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STUDY OF A TANDEM FUEL CYCLE BETWEEN A BRAZILIAN PWR (ANGRA-I) AND AN ARGENTINIAN CANDU (EMBALSE)

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Abstract—The introduction of advanced fuel cycles in commercial reactors provides a better utilization of natural resources, increases the efficiency and contributes to reduce the amount of wastes to be disposed.

On face of the nuclear programs of Brazil and Argentina, the TANDEM cycle could be considered a convenient way to integrate both fuel cycles, achieving some of the mentioned advantages.

This paper describes a first study of this synergistic fuel cycle, between the Brazilian PWR (Angra-I) and the Argentinean CANDU reactor (Embalse).

Calculations of several parameters of the cycle were performed, as determination of the compositions of the PWR's spent fuel for different cooling times, optimum blending ratio considering that the fuel will be diluted with natural uranium, extraction burn-up for the CANDU with MOX fuel, mass flows in the bi-national system, multiplication factors for the new fuel, and estimations of the fuel cycle costs.

The study shows that, if the main goal is to minimize the bi-national uranium consumption, the ideal blending for the fuel is 38% of natural uranium in heavy metal (U and Pu), which comes from coprocessed spent fuel of the PWR, considering one year of cooling time.

Using this blending ratio, the extraction burn-up of the CANDU is increased up to 22,500 MWD/ton U, giving an economy of 84 ton U/year, nearly 50% for the bi-national system. The fuel cycle cost did not show significant variations compared with the natural uranium fuel cycle.

Finally, a calculation of the ingestion toxicity was made for the TANDEM cycle and compared with the isolated reactor cycles, showing a reduction of at least 20% during a one million years period.

INTRODUCTION

The advanced fuel cycle called TANDEM was proposed some years ago as an option to save natural uranium resources, and also to reduce the quantities of wastes with high level of radioactivity (Veeder and Didsbury, 1985; Boczar *et al.* 1989).

The basic idea of this TANDEM cycle is to burn in heavy water reactors, especially of CANDU (Canadian-deuterium–uranium) type, the remaining fissile material of spent fuel elements from PWRs, which still contain approx. 1.5% of U^{235} and plutonium; after its extraction from the PWR, the fuel is chemically decontaminated or coprocessed, removing the fission products and extracting uranium and plutonium together, without separating them into different streams; this material is afterwards blended with natural or depleted uranium, to be used in the CANDU reactor as mixed oxide fuel, MOX [$(U–Pu)O_2$]. In the case of this paper natural uranium was chosen as blending material. Figure 1 shows a scheme of a TANDEM fuel cycle.

Argentina and Brazil, neighbour South American countries, have initiated their nuclear programs almost at the same time (in the decade of the 1970s), and at present time they have achieved almost the same level of technical development.

In choosing their reactors, Argentina took the line of natural uranium – heavy water nuclear power reactors, having at present a KWU-Siemens PHWR (Atucha-I; 326 MWe) and a Canadian CANDU reactor

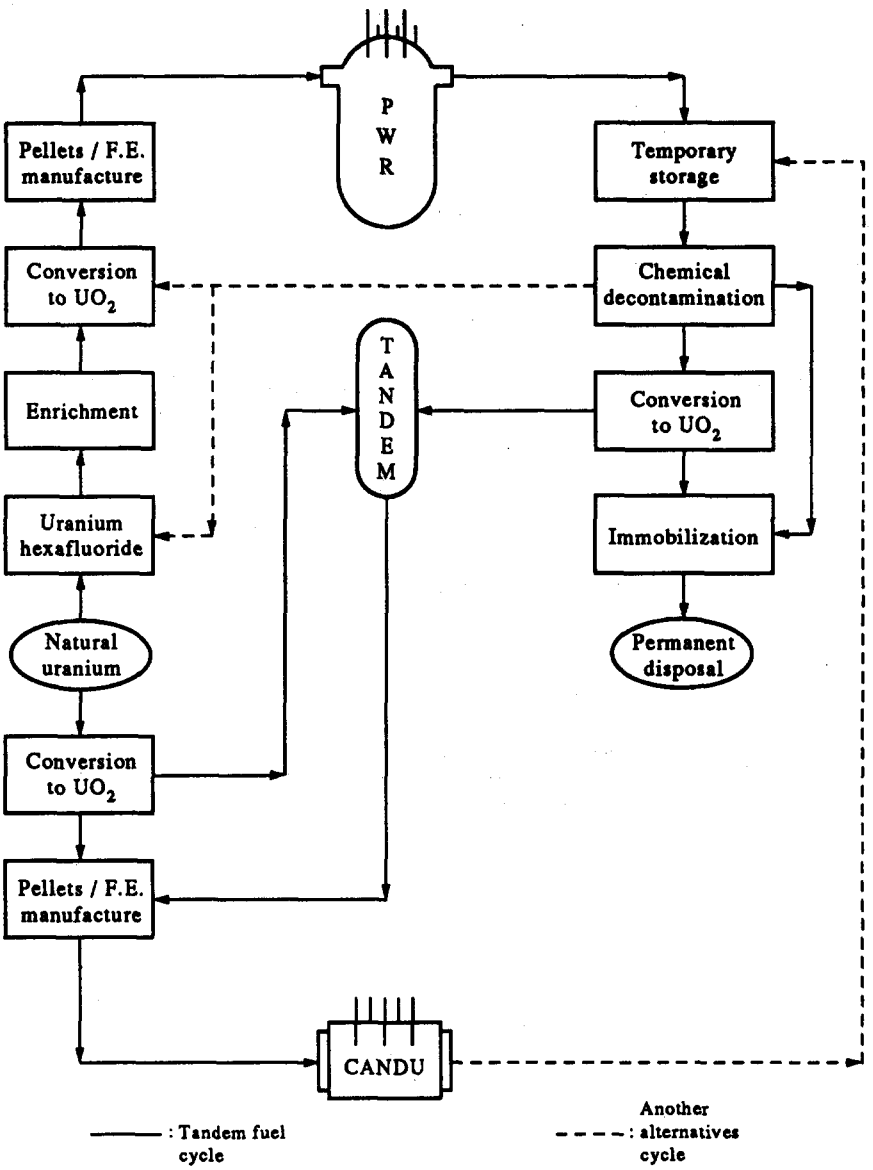

Fig. 1. Scheme of a TANDEM fuel cycle.

(Embalse, 608 MWe) under operation, and another PHWR, also of KWU-Siemens (Atucha-II, 692 MWe), under construction. Brazil had chosen the line of enriched uranium – light water reactors, having a Westinghouse PWR (Angra-I, 626 MWe) under operation, and a KWU-Siemens PWR (Angra-II, 1200 MWe) under construction.

The nuclear reactor choice of these two countries, their proximity, and the recent economical and political approximations, justify the performance of a feasibility study of a TANDEM fuel cycle between their reactors, particularly between the PWR Angra-I, and the CANDU reactor Embalse. Table 1 shows the main characteristics of these reactors.

Between the two Argentinian reactors, Embalse was chosen because its fuel elements are shorter, with lower fabrication costs, easier manipulation, better neutronic behavior and more flexible possibilities for fuel management strategies.

Table 1. Main characteristics of the reactors involved in the study

REACTOR	ARGENTINA	BRAZIL
Type of reactor	CANDU-6	PWR
Nominal electric power	608 MW	626 MW
Thermal power (coolant)	2105.4 MW	1876 MW
Specific power	34.77 kW/kg	37.75 kW/kg
Moderator temperature	71 °C	-
Coolant temperature (in)	266 °C	287 °C
Coolant temperature (out)	305 °C	324.4 °C
Coolant pressure	10 MPa	15.2 MPa
Radius of the active core	314.27 cm	122.5 cm
Axial length	594.36 cm	365.8 cm
Number of channels	380	-
Lattice	Square (Pitch=28.575 cm)	Square (Pitch=19.83 cm)
FUEL ELEMENT		
Maximum power	830 kW	9021 kW
Number of rods	37	235
Radius of the second ring	1.488 cm	-
Radius of the thrird ring	2.875 cm	-
Radius of the fourth ring	4.331 cm	-
FUEL ROD		
Outer radius	0.698 cm	0.475 cm
Radius of the pellet	0.608 cm	0.409 cm
Number of pellets in each rod	29	272
Clad inner radius	0.650 cm	0.418 cm
Clad thickness	0.049 cm	0.057 cm
Clad material	Zircaloy-2	Zircaloy-4

Many parameters of the fuel cycle were calculated in this work, as determination of the compositions of the PWR's spent fuel for different cooling times, optimum blending ratio with natural uranium, extraction burn-up for the new CANDU configuration with MOX fuel, mass flows in the bi-national system, multiplication factors for the new fuel, estimations of the fuel cycle costs, and ingestion toxicity.

CALCULATIONS, ANALYSIS AND RESULTS

All the calculations of this TANDEM cycle were made using ORIGEN2.1 (Croff, 1983); WIMS-D/4 (Askew *et al.*, 1966; Taubman, 1975) and PERCICO (Passadore, 1992) codes, and a simple and very convenient methodology using the concepts of Equivalent Plutonium and Equivalent Peak Factor (Perez Tumini, 1993).

The amount of uranium and plutonium produced at the discharge of Angra-I was calculated with ORIGEN2.1, for three different cooling times (1, 3 and 5 years) before its coprocessing and use in the

Table 2. Discharge of Angra-I was calculated with ORIGEN2.1 for 1, 3 and 5 years cooling times (g/F.E.)

YEAR	U-235	U-236	U-238	Pu-239	Pu-240	Pu-241	Pu-242
1	3.463+3	1.631+3	3.711+5	1.974+3	8.930+2	4.438+2	1.652+2
3	3.463+3	1.631+3	3.711+5	1.974+3	8.934+2	4.028+2	1.652+2
5	3.463+3	1.631+3	3.711+5	1.974+3	8.937+2	3.659+2	1.652+2

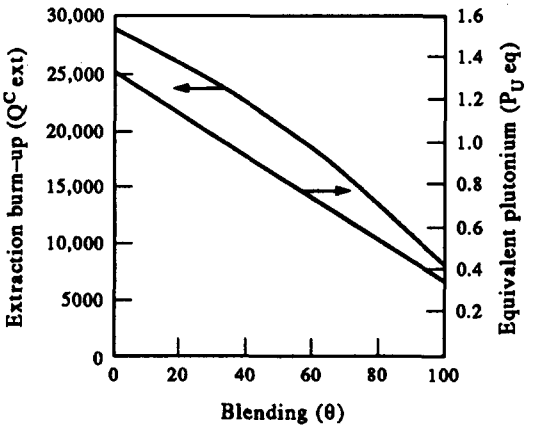

Fig. 2. Equivalent plutonium and burn-up vs blending ratio.

CANDU, and considering an equilibrium cycle for the PWR with an average enrichment of 3.4% at the beginning of the cycle, and an extraction burn-up of 33,000 MWd/ton U. Table 2 shows these results.

For this type of reactor and blending material, a quantity called Equivalent Plutonium (Pu^{eq}) can be easily computed for each composition of the fuel, and therefore for different blending ratios (ratio between the amount of natural uranium and the amount of uranium and plutonium coming from the decontaminated PWR fuel), using the expressions found in the reference (Perez Tumini, 1993); it is also possible to define a correlation between the Equivalent Plutonium of each composition and its correspondent burn-up.

The equation which corresponds to that correlation can be inverted, and in this way it is very easy to determine a very good approximate value for the extraction burn-up of the Candu reactor (Q^C_{ext}), as a function of the Equivalent Plutonium, and consequently of the blending ratio θ.

In Fig. 2, the variations of the Pu^{eq} and Q^C_{ext} with the blending ratio (θ) are shown.

In the same way as Equivalent Plutonium is defined, a quantity called "Equivalent Peak Factor" can also be calculated, relating the multiplication factor at the beginning of the cycle ($K_{eff(0)}$) with the composition of the fuel for the CANDU reactor.

Using the same procedure as before, PF^{eq} and $K_{eff(0)}$ can be determined as a function of the blending ratio, as shown in Fig. 3.

As in any other fuel cycle analysis, to determine the ideal blending ratio one should first decide which of the cycle parameters will be optimized, because the value of K_{eff} at the beginning of the cycle will be related to many other quantities, such as utilization of uranium resources, cost of energy, amount of radioactive wastes, etc.

In this paper the goal is to optimize the utilization of the uranium resources of both countries; then, taking several values of $K_{eff}(0)$, and its correspondent blending ratio (θ), a flow mass of uranium in the bi-national system (see Fig. 1) can be calculated for each blending ratio. Figure 4 shows the consumption of uranium for the bi-national system normalized to 1 GWe-year (where it has been assumed that both reactors have the same capacity factor) as a function of the initial multiplication factor chosen for the CANDU.

The minimum value of the bi-national uranium utilization curve indicates an optimum initial multiplication factor of 1.32–1.33, which agrees with the value reported in the literature for similar cases [$K_{eff}(0) = 1.32763$, (Perez Tumini 1993)].

Therefore, using this value of $K_{eff}(0)$, the blending ratios for the considered cooling times should be:

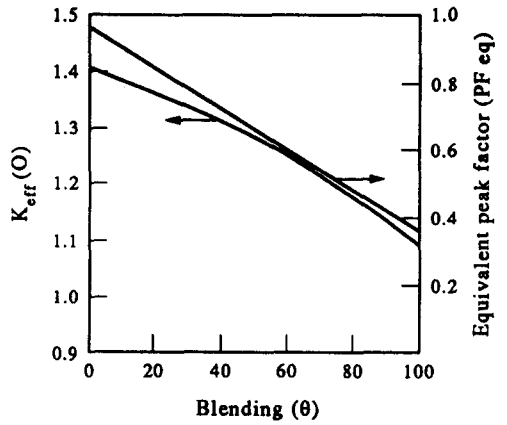

Fig. 3. Equivalent peak factor and k-effective for the fresh fuel, vs blending ratio.

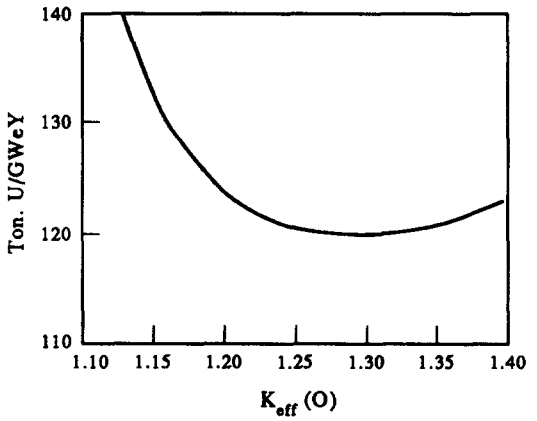

Fig. 4. Uranium bi-national consumption vs k_{eff} at the beginning of the cycle.

$$\theta(1 \text{ year}) = 0.38$$
$$\theta(3 \text{ years}) = 0.36$$
and
$$\theta(5 \text{ years}) = 0.34.$$

It should also be noted that the blending ratios obtained in this work for 5 years of cooling time agrees with the ones reported in the literature (Veeder and Didsbury, 1985).

With those blending ratios, the extraction burn-ups obtained for the CANDU are:

$$Q^{C}_{ext}(1 \text{ year }) = 22{,}525 \text{ MWd/ton U},$$
$$Q^{C}_{ext}(3 \text{ years}) = 22{,}686 \text{ MWd/ton U}$$
and
$$Q^{C}_{ext}(5 \text{ years}) = 22{,}835 \text{ MWd/ton U},$$

which shows a very important increase (of about 3 times) over the actual CANDU extraction burn-up with natural uranium ($Q_{ext} = 7500$ MWd/ton U) in all the cases, and a very low sensitivity to the considered cooling time in the range of 1–5 years.

With these blending ratios, and using the data from Table 2, the atomic concentrations of the uraniums

Table 3. Atomic concentrations of the uraniums and plutoniums for 1, 3 and 5 years cooling times used in the WIMS-D/4 code with 0.34, 0.36 and 0.38 blending ratios (at/b.cm)

YEAR	U-235	U-236	U-238	Pu-239	Pu-240	Pu-241	Pu-242
1	1.897-4	6.042-5	2.223-3	7.222-5	3.261-5	1.601-5	5.973-6
3	1.906-4	6.251-5	2.222-2	7.469-5	3.350-5	1.512-5	5.973-6
5	1.915-4	6.451-5	2.222-2	7.693-5	3.462-5	1.401-5	6.197-6

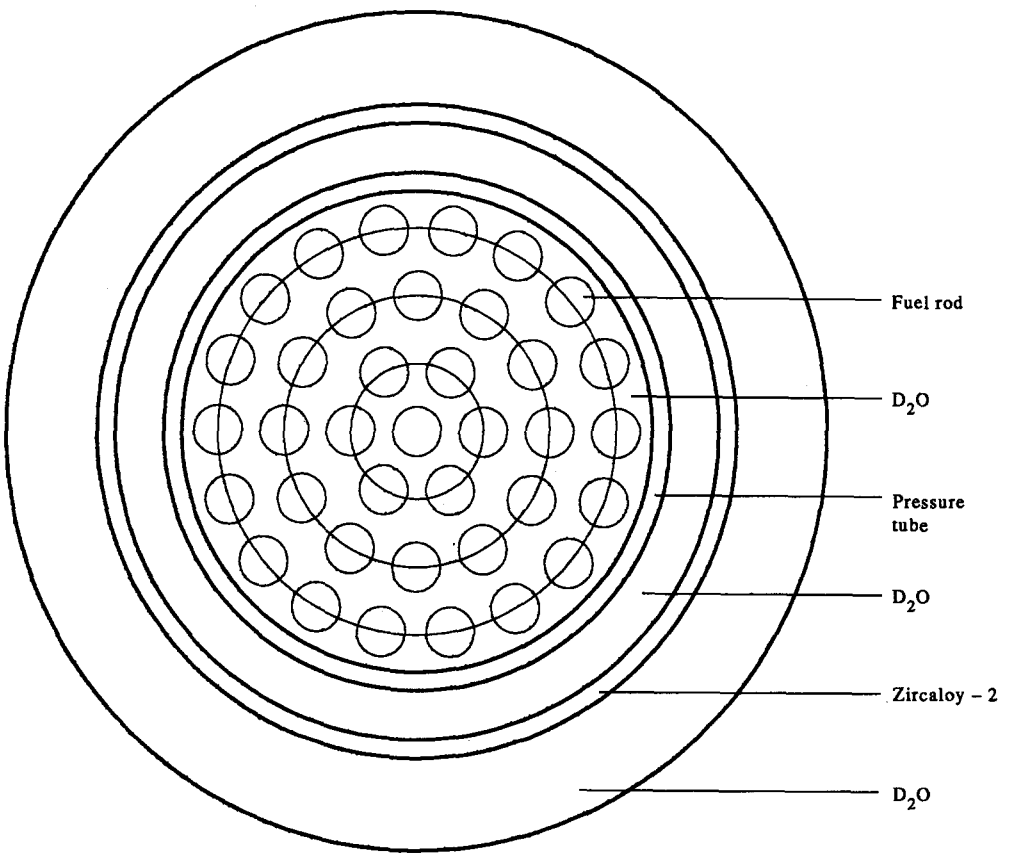

Fig. 5. Schematic of a CANDU cell.

and plutoniums in the MOX fuel can be calculated (see Table 3) and used in the WIMS-D/4 code to make a detailed calculation of the typical cells for the CANDU reactor (Fig. 5).

The initial values of the multiplication factor calculated by the WIMS-D/4 code for the considered cooling times were:

$$K^{O}_{eff}(1 \text{ year}) = 1.30926$$
$$K^{O}_{eff}(3 \text{ years}) = 1.30998$$

and

$$K^{O}_{eff} \ (3 \text{ years}) = 1.30927.$$

It should be noted that the excess of reactivity for the MOX fuel is high; it indicates that some changes could be necessary, as the usage of a different fuel management strategy (check-board type), or the inclusion of burnable poisons.

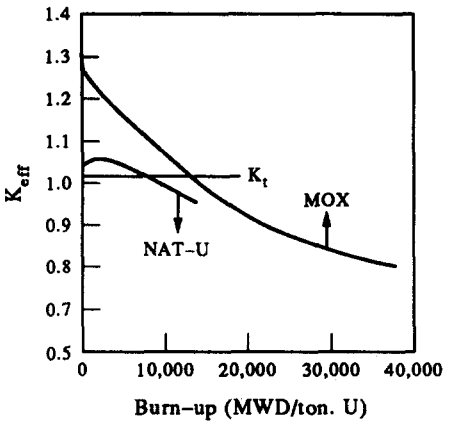

Fig. 6. Variation of K-eff with burn-up, for MOX fuel with a blending ratio of 0.38 and for natural uranium fuel.

The variation of K_{eff} with burn-up, calculated by WIMS-D/4 for the mixed oxide fuel, considering 1 year of cooling time and a blending ratio of 0.38, is shown in Fig. 6.

In the same figure K_{eff} vs burn-up for a natural uranium CANDU cell is shown, as well as the work multiplication factor for Embalse ($K_t = 1.02028$), which is the multiplication factor in which the reactor operates during its life time. Using the K_t value, the average and extraction burn-ups can be determined for the two cycles (natural uranium and TANDEM).

The extraction burn-up for the CANDU reactor with natural uranium is 7500 MWd/T, and the value of burn-up obtained for the new TANDEM cycle is 22,500 MWd/T, which confirms the preliminary result obtained with the methodology of Equivalent Plutonium.

As it was previously said, the neutronic behaviour of a mixed oxide fuel CANDU is not sensitive to the cooling time used for the chemical decontamination.

It should also be noted that the multiplication factor calculated by WIMS has a difference of approx. 1800 pcm (1.5%) with the value obtained with the methodology of Equivalent Parameters (correlations), while in burn-ups the results are almost equal. These differences are very low and completely acceptable considering the simplicity of the method; this result confirms the adequacy of the method of Equivalent Plutonium for this case, if the purpose is the estimation of the main fuel cycle parameters.

In order to establish a mass flow of uranium between the two reactors, the mass balance can be defined as:

$$\frac{P_{PWR} f_{PWR} Q_{ext}^{PWR}}{P_{CANDU} f_{CANDU} Q_{ext}^{CANDU}} = \frac{1-\theta}{\eta},$$

where P, f and Q are the power, capacity factor, and burn-up, respectively, and η is the efficiency in the decontamination process, assumed in this case as $\eta = 0.99$.

Thus, using the data of Table 1, and assuming $f_{PWR} = f_{CANDU}$, for an extraction burn-up of 33,000 MWd/ton U for the PWR, the extraction burn-up for the CANDU with fuel made with heavy metal with 1, 3 and 5 years of cooling time would be 22,000; 22,709; and 22,419 MWd/ton U respectively.

Therefore, comparing these numbers with the calculated extraction burn-up for the CANDU reactor, it can be seen that there is a very small deficit of mass to feed it, and so it can be roughly assumed that Angra-I can feed Embalse, more or less in a 1.0 to 1.0 relation.

Finally, assuming that an equilibrium feed of Angra-I is 15.7 ton U/year, the heavy metal (U–Pu) produced would be 14.8 ton HM/year (Mai and Maiorino, 1993), and that a feed of heavy metal in the CANDU is

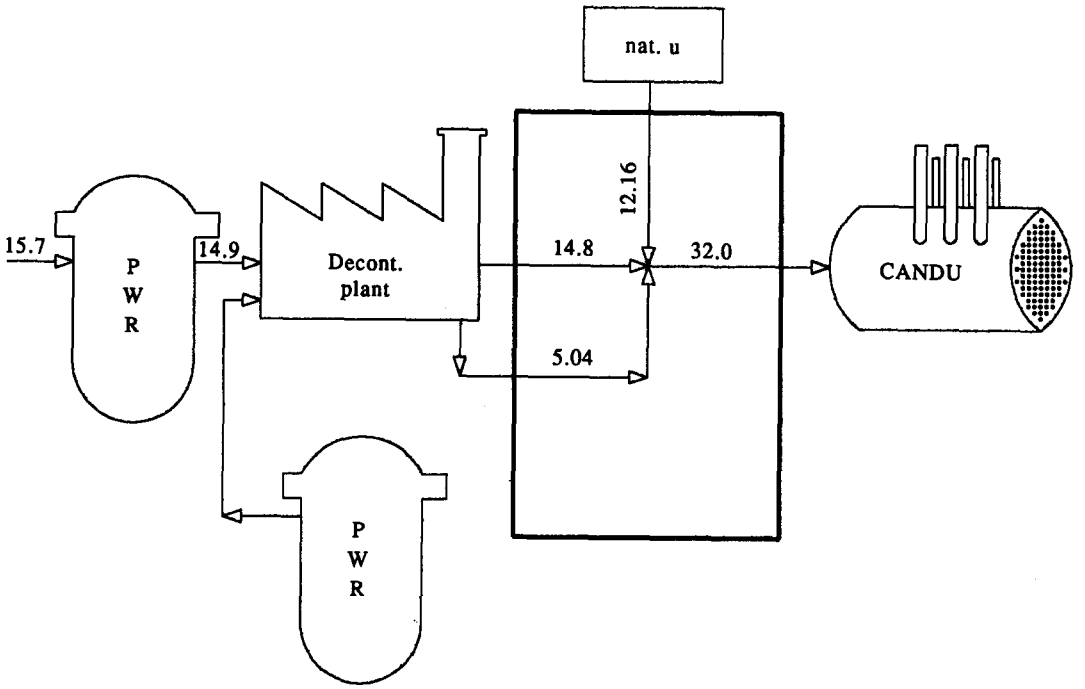

Fig. 7. Mass flow between both reactors.

Table 4. Values used in Argentina for the fuel cycle cost estimation

Yellow cake cost	80 US$/kg
UO_2 conversion	5 US$/kg
UF_6 conversion	5 US$/kg
Wet storage	60 US$/kg HM
Dry storage	20 US$/kg HM
Transport	40 US$/kg HM
Final Disposal	350 US$/kg HM
Reprocessing	650 US$/kg HM

32.0 ton HM/year (for a burn-up of 22,500 MWd/ton HM), with a blending ratio of 38% of natural uranium the resultant mass flow between Angra-I and Embalse can be seen in Fig. 7.

In order to obtain an estimation of the fuel cycle cost, the code PERCICO (Passadore, 1992) and the data shown in Table 4 (Bergallo and Barcelo, 1993) were used.

The Fig. 8 shows the obtained results for the fuel cycle cost, as a function of the blending ratios (θ).

From that figure it should be noted that, for the ideal blending obtained in this work, the fuel cycle cost is around 7.5 mills/kWh, which is almost the same as the one for the natural uranium fuel cycle.

The result shows that, at the present time uranium cost, a TANDEM cycle blending with natural uranium will not significantly change the economy. However the increment of the uranium price would make TANDEM cycle even more interesting.

Regarding the utilization of the uranium, as the burn-up is almost triplicated (from 7500 MWd/THM to 22500 MWd/THM), nearly 84 ton U/year are saved, producing an economy of approx. 50% of the uranium supply for the bi-national system.

It can also be noted that, at the beginning of the cycle, the excess of reactivity for the MOX fuel is high; it indicates that some changes could be necessary, as the usage of a different fuel management strategy (check-board type), or the inclusion of burnable poisons. The possibility of keeping in the fuel some transuranics, as americium or curium should be considered, because they could act as the needed poisons.

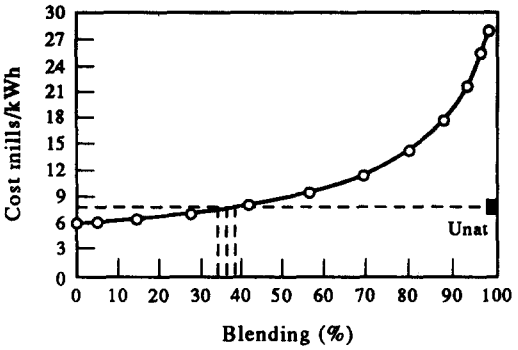

Fig. 8. Fuel cycle cost vs blending ratio.

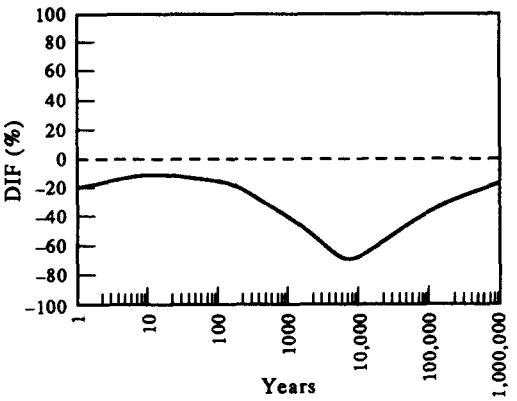

Fig. 9. Difference in the activity of the fuel with and without synergism between both reactors.

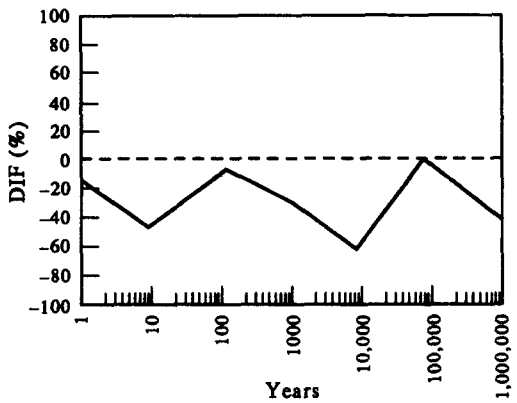

Fig. 10. Difference in the toxicity of the fuel with and without synergism between both reactors.

Finally, the variation with time of the activity of the fuel and the ingestion toxicity (Benedict *et al.*, 1981) were calculated up to one million years. Ingestion toxicity is defined as:

$$T = \Sigma\, A_i/(\text{mpc})$$

where A_i is the activity of the fission product i and (mpc) is its maximum permissible concentration (Benedict *et al.*, 1981). The calculations were made by ORIGEN2.1, for a once through LWR (Angra-I) and for the CANDU reactor (Embalse) used in a natural uranium fuel cycle and in the TANDEM fuel cycle.

The Figs 9 and 10 show the percentual differences for both parameters, between both reactors used

separated (Angra plus Embalse with natural uranium) or in a synergistic way (Angra plus Embalse in TANDEM). We note a lessening of the order 20% in both cases.

Due to the big relative importance of the actinides in the activity of the wastes especially at very long times, it is considered of interest to analyze the possibility of including them in the MOX fuel for the TANDEM cycle, also as a way to burn them. It would be performed in the next step of this work, because new nuclear data libraries are needed.

CONCLUSIONS

The results of this preliminary study were very promising.

Considering as the main goal the minimization of the bi-national uranium consumption, it confirms that the TANDEM fuel cycle is a very attractive and convenient option for both countries in the considered case.

The blending ratio (between natural uranium and decontaminated spent fuel) to be used in the fabrication of the MOX fuel for the CANDU reactor, depends only slightly from the cooling time before coprocessing, and from one year on the variations are not significant. It can be concluded that 38% of natural uranium can be taken as reference value and it minimizes the bi-national consumption.

Using this blending ratio, the extraction burn-up of the CANDU is increased up to 22,500 MWd/THM, approximately three times the present value, which implies an economy of 84 ton U/year, nearly 50% for the bi-national system. This circumstance is very important because it implies a big reduction of wastes in the different steps of the fuel cycle processing.

In this particular case, the flow mass from PWR to PHWR results in 14.8 ton/year, which means a deficit of 5 ton/year. From a practical point of view, this quantity should be supplied from stocks, or a dilution increment should be done.

The estimated cost for the kWh in this TANDEM cycle is maintained in the order of the one of the natural uranium cycle (7.5 mills/kWh).

Finally, the calculation of the ingestion toxicity of this TANDEM cycle compared with the fuel cycles without synergism, showed a reduction of at least 20%, during a one million years period.

Other alternatives for dilution material as depleted uranium, HWR decontaminated spent fuel, etc., would be considered in the future instead of natural uranium, and some of them could imply better characteristics.

Further calculations must also take into account a better treatment of actinides (for example inclusion of curium, neptunium, and americium isotopes) which play a very important role in this type of fuel cycle. It implies that new nuclear data libraries should be used.

It can also be noted that, at the beginning of the cycle, the excess of reactivity for the MOX fuel is high; it indicates that some changes could be necessary, as the usage of a different fuel management strategy (checkboard type), or the inclusion of burnable poisons. The possibility of keeping in the fuel some transuranics, as americium or curium should also be considered, because they could act as the needed poisons.

Finally, it was verified that the methodology which makes use of the concepts of Equivalent Plutonium and equivalent peak factor greatly simplifies the burn-up and blending ratio calculation for preliminary fuel cycle analysis, giving results with very good approximation.

Considering the very interesting and promising results obtained, a new step of calculations, design oriented, will be performed, reviewing the numbers presented here. The economical analysis of this new fuel cycle needs also further refinement.

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