 $CAN/kg. On the other hand, the cost of separative work is relatively high, at approximately 100 $US/SWU, or 150 $CAN/SWU. This cost ratio of natural uranium to separative work suggests an optimal tails assay at the enrichment plant of about 0.35%;
- we assume that in the future, the price of natural uranium will rise (with increasing demand and depleting resources), while the price of separative work will decrease due to improvements in the technology (such as laser seperation) and increased competition. We have assumed a future price of 100 $CAN/kg for natural uranium, and a price of 100 $CAN/SWU for enrichment services. This would bring down the tails assay to 0.2%.
- fuel bundle fabrication costs will be higher for enriched fuel, particularily with bundles containing burnable poisons. On the basis of current fabrication costs of approximately 2000 $CAN per bundle for natural uranium fuel, we have assumed fabrication costs of $2500./bundle for SEU fuel, and $3000./bundle for SEU with poisons.

Results for annual fuelling costs are shown in Table 5, assuming 80% capacity factor in a CANDU 6 reactor.

According to our calculations, annual fuelling costs could be reduced significantly, by as much as 30%, by adopting the SEU fuel cycle immediately. This again illustrates that natural uranium is not optimal for a CANDU reactor with a lattice pitch of 28.6 cm. Of course, many other aspects are considered in the design, but the fact remains that our present CANDU lattice is over-moderated. One avenue to reduce void reactivity in the (long-term) future would therefore be to reduce the lattice pitch.

However, as discussed above, advanced fuel cycles offer the possibility of reducing the void reactivity, particularly with the use of burnable poisons. Comparing the predicted annual fuelling costs with the reference values in Table 5, we see that *the economic penalty associated with void reactivity reduction is quite large.* Plotting this penalty as a function of the void reactivity, we obtain Figure 11. From this figure, we note:

- the economic penalty is nearly linear when reducing void reactivity down to half the current value. Thus, in the range of void reactivity from 12 mk to 5 mk, *an economic penalty of approximately $1M/y per mk reduction* is to be expected;
- this penalty is expected to increase by about 20% in the future, when the price of natural uranium increases;
- further reduction of void reactivity, in the range of 5 mk to 0 mk, will be even more costly, at approximately $2M/y per mk reduction;
- *completely eliminating void reactivity is an expensive proposition,* leading to increases in annual operating costs between $12.5M/y and $23.5M/y.

V. CONCLUSION

The burnup penalty associated with a 25% increase in P/T thickness for NU fuel is of the order of 14%, which represents a few million dollars every year. For the same increase in tube thickness in a CANDU 6 fuelled with SEU12 fuel (2 bundle-shift) yields a penalty of only 3.2%, or a few 100k$'s per year. This reduction by a factor of 4 in the burnup penalty for the same pressure tube thickness increase illustrates the fact that SEU possesses high superiority over NU for increased P/T thickness design in the future.

Dy was found to control coolant void reactivity (CVR) effectively when it is used in the inner 8 pins with depleted uranium. CVR can be reduced to any desired value, even below zero. We found that zero CVR could be reached by mixing about 13.5% Dy with depleted uranium in the inner 8 pins, even with a 25% increase in P/T thickness. However, the discharge burnup is reduced by 70% compared to the case without the poison. In terms of annual fuelling costs, this represents a three-fold increase.

By comparison, the amount of Gd required to achieve the desired CVR is generally higher than that of Dy. Also, because of a more pronounced self-shielding effect with Gd, large variations in the instantaneous CVR with fuel burnup were observed, while the Dy shows relatively uniform control of CVR throughout the fuel burnup. Therefore, Dy appears to be more effective than Gd for the reduction of CVR.

We also conclude that reduction in void reactivity can be achieved with SEU 1.2% at the cost of approximately 1000 MWd/t(U) in burnup penalty per mk decrease in coolant void reactivity, regardless of the type of burnable poison used in the fuel.

Our calculations are very preliminary, and do not pretend to reflect an optimized LVRF design. For many reasons, including the economic penalty refered to above, low void reactivity is preferable to zero. In terms of annual fuelling costs, the economic penalty associated with void reactivity reduction is very significant. However, considering the inherent safety advantages provided by LVRF, it may well be worth it.

REFERENCES

1. M. H. Younis, P.G. Boczar, "Equilibrium Fuel Management Simulations for 1.2% SEU in a CANDU6", *Can. Nucl. Soc. 10th Ann. Conf*, Vol 2, June 4-7, 1989, Ottawa, Canada (1989).
2. P.S.W. Chan, J. Pitre, "The physics of disposing of Weapons-Grade Plutonium in CANDU Reactors", *Proc. Of the Am. Nucl. Soc. Tpl. Mtg. – Adv. In Nucl. Fuel Management II*, Mar. 23-26, 1997, Myrtle Beach, South Carolina, USA (1997).
3. Hangbok Choi, Bo W. Rhee, Hyunsoo Park, "Physics Study of Direct Use of Spent PWR fuel In CANDU (DUPIC)", *Nucl. Sci. Eng.*, **126**, 80, 1997.
4. W. Shen and D. Rozon, "Study of DUPIC Fuel Cycle in CANDU 6 Reactor with DRAGON/DONJON", *Intl. Conf. on the Physics of Nuclear Science and Technology*, Long Island, N.Y., October 1998.
5. P. G. Boczar et al., "A Low Void Reactivity CANDU Fuel Bundle", *Third International Conference on CANDU Fuel*, 1992 October, Chalk River, Canada.
6. A.R.Dastur, D.B.Buss, « The influence of Lattice Structure and Composition on the Coolant Void Reactivity in CANDU », *Proc. of the 11th Annual CNS Conference*, June 1990, Toronto, Canada.
7. A.R. Dastur, P.S.W. Chan, D. Bowslaugh, "The Use of Depleted Uranium for the Reduction of Void Reactivity in CANDU Reactor", *Proc. of the 13th Annual CNS Conference*, June 7-10 1992, Saint John, New Brunswick, Canada.
8. B.W.Rhee, H.B.Choi, et al, "A Comparative Analysis on Low Void Reactivity DUPIC Fuel Bundle", *Proc. Int. Conf. on Math., Compt. Reactor Physics, and Enviroment Analysis*, April 30-May 4, 1995, Portland, Oregan, USA.
9. H.P. Gupta, H.B. Choi, et al., "Burnable Poison Option for Reducing Void Reactivity of a DUPIC Fuel Bundle", *Am. Nucl. Soc.*, 75, 330, 1996.
10. G. Marleau, A. Hébert and R. Roy, *A User's Guide for DRAGON*, Report IGE-174 Rev 1, École Polytechnique de Montréal, Canada, March 1996.
11. E. Varin, A. Hebert, R. Roy and J. Koclas, *A User's Guide for DONJON*, Report IGE-208, Ecole Polytechnique de Montreal, Canada, April 1996.
12. D. Rozon, Wei Shen, "Comparison of Slightly Enriched Uranium fuel and MOX fuel in CANDU-6 Reactor", *Proc. of 19th Annual Conference of the Canadian Nuclear Society*, October 1998, Toronto, Canada.
13. M.T. Sissaoui, G. Marleau and D. Rozon, "CANDU Reactor Simulations using the Feedback Model with Actinide Burnup History", *Nuclear Technology, vol. 125,* Feb. 1999.

Table 1: Effect of pressure tube thickness on fuel discharge burnup and average void reactivity (mk) in CANDU6 with different fuel types

Fuel Type	Discharge Burnup (MWd/T)		Average Void Reactivity (mk)	
	100%P/T	125%P/T (Δ%)	100%P/T	125%P/T
Nat. U	7315	6286 (14.0%)	14.03	14.85
MOX 0.9 w/o	5899	5407 (8.3%)	11.61	12.20
MOX 1.2 w/o	12233	11712 (4.3%)	12.41	13.05
SEU 0.9 w/o	14006	13245 (5.4%)	13.69	14.39
SEU 1.2 w/o	21401	20712 (3.2%)	13.71	14.40

Table 2: Void reactivity (in mk) of CANDU6 with different fuel types

Fuel Type	2D Lattice Void Reactivity			3D System Void Reactivity (BS)
	Fresh	Average	Discharge	
Nat. U	17.93	14.85	13.50	15.39 (8BS)
SEU 0.9 w/o	16.57	14.39	12.51	14.72 (4BS)
SEU 1.2 w/o	15.22	14.40	11.59	14.30 (2BS)
MOX 0.9 w/o	12.54	12.20	11.76	12.12 (4BS)
MOX 1.2 w/o	13.44	13.05	11.49	12.56 (2BS)

Table 3: Effect of Dy on SEU12 CANFLEX fuel performance

Dy amount (wt%)		100%P/T		125%P/T	
Ring-1	Ring-2	Discharge Burnup MWD/T	Void Reactivity mk	Discharge Burnup MWD/T	Void Reactivity mk
0	0	21603	11.65	20956	12.27
0.5	0.5	17097	8.39	16438	8.97
1.0	1.0	12269	4.26	11461	4.68
1.1	1.1	11150	3.23	10264	3.58
1.2	1.2	9921	2.07	8916	2.32
1.3	1.3	8525	0.75	7319	0.84
1.4	1.4	6851	-0.80	5207	-1.01

Table 4: Comparison of Dy and Gd for SEU12 CANFLEX fuel (100%P/T)

BP amount (wt%) Ring-1 only	Dy Discharge Burnup MWD/T	Dy Void Reactivity mk	Gd Discharge Burnup MWD/T	Gd Void Reactivity mk
0	21430	13.34	21430	13.34
1	20312	12.25	21304	12.75
5	16658	8.24	19890	10.82
7.5	14957	6.26	18627	9.48
10	13707	4.83	16876	7.82
15	12251	3.25	12470	2.82
20	11513	2.53	11920	2.61
30	10785	1.87	11621	2.39
90	9665	-0.17	11317	1.68

Table 5: Fuelling costs estimate ($M/y)

	Current	Future
Natural uranium, $/kg	50	100
Separative work, $/SWU	150	100
Tails assay, w/o	0.35	0.2
Reference fuelling costs* $M/year		
Nat. U	13.84	18.21
SEU09	10.59	13.50
SEU12	*9.53*	*11.96*
LVRF(1.2%)		
Dy (1 Pin) 10 mk	11.24	14.04
5 mk	15.10	18.86
0 mk	*22.07*	*27.56*
Dy (8 Pins) 10 mk	11.97	14.12
5 mk	17.27	20.84
0 mk	*29.36*	*35.44*

* Assuming 80% capacity factor in CANDU-6, and bundle fabrication costs of $2000./bundle for NU, $2500./bundle for SEU and $3000./bundle for SEU with poisons. (100% P/T)

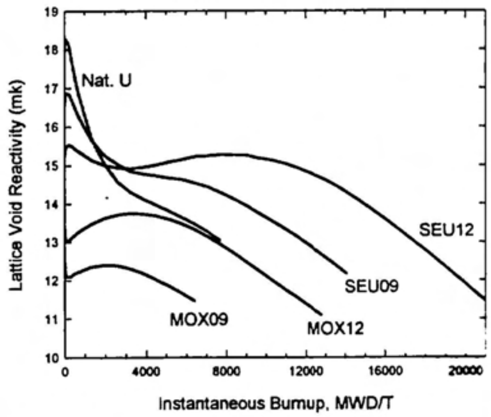

Figure 1: CANDU Lattice Void Reactivity vs. Instantaneous Burnup for Various fuels (125%P/T, CANFLEX)

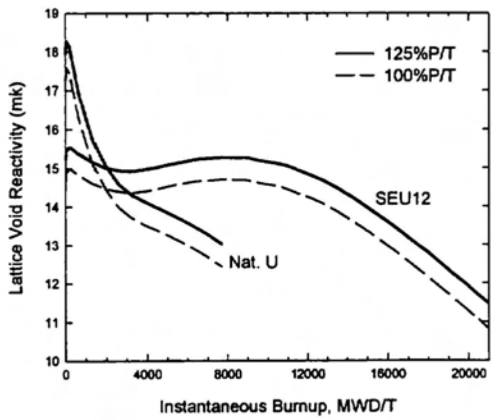

Figure 2: CANDU Lattice Void Reactivity vs. Instantaneous Burnup for SEU12 and NAT fuels (CANFLEX)

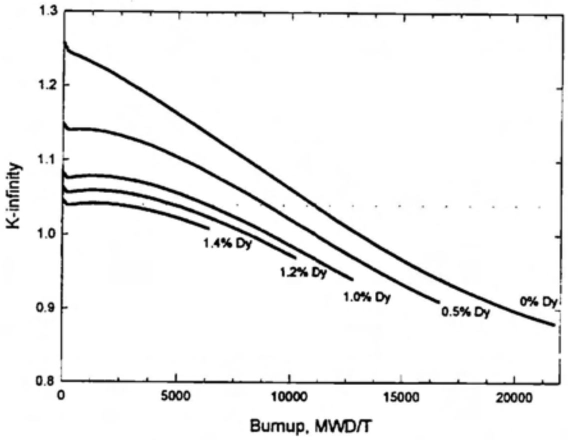

Figure 3: CANDU Lattice K-Infinity for SEU12 fuels
(125%P/T, CANFLEX, Dy+depleted U in inner 8 pins)

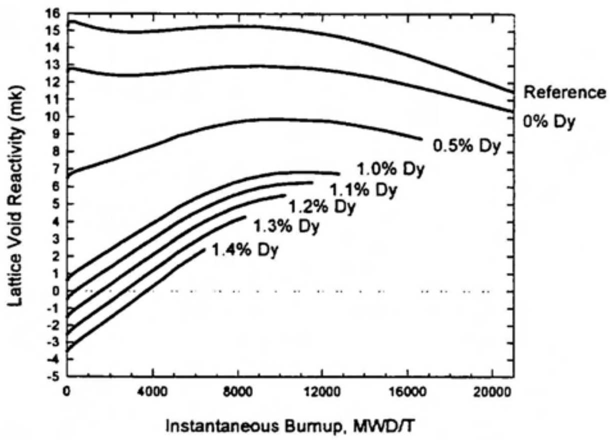

Figure 4: CANDU Lattice Void Reactivity for SEU12 fuels
(125%P/T, CANFLEX, Dy+depeleted U in inner 8 pins)

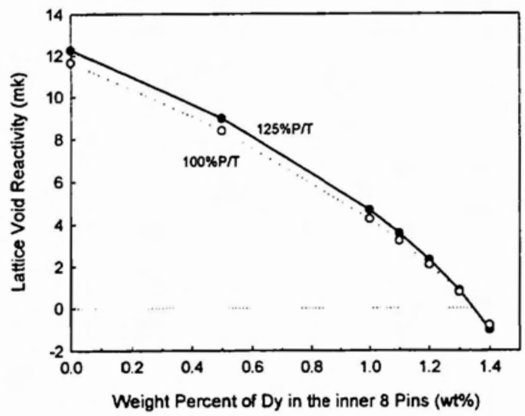

Figure 5: Equilibrium Lattice Void Reactivity Vs. Dy Content in the Inner 8 Pins (SEU12, CANFLEX)

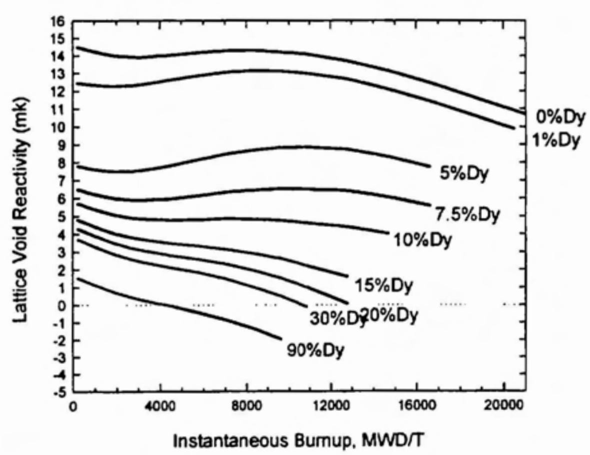

Figure 6: CANDU Lattice Void Reactivity for SEU12 fuels (100%P/T, CANFLEX, Dy+depleted U in the central pin)

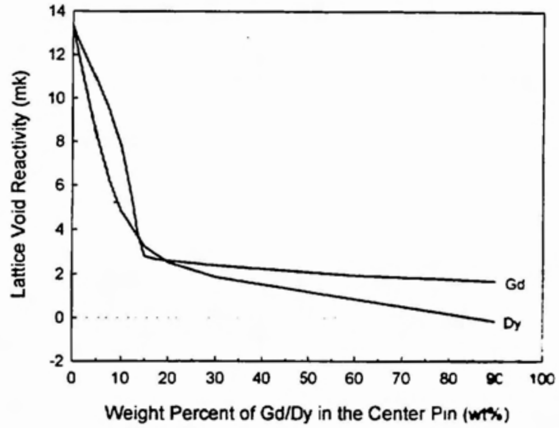

Figure 7 : Equilibrium Lattice Void Reactivity Vs. Gd/Dy Content in the Central Pin (SEU12, 100% P/T, CANFLEX)

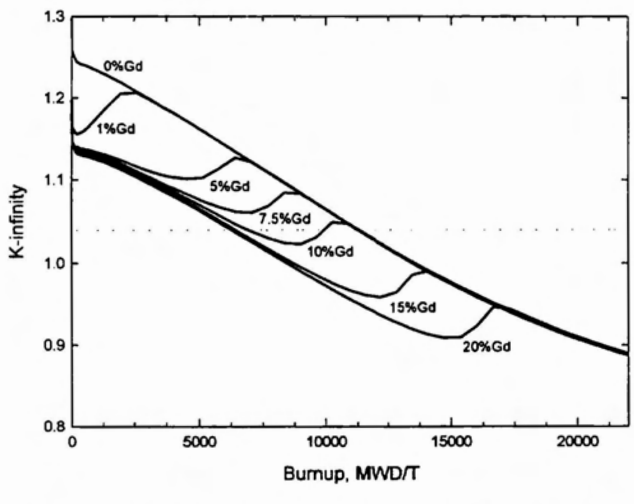

Figure 8: CANDU Lattice K-Infinity for SEU12 fuels (100%P/T, CANFLEX, Gd+depleted U in the central pin)

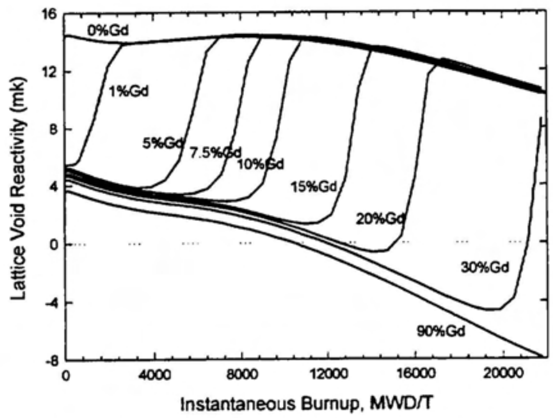

Figure 9: CANDU Lattice Void Reactivity for SEU12 fuels (100%P/T, CANFLEX, Gd+depleted U in the Central Pin)

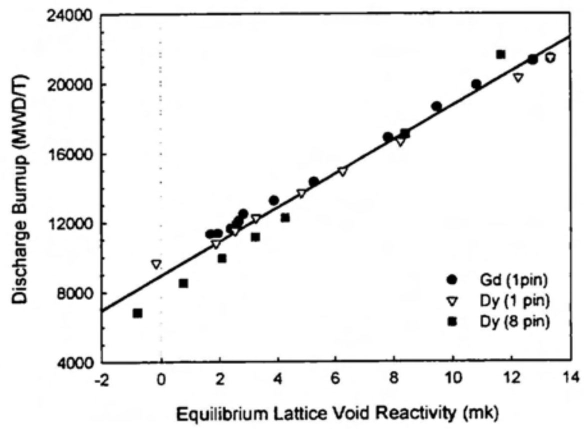

Figure 10: Fuel Discharge Burnup Vs. Lattice Void Reactivity (SEU12, 100%P/T, CANFLEX)

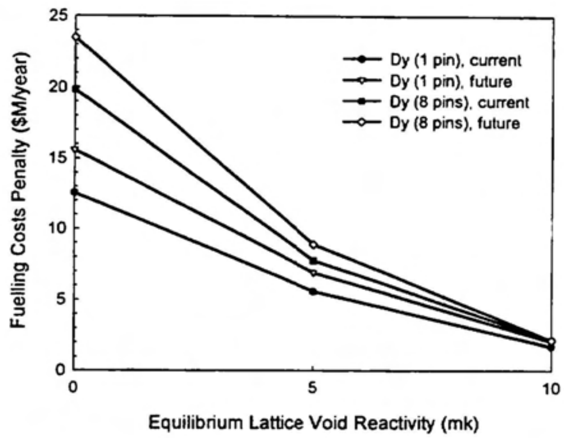

Figure 11: Fuelling Costs Penalty Vs. Lattice Void Reactivity
(SEU12, 100%P/T, CANFLEX)