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Research Article

Conceptual Engineering of CARA Fuel Element with Negative Void Coefficient for Atucha II

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Experimentally validated void reactivity calculations were used to study the feasibility of a change in the design basis of Atucha II Nuclear Power Plant including the Large LOCA event. The use of CARA fuel element with burnable neutronic absorbers and enriched uranium is proposed instead of the original fuel. The void reactivity, refuelling costs, and power peaking factors are analysed at conceptual level to optimize the burnable neutronic absorber, the enrichment grade, and their distribution inside the fuel. This work concludes that, for the considered plant conditions, either a void reactivity coefficient granting no prompt critical excursion on Large LOCA or negative void reactivity is achievable, with advantages on refuelling cost and linear power density.

1. Introduction

In the three Argentinean Nuclear Power Plants (NPPs) in operation and construction, the heavy water is the neutron moderator and primary coolant (PHWR): Embalse NPP is a pressure tube CANDU 6 reactor designed by AECL, and Atucha I and Atucha II (currently under construction) are pressure vessel PHWRs designed by Siemens. This design feature produces a positive coolant void coefficient.

Atucha II has a greater core hence, its coolant void reactivity is larger than the delayed neutrons fraction (β), which could lead to a prompt critical condition on a postulated Large LOCA event. Embalse, despite having a void coefficient slightly greater than β (which has been reduced by dividing the primary circuit in two loops), can be considered as prompt subcritical on a postulated Large LOCA provided its prompt neutron lifetime is larger than that for LWRs [1]. Atucha I has a positive void coefficient, but the smaller core size reduces the total reactivity effect on a postulated large LOCA.

The CARA fuel element [2] is a concept designed to replace the original fuel elements of all PHWRs operating in Argentina with the same bundle. The advantages of the CARA fuel are its lower cycle cost in comparison to Embalse, Atucha I and Atucha II, its lower linear and surface power, which leads to greater DNBR and less pellet-cladding interaction.

The key differences between CARA (Figure 1) and the current fuels are in its larger number of rods (52 instead of 37) with collapsible cladding, its optimized enrichment achieving lower cost, its lower pressure drop spacer grid design, and its overall dimensions that allow it to be used in the three NPPs. An additional assembly system enables its use in the vertical coolant channels of the Atucha reactors [3].

It must be said that at the relative low burnup required in an HWR (even when SEU is used), the same collapsible fuel rods could be used in both Atucha and CANDU reactors. This was calculated in the conceptual design stage of the CARA fuel [4], and was supported by the assessment of the different fuel failure design criteria originally used for the two fuels [5].

In this work, the main features of CARA mentioned above are conserved while adding different Burnable Neutronic Absorbers (BNA) and different uranium enrichment

Figure 1: CARA Fuel.

grades to achieve a smaller positive void reactivity, considering the costs and its use in the three NPP in Argentina, at conceptual level.

2. Void Coefficient Neutronics and Validation

Void coefficient neutronics in PHWRs has been studied for many years [6] and it shows to be quite complex. A brief summary is given of what is known at present. A conceptual study about how to achieve a given void coefficient needs to include the difference between the calculated values and the experimental results, in order to ensure that values of the real cores operate under the prescribed limit. Then an experimental validation is presented for the neutronic codes and models used in this work, to quantify the difference between the calculated and experimental values.

2.1. Void Coefficient Neutronics. Heavy water moderated reactors increase their reactivity when they undergo coolant water voiding. The main consequences of coolant voiding on the fuel element neutron physics are as follows [7].

Spectral Changes.

(1) Decrease in epi thermal neutron flux and increase in fast neutron flux within the bundle. These neutrons whose energy increases are those normally moderated by the coolant.

   (a) Less resonance absorptions and more fast fissions on ^{238}U

(2) Cooling down of the mean neutron temperature. In the PHWRs, the neutrons are moderated at an intermediate temperature between moderator and coolant temperatures. The spectral effect of the coolant is to rise up the neutron temperature. Therefore, a coolant void fraction leads to a cooler neutron temperature.

   (a) Less resonance absorptions on ^{238}U. Idem with ^{240}Pu.

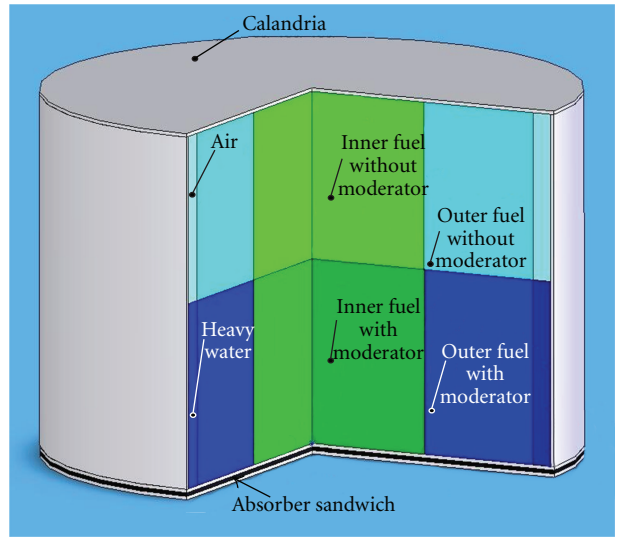

Figure 2: DCA Core zones.

   (b) Less absorptions on ^{239}Pu (this isotope also decreases its fissions, but in a smaller percentage). Idem with ^{241}Pu.

Spatial Changes.

(1) less self-shielding in the bundle due to larger migration area.

   (a) Importance increase for the inner rods in the bundle. Absorptions/fissions change depend on the composition of the inner rods compared with that of the outer rods. Normally inner rods are fresher, that is, have more fissile material and less fission product absorbers, thus introducing positive reactivity.

   (b) More leakage from the whole core due to larger migration area.

All of the items mentioned above represent a positive contribution to reactivity with coolant voiding, whereas for the last one there is a negative contribution because of the increase in core leakage. For this reason, smaller cores like Atucha I have smaller Void Reactivity, compared with larger cores, like Atucha II.

2.2. Validation. The uncertainties in the void coefficient calculation were evaluated by modelling an experimental criticality benchmark of the Deuterium Critical Assembly (DCA), [8, 9]. The DCA benchmark is an experimental benchmark in which the criticality is achieved by controlling the moderator heavy water level. The cores are square lattices of vertical fuel bundles in a cylindrical core tank in a geometry similar to a vertical CANDU or Atucha core. The experimental values where obtained with different uranium and plutonium isotopic compositions in the fuel bundles, with and without heavy water in the coolant channel.

Table 1: Validation results on the effective multiplication factor.

Core*	WIMSD-5–CITATION		MCNP[KAERI] [8]		WIMS-ATR–CIT[KAERI] [8]	
	With coolant	100% Void	With coolant	100% Void	With coolant	100% Void
1.2% U (97)	1.00394	0.99910	0.99851	0.99712	0.99627	0.99739
5Spu (25)	1.00274	0.99865	0.99432	0.99345	0.99383	0.99508
8Spu (25)	1.00236	0.99832	0.99635	0.99530	0.99317	0.99563
0.7% U (25)	0.99646	0.99215	1.00070	0.99959	0.99827	1.00203
1.5% U (13)	1.00205	0.99832	1.00041	0.99875	0.99635	1.00933
Average	1.00151	0.99730	0.99806	0.99684	0.99558	0.99989
St. Dev. (pcm)	350		250		480	

*The core description corresponds to that in reference [6].

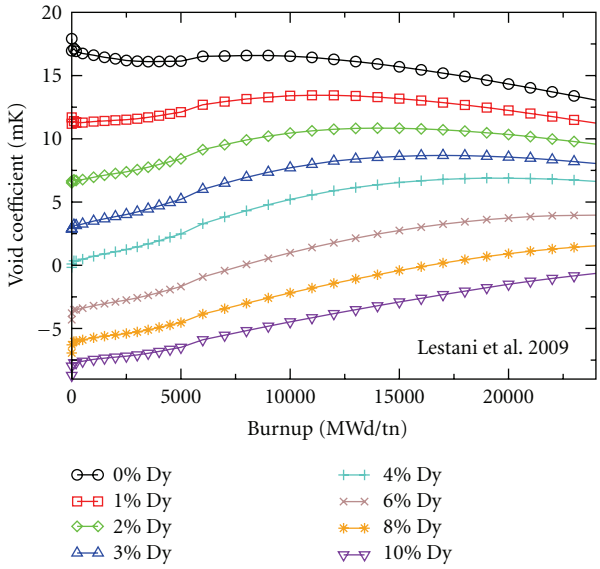

Figure 3: Evolution of coefficient with burnup for different Dy contents.

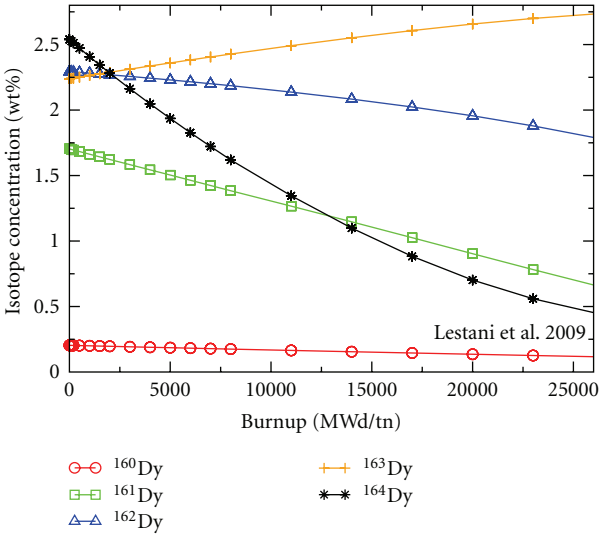

Figure 4: Dy isotopes weight percent evolution with burnup.

The DCA core model has different homogeneous zones shown in Figure 2.

The neutronic models of the DCA cores were calculated using the WIMSD-5 cell code [10] to produce the macroscopic cross-sections for each homogeneous core zone, and CITATION [11] diffusion core code was used to calculate the effective multiplication factor using the cross sections supplied by WIMSD-5.

The cell code model implied the following simplifications:

(i) moderator cylindrization for each cell,

(ii) no end-caps nor gas plenum,

(iii) no grid spacers.

A model input for the 1.2% enriched ^{235}U fuel is given in Appendix A (see Appendix A in Supplementary Material available online at doi:10.1155/2011/264235) for the sake of repeatability, where special attention must be put on some details that helped to get better results: 69 energy groups, PIJ method, thin annular discretization with a forced water region between the outer rods and the pressure tube (this should be verified in the "edit regions" of the output file), negative spectrum number for the gases (which implies that they are excluded from resonance treatment), critical buckling on the edit data section (an extra run of the code is required), and Benoist diffusion coefficients. Besides, WIMSD-5 code (obtained from the NEA data base [10]) was modified to allow printing of the scattering matrices of the individual materials to be used by CITATION. The WLUP 69 groups library ("iaea.lib", obtained from [12]) was used.

Cross-sections for simple materials and for the homogenized cell were extracted from the cell calculations and processed by tools developed in C++. The energy group structure had the following limits: 10 MeV, 821 KeV, 9.118 KeV, 4 eV, 1.15 eV, 0.972 eV, 0.625 eV, 0.14 eV and 0 eV. These cross-sections were used in the CITATION core model, that implied the following simplifications:

(i) replacement of all the structures above the fuel region by a 2.6 cm thick aluminium plate,

(ii) homogenization of the bottom absorber sandwich, formed by two layers of aluminium and one boral layer in the middle,

(iii) replacement of a small annulus of D_2O by the corresponding aluminium or absorber sandwich radial extension,

(iv) homogenization of the bottom aluminium spacers with the surrounding D_2O. This part of the core has a significant influence on reactivity and its description on reference [8] needed to be complemented by reference [9],

(v) The lower grid plate was modelled as a uniform material, ignoring the holes for positioning of the calandria tubes,

(vi) exclusion of the guide tubes for control devices and for the neutron source,

(vii) the void tank was ignored.

A model input for the two zones core with 25 "5Spu" Plutonium fuels in the inner radial zone is shown in Appendix A.

The results of these calculations are presented in Table 1. The "WIMSD-5–CITATION" column corresponds to the results obtained in this work, and the other columns correspond to results from the reference [8]. All the calculated cores are critical configurations, which means that the column corresponding to experimental values is filled with 1.00000.

Regarding the experimental measurements uncertainty, following the "*Guide to the Expression of Uncertainties*" [13] and the measurements reported values on reference [9], the empirical uncertainty was estimated on 140 pcm. This uncertainty is not only related to the experiment, but also to the weight that the calculation model gives to each parameter.

The standard deviation (St. Dev.) obtained is smaller than that calculated with the WIMS-ATR–CITATION chain and larger than the MCNP value. MCNP and WIMS-ATR–CITATION show a tendency to underestimate 8 of 10 cores. MCNP published values show an average calculated value at the limit of one standard deviation. The systematic bias in MCNP and WIMS-ATR–CITATION could not be used as a systematic correction factor for the calculated values, because the overestimation cases are always in the same state (with/without coolant), so this method will increase the uncertainties in the void coefficient. However, a clear reduction on K_{eff} with coolant voiding appears in the WIMSD-5–CITATION results, but there should be no change in reactivity provided both configurations (with and without coolant) are critical. Hence, the void reactivity coefficient should be validated apart from K_{eff}. Void reactivity results calculated as $(1/K_{coolant} - 1/K_{void})$ are presented in Table 2.

Calculating the deviations of the estimated void reactivity for each core against the experimental value and applying minimal statistics, 144 pcm is obtained for the standard deviation and 242 pcm for the maximum deviation. Thus, if a given value of void reactivity must be certified, a certain margin should be taken according to this uncertainty obtained.

Table 2: Validation results on the void reactivity.

Core	W5-CIT	Experim.[KAERI] [8]	MCNP[KAERI] [8]
1.2% ^{235}U	−47	−44	243
5 Spu (1)	−199	−441	143
5 Spu (5)	−712	−928	−436
5 Spu (9)	−1207	−1410	−933
5 Spu (13)	−1624	−1791	−1343
5 Spu (21)	−2152	−2306	−1838
5 Spu (25)	−2354	−2406	−2048
8 Spu (1)	−407	−629	−78
8 Spu (5)	−1821	−1918	−1532
8 Spu (9)	−2977	−3165	−2845
8 Spu (13)	−3845	−3786	−3596
8 Spu (21)	−4934	−4836	−4786
8 Spu (25)	−5195	−4980	−4998

In this work, 150 pcm (1 St. Dev.) will be taken as margin. This means that there is a probability of 67% that the real void reactivity is the one obtained with this calculus chain. Once the uncertainty margin is estimated, the optimization process looking for negative void reactivity modifying the fuel element can be performed.

A method for void reactivity reduction suggested by Dastur and Buss [7] consists on putting neutronic absorbers in the inner rods of the fuel element. After doing this, the infinite multiplication factor (k-inf) associated to the inner rods is less than the mean value and the inner importance increase on coolant voiding introduces negative reactivity.

3. Fuel Element Conceptual Design

The addition of burnable absorbers in the inner rods of the fuel element rises the refuelling cost mainly due to a burnup reduction, but also due to the absorber cost (which represents 5%–10% of refuelling cost). Besides, the inner poisoning rises the Power Peaking Factor (PPF) by increasing the thermal flux depression in the bundle. In this work neutronic economy is compensated with slightly enriched uranium (SEU) distributed among the rods in a way that minimizes the PPF.

The fuel element conceptual design is therefore pursuing three objectives.

(i) Safe Coolant Void Reactivity. Void reactivity is calculated with WIMSD-5. Considerations regarding the applicability of point kinetics on sudden, large and nonuniform reactivity insertions for large reactors suggest [14] that maximum local reactivities should be looked for instead of core averaged values. For this reason core calculations are ignored and maximum reactivities during burnup are analysed on the cell calculation results. Dependence of void coefficient with burnup is calculated on a perturbation basis, with infinitesimal burnup steps without coolant.

(ii) Low Fuel Cost (at least equal to that of current fuels). The economic analysis is based on refuelling cost as it contemplates not only neutronic economy but also enrichment cost. The costs evaluated include enriched uranium, burnable poisons, cladding, and fuel assembling. First core costs were not taken into account as CARA is meant to replace an operating core and not to start a new NPP. Fuel costs were levelled using an 8% discount rate. Enrichment cost was calculated in the base of Separative Work Units (SWU) price. The data used for the economical calculation can be seen in Table 3.

The costs are not absolute values they are mainly comparative. The main reason is that cost evaluations are always time dependent, and Table 3 shows values for the U_3O_8 price and the discount rate that are hardly achievable for nuclear projects in Argentina. Besides, the enrichment cost on a SWU base might be replaced for a simpler linear cost according to downblending of commercial enriched uranium (considering that SEU is obtained from down-blending in Argentina). This could rise low enrichment costs and reduce higher enrichment costs due to the world scale for commercial uranium, shifting the optimum towards higher enrichments. However, the refuelling cost, despite being outdated or subject to commercial conditions of doubtful application to Argentina, has much more information than the exclusively neutronic criteria and its uncertainty reflects a true fact on nuclear policies.

(iii) PPF that assures no derating of reactor power is needed. PPF in the fuel bundle is also studied for each fuel configuration as an operational restriction. Margins such as DNBR and linear power limit are tighter in few fuel rods on certain core locations. These locations have higher power due to core and fuel PPF. Limits were applied to fuel PPF to achieve safe operating conditions (DNBR and linear power). The fulfillment of the "Less or Equal linear power in CARA than that of Atucha II" condition was achieved by the following relation on the PPF that takes into account the different number of rods (#):

$$\mathrm{PPF}_{\mathrm{CARA}} = \mathrm{PPF}_{\mathrm{Atucha}} * \frac{\#_{\mathrm{CARA}}}{\#_{\mathrm{Atucha}}} = 1.097 * \frac{52}{37} = 1.54. \quad (1)$$

These three conditions on the fuel element are used to define all the variables: enrichment in each ring of rods and type and amount of absorbers in the two inner rings of rods. All these parameters were changed automatically to run WIMSD-5 neutronics code. After reading its output (mainly multiplication factor and PPF through burnup) the corresponding fuel cycle cost was determined, which allowed to explore the three merit figures in all possible configurations. The fuel was modelled with the temperatures, power densities, and coolant channel corresponding to Atucha II, as described in [15].

Table 3: Data used for cost evaluation.

Core data	
U inventory	88.74 tn
Thermal power	2160 MW
Refuelling zones	451-continuum
Load factor	95%
Thermal efficiency	35%
Cost data	
Item	Cost (Time required)
U_3O_8	70 U$S/KgU (2.5 years)
UF_6 Conversion	8 U$S/KgU (2 years)
Enrichment	140 U$S/KgU (1.5 year)
UO_2 conversion	8 U$S/KgU (1 year)
Cladding-assembling	250 U$S/KgU (0.5 years)
Discount rate	8%
First core amortization	30 years

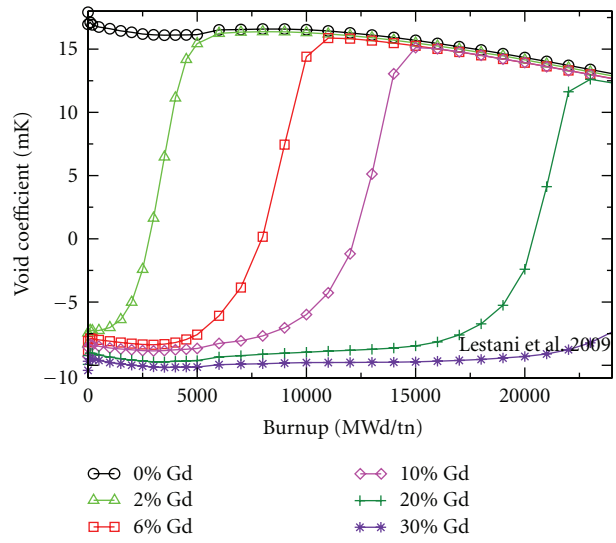

Figure 5: Evolution of coefficient with burnup for different Gd contents.

3.1. Absorbers Choice. To introduce negative reactivity on coolant voiding, absorbers must fulfill three conditions.s

(i) *Inner Placing.* Importance increase on coolant voiding occurs only for the inner rods (because of the flux flattening). This is not an absorber condition, but an absorber use condition. So, this condition forces designers to place absorbers in the bundle center but does not help on the absorber selection. This condition explains why naturally generated strong absorbers, as ^{135}Xe, have a negligible negative contribution to void reactivity: it is due to faster ^{135}Xe poisoning on external rods.

(ii) *Minimal Epithermal Absorption.* Decrease on epithermal neutron flux over 3 KeV due to coolant voiding

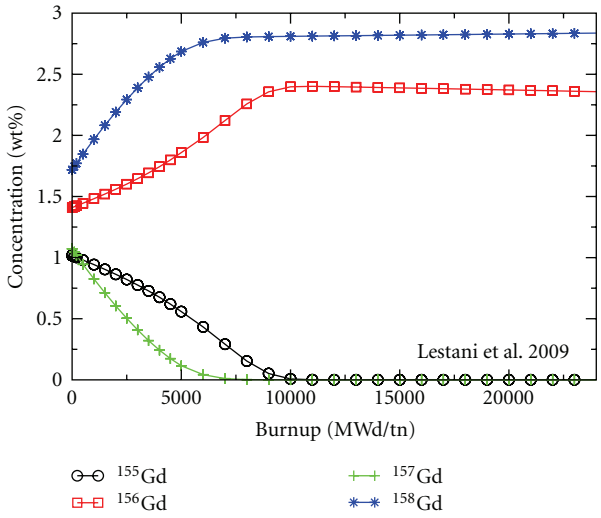

Figure 6: Gd isotopes weight percent evolution with burnup.

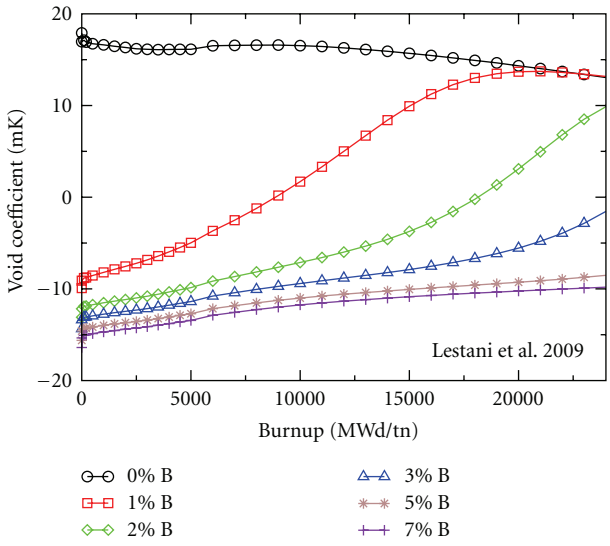

Figure 7: Evolution of coefficient with burnup for different B contents.

introduces considerable positive reactivity when the absorption resonance integral is large. An excluding condition for absorbers selection is that the increase on absorptions due to flux flattening on voiding should be higher than the epithermal decrease due to spectral changes.

(iii) *Burnup Rate.* Absorbers effect on the void coefficient must remain on the fuel during its whole in core life. Fast depletion of absorbers implies an excessive beginning of life (BOL) poisoning, and the consequent cost rise. This condition leads to different results depending on the design basis: designer may look for either mean or maximum coefficient values. Looking for maximum in-core life coefficient values favors the slower burnup rate absorbers, and vice versa.

Considering this three elements, a preliminary selection of suitable absorber candidates has been performed.

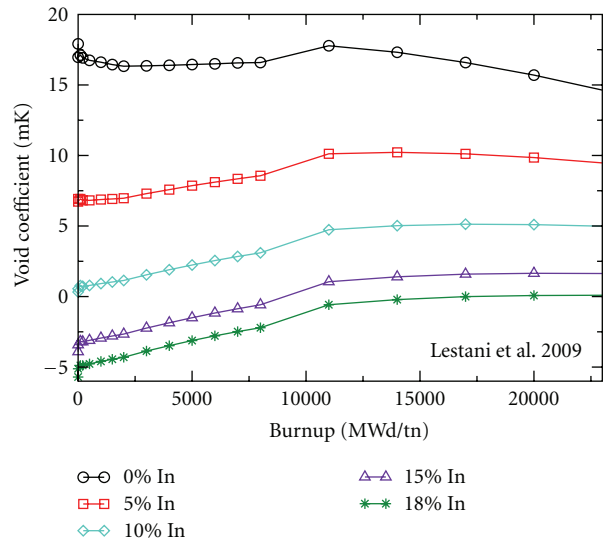

Figure 8: Evolution of coefficient with burnup for different In contents.

Dysprosium. shows excellent behaviour on coolant void reactivity reduction. Figure 3 illustrates the effect on void coefficient of inner poisoning with dysprosium against burnup. A clear reduction is observed. Dy price used for cost evaluations was 1160 U$S/Kg. However, this cost only represents about 5% of total refuelling cost. Therefore, poison price does not have a strong influence on poison selection.

Figure 4 shows dysprosium content against burnup. ^{164}Dy is the strongest absorber among dysprosium isotopes, which reduces its concentration 4 times at 20000 MWd/tn of burnup (Cost optimization explains the importance of burnup reaching 20000 MWd/ton.)

Gadolinium. Void coefficient reduction behaviour against burnup is not as good as for Dy case. This is mainly due to its high burnup rate, which leads to a short time effect on coefficient reduction, while having huge void coefficient reduction effect for BOL. Figure 5 shows the effect of inner poisoning with gadolinium on void coefficient.

The Gd contribution to void coefficient on BOL is specifically made by ^{155}Gd and ^{157}Gd isotopes, which are strong thermal absorbers. As they quickly burnup, they generate ^{156}Gd and ^{158}Gd which are mainly epithermal absorbers, and this causes the loss on void coefficient reduction. Gadolinium isotopes evolution with burnup is shown on Figure 6 for a 6 wt % total content. The coincidence of the ^{156}Gd and ^{158}Gd build up with the corresponding void coefficient increase can be seen from Figures 5 and 6.

Apart from the high burnup rate problem (which could be solved by adding more Gd content), the epi-thermal resonant absorbers built up with burnup worsens the neutronic economy without adding a negative component to void coefficient. The result is an expensive fuel with a poor negative contribution to void coefficient compared with other poisons. Also it lasts only a short period of burnup.

Boron. Shows good results, as can be seen on Figure 7. However, it burns out too fast and generates ^{11}B (already present at natural boron, 80%), which has a small epi-thermal resonance and negligible thermal absorption.

In comparison with Dysprosium, using Boron as poison leads to more expensive fuels due to the excessive poisoning needed to mitigate fast burnup. Nevertheless, costs obtained are not prohibitive and boron remains as an alternative.

Indium. Shows excellent behaviour on coolant void reactivity reduction. Figure 8 illustrates the effect on void coefficient of inner poisoning with Indium against burnup. A clear reduction is observed plus a small variation with burnup.

Other Absorbers. Hf and Cd were also tested as inner absorbers to reduce coolant void reactivity coefficient. None of them showed better and cheaper results than Dy or In.

Enrichment Grade. A low-cost objective implies the use of SEU. Figure 9 shows the dependence of refuelling and cycle costs versus enrichment (uniformly distributed on the three outer rings of rods). The lower-cost criterion can be satisfied using an enrichment that minimizes the refuelling or cycle cost.

Refuelling cost is the cost of every new fuel element needed in the refuelling strategy per KWh produced. Cycle cost is the sum of refuelling cost and first core amortization. CARA design requires minimization of refuelling costs only, as amortization of first core is not needed on a replacement fuel for Atucha I and Embalse. For Atucha II, first core amortization cost could be included depending on the core transition from the first load up to reach an equilibrium core.

As can be seen from Figure 9, refuelling cost on a poisoned fuel keeps fading even over 4% enrichment (uniformly distributed). However, this isolated criterion would lead to prohibitive PPF values. Hence, the enrichment level has to be defined, along with its distribution on the different rings of rods, by the PPF minimization criterion.

Enrichment Distribution. Heavy water reactors have bundle shielding effect because neutrons are moderated outside the coolant channel, hence, generating more power in the outer rods of the bundle. Finding a fuel design with negative coolant void coefficient worsens this feature: the radial gradient of k-inf needed to decrease void coefficient is opposed to the one that minimizes PPF.

For any enrichments used in the first and second rings of rods, the dependence of PPF on the 3rd and 4th rings enrichment (E_3 and E_4, resp.) is shown on Figure 10 The figure shows the PPF related to power on the 3rd or 4th ring, depending on the enrichment. An optimum relation between these enrichments can be clearly seen in the figure, $E_4 \approx E_3/1.2$. If the enrichment in the 3rd ring (or 4th) is higher than that given by this relation then, that ring produces more power than the 4th ring (or 3rd) rising the PPF. This relation is slightly modified by the enrichments and poison contents in the 1st and 2nd rings of rods.

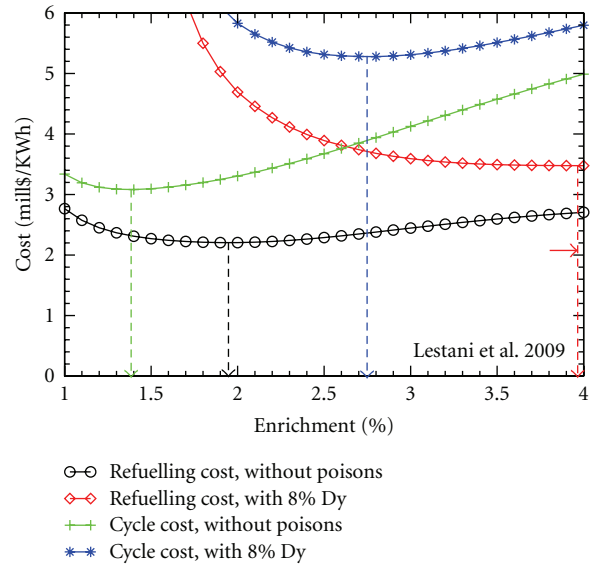

Figure 9: Fuel cost variation with UO_2 enrichment.

With the 3rd and 4th enrichments fixed by the relation that minimizes PPF, an increase in the enrichment of the 2nd ring of rods reduces the PPF because of the power increase in the 2nd ring. Simultaneously, an increase in the 2nd ring enrichment lowers the cost, but due to the importance increase in the 2nd ring during coolant voiding, it leads to a positive contribution to void reactivity.

The influence of the enrichment in the 1st ring of rods is similar to that of the 2nd one, with less effect on cost and PPF due to the fewer rods involved, but with more effect on reactivity change during voiding due to its central localization. For this reason and because of its mixture with absorbers, the best enrichment for the 1st ring is 0.35% (depleted Uranium), maximizing the negative reactivity introduced on voiding and having a negligible negative influence on cost and PPF.

The optimization of many variables in order to satisfy the three constraints exceeds the rational analysis of the separate effects and requires a technique able to explore all the possible combinations. The location of all the configurations in the phase space (composed by void coefficient, cost, and PPF) has proved to be a successful technique.

4. Design Basis Definition and Fuel Optimization

The phase space defined by the void coefficient, the refuelling cost and the PPF can represent all the fuel configurations studied and allows selecting those that simultaneously meet the three mentioned objectives of CARA fuel design. Representing all the configurations in the phase space a cloud of points is obtained. Figure 11 shows the lower envelope of the studied configurations. The lower envelope is the set of points that minimizes the cost for each ordered pair (void coefficient, PPF). The poisoning was tried either mixed with the UO_2 in the 14 inner rods or as a pure absorber ceramic in

Table 4: Main results obtained for CARA fuel in Atucha II with safe coolant void coefficient compared with the original Atucha II fuel bundle.

FUEL	1st ring	2nd ring	3rd ring	4th ring	PPF	Void coeff (mK)	Ref. cost (mill$/KWh)
Atucha II original	nat	nat	nat	nat	1.098	15.36	6.46
CARA $\rho < \beta$	2 0.25 cm radius Dy_2O_3 rods+2 0.35% UO_2 rods	1.4	2.4	1.9	1.187	5.36	3.54
CARA $\rho < 0$	2 0.425 cm radius Dy_2O_3 rods+2 0.35% UO_2 rods	1.4	2.4	1.9	1.22	−1.54	4.96

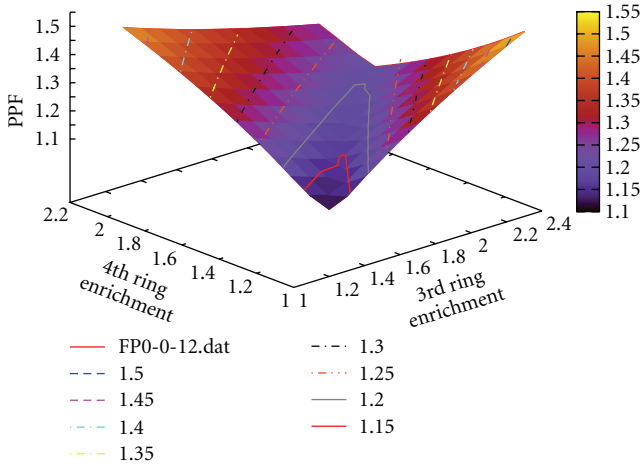

Figure 10: PPF dependence on 3rd and 4th ring enrichments.

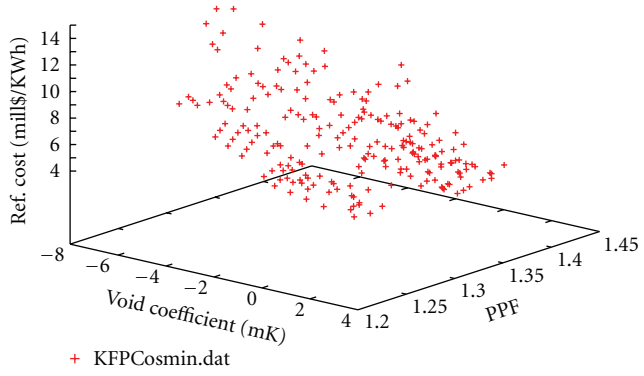

Figure 11: Phase space representation of the calculated configurations.

two of the 4 inner rods. The enrichments studied range from 0.35% to 2.4%. This upper limit was given by the fact that the lower-cost objective was fulfilled and by the suggestion of Argentinean designers to limit enrichment to avoid Xe oscillations problems. At this stage, the Atucha II nominal conditions at full power [15] were used to model CARA. Power cycles or startup with boron diluted in the coolant are excluded from this analysis.

Two of the merit figures should be as low as possible: cost and PPF. Void reactivity, however, due to the cost rise that it implies (as can be seen Figure 11), cannot be asked to be as low as possible. Hence, there is a necessity to adopt a Design Basis that establishes a minimum requirement.

Two Design Basis can be thought in terms of void reactivity:

(i) Less than β (the delayed neutrons fraction): this requirement avoids catastrophic consequences for the fuel elements' integrity after an eventual Large-LOCA.

(ii) Negative: this requirement places the Large-LOCA in the Design Basis with the minimum consequences, without taking the fuels out of their operational conditions and setting the core as passively safe against this accident.

Fuel optimization using the phase space has been performed giving the results shown in Table 4 for each Design Basis mentioned above.

5. Conclusions

(i) A good estimation of the uncertainty in the void coefficient calculation allows taking a margin on the design target coefficient. In this work, a margin of 150 pcm was found to assure 67% probability that the real value of void reactivity fulfills the Design Basis.

(ii) Two fuels (described in Table 4) meet all three design objectives, one for each Design Basis mentioned (Although other configurations and other absorbers also fulfill the design criteria, these are the ones that best suits them all).

(iii) If the decision to change the Design Basis and improving the fuel performance on Atucha II is taken, yet more work would have to be done considering all the plant conditions relevant for a safety transient and regarding fuel certification. In particular, those plant conditions with higher void coefficient, like the reactor startup in Atucha II (which includes boron diluted in the primary coolant) need to be specially considered if it is decided to change the Design Basis. Some remaining tasks regarding fuel certification would be an endurance test, fuel behaviour and Pellet Cladding Interaction, experimental verification of the low pressure drop spacer grid and pellets irradiation, analysis of Xe oscillations behaviour of CARA fuel and revision of

the refuelling strategy and refuelling speed (due to the reactivity insertion of a higher enrichment fuel).

Nomenclature (symbols and Acronyms in Alphabetical Order)

β: Delayed neutrons fraction
BNA: Burnable neutronic absorber
BOL: Beginning of life
DCA: Deuterium critical assembly
DNBR: Departure from nucleate boiling ratio
K: Neutron multiplication factor
LOCA: Loss of coolant accident
LWR: Light water reactor
NPP: Nuclear power plant
PHWR: Pressurized heavy water reactor
PPF: Power peaking factor
SEU: Slightly enriched uranium
SWU: Separative working units
WLUP: Wims library update program.

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