Optimization of CARA Fuel Element with negative coolant void coefficient

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Abstract: Analysis is made on CARA fuel element design to achieve a negative coolant void coefficient in Argentinean nuclear power plants, looking for lower cost and preserving its advantages on operational performance. Different fuel settings were found to meet the safety, economical and performance combined criteria, taking as the reference case the Atucha II nuclear power plant.

1. INTRODUCTION

In the three Argentinean Nuclear Power Plants (NPPs) the heavy water is the moderator and the coolant (PHWR): Embalse NPP is a CANDU reactor, and Atucha I and II (currently under construction) are pressure vessel type PHWR designed by Siemens. This design feature produces a positive coolant void reactivity. Moreover, the 3rd NPP that is still under construction and is planned to start operating on 2012, Atucha II, has a positive power coefficient on equilibrium burnup[1].
The positive power coefficient on Atucha II is related to a weak negative Doppler coefficient, due to 239Pu build up, and a strong positive coolant void coefficient. Hence the great importance of coolant void coefficient besides the likely improbable LOCA event: it is related to the power instability of the plant.

To look for design alternatives for the PHWR a detailed analysis on the void coefficient neutronic and the solution alternatives are needed, considering the special condition of the three different plants available in Argentina

2. COOLANT VOID REACTIVITY

Heavy water moderated reactors increase their reactivity when coolant voiding occurs. The main consequences of coolant voiding on the fuel element neutron physics are [2]:

3. SPECTRAL CHANGES

Decrease in epi-thermal neutron flux and increase in fast neutron flux within the bundle. Neutrons normally moderated by the coolant are those whose energy increase:

- Less resonance absorptions and more fast fissions on 238U
- Mean neutron temperature cooling down. In the PHWRs the neutrons are moderated at an intermediate temperature between moderator and coolant temperatures. The spectral effect of coolant is to rise up the neutron temperature, and then voiding leads to a cooler neutron temperature:
- Less resonance absorptions on 238U. Idem with 240Pu.
- Less absorptions on 239Pu (this isotope also decreases its fissions, but in a smaller percentage). Idem with 241Pu.

4. SPATIAL CHANGES

Less self shielding in the bundle due to larger migration area:

Importance increase for the inner rods in the bundle. Absorptions / fissions rate change depends on the composition of the inner rods compared the outer rods. Normally inner rods have more fissile material and less fission product absorbers, thus introducing positive reactivity.

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, except for the last one. For this reason, smaller cores have smaller positive Coolant Void Reactivity.
In addition to this neutronic feedback well known for the CANDU reactors, the boron dilution in the coolant during start up in Atucha II also increases de void coefficient due to the decrease in boron capture.

A method suggested by A. R. Dastur et al. [2] consists on locating 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 lower than the mean value, and the inner importance increase on coolant voiding introduces negative reactivity. Neutronic economy is compensated by the use of slightly enriched uranium (SEU) with a distribution that minimizes the Power Peaking Factor (PPF). In this work such method was applied on CARA Fuel optimizing cycle costs and PPF for a required Coolant Void Reactivity.

5. CARA FUEL ELEMENT

The CARA [3][4] fuel element was designed to replace the original fuel elements of both PHWR NPPs operating in Argentina. The advantages of the CARA fuel are its lower cycle cost compared with Embalse and Atucha I fuels and its lower linear power, which leads to greater DNBR and less pellet-cladding interaction (due to lower centre temperature in the fuel pellets).

The key differences between CARA and the current fuels are its larger number of rods (52 instead of 37) with collapsible cladding, its optimized enrichment achieving lower cost, its lower spacer grid pressure drop design, a single rod diameter for the whole bundle (a key difference compared with other advanced PHWR bundles) and its overall dimensions that allow it to be used in both NPPs.
Multidimensional Analysis

CARA optimization pursues three objectives:

- Safe Coolant Void Coefficient of Reactivity (fulfillment of negative power coefficient)
- Lower Fuel Cost, or at least equal to that of current fuels
- PPF that assures that no derating of reactor power is needed

To achieve the first goal several absorbers were tried (pure and mixed with uranium oxide), in the 14 inner rods of the CARA fuel element. The second objective forces the use of uranium enrichments higher than natural, increasing the burnup and therefore reducing cost. These actions increase the shielding in the bundle and enrichment redistribution is required to satisfy the third objective. A set of 8 parameters are needed to be studied: enrichment in each of the 4 rings of rods, absorber isotope and content in the 2 inner rings of rods, and whether to use absorber mixed with UO2 or in pure state.

This work was performed taking Atucha II at full power as a reference plant, using reference data from [1] in order to analyze the feedbacks and main parameters involved in optimal solution of the CARA fuel void coefficient.

The neutronic calculations were carried out with WIMSD-5 cell code. The coolant void coefficients were calculated for a 100% void fraction and its dependence with burnup was observed to satisfy the requirements on the void coefficient over the entire in-core life of the fuel. Dependence of void coefficient with burnup is calculated on a perturbation basis, with infinitesimal burnup steps without coolant.

Economic evaluations were made with each fuel parameter variation to verify the cost advantage of CARA over the original fuel elements. The costs compared include enriched uranium, burnable poisons, cladding and assembling for every new fuel element following the refuelling strategy of the original cores. 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 cost was 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.

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)
U3O8	70 U$S/KgU (2.5 years)
UF6 conversion	8 U$S/KgU (2 years)
Enrichment	140 U$S/UTS (1.5 years)
UO2 conversion	8 U$S/KgU (1 years)
Cladding - assembling	250 U$S/KgU (0.5 years)
Discount rate	8%
First core amortization	30 years

Table1. Data used for cost evaluation

Power peaking factors in the fuel bundle were 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). To obtain in CARA the same linear power as Atucha II will have, and considering the higher number of rods, the following consideration is done:

PPFCARA=PPFAtucha*#CARA / #Atucha = 1.097*52/37= 1.54.
Due to the higher number of rods in the fuel element (comparing with the original fuel) a greater PPF is admitted. The use of rods with higher enrichment in the outer rings (that the greater PPF allows) lowers the cost.

As can be seen, the fuel design has many degrees of freedom: type and amount of absorbers in the first and second rings of rods (numbering from inner towards outer) and enrichment level in the four rings of rods (one for each ring). All these parameters were changed automatically by a program that runs WIMSD-5 neutronics code and after reading its output (mainly multiplication factor and PPF through burnup) the corresponding fuel cycle cost was determined, which allowed to explore all the possible configurations.

6. ABSORBERS CHOICE

To introduce negative reactivity on coolant voiding, absorbers must fulfill three conditions:

- Inner placing: importance increase on coolant voiding occurs only for the inner rods. This is not an absorber condition, strictly speaking, but an absorber use condition. So this condition forces designers to place absorbers in the bundle centre, but does not help on the absorber selection. This condition explains why naturally generated strong absorbers, as 135Xe, have a negligible negative contribution to void reactivity: it is due to faster 135Xe poisoning on external rods.
- No epi-thermal absorption: decrease on epi-thermal neutron flux due to coolant voiding introduces positive reactivity when the absorption resonance integral is greater than the thermal absorption cross section[1]. An excluding condition for absorbers selection is that the increase on thermal absorption should be higher than the epi-thermal decrease.
- Burnout 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 burnout rate absorbers, and vice versa.

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

Dysprosium: shows excellent behavior on coolant void reactivity reduction. **Error! Reference source not found.** 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 less than 2% on refueling cost. Therefore, poison price does not have a strong influence on poison selection.

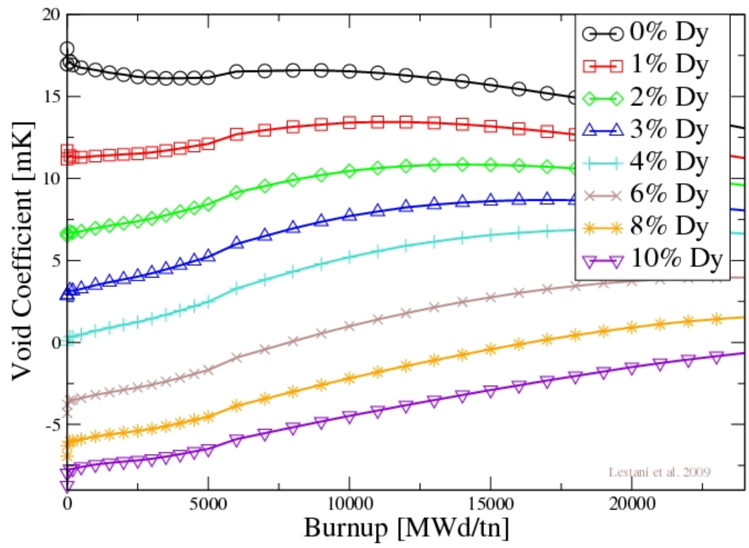

Fig. 1. Evolution of coefficient with burnup for different Dy contents

shows dysprosium content against burnup. 164Dy is the strongest absorber among dysprosium isotopes, which reduces its concentration 4 times at 20000 MWd/tn of burnup[2].

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[1] Strictly speaking, reaction rates changes with voiding have to be compared instead of cross sections.

[2] Cost optimization explains the importance of burnup reaching 20000 MWd/ton.

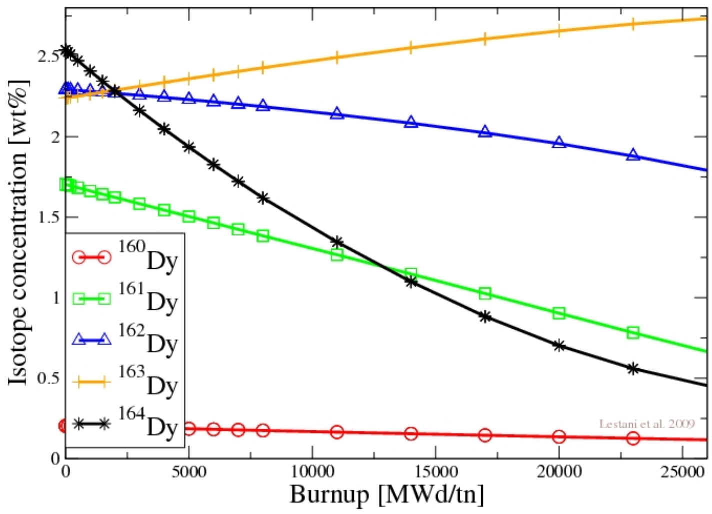

Fig. 2. Dy isotopes weight percent evolution with burnu

Gadolinium: Void coefficient reduction behavior against burnup is not as good as for Dy case. This is mainly due to its high burnout rate, which leads to a short time effect on coefficient reduction, while having an enormous void coefficient reduction effect for BOL. **Error! Reference source not found.** shows the effect of inner poisoning with gadolinium on void coefficient.

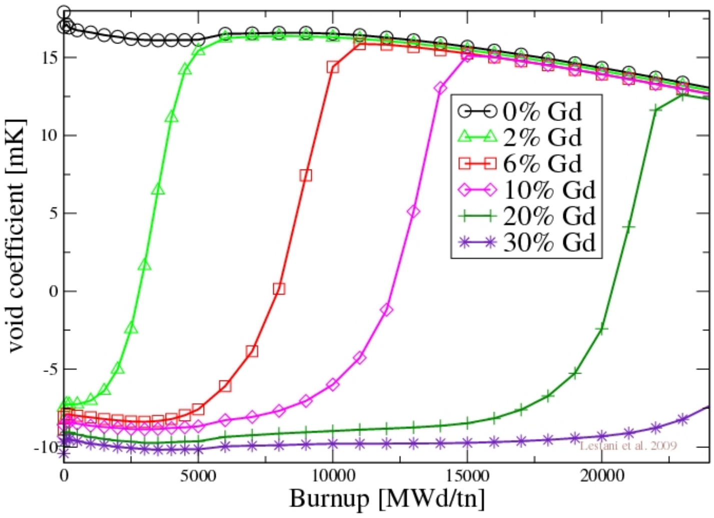

Fig. 3. Evolution of coefficient with burnup for different Gd contents.

The Gd contribution to void coefficient on BOL is specifically made by 155Gd and 157Gd isotopes, which are strong thermal absorbers. As they burnout quickly, they generate 156Gd and 158Gd which are mainly epi-thermal absorbers, and this causes the loss on void coefficient reduction. Gadolinium isotopes evolution with burnup is shown on **Error! Reference source not found.** for a 6 wt% total content. The coincidence of the 156Gd and 158Gd build up with the corresponding void coefficient increase can be seen from **Error! Reference source not found.** and **Error! Reference source not found.**.

Besides the high burnout 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.

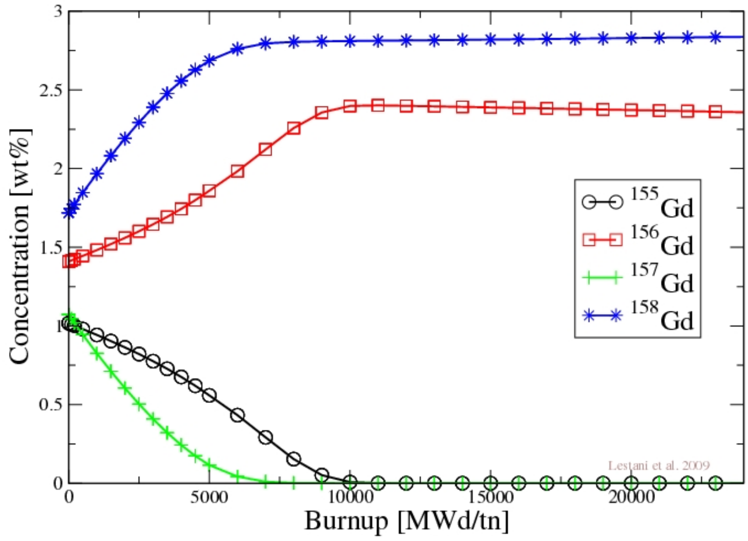

Fig. 4. Gd isotopes weight percent evolution with burnup

Boron: shows good results. However it burns out too fast and generates 11B (already present at natural boron, 80%), which has a small epithermal resonance, and negligible thermal absorption. The effect with burnup is similar but smaller than that explained for Gadolinium.
In comparison with Dysprosium, using Boron as poison leads to more expensive fuels due to the excessive poisoning needed to mitigate fast burnout. Nevertheless, costs obtained are not prohibitive, and boron remains as an alternative.

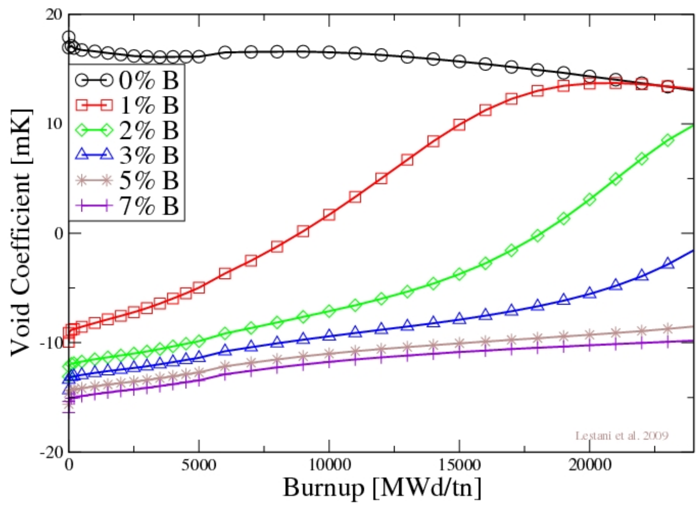

Fig. 5. Evolution of coefficient with burnup for different B contents.

Indium: shows excellent behavior on coolant void reactivity reduction. **Error! Reference source not found.** illustrates the effect on void coefficient of inner poisoning with Indium against burnup. A clear reduction is observed plus a small variation with burnup.

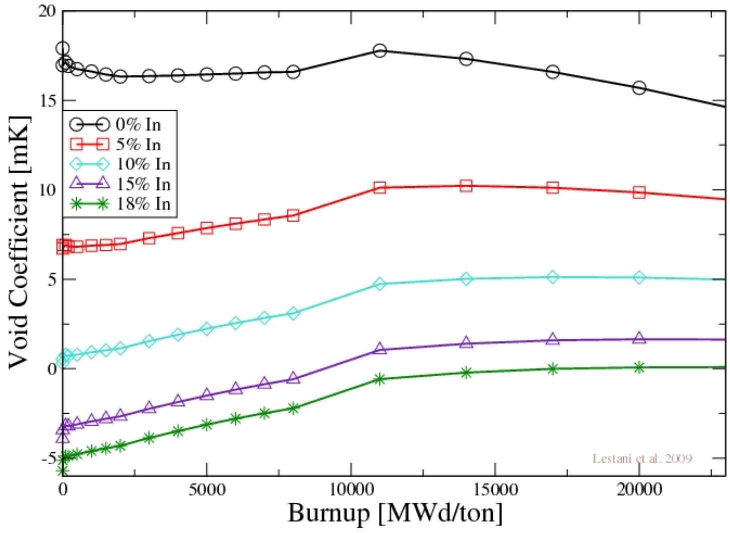

Fig. 6. Evolution of coefficient with burnup for different B contents.

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 level

A low cost objective implies the use of SEU. F 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.

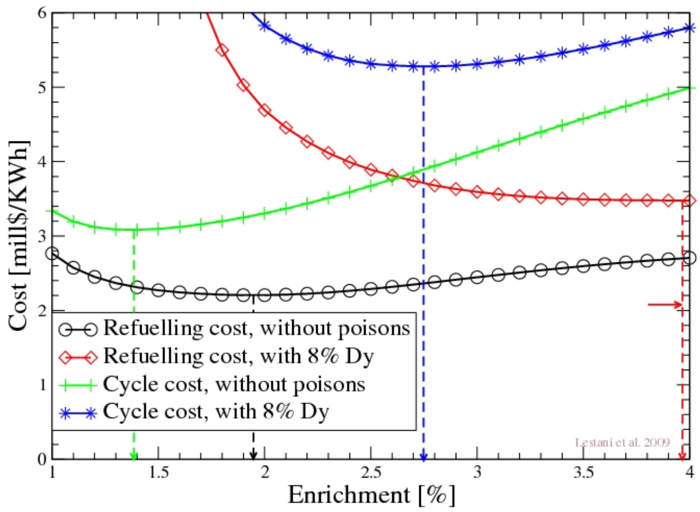

Fig. 7. Fuel cost variation with UO2 enrichment

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 cost 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 the equilibrium core.
As can be seen from F refuelling cost on a poisoned fuel keeps diminishing 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.

7. ENRICHMENT DISTRIBUTION

Heavy water reactors have bundle shielding effect because neutrons are moderated outside the coolant channel. 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 (E3 and E4, respectively) is shown on **Error! Reference source not found.**. 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, E4≈E3/1.2. If the enrichment in the 3rd ring (or 4th) is higher than that given by the 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.

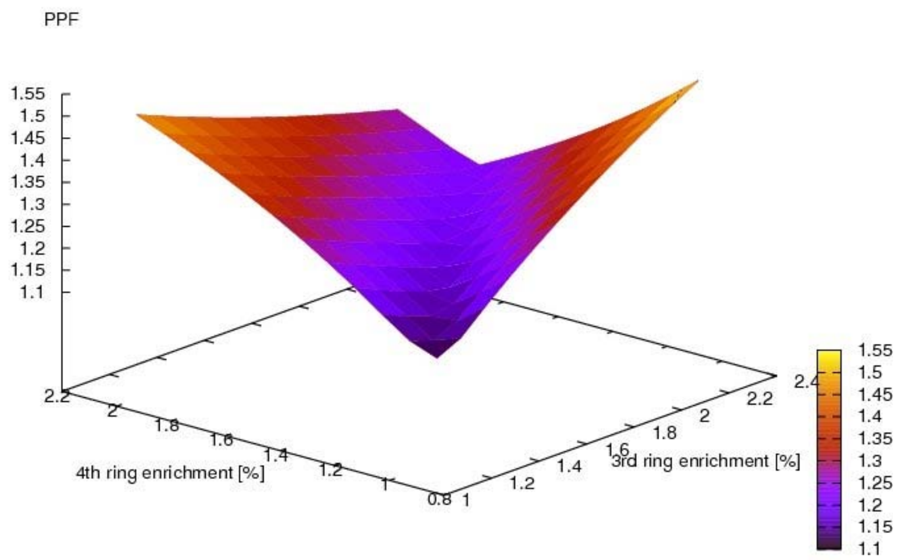

Fig. 8. PPF dependence on 3rd and 4th ring enrichments

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 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 possible combinations. The location of all the configurations in the phase space (composed by void coefficient, cost and PPF) proved a successful technique.

8. THE PHASE SPACE

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. The poison content studied range from 0% to a content achieving negative void coefficient: 9% for Dy, 18% for In and 4% for B. 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 the suggestion of Argentinean designers to limit enrichment to avoid Xe oscillations problems.
Error! Reference source not found. shows the lower envelope[3] of the studied configurations. By changing the freedom degrees (enrichment level and distribution, and poisons content) in the ranges described above, each calculation will result in a point on this phase space. An optimal solution for a given peaking factor and void coefficient will correspond to the one with the lower refuelling cost, creating a lower limit on the envelope to all the possible configurations.

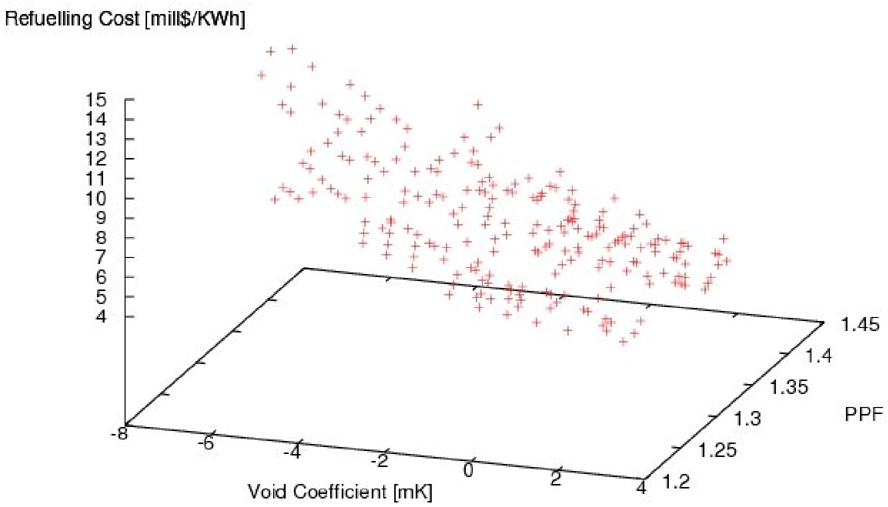

Fig. 9. Phase space representation of fuel configurations (the lower envelope of the configurations studied)

In the figure above the cost rise as a consequence of void reactivity reduction can be clearly seen. The effect of PPF does not seem to affect the cost significantly, although the number of low PPF configurations seems to decrease as a more negative void coefficient is required.
Considering in this work that a slightly negative void coefficient satisfies the 'Safe coolant void coefficient' criterion, two designs satisfying all objectives are shown in the Table 1, along with the original fuel of Atucha II.

FUEL	1st ring enrich.	2nd ring enrich.	3rd ring enrich.	4th ring enrich.	PPF	Void Coeff [mK]	Ref. Cost [mill$/ KWh]
Atucha II original	nat	nat	nat	nat	1.097	15.45	6.53
CARA Dy	0.35% +10.3% Dy2O3	1.4%	2.3%	1.9%	1.26	-0.22	5.29

[3] The lower envelope is the set of points that minimizes the cost for each ordered pair (void coefficient, PPF)

CARA In	0.35% +21.75% In2O3	1.0%	2.3%	1.9%	1.29	-0.21	5.13

Table 1. Main results obtained for CARA fuel in Atucha II with safe coolant void coefficient compared with the original Atucha II fuel bundle.

The optimization procedure described above can be repeated for geometries with two pure absorber rods in the 1st ring, instead of four mixed absorber-fissile rods. The results, shown in Table, can be even better than those for the mixed absorber-fissile rods geometry.

FUEL	1st ring		2nd ring enrich.	3rd ring enrich.	4th ring enrich.	PPF	Void Coeff [mK]	Ref. Cost [mill$/ KWh]
CARA Pin	Two 0.8cm, Dy2O3 rods	Two 1.01cm, 0.8%UO2 rods	1.2%	2.3%	1.9%	1.24	-0.045	4.79

Table 3. Main results obtained for CARA fuel in Atucha II, with safe coolant void coefficient, with two pure absorber rods in the 1st ring, called CARA Pin

9. DESIGN BASIS AND THE CORRESPONDING FUEL ELEMENT

If a new Design Basis (DB) must be introduced in a nuclear reactor, this should be done after a thorough discussion on the neutronical, thermal, safety, economical and operational consequences of the required coefficients for the fuel. The CARA optimization in this work was done by considering the need of a negative coolant void coefficient in Atucha II core at full power. This is a very challenging target.

A negative power coefficient on Atucha II can be completely guaranteed with negative coolant void coefficient provided that at least a weak negative Doppler coefficient remains at equilibrium burnup. However, other design basis might be adopted, with different results.

Argentinean designers have experience using SEU on heavy water reactor. Atucha I fuels were changed from natural to 0.85% uranium on late ‘90s. This reference, although involving minor changes in comparison with those needed to satisfy the design basis pursued in this work, gives vital experience and points some key issues, as Xenon oscillations phenomena, which might impose a limit on enrichment increase, changing the design basis. In Canada there is also experience with the use of SEU in Candu reactor and the use of Dy in order to have a negative void coefficient [5].

10. CONCLUSIONS

A fuel design with 4-10-16-22 rods geometry could replace the original fuels of Argentinean NPPs adding two advantages: negative coolant void coefficient of reactivity and lower refueling cost, without derating of reactor power needed. This design has poison mixed with UO2 in the 4 inner rods and different uranium enrichment in the rings of rods. In or Dy could be used, both satisfying the design criterion.

Alternatives exist to avoid eventual difficulties on the sintering of UO2-Poison oxide mixed powders. These alternatives are based on the replacement of two central fuel rods by two pure absorber rods. This solution is feasible because of the larger number of rods in the 4-10-16-22 rods geometry in comparison with the original geometry (1-6-12-18). In this geometry, only Dy achieves negative void coefficient. In is not a strong enough absorber.

The use of Boron is also a good choice for coolant void reactivity reduction. Its comparison against Dy and In is strongly affected by the selection criterion adopted. Dy and In have better behavior during burnup and lead to lower cost configurations.

Inner poisoning is not sufficient condition to achieve satisfactory effect on void coefficient during fuel burnup. In the selection of the neutronic absorber special care has to be taken on the existence of big epi-thermal resonances in both, the natural isotopes and those generated with burnup.
CARA fuel still has margin on cost (in comparison with Atucha II fuel) and PPF (due to its larger number of fuel rods, CARA obtains the same linear power with a PPF equal to 1.54). Other design basis might be adopted having satisfactory results, considering that the one adopted in this work is a very challenging basis.

These positive results in void coefficient for Atucha II using average data at full power encourage studying the DB change feasibility.

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