Gas-cooled Reactor Core Physics R&D Activities In France

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Outline

- Introduction
- GFR Design and Safety Project
- Results of GFR concept studies at CEA
- The Exp. Research and Technology Development Reactor
- Data/method/code development and validation needs
- GFR physics experiments in MASURCA
- Conclusion

Introduction

- **This presentation**
  - focuses on the **GFR concept**
  - is essentially a CEA viewpoint
  - will try to complement others'
- **Other Gen-IV systems of interest to France**
  - **VHTR**
    - ✓ See PHYSOR-2004 presentation by J.-C. Gauthier and
    - ✓ Contributions of CEA to reactor core physics **code development and validation**, mainly for GT-MHR concept
      See PHYSOR-2004 papers by F. Damian et al., P. Blanc-Tranchant et al.
  - **SFR**
- **Lower interest in France for SCWR, LFR, MSR** concepts

Introduction

- **In France, two major R&D axes in the areas of innovative reactors, fuels, and fuel cycle technologies**
  - **Innovation for PWRs**
    - ✓ Economics and safety
    - ✓ Pu recycling, and possibly MA
    - ✓ Fuel cycle improvements (separation of MA)
  - **Gen-IV nuclear systems**
    - ✓ Sustainability
    - ✓ Improved economics and safety
    - ✓ Proliferation resistance
    - ✓ Applications other than electricity production
      - Hydrogen production
      - Desalination
- **For CEA, major interest in GFRs**
  - Modular version, T = 850 °C → around 2020
  - Upgraded version, T > 950 °C → massive production of H
  - Self-sufficient system with full recycling → sustainable nuclear technology

GFR Design & Safety Project (still under discussion)

➢ General R&D framework

- **GFR R&D plan** under discussion, to meet Gen-IV objectives → see Technology Roadmap submitted to NERAC, Sept. 2002
- Several projects, including ***Design & Evaluation + Safety***
- Each project organised in Work Packages with Task Sheets, to address **key viability issues** in **viability phase** (2004-2012)
- Contributions from various countries represented by ANL, BNFL, CEA, JNC, KAERI, PSI, … + partner organisations
- **Scope of Design and Safety Project** includes conceptual studies of reference GFR system (core and system studies), assessment of alternate options, safety approach, development of computational tools, economics assessment
- Includes **design, safety and development** studies of ***Exp. Research and Technology Development Reactor*** (ETDR)
- Feed to / Get input from technological developments in companion projects (fuels, components,…)

Objectives

- Definition of **reference GFR concept** and **back-up options**

  Core design requirements:
  - ✓ Refractory fuels, high FP retention capability at high T (up to 1600 °C)
  - ✓ No fertile blankets, BG ~ 0 (CR ~ 1)
  - ✓ Pu and MA multi-recycling, high burn-ups (10 at% FIMA)
  - ✓ Minimize fuel inventory
  - ✓ Adequate power density level for economics & safety
  - ✓ High coolant outlet temperature for hydrogen production

- **Safety analyses** of reference and alternative GFR concepts

- **ETDR design and safety analysis**

- Development and validation of **calculation codes** for core physics analysis, safety evaluation, operation and control

- **Economics** assessment

GFR Design & Safety Project (still under discussion)

➢ Tentative schedule

- ❑ 2004-2005 — Preliminary GFR studies → reference concept
- ❑ 2006-2007 — Pre-design studies → prelim. **viability report**
- ❑ **2008** — Decision on **ETDR** construction
  → start design studies, V1 code systems
- ❑ 2008-2015 — ETDR construction
- ❑ **2015**-… — **ETDR start of operation** - Start-up core, then *demonstration core* with test of GFR fuel S/A's
- ❑ 2008-2013 — GFR concept studies
- ❑ 2013 — Selection of GFR prototype design options
- ❑ **2019** — Decision on **GFR prototype** construction, incl. feedback from ETDR operation and fuel tests
  → start design studies, V2 code systems

Results of GFR Concept Studies at CEA

- **Recent GFR concept studies at CEA (2002-2003)**

  - **Design characteristics**
    - ✓ P = 600 MWth or 2400 MWth
    - ✓ High-density macro-dispersion (U,Pu)C fuel, SiC matrix
    - ✓ Pu fraction ~ 15-16%
    - ✓ Plate- or pin-type, T_{max} = 1200 °C
    - ✓ Helium pressure = 70 bars, Core pressure drop ≤ 0.5 bar
    - ✓ Helium inlet / outlet temperatures = 480 / 850 °C
    - ✓ **EOC BG = 0**, three-batch management scheme
    - ✓ Cycle length determined so that burn-up = given value

  - **Results** → see tables and references

- **References**

  - G. Rimpault et al., “A feasibility Study of a 600 MWth Gas-cooled Fast Reactor”, GLOBAL-2003

  - J.-C. Bosq et al., “Parametric Approach and Neutronic Studies of a Large Core Design for GCFRs”, PHYSOR-2004

Results of GFR Concept Studies at CEA

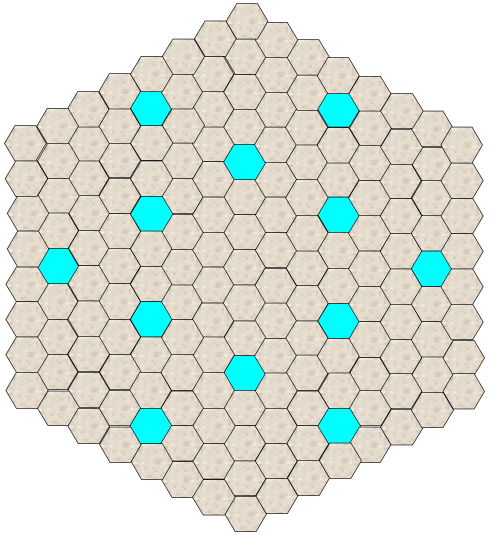
	CERCER 50/50, plates	CERCER 50/50, plate	Carbide fuel pins, SiC clad
Power	600 MWth 275 MWe	2400 MWth 1100 MWe	2400 MWth 1100 MWe
Power density	56 MW/m^3	96 MW/m^3	96 MW/m^3
Core volume	10.7 m^3	25.0 m^3	25.0 m^3
Core Δp	0.2 bar	0.5 bar	0.5 bar
Fuel	UPuC/SiC (50/50)	UPuC/SiC (50/50)	UPuC (20%) SiC (15%)
Max fuel temp.	1174 °C	1200 °C	1500 °C
Mass of HA	30 t	62 t	53 t
Core loading	3 x 830 EFPD	3 x 966 EFPD	3 x 745 EFPD
Burnup	5% FIMA	10% FIMA	10% FIMA
EOC Doppler coeff. / βeff / Void coeff.	- 1540 356 pcm + 230 pcm	- 1278 342 pcm + 212 pcm	- 968 352 pcm + 554 pcm

- **Objectives of the ETDR**
  - **Irradiation of prototype fuels/innovative materials** in normal operational conditions as well as in operational transients
    → Evolutionary core configurations
    → Need for a **highly flexible** reactor
  - **Evaluation** of coolant density/flow transients, temperature coefficients, decay heat, core control and monitoring systems, etc.
  - **Validation of calculation codes**
  - **Validation of first safety analysis**
  - **International project**
- **For CEA, the ETDR is a major step in the demonstration of the feasibility of high temperature GFRs**

The Exp. Research and Technology Development Reactor

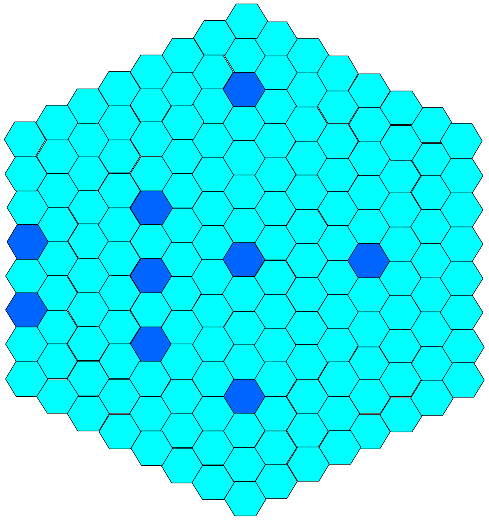
➢ **Start-up core**

- ❑ P = 50 MWth, V = 238 l → 210 MW/m^3
- ❑ Pin-type U+Pu fuel, proven technology
- ❑ Helium temperature ~ **650 °C**
- ❑ …



➢ **Demonstration core**

- ❑ P = 50 MWth, V = 238 l → 210 MW/m^3
- ❑ CERCER fuel
- ❑ MA-loaded fuel S/A's
- ❑ Helium temperature ~ **850 °C**



Data/Method/Code development and validation needs

- **REDT/GFR will have innovative features with respect to SFRs**
  - Dense carbide or nitride fuel
  - Degraded Pu isotopics, high MA content
  - SiC or ZrN matrix
  - No fertile blankets, new reflector materials (ZrC, Zr_3Si_2,…)
  - Gas coolant, fraction ~ 40 to 67%, high pressure, high temperature

- **Consequences**
  - New materials, possibly in large quantities → different detailed structure of the neutron spectrum
  - Graphite → Softer spectrum → Different reactivity effects
  - Gas channels → Streaming effects, high dilution
  - Different temperatures → Different thermal expansion
  - Gas depressurisation/injection reactivity effect
  - Etc.

See H. Khalil's PHYSOR-2004 presentation on "Advances needed in Reactor Physics for the Design of Gen-IV Systems"

➢ Current code systems such as ERANOS

- ❑ Have most of the necessary modelling options for calculating GFR's
  - ✓ Some extensions needed → nuclear data, methods
  - ✓ To be discussed this afternoon
  - ✓ At this stage, priority should be given to those actions that
    - – Are the most generic
    - – Have quantitative justification
    - – Are characterized by long lead times
- ❑ But are **not** validated for such applications ⇒ performance (C/E) not known

Data/Method/Code development and validation needs

- **Integral experiments: database is limited**
  - MASURCA 1A': 60's, small core, Pu metal, 25% Pu + C
  - MASURCA 1B: 60's, small core, U metal, 30% U-235 + C
  - ZPR9/GCFR: 70's, large cores, simulated oxide fuel, 20% Pu, platelets → See PHYSOR-2004 Paper by J. Tommasi
  - PROTEUS: 70's, central fast zone $(U,Pu)O_2$, 15% Pu

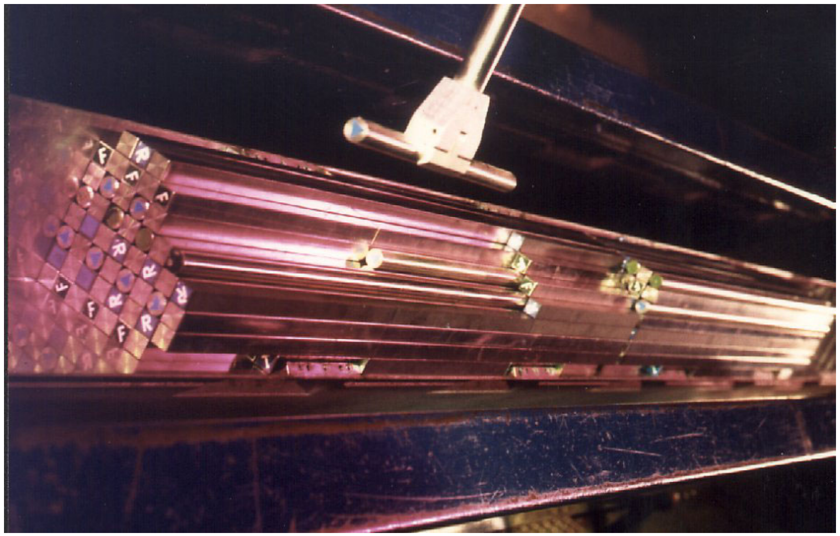
⇒ proposal for a **complementary experimental programme in MASURCA** to get the needed validation data:

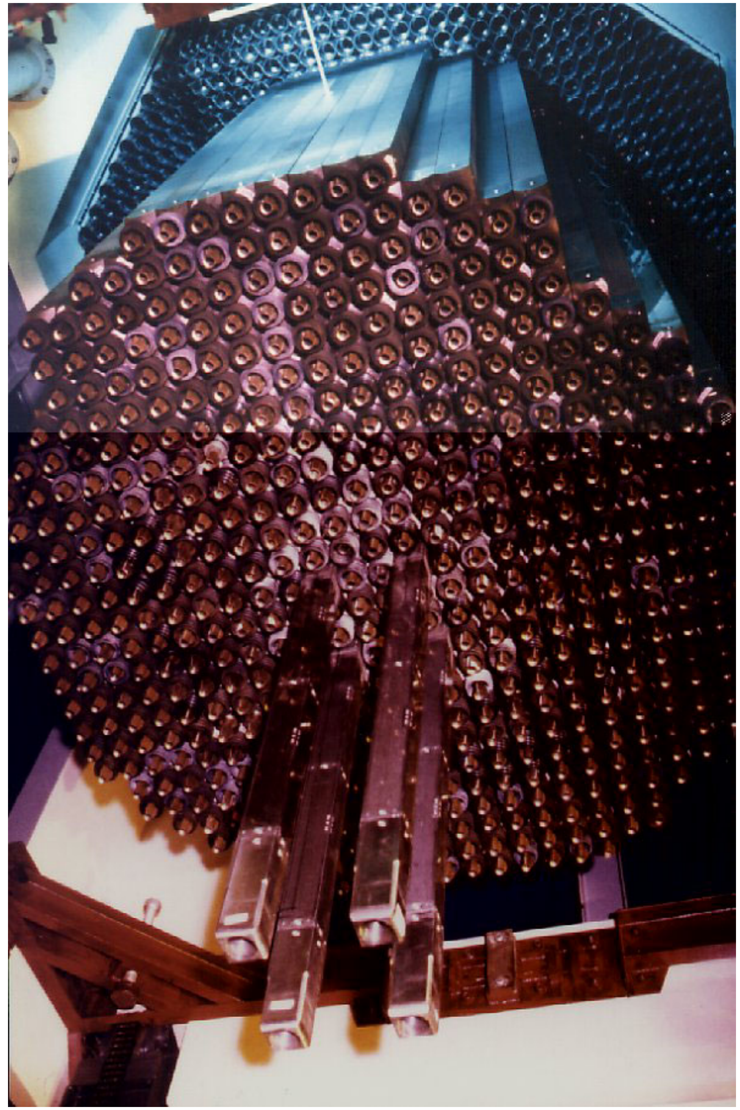
Experimental Neutronic Investigation of Gas-cooled configurations in Masurca (ENIGMA)

Reference cell and core configurations have been defined by J. Tommasi, with contributions from ANL

GFR Physics Experiments in MASURCA

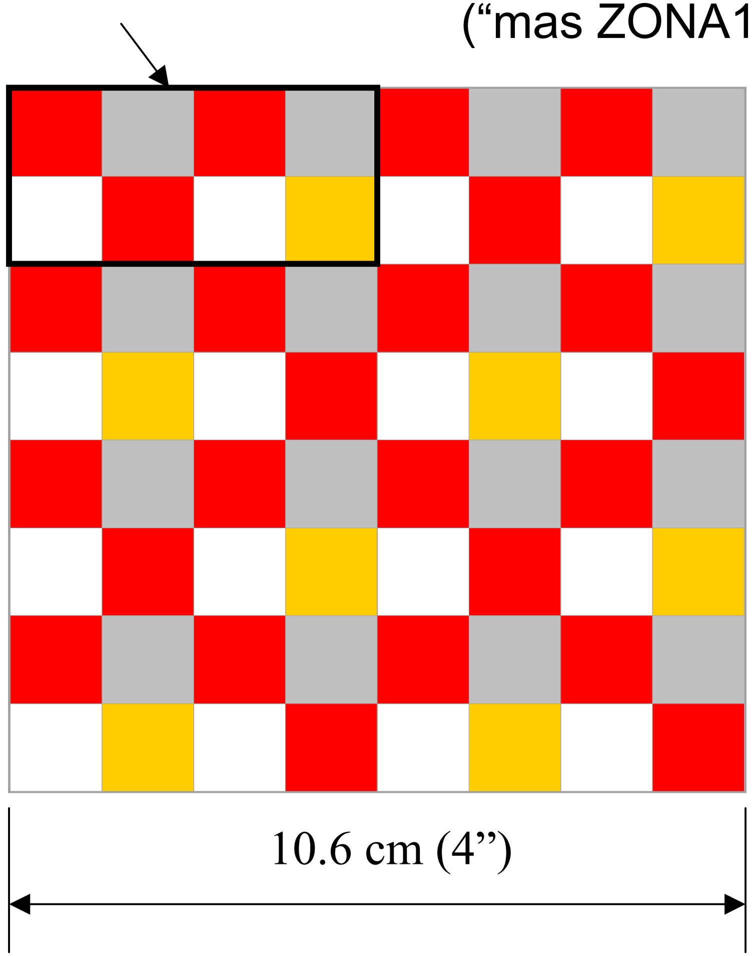
- **The MASURCA facility**





➢ ENIGMA reference subassembly

Reference cell = 3 UO_2-PuO_2 + 1 UO_2 + 2 C + 2 void
("mas ZONA1 C Vide")

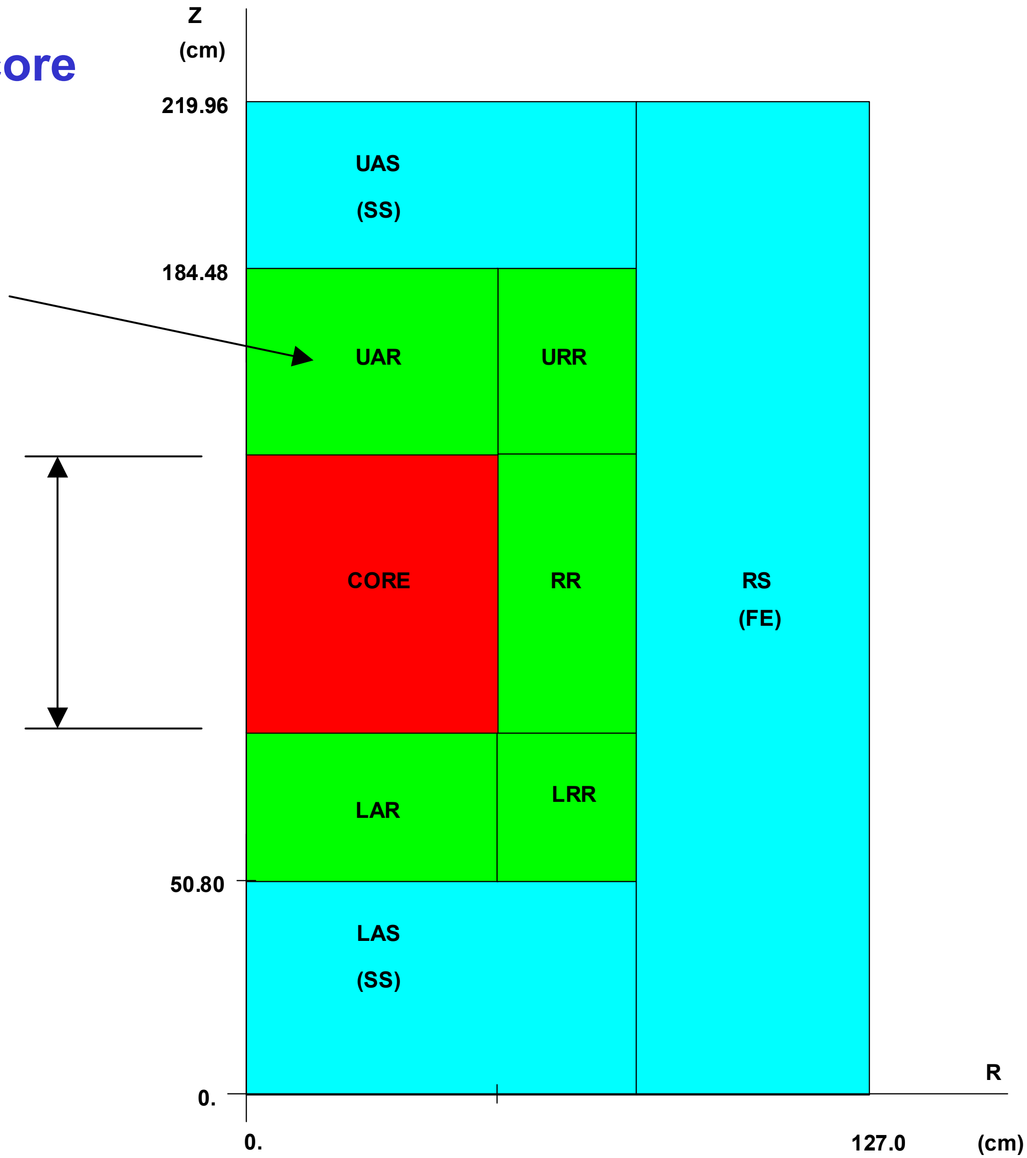


	UO_2-PuO_2 (24)
	UO_2 (8)
	C (16)
	Air (16)

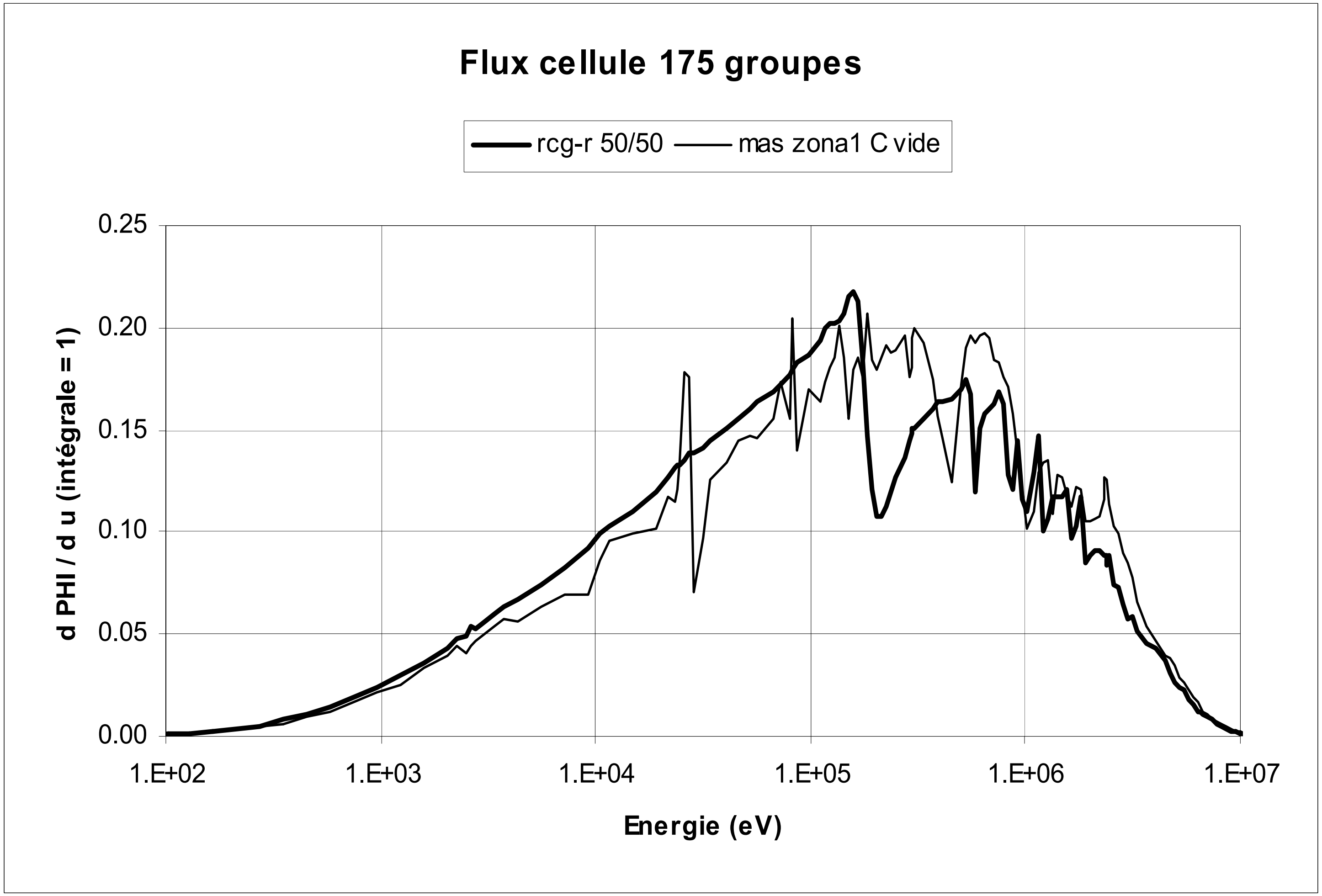
- **ENIGMA reference core**

Test of reflector materials

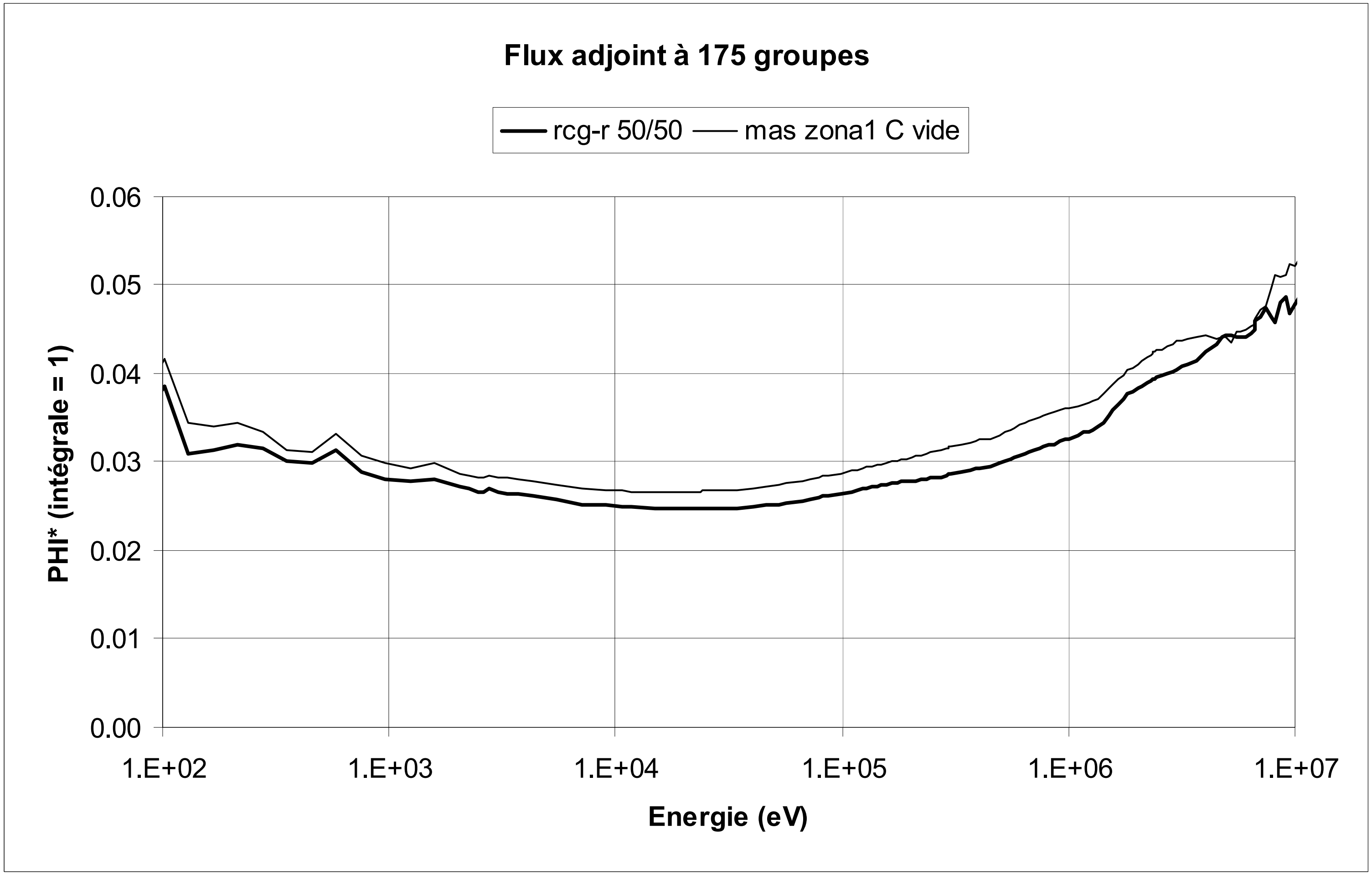
Active core height = 91 cm



➢ Neutron spectrum



Adjoint spectrum



Representativity study with respect to GFR 600 MWth “50/50”

Representativity improves mainly with

- ✓ Graphite introduction
- ✓ Core size increase

$$r^2 = ({}^{T}S_R\, D\, S_E)^2 / [({}^{T}S_R\, D\, S_R) \times ({}^{T}S_E\, D\, S_E)]$$

r values for keff and two spectral indices

D = Dispersion matrix for ERALIB1 library

	keff	F9/F5	F8/F5
H=61 cm, R=45 cm, ZONA2, no C	**0.471**	**0.517**	**0.718**
H=61 cm, R=45 cm, ZONA2, C in ½ void	**0.659**	**0.862**	**0.865**
H=61 cm, R=45 cm, ZONA2, C in all voids	**0.710**	**0.954**	**0.919**
H=91 cm, R=54 cm, ZONA2, C in ½ void	**0.756**	**0.938**	**0.897**

GCFR Physics Experiments in MASURCA

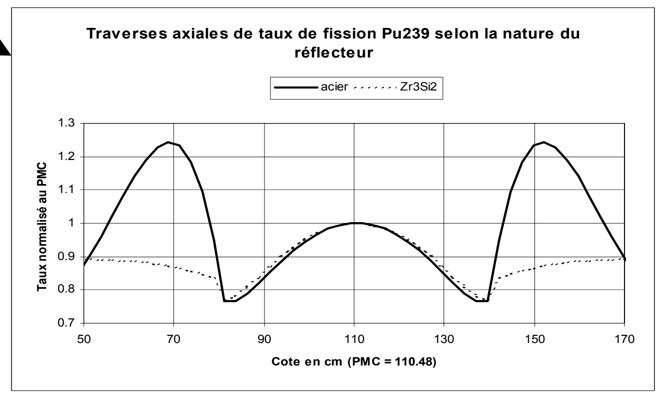
➢ Reflector studies

H = 91.44 cm

Critical radius in cm

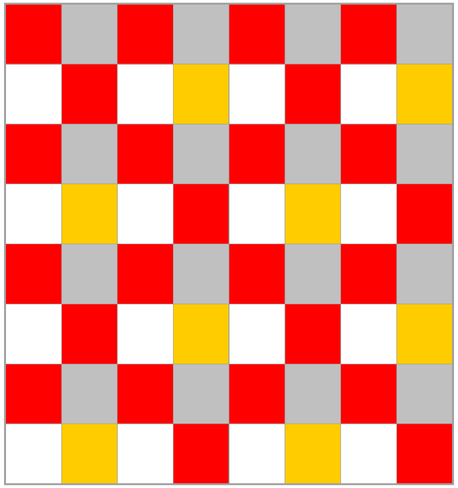
Axial Refl..(→) Radial Refl.(↓)	Steel	C	SiC	ZrC	Zr3Si2
steel	55.7	53.4	53.5	53.4	54.2
C		49.1			
SiC			49.1		
ZrC				48.7	
Zr3Si2					51.2

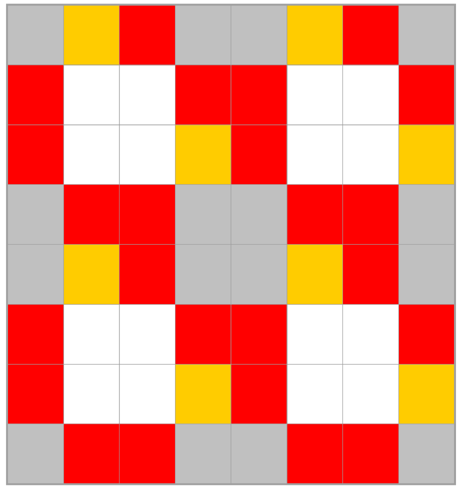
Pu-239 fission axial traverse

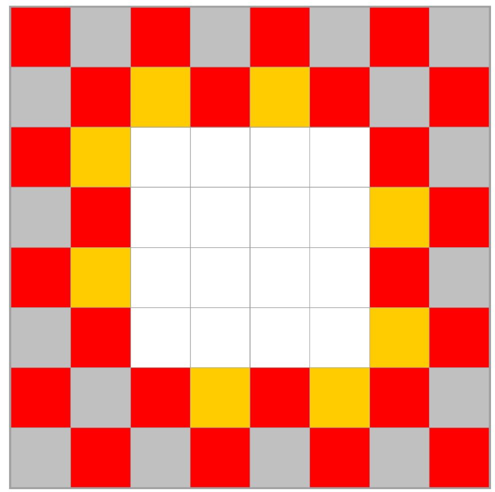


➢ Neutron streaming studies

(red)	UO_2-PuO_2 (24)
(yellow)	UO_2 (8)
(grey)	C (16)
(white)	Air (16)

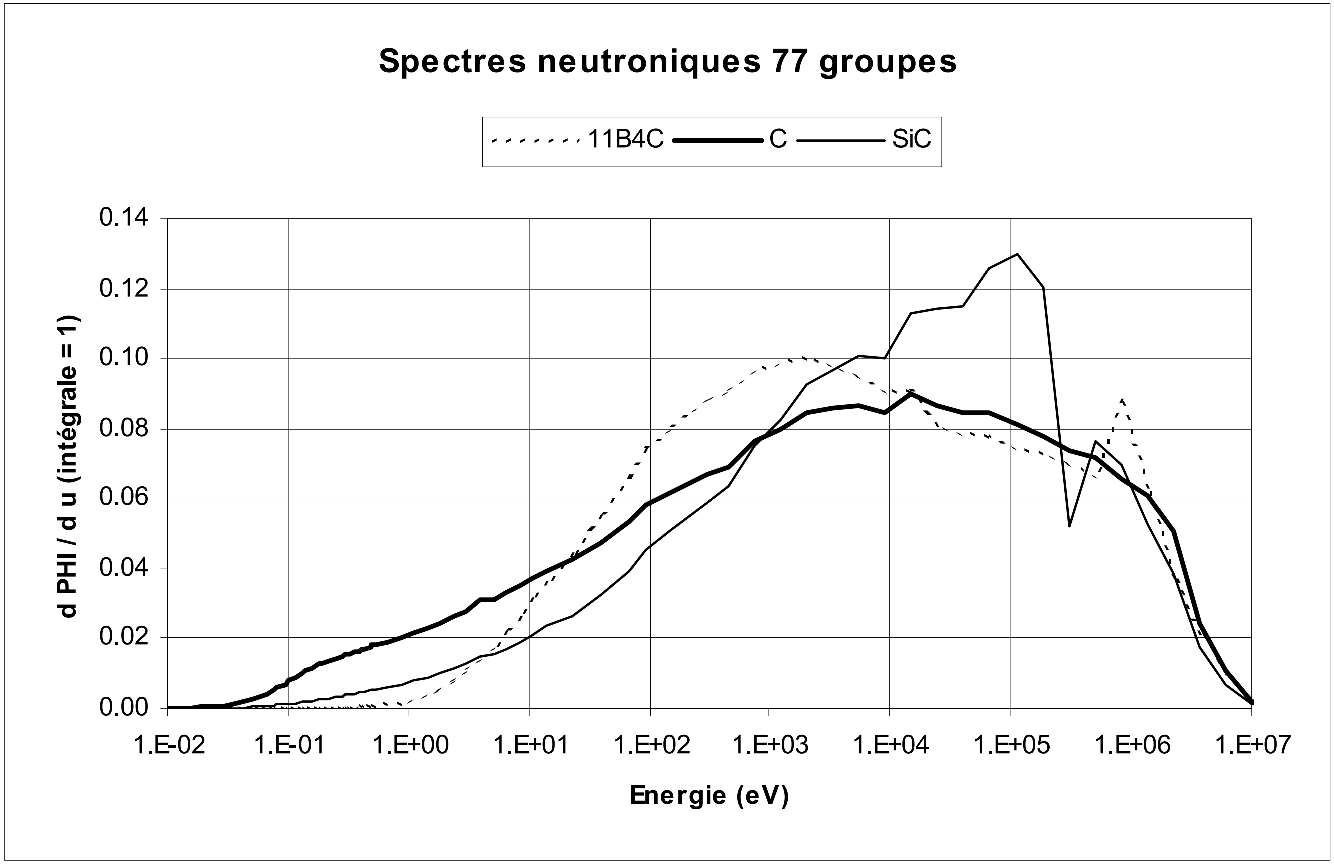


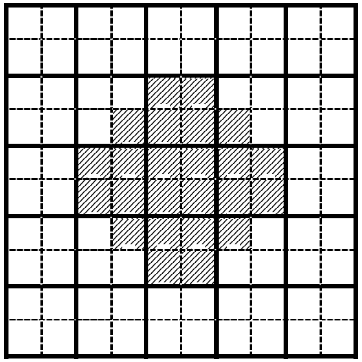




➢ Central substitutions

Replacement of 6 subassemblies at the core centre (R = 15 cm)
For example: $^{11}B_4C$, C, SiC, fuel with high Pu-240 content,…





GCFR Physics Experiments in MASURCA

➢ Schedule

- ❑ **2005-2006** **ENIGMA-1**
  Focus on "generic" GFR physics issues
  Reference core characterisation study
  + central substitutions (C, SiC, degraded Pu, absorbers,…), reflectors, streaming studies

- ❑ 2007 MASURCA shutdown for refurbishing

- ❑ **2008-…** **ENIGMA-2**
  Complements to Phase 1 + specific design options
  ETDR start-up core mock-up

➢ Programme

- ❑ Will be part of EC 6th FP program (GCFR)

- ❑ **Is open to external participation**
  Contributions to measurements are particularly welcome

Conclusions

- **In Gen-IV, CEA gives high priority to GFRs**

- **CEA Gen-IV R&D activities in reactor physics → *Design and Safety* Project**
  - 2004-2007 Prelim. GFR studies, reference concept, ETDR
  - 2008-2015 ETDR construction and GFR concept studies
  - 2015 ETDR start-up

  Close contact with other Gen-IV WPs (Fuels) is essential

- **ETDR**
  - A **major step** to demonstrate the feasibility of high-T GFRs
  - Intended to be an **international project**

- **Current neutronics data and codes developed for SFRs**
  - Modelling capabilities OK for viability phase, with some extensions
  - Need of assess their performance for GFRs → **experiments**

- **Experimental GFR physics program in MASURCA**
  - Will be part of EC 6^{th} FP program (GCFR)
  - Is open to external participation