PWR with hardened spectrum for improved conversion ratio

H. Golfier, A. Bergeron, A. Conti, F. Damian, J-M Do,
S. Douce, B. Gastaldi, F. Moutin, D. Pialla

CEA, FRANCE

hgolfier@cea.fr

Contents

Outlines

- The reactors of the third generation (60 years)→ the main part of the constructions for the next half century
  - At present, 80% of the nuclear power capacity
  - But : low Uranium consumption ~1% of U
- Thus, the continued deployment of LWR with their low uranium utilization leads to review alternative LWR
  - flexibility in fuel cycle and in economy based on well-proven technologies
- In a context of sustainable nuclear energy, systems with efficient uranium management :
  - **The Pu Recycling** and **the stabilization of the Pu isotopic vector** dedicated to a deployment of Generation IV reactors

Conversion in LWR : Objective

- System flexible enough in order to meet the future challenges
  - convertible core with an optimized use of uranium and via an increase of the conversion ratio factor (CR).
  - design evolutionary enough to use plutonium in multi-recycling strategy

- The conversion factor (FconvNL or CR) = good criteria (Resource/ isotopic Pu Vector)
  - The conversion factor is defined as the ratio of fissile Pu content between Beginning of Irradiation (BOI) and End of Irradiation (EOI)

- Objective : Conversion ratio in the range of 0.8 to 0.9
  - conversion ratio of about 0.3-0.5 in standard PWR.

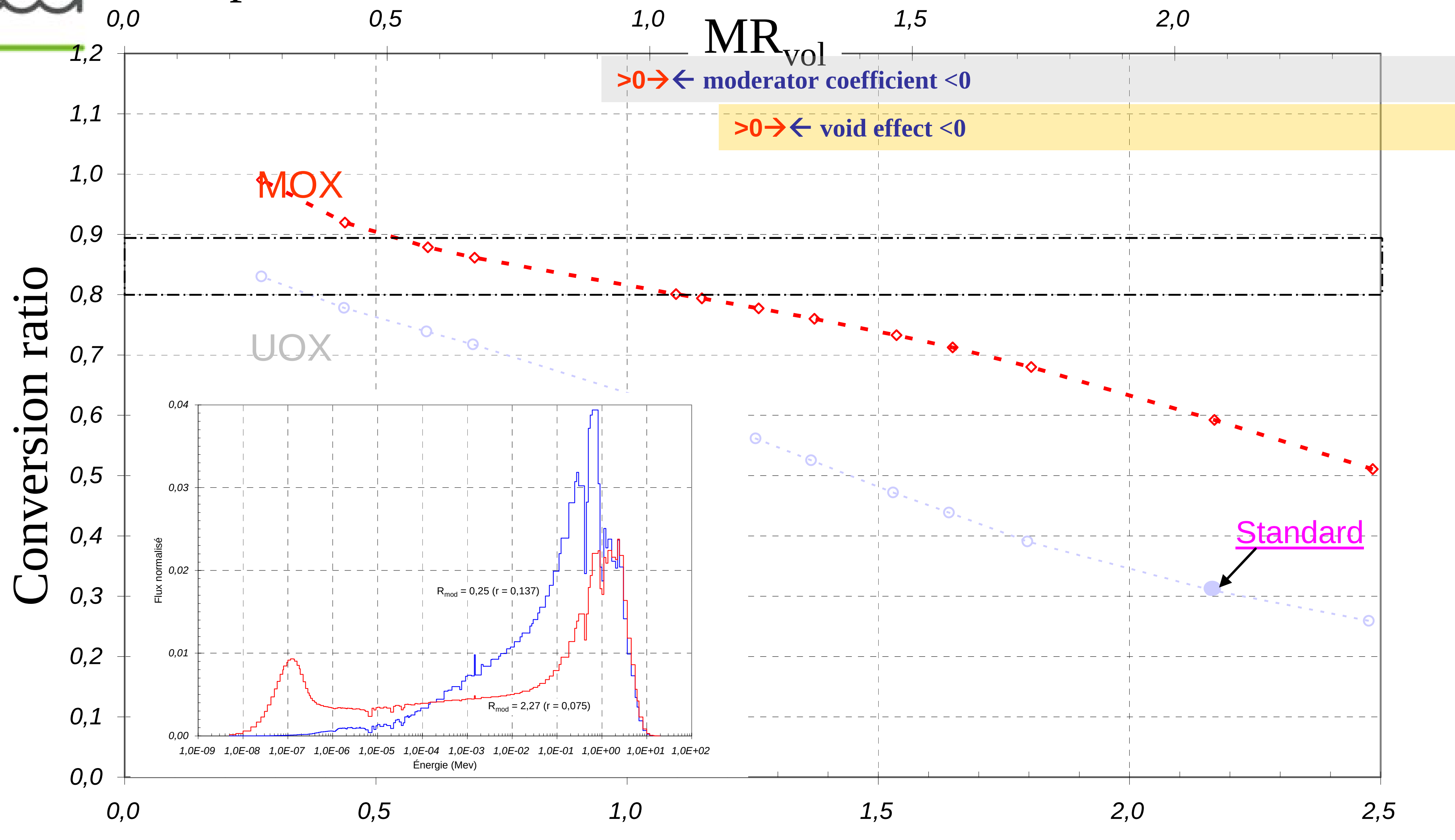
Conversion in LWR : How to improve it? (1/5)

- ❑ Important feedback in terms of the past experiments and the past studies

- ❑ Different options to harden the neutron spectrum
  - 1 - by reducing the moderation ratio
  - 2 - by increasing the fertile material mass in the core
    - Different scales : homogeneous / heterogeneous ways
  - 3 - by shifting the neutron spectrum

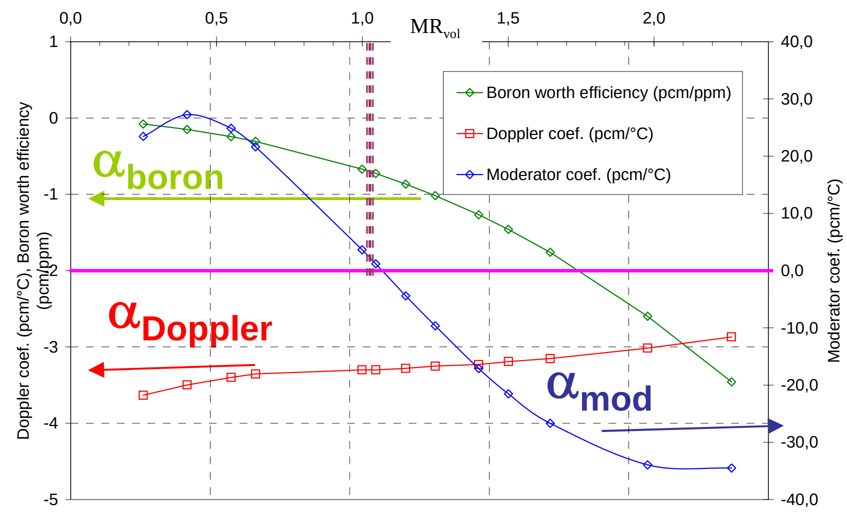
Conversion in LWR : Main design considerations (2/5)

Neutronic aspects with APOLLO2, ¼ sequences, discharged burnup of 60 GWd/t, infinite media condition

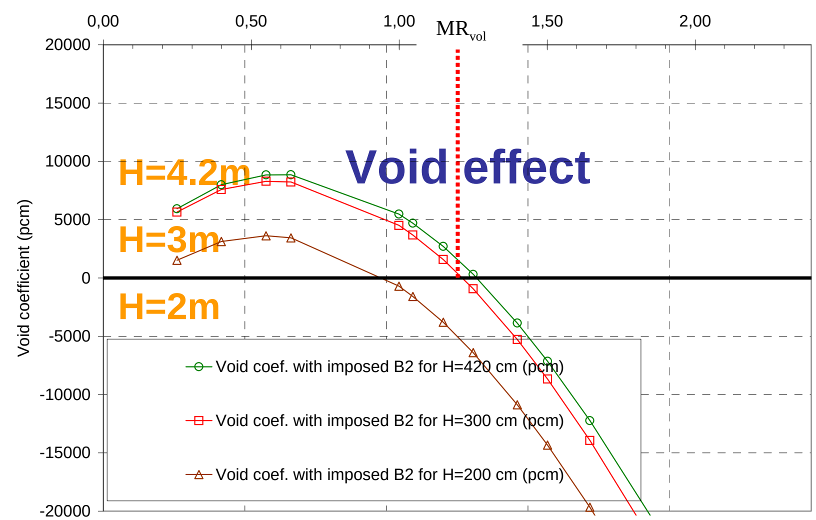


Conversion in LWR : Main design considerations (3/5)

- The limitations consist in keeping a negative coolant void reactivity effect, and satisfactory control margins in the core.



- Pu use constraints
  - Reduction of boron efficiency ➔ lower control capability of the core
  - Moderator coef. >0 at MR~1
  - Void effect : strong dependence with MR and H
  - Void effect >0 at MR~1.2
    - Increasing the axial leakage
    - Inserting ^{238}U elements, solid moderator rods
    - MOX-UE…

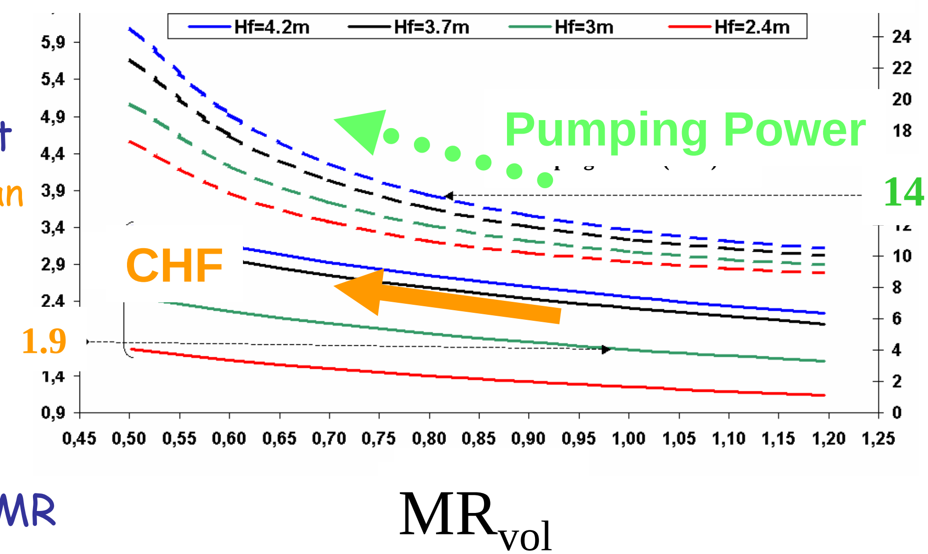


Conversion in LWR : Main design considerations (4/5)

- The modification of the moderation ratio with regard to Thermal-hydraulic parameters
  - MR > 0,8 → pumping power < 14MWe and pressure drop < 12 bar

The main criteria :
•Pumping power <14 MWe
•Critical heat flux margin at 70% primary flow > 1,9

- The reduction of the fissile height
  - Active height > 3 meters to keep an acceptable linear power.



- A modification of the operating conditions envisaged for very low MR

<u>The possible range of moderation ratio should be between 0.8 and 1.2.</u>

Conversion in LWR : Main design considerations (5/5)

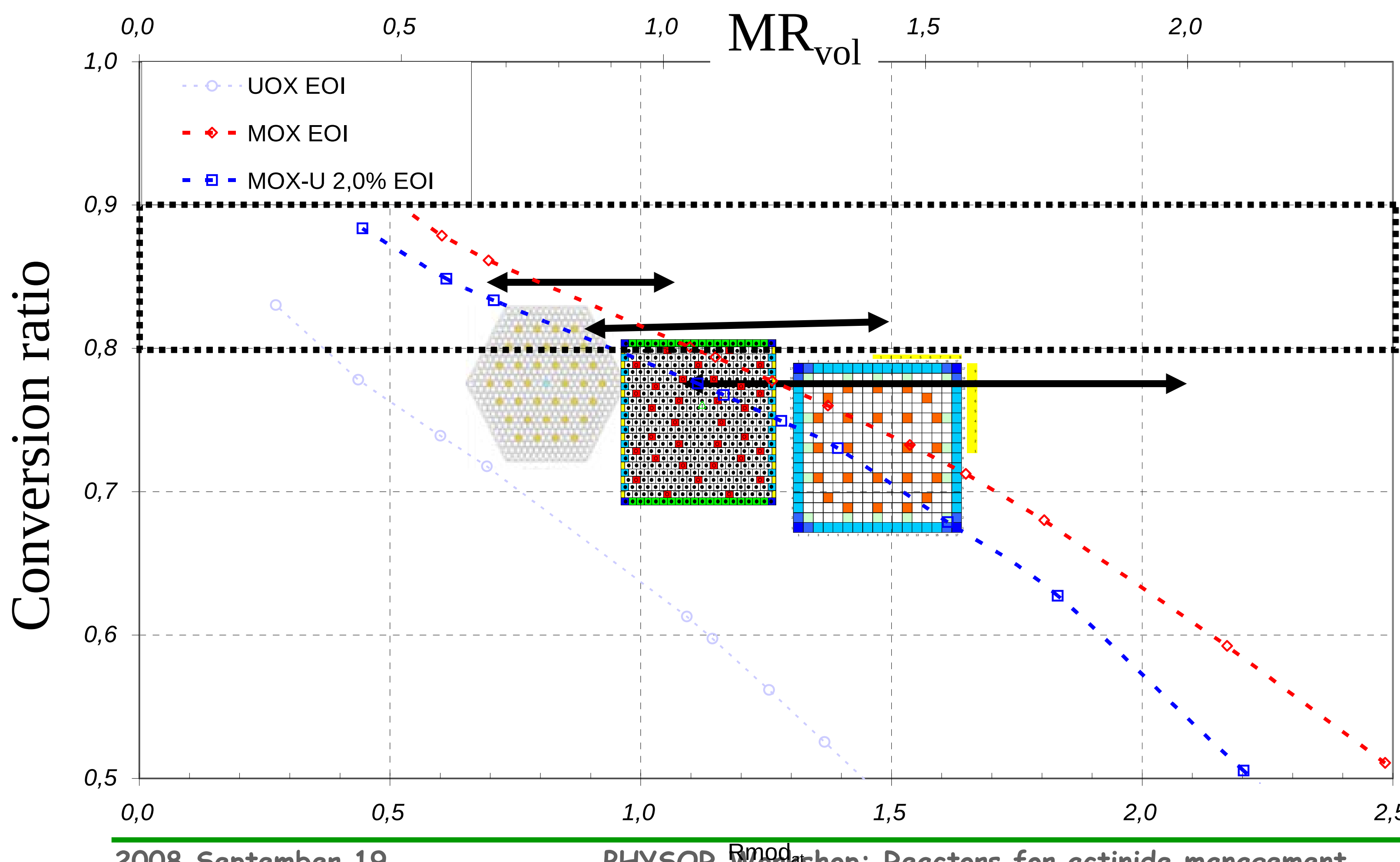
- Inter-dependence of the main neutronic&thermal-hydraulic parameters

- The preliminary studies shown 2 interesting MR ranges
  - 1 <MR< 1.2 : CR ~ 0.8-0.85
    - To minimize modification in PWR, a square-cross-section fuel assembly with square or triangular array
  - MR< 1 : CR ~ 0.85-0.9
    - To obtain a very low moderation ratio, a tight lattice with a triangular arrangement (hexagonal array sub-assembly)

- The lowest value of MR → the limit taking into account serious difficulties in Thermal-hydraulic

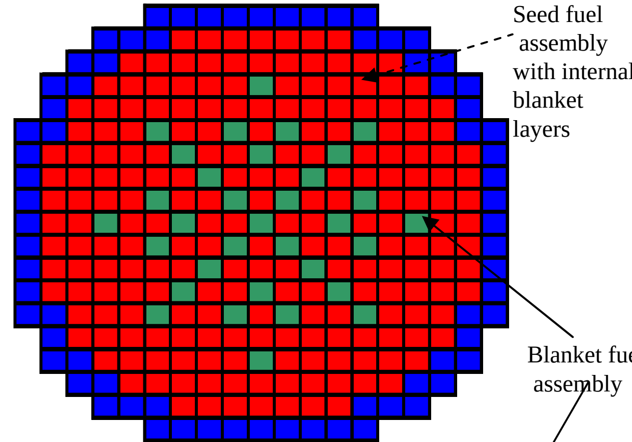
High CR core : core design characteristics (1/6)

- Exploratory studies performed to make a pre-design, to select the cases to treat in detail and to launch fuel assembly (FA) design studies with APOLLO2 and equilibrium cores analysis with CRONOS2 and FLICA4



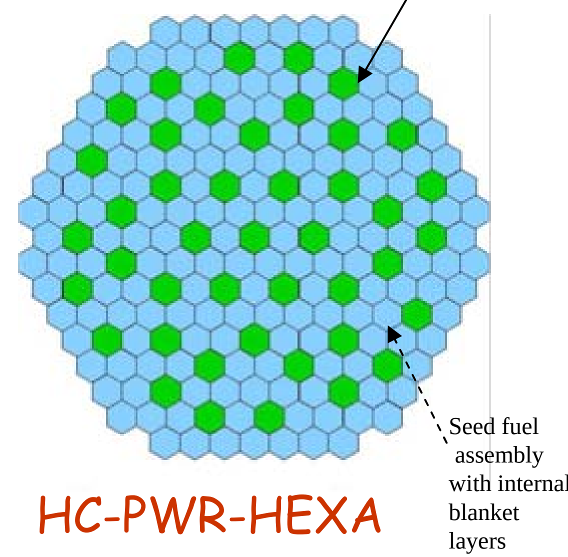
High CR core : core design characteristics (2/6)

- HC-PWR-19x19 : Vm / Vu = 1,26
  - More conventional design
  - Smaller technical gaps
  - no significant change of reactor systems
- HC-PWR-HEXA: Vm / Vu = 0.83
  - higher conversion ratio expected
  - modifications of the reactor core: pressure vessel internals, the control element penetration…
- Radial and axial structures : heterogeneous (optimization in progress)
- Fuel loading patterns : 4 batch-core (optimization underway)



HC-PWR-19x19

Vm / Vu = 1,26, active height = 3-3.5m



HC-PWR-HEXA

Vm / Vu = 0,83, active height = 3.5m

High CR core : core design characteristics (3/6)

Item	HC-PWR-19x19	HC-PWR-HEXA
Thermal Power	**4250 MW**	
Core Diameter	**3.77 m, heavy reflector**	
No. of Assembly (fissile/fertile)	241 (208/33)	211 (192/19)
No. of Control Rod	89, B4C, enriched ^{10}B	NE , B4C, enriched ^{10}B
Shape of Assembly	**Square, standard section**	**Hexagonal**
Fuel Rod Lattice	Square	Triangular
No. of rods (Fuel Rod/Thimble tube) per Assembly	361 (337,24)	469 (439/30)
Fuel Rod Pitch	1.13 cm	1.15 cm
Fuel Rod Diameter	**0.95 cm, standard**	
Assembly pitch	21.61 cm , **standard**	21.70 cm
Assembly height	**3m , 20 layers**	**3.5m, 7 layers**
Core radial Structure	**Heterogeneous with fissile and fertile assemblies**	
Core Axial Structure	10x { Blanket (5 cm) MOX (25 cm) … }	MOX (79 cm) Blanket (23 cm) MOX (61.5 cm) Blanket (23 cm) MOX (61.5 cm) Blanket (23 cm) MOX (79 cm)
Fertile % in core	**~27%**	**~27%**

High CR core : core design characteristics (4/6)

- Analysis performed to estimate preliminary 100% MOX core performances (Pu-2035)
  - Small Pu quality degradation.
  - Pu multi- recycling possible by mixing Pu with good quality discharged from UOX-PWR

Items	HC-PWR- 19x19	HC-PWR-HEXA
Core height	300 cm	350 cm
Fissile plutonium (Puf)	**19.7 %**	**19.9%**
Discharged burnup	4 x 10500 MWd/t	4 x 11000 MWd/t
Cycle length (EFPD)	4 x 290	4 x 390
Pu Consumption	**-47.4 Kg/TWhe**	**-33.5 Kg/TWhe**
Conversion ratio	**0.84**	**0.89**
Pu, HN inventory	**16.1 , 115 ton/core**	**21.5 , 147 ton/core**
Fissile Pu (BOI→EOI,%)	56→55.6%	56→55.4%
MA Production	+17.3 Kg/TWhe	+15.9 Kg/TWhe

Pu-2035	Pu isotopic composition (wt%)
^{238}Pu	3.03
^{239}Pu	48.73
^{240}Pu	30.36
^{241}Pu	7.34
^{242}Pu	9.80
^{241}Am	0.74
Fissile content	56%

NE : Not Evaluated

High CR core : core design characteristics (5/6)

- Shutdown margin evaluated at HZP : 89, B4C enriched ^{10}B
  - Cooling transient analysis will determine if the margins are sufficient
- Void reactivity coefficient : primary concern
  - HC-PWR-HEXA: $\Delta\rho_{void}>0$
    - 19→49 fertile assemblies : $\Delta\rho_{void}$=+1465→-380pcm (-25EFPD)
    - fuel rods replaced by ZrH2 pins (12 – 24) ➔ Core analysis underway.

Items	HC-PWR- 19x19	HC-PWR-HEXA
Core height	300 cm	350 cm
Conversion ratio	**0.84**	**0.89**
α_{mod}, $\alpha_{Doppler}$, α_{bore} Critical boron concentration	-17.8 pcm/°C, -3.2 pcm/°C, -3.5 pcm/ppm (50%B10) 560 ppm	NE
Margin at Hot Shutdown	~-4600 pcm	NE
Void effect	**-720 pcm , <0**	**+1465 pcm, >0**

NE : Not Evaluated

High CR core : core design characteristics (6/6)

- Acceptable CHF margin at reduced primary flow
  - Lower average linear power for the HC-PWR-HEXA

- A relative small reduction of the coolant flow (15%) for the HC-PWR-HEXA for an acceptable pressure drop (reduction of the output power of ~1% ~15 MWe).

Items	HC-PWR- 19x19	HC-PWR-HEXA	PWR (ref)
Core height	300 cm	350 cm	420 cm
Average Linear Power	174 W/cm	140 W/cm	158 W/cm
Max. Linear Power	417W/cm	300W/cm	380W/cm
Primary flow/current flow	100%	85% (100%)	100%
Departure from Nucleate Boiling Ratio (DNBR) at 70% of primary flow	1.9	1.7	>1.5
ΔP core (MPa) Pumping Power (MWe)	3.1 9.7	3.7 (5.4) 7.9 (12.1)	2.4 9

Introduction of HC-PWR in a nuclear park

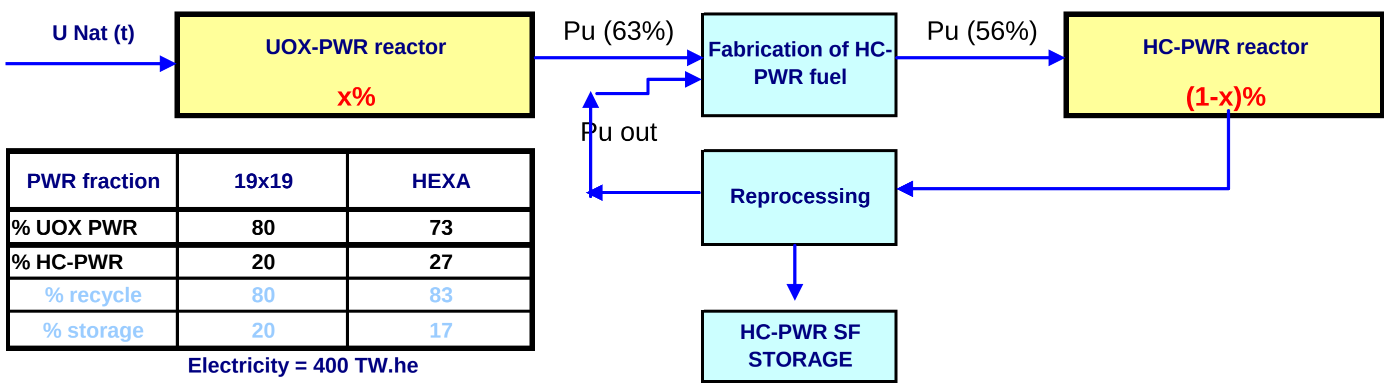
- **The key parameters for the introduction of HC-PWR in a nuclear park :**
  - Conversion ratio
  - Discharged Pu fissile quality
  - Initial Pu inventory

- **Two components model with a constraint : Pu quality**

U-PWR			
discharged burn-up		GWd/t	61
conversion ratio		%	0.29
Exchange discharge	Pu	t/Gwe/yr	0,19
	Pu fissile	t/Gwe/yr	0,12

HC-PWR-19x19			
discharged burn-up		GWd/t	42
conversion ratio		%	0,84
Initial loading	Pu	t/Gwe	11,7
	Pu fissile	t/Gwe	6,5
Exchange loading	Pu	t/Gwe/yr	3,35
	Pu fissile	t/Gwe/yr	1,88
Exchange discharge	Pu	t/Gwe/yr	2,97
	Pu fissile	t/Gwe/yr	1,60

HC-PWR-HEXA			
discharged burn-up		GWd/t	42
conversion ratio		%	0.9
Initial loading	Pu	t/Gwe	14,2
	Pu fissile	t/Gwe	8,0
Exchange loading	Pu	t/Gwe/yr	3,34
	Pu fissile	t/Gwe/yr	1,88
Exchange discharge	Pu	t/Gwe/yr	3,14
	Pu fissile	t/Gwe/yr	1,73



PWR fraction	19x19	HEXA
% UOX PWR	80	73
% HC-PWR	20	27
% recycle	80	83
% storage	20	17

Electricity = 400 TW.he

- U-Nat saving around 20 to 27%
- With the Pu quality constraint, 80% SF from HC-PWR recycled

CONCLUSION (1/2)

- Conversion ratio in the range of 0.8 to 0.9 appears feasible.
  - better utilization of resources,
  - Pu multiple recycling possible,
  - based on the PWR technologies.

- Improvement of core performances and the optimization of the core (loading pattern, axial and radial structures…)
  - Burnup : > 45 GWd/t
  - Pu inventory : ~ 20 t/reactor
  - Conversion ratio : ~0.85-0.9
  - Void reactivity coefficient : negative
    - Upper and lower blanket
    - solid moderator
    - Appropriate addition of ^{235}U to Pu
    - Mechanical spectrum variation device

and the safety analysis

CONCLUSION (2/2)

- The main R&D issues
  - Reactor Physics
    - Core design : verification of core performances such as conversion ratio, negative void coefficient, Sensitivity of fuel composition and of multi-recycling strategies…
    - Thermal-hydraulic analysis
    - Benchmarking for fuel assembly and for core
  - Safety
    - Transient and safety analysis :LOCA, reflooding and ATWS conditions.
    - Accident management
    - Risk of re-criticality
    - …

THANK YOU FOR YOUR ATTENTION