Optimization of CARA Fuel Element with negative coolant void coefficient

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- Introduction
  - Argentinean NPPs and motivation for void coefficient Study
  - CARA Fuel Element
  - Void Coefficient Neutronics
- Multidimensional Analysis
  - Absorbers Choice
  - Enrichment Level
  - Enrichment Distribution
- Phase Space Analysis
- Conclusions

Argentinean NPPs and motivation for void coefficient Study

- Embalse: CANDU 600 ⟶

Positive void coefficient

- ⟵ Atucha: Siemens designed Pressure Vessel type PHWRs

A I: 340 MWe, uses SEU, positive void Coefficient

A II: 690 MWe, void coefficient greater than β with positive power coefficient on Equilibrium Burnup.

CARA Fuel Element

Concept

- Replacement Fuel compatible with the 3 NPPs
- 52 rods instead of 37
- Collapsible Cladding
- Use of SEU

Objectives

- Passive Safety feature: Negative Void Coefficient
- Lower Cost
- PPF that assures no derating is needed

Variables

- Isotope, chemical state and amount of absorber
- Enrichment level and distribution

Void Coefficient Neutronics

- Spatial change
  - Less self shielding in the bundle: inner importance increase
  - More leakage in the core

- Spectral change
  - More Fast Neutrons
  - Less epithermal Neutrons (upper energy limit)
  - Cooler neutron temperature

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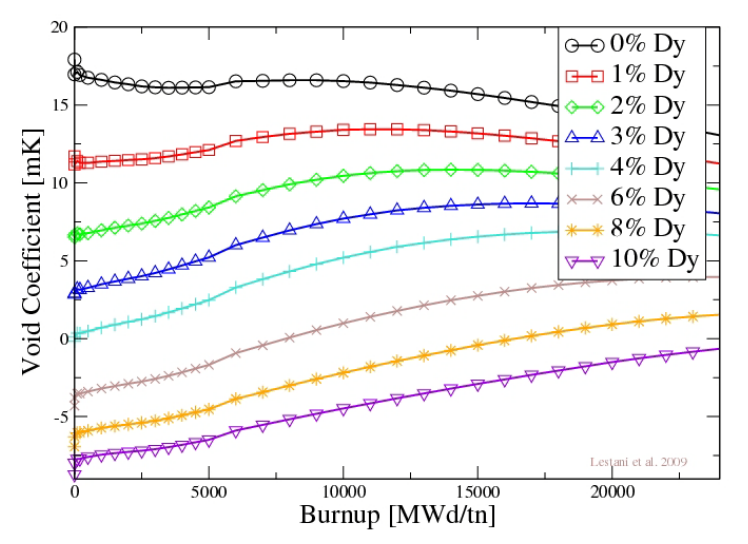
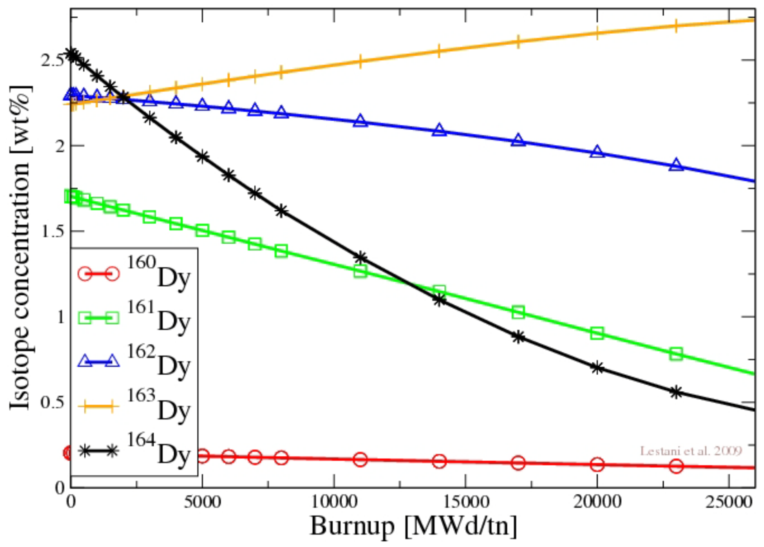
Absorbers Choice

- Dysprosium

Excellent behaviour, void coefficient reduction up to negative values, lasting the whole in-core life. Design objectives can be fulfilled.



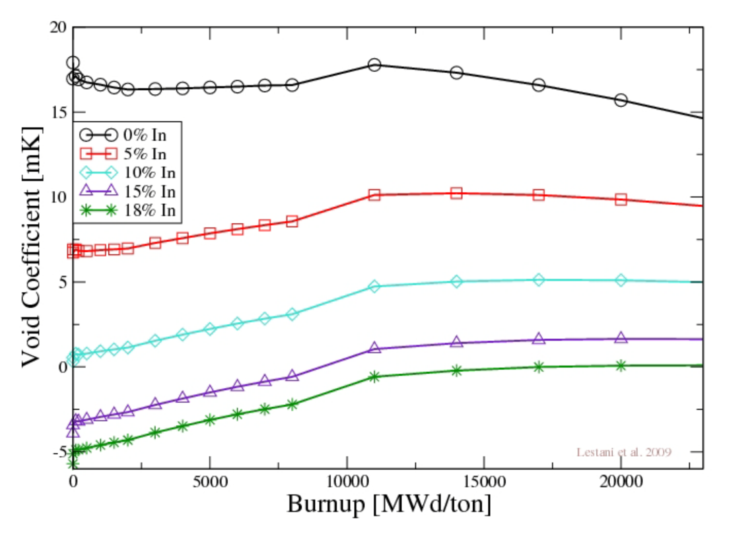

Isotopic evolution for 9% total content

The most absorber isotope, ^{164}Dy, reduces its concentration to 1/4th by 20.000 MWd/ton

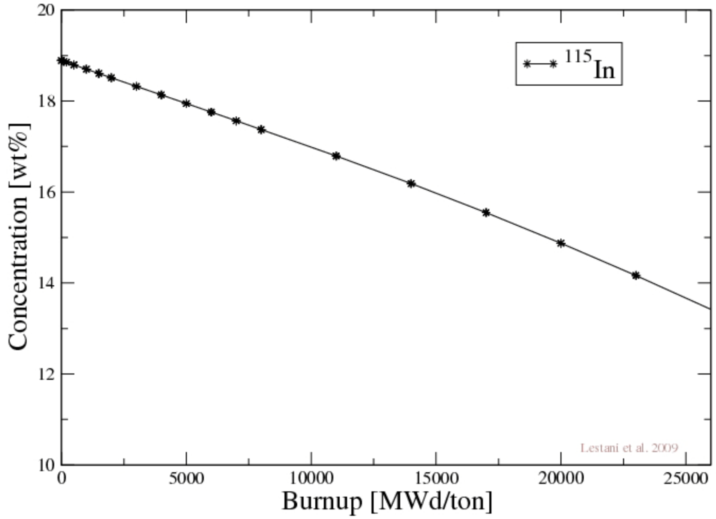
Absorbers Choice

- Indium

Excellent behaviour, slow burnout and constant effect on void coefficient.
Design objectives can be fulfilled.



Isotopic evolution for 19% total content

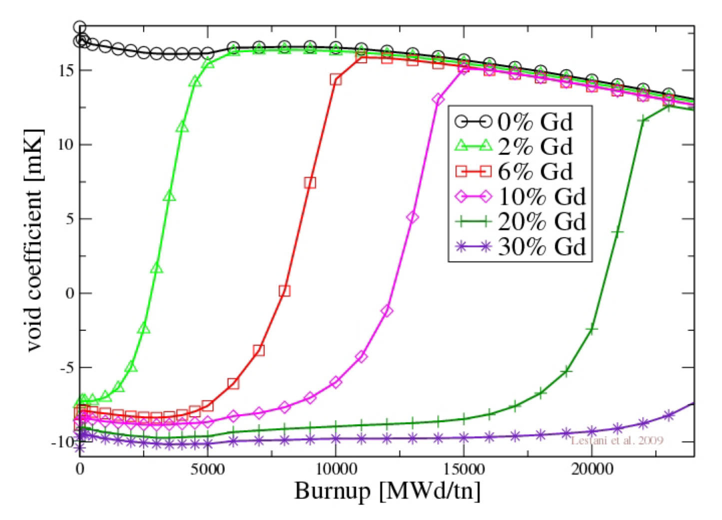


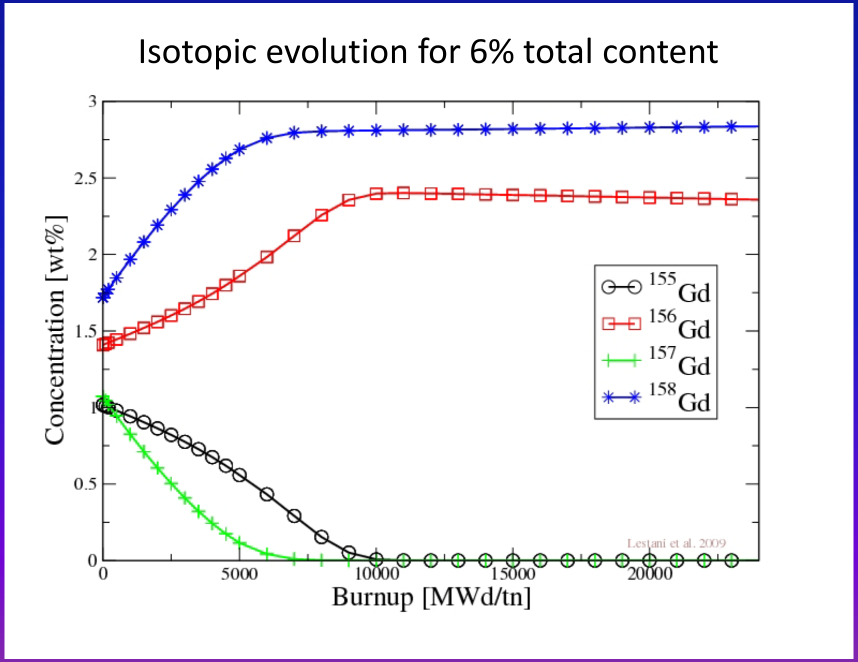
More than 2/3rd of the initial concentration remain after 20.000 MWd/ton

Absorbers Choice

- Gadolinium

Extremely fast burnout. Strong void coefficient reduction during a short period of burnup →



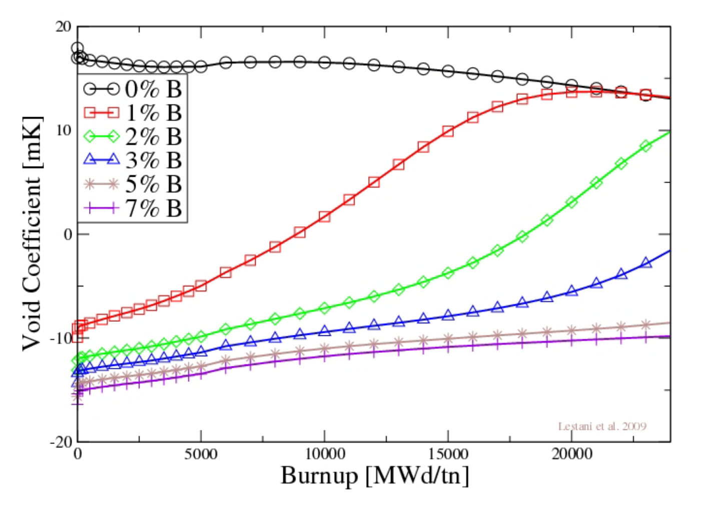

Isotopic evolution for 6% total content

← ^{155}Gd and ^{157}Gd burnout and ^{156}Gd and ^{158}Gd build up coincides with void coefficient rise up

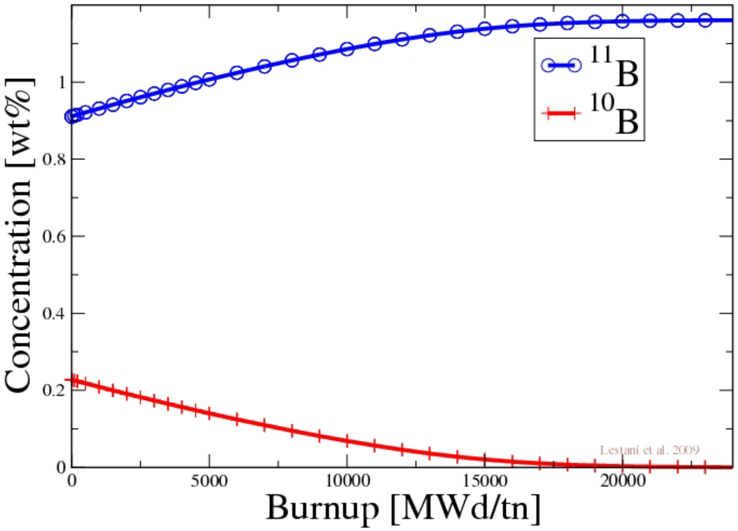
Absorbers Choice

- Boron

Fast burnout. However, good results fulfilling design objectives are obtained.

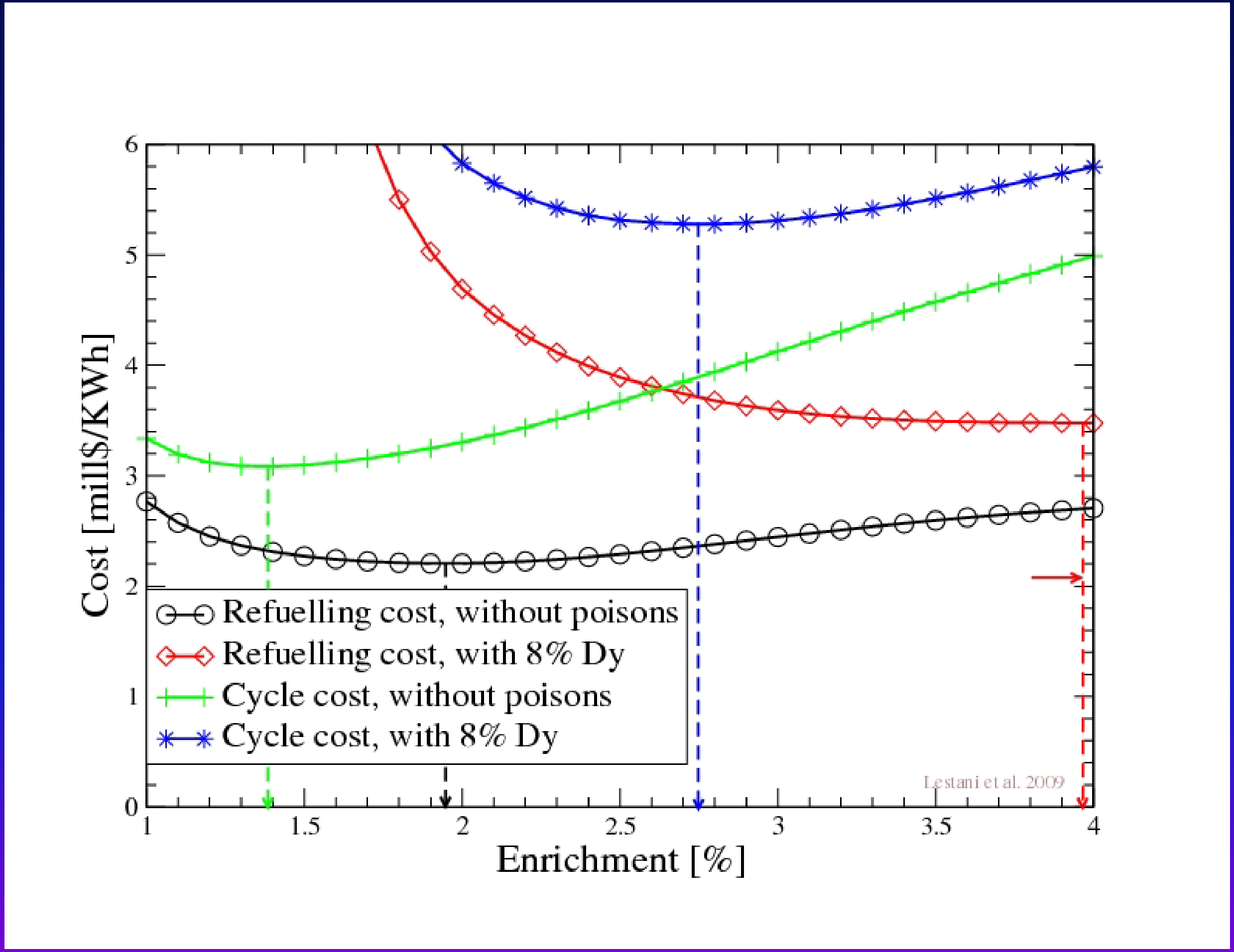


Isotopic evolution for 1% total content



With 1% of Boron at BOL, practically no content remains at the end of burnup

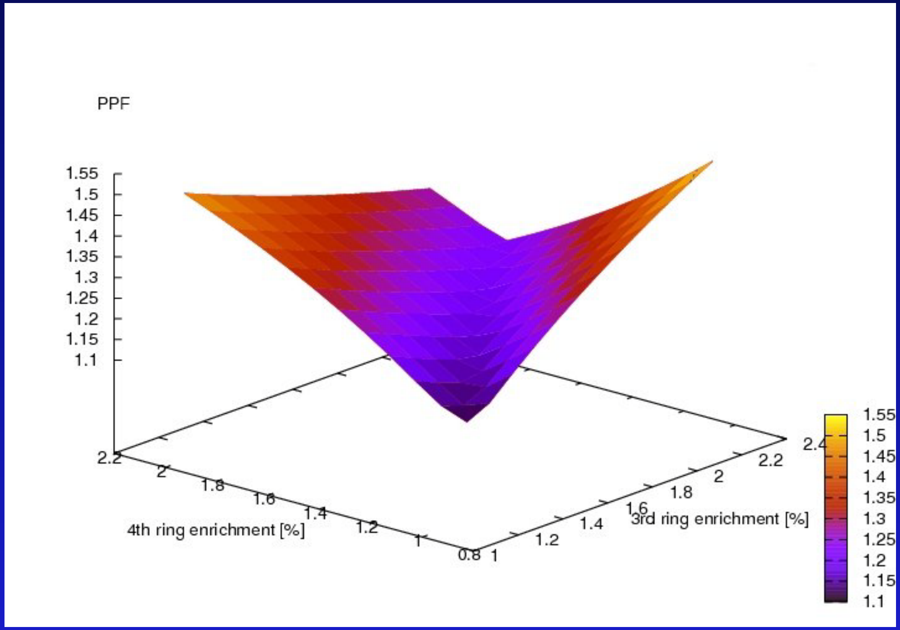
Enrichment Level: Cost Optimization



Cost optimization explains the use of SEU and high burnup levels (for a PHWR) but this isolated criterion would lead to prohibitive PPF values.

Enrichment distribution: PPF minimization

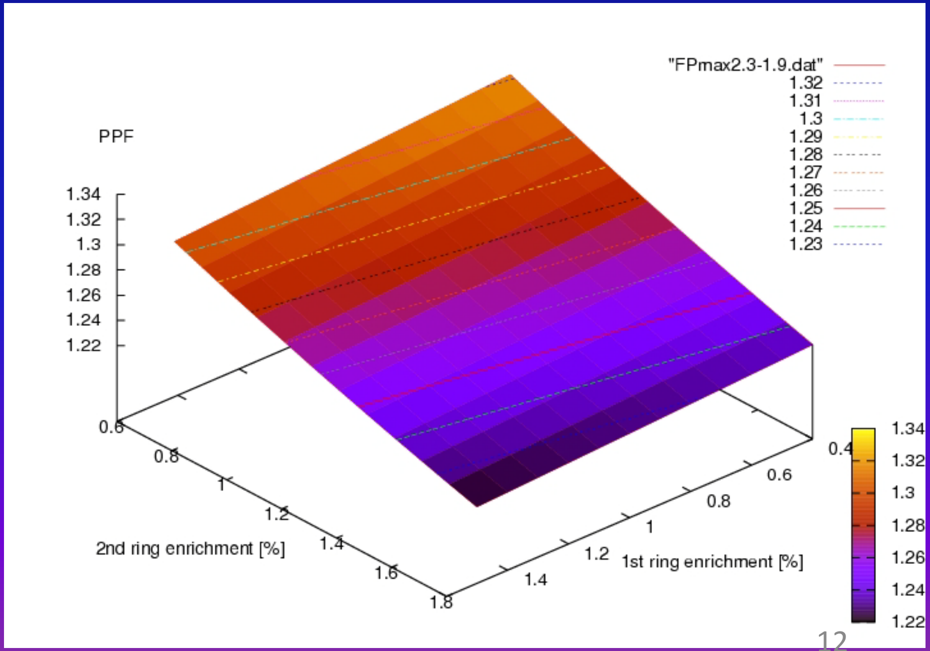
3rd and 4th rings enrichments



Optimum enrichment ratio:
$E_3 \approx 1.2 * E_4$

1st and 2nd rings enrichments

3rd and 4th rings enrichment



Observations on the multidimensional analysis

- Dy, In and B can be used to obtain negative void coefficient. The amount used depends on the coefficient required, on the enrichments used, and on the manner in which absorbers are used (pure or mixed with uranium).
- The higher the enrichment, the lower the cost (up to 4% of enrichment for a poisoned fuel)
- A relation between E_3 and E_4 that clearly minimizes PPF exists. PPF is reduce by increasing E_1 and E_2.
- The enrichment gradient that minimizes PPF is opposed to the one that minimizes void coefficient

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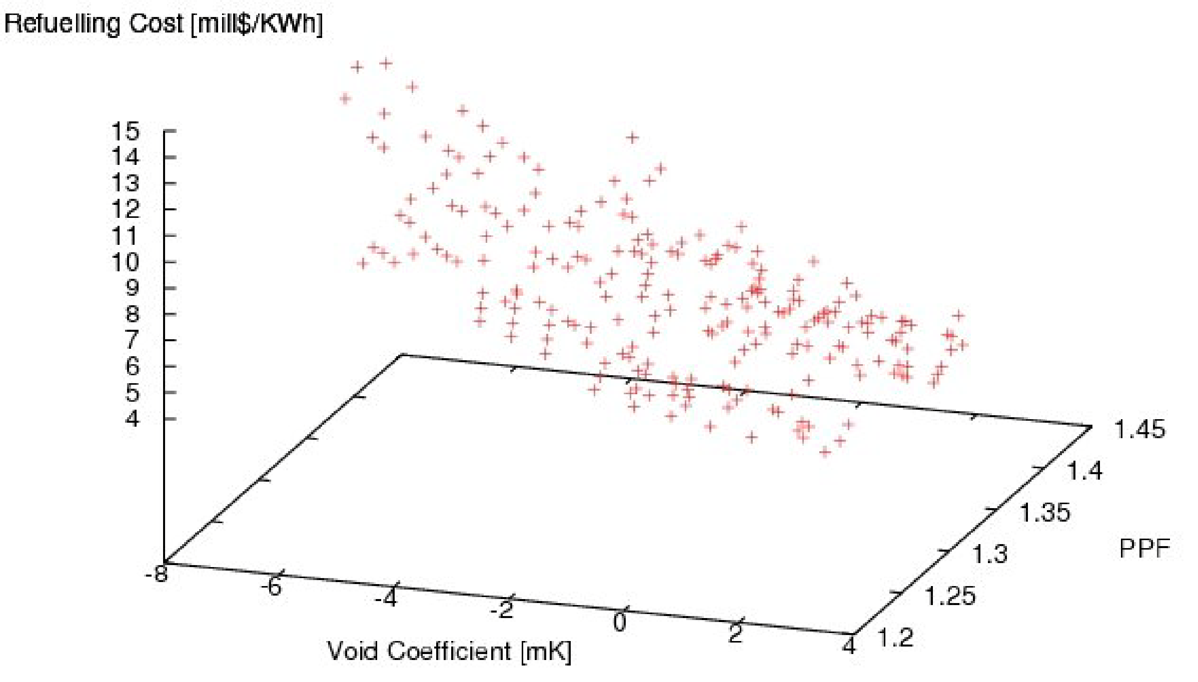
Phase Space Analysis



← Lower envelope of the evaluated fuel configurations

Phase Space Analysis

Results for weak negative void coefficient

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% Dy_2O_3	1.4%	2.3%	1.9%	1.26	-0.22	5.29
CARA In	0.35% +21.75% In2O3	1.0%	2.3%	1.9%	1.29	-0.21	5.13

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, Dy_2O_3 rods	Two 1.01cm, $^{0.8\%}UO_2$ rods	1.2%	2.3%	1.9%	1.24	-0.045	4.79

Concluding Remarks

- 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.
- An alternative exists to avoid eventual difficulties on the sintering of UO_2-Poison oxide mixed powders. This alternatives is based on the replacement of two central fuel rods by two pure Dy_2O_3 rods.
- 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.
- CARA fuel still has margin on cost (in comparison with Atucha II fuel) and PPF. Other design basis might be adopted having satisfactory results.
- These positive results in void coefficient for Atucha II using average data at full power encourage studying the DB change feasibility.

Thanks for your attention