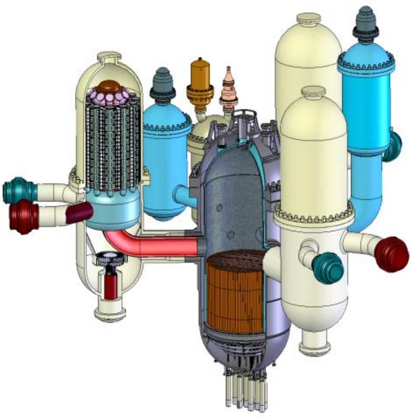
DE LA RECHERCHE À L'INDUSTRIE



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Séminaire
FLUIDES CALOPORTEURS POUR LES RNR

Académie des sciences
Fondation Simone et Cino del Duca, Paris 8e
19 et 20/02/2013

RNR-G,
INCIDENCE DU CHOIX DU GAZ, HÉLIUM EN PARTICULIER, SUR LA CONCEPTION ET LE FONCTIONNEMENT DU RÉACTEUR, SÛRETÉ

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CONTENT

THE GFR: AN ALTERNATIVE FAST REACTOR FOR LONGER-TERM

A program with a number of R&D challenges

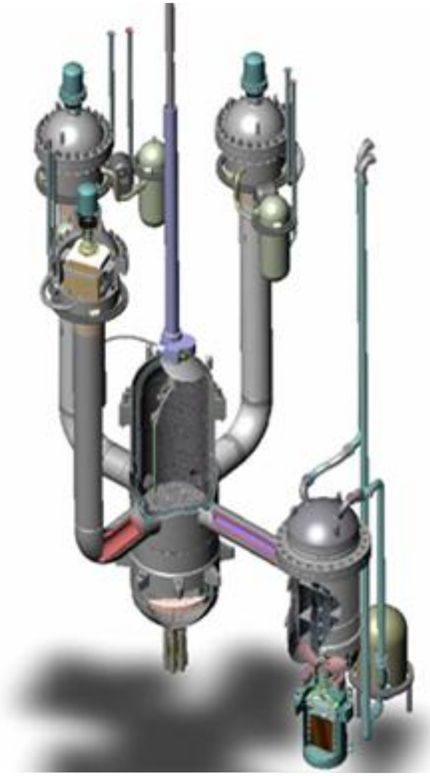
1) A fuel element able to withstand high temperature and fast neutrons
2) innovation on nuclear reactor and energy conversion system
3) safety demonstration (LOCA and sever accident)

Feasibility is to be proved with a small power demonstrator

→ **Allegro**

A demonstrator of 75 MWth :

1. Feasibility of the GFR
2. Test of componants
3. Fuel development
4. Service for fast neutron irradiation
5. Coupling to heat process



A collaborative program with Tchéquie, Slovaquia, Hongria, Poland in support of an ESFRI project (European Strategic Forum on Research infrastructures)

SELECTION OF HE COOLANT FOR THE GFR R&D PROJECT

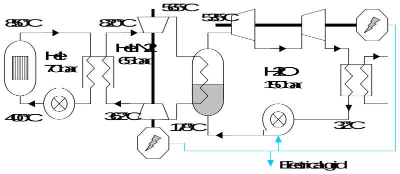
Decided at the very beginning of the project

- Because of its physical, chemical, neutronics properties
- Alternative : CO_2

Safety (He)

- Great neutron transparency, acceptable gas voiding reactivity effect < 1$
- No threshold effect: single phase cooling, chemical inertness (air, water)
- Potential for In-Service Inspection, T° instrumentation: optical transparency

Competitivness (He)



- **High temperature**, potential for:
  - high energy conversion efficiency (45% - 48%)
  - industrial applications (process heat, …)
- Simplification for repairing & decommissioning: non toxic coolant, not activated, optical transparency

MAJOR GFR DESIGN OPTIONS

Reactor concept (fuel managt.) and Decay Heat Removal issue:

- A power density ≅ **100 MW/m3** (trade-off neutronics performance vs safety issue)
- Very limited thermal inertia in the core area (vs HTR & graphite blocks)
- Challenging concept, combining **poor thermal properties of gas (Helium coolant)** with significant power density:

Current major reactor design options

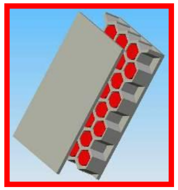
- **A fuel based on high thermal conductivity and refractory materials, to withstand high temperature : (U, Pu)C & reinforced ceramic composite clad** **(**safety**)**
  - "Cold" operating clad/fuel temperature: ≅ **1000/1300°C** (margins / accident)
  - Boundary accidental clad T° (**DBA, 4th cat.**): **1600°C / < ≅1h** **(**FP confinement, 1st barrier)
  - Ultimate accidental clad T° (SA prevent.): **2000°C / < some min?** (no loss of geometry)

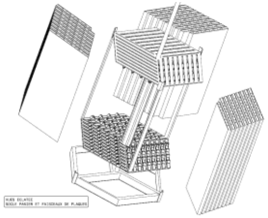
+600°C

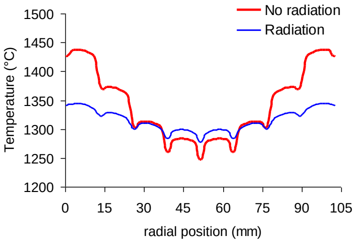
+1000°C

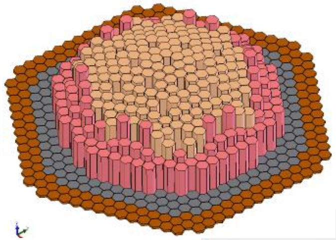
- **2400 MWth, $T°_{\text{inlet/outlet}}$ RPV : 400/850°C** (economy of scale, trade-off energy conversion η vs materials and safety issues)
- **Pressurized cool.: 7 MPa**; with **limited $\Delta P_{\text{primary}}$** to ease the gas circulation: **$\Delta P_{\text{core}} \leq$ 0.15 MPa**; core designed with **favourable reactivity effects**… (safety)

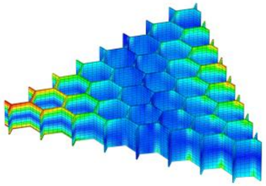
GFR 2400 MWTH FUEL & CORE DESIGN

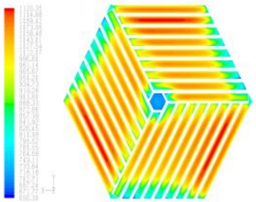


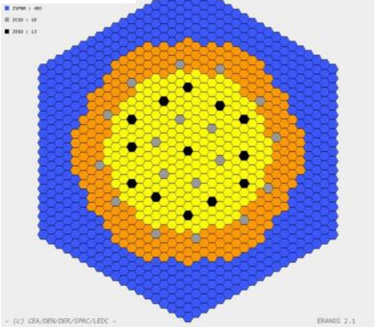












FUEL DESIGN & FABRICATION

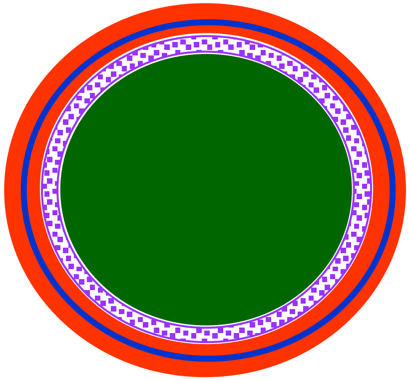
Fuel : UPuC (density & conductivity)

Clad : SiC$_f$-SiC (thermal and mechanical properties, high meting temperature)

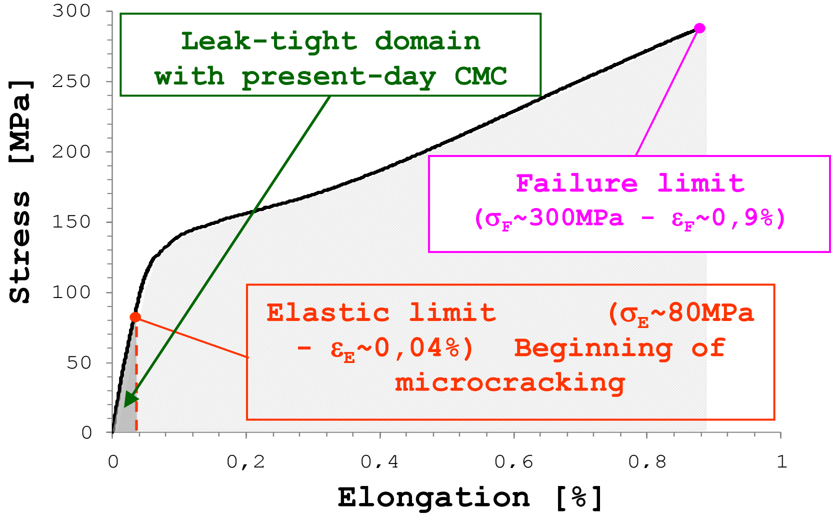
SiC$_f$-SiC ⇒ Leaktightness needs a liner

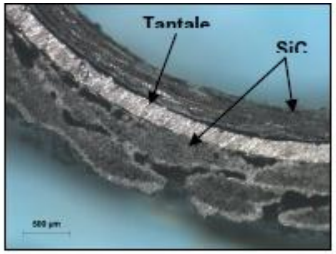
1. **Sandwich → SiC$_f$-SiC / métal / SiC$_f$-SiC**
2. **Duplex → SiC / SiC$_f$-SiC**

Fuel/clad gap : He bonded or a buffer (C et/ou SiC)

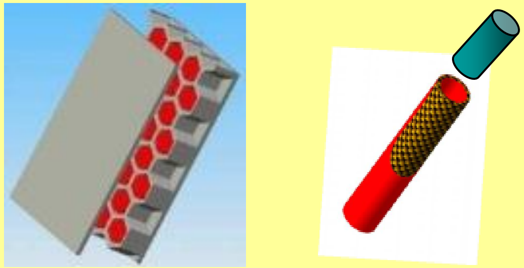


Courtesy of C. Sauder & C. Lorrette (CEA)





CORE PERFORMANCES



Similar performances, the initial expected values being reached:

- **Moderate ΔP_{core}**
- **High energy conversion η**
- **Self breeding gain (without fertile blanket)**
- **Reasonable Pu Inventory required (reactor fleet deployment)**
- **Favourable reactivity coefficients (high doppler, voiding effect < 1 $)**

Manufacturing of ceramic clad: ☺ with pin-type fuel element

	Plate-Type Core « 12/06 »	Pin-Type Core « 03/09 »
PLANT CHARACTERISTICS (reactor nominal condition)		
Power Density (MW/m^3)	91.5	100
Pressure (MPa)	7	
T_vessel in/out (°C)	400/**850**	
Core Pressure Drop (bar)	**1.40**	**1.45**
Tmax_cladding (°C)	**920**	**993**
Tmax_fuel BOL/EOL (°C)	1324	1275
Corresponding energy conversion η (%)	**48**	
CORE – SUB-ASSEMBLY		
H/D Fissile Core	0.62	0.39
Nb of S/A Rows x Nb of Fuel elements per S/A	9 x 27 Fissile column divided in 9 modules	13 x 217 Fissile column divided in two « half pins »
Fissile Height (mm)	2349	1650
FUEL ELEMENT		
Fuel element external dimension (mm)	8.4	9.16
Pellet dimensions (d (mm) x h(mm))	11.285 x 6.5	6.71 x 10
Clad thickness (mm)	0.85	1
Length of a fuel module/element (mm)	257.3 (9modules)	1500 (2 half-pins)
Vol. fracti. (%): Fuel / Struct. / Cool. / He gap	23/29.7/36.0/11.3	27.9/26.8/42.9/2.5
NEUTRONIC FEATURES		
Fraction of MA considered in the fuel (%)	1.1 (self-recycling)	
Mean Pu Enrichment at equilibrium (%)	17.6	16.3
Pu inventory at equilibrium (tons / GWel)	**10.1**	**9.6**
Fuel Burnup, Mean/Max (at%)	**4.3/6.3**	**5.0/7.3**
Fuel Management (EFPD)	3 x 450 = 1350	3 x 481 = 1443
Effective breeding Gain at equilibirum	**+0.03**	**+0.02**
Doppler Constant at equilibrium ($, BOL/EOL)	**-2.94 / -2.46**	**-2.70 / -2.39**
He Depressurization at equilib. ($, BOL/EOL)	**0.88 / 0.93**	**0.85 / 0.89**
Delayed Neut. Fract. at equil..(pcm, BOL/EOL)	356 / 346	369 / 360
MATERIAL CHOICES		
Wrapper / Internal wrapper structures / clad	SiCf/SiC	
Internal Liner	W–14%Re + Re (40 μm + 10 μm)	
Fuel	(U, Pu)C	

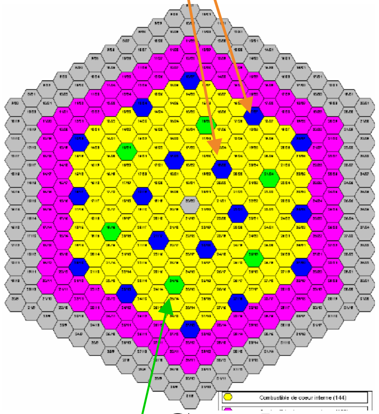
CONTROL ROD AND SHUTDOWN SYSTEMS

CSD & DSD , 2 redundant and diversified shutdown devices:

- Gravity drop of absorber elements
- Specific reinforced wrapper tube

Control rod & Shutdown Device (18 CSD)

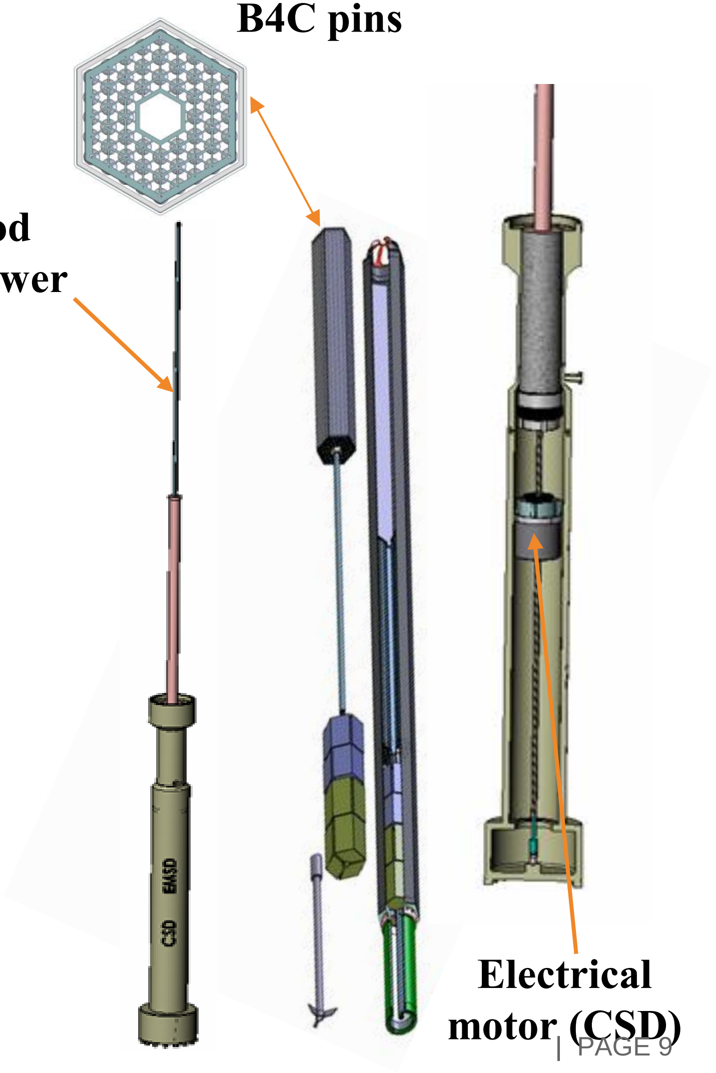
- **electrical motor in connection with a threaded rod**



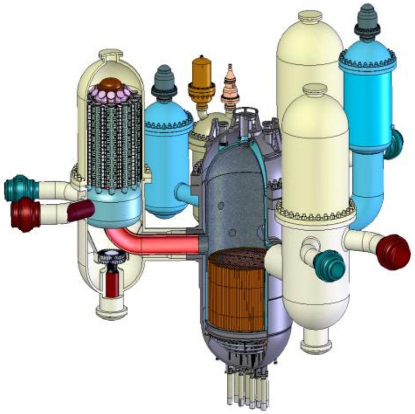
Core layout

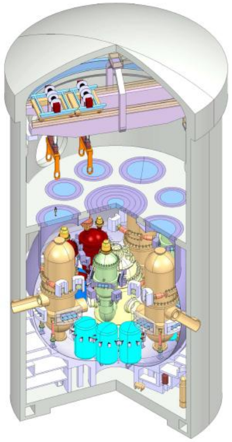
Diversified Shutdown Device (6 DSD)

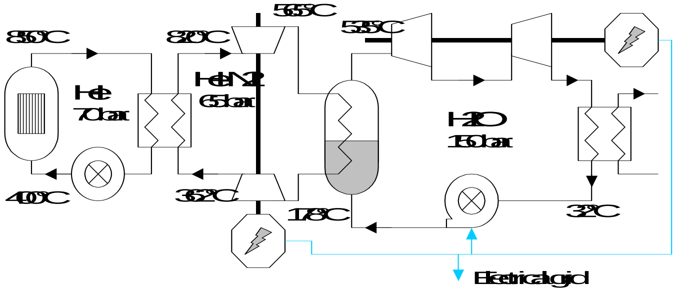
-pneumatic action, two positions (up, down)



GFR 2400 MWTH REACTOR & & SYSTEM DESIGN







REACTOR PRESSURE VESSEL

- RPV similar to GT-MHR
- 7.3 m diameter metallic vessel
- 7 MPa, 400-850°C

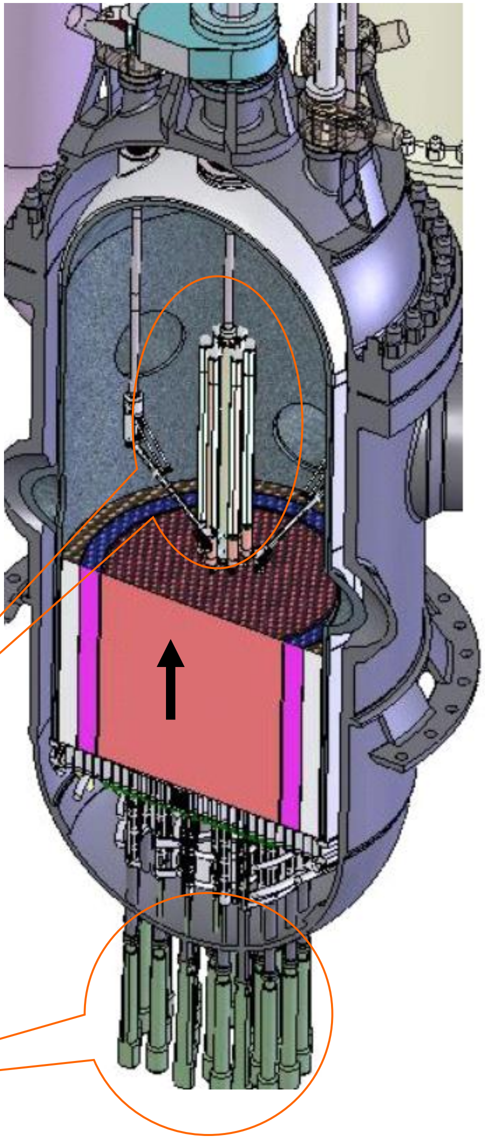
boundary accidental structure T°
(DBA, 4th cat.): 1250°C, < a few hours

- Vessel material : 9Cr1Mo or 316
- Thermal shielding, cross-duct…

Leak Before Break approach

- Upward core cooling

To enhance natural convection

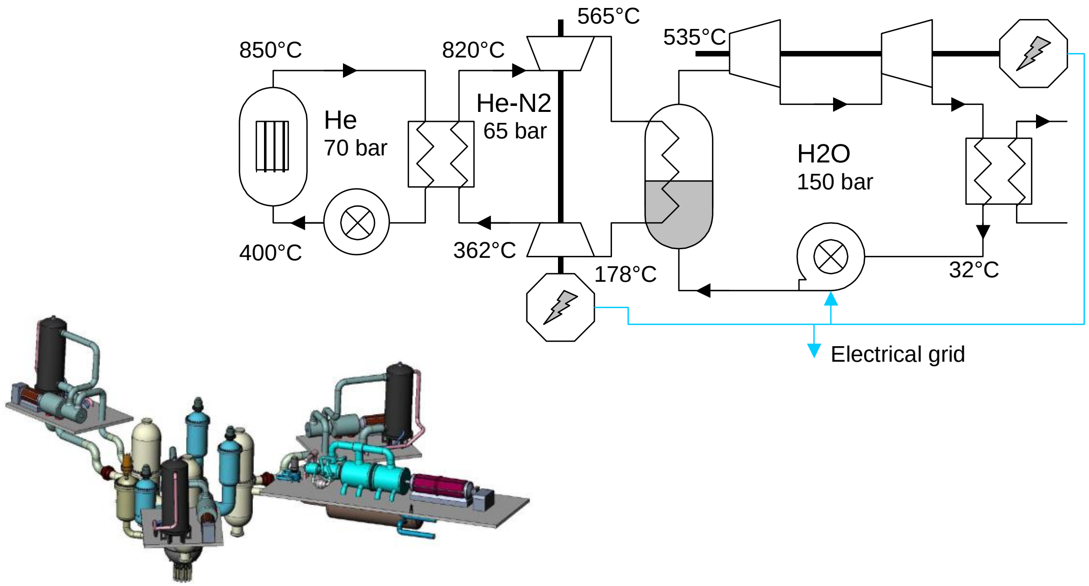


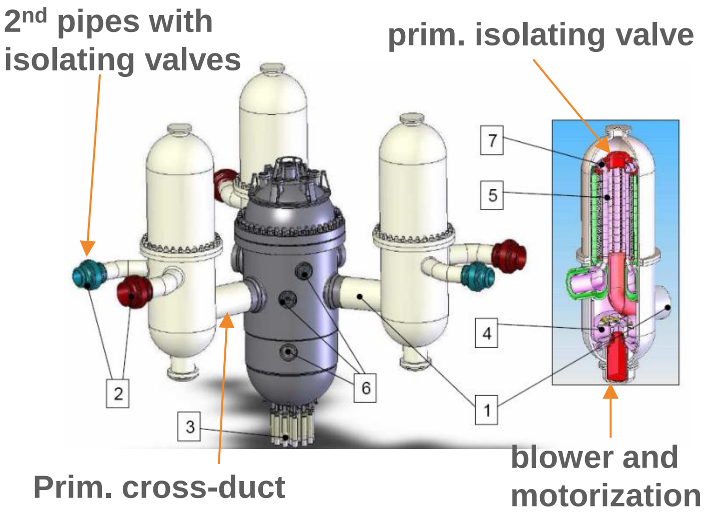
Fuel handling: upper plenum

Control rod drive mechanisms: lower plenum
Absorber rod: above the core

PRIMARY CIRCUIT, ENERGY CONVERSION

Indirect combined cycle: He-Gas with a tertiary steam cycle





High efficiency (potential up to 48%), similar to the direct cycle with lower inlet core temperature (400°C)

Compactness of the primary circuit, easier to integrate in a compact close containment (DHR strategy)

Decoupling the nuclear island from power conversion, high temperature industrial process

CLOSE CONTAINMENT, REACTOR INTEGRATION

Trade-off between targeted backup pressure / dimensions of primary components / mechanical resistance

- Metallic close containment, spherical, Φ 33 m
- Free volume ≅ 11000 m3
- Unpressurized nitrogen as initial atmosphere
- P_{backup} max. : 1 MPa
- P_{backup} 24h ≅ 0.4 Mpa

| PAGE 13

SYSTEM DESIGN, DECAY HEAT REMOVAL (DHR)

Decay Heat Removal is a key design issue for the GFR

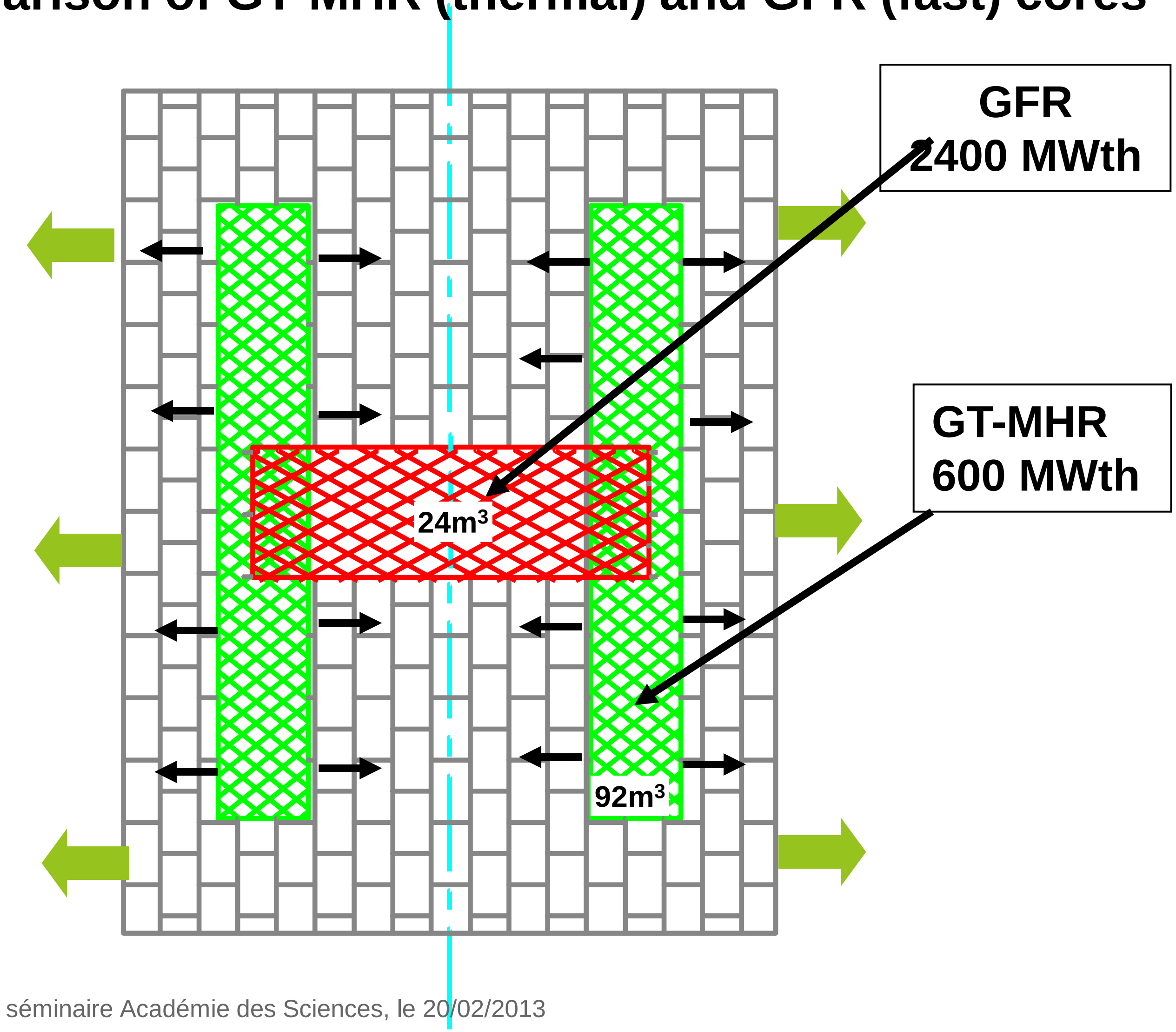
➔Conduction & Radiation used in HTR are no longer applicable because of the high core power density and the limited thermal inertia in the core region

Alternative “passive” mechanisms ?
in-core Heat Sinks, additional core thermal inertia, …
not really compatible with the core neutronic constraints

➔Core cooling using <u>gas circulation</u> with <u>appropriate design options</u> appeared the best choice

SYSTEM DESIGN, DECAY HEAT REMOVAL (DHR)

Comparison of GT-MHR (thermal) and GFR (fast) cores



GFR
2400 MWth

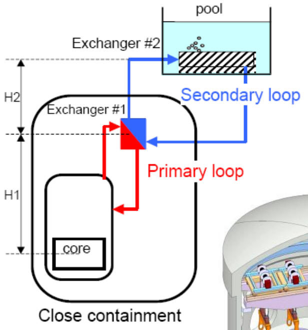
GT-MHR
600 MWth

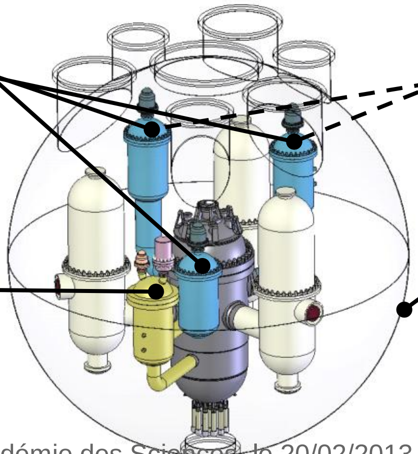
SYSTEM DESIGN, DECAY HEAT REMOVAL (DHR)

Decay Heat Removal strategy: close containment enclosing the primary circuit, diversified DHR systems to ensure gas circulation in all situations

- **Exploiting the 3 normal loops (most frequent situations, primary integrity)**
  - **main blowers with pony motor** (being supplied by Diesel): **1°) DHR using steam generator** (by-pass of the turbine), **2°) in case of electrical grid loss, backup using a dedicated air cooler circuit (natural convection)** plugged in 2nd

- **Dedicated DHR systems**
  - **R**eactor **H**igh **P**ressure cooling system **(in blue): 3 x 100%** with **blowers as normal systems** (0.4-7 Mpa) **& 2 x 100%** with **natural convect. as backup syst.**
  - **R**eactor **L**ow **P**ressure cooling system **(in yellow): 1 x 100% with blower designed for very low pressure (0.4-0.2 MPa)**



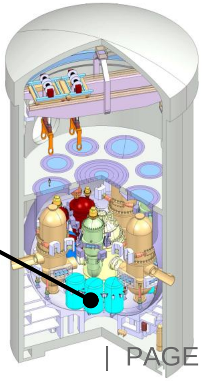


3 RHP, blowers (0.4-7 MPa)
axial mono stage,
Ptot < 500 KWe

1 RLP, blower (0.4-0.2MPa)
Motorized blower
≅ 3 MWe

2 RHP, natural convection capability
$H1^{st} + 2^{nd} \cong 20$ m

Close containment



heavy gas injection tanks

(4th category and beyond)

SAFETY APPROACH (1/2)

1- Governing principles

- Defence in depth (DiD) concept
- Principle of physical barriers
- The safety functions
- ALARA approach for radiation protection

2- General frame of the safety analysis

- **Identification and preliminary categorization of initiating events (IEs)**
- **Deterministic rules for the safety analysis**
  - Categorization of bounding situations resulting from IE + single aggravating failure (only the safety systems are considered available for DBAs)
  - Categorization of complex sequences
- **Proposition for a combination of deterministic and probabilistic methods**
  - LOP, study of operating conditions, PSA and feed-back on categorization
  - Objective provision trees as an help to draw an invetory of safety provisions

SAFETY APPROACH (2/2)

3 - LOCAs preliminary discrimination and classification status

- Small leaks compensable with the Helium Supply System (limit size to be defined)
  - **Category 2**
- Small breaks controllable with natural convection in case of failure of the forced convection means
  - **Up to 2 inches, Category 3**
- Large breaks inducing a reverse flow in the core
  - **could require an additional decoupling criterion on the cooling transient on clads and vessel**
  - **Larger than 3 inches, Category 4**
- Intermediate breaks between 2 and 3 inches
  - **Category 4**

DETERMINISTIC ANALYSIS (1/3)

4 - Transient analysis

Objectives : assessment of the performance and of the robustness of the DHR system (DBA), including cross failures (DEC)

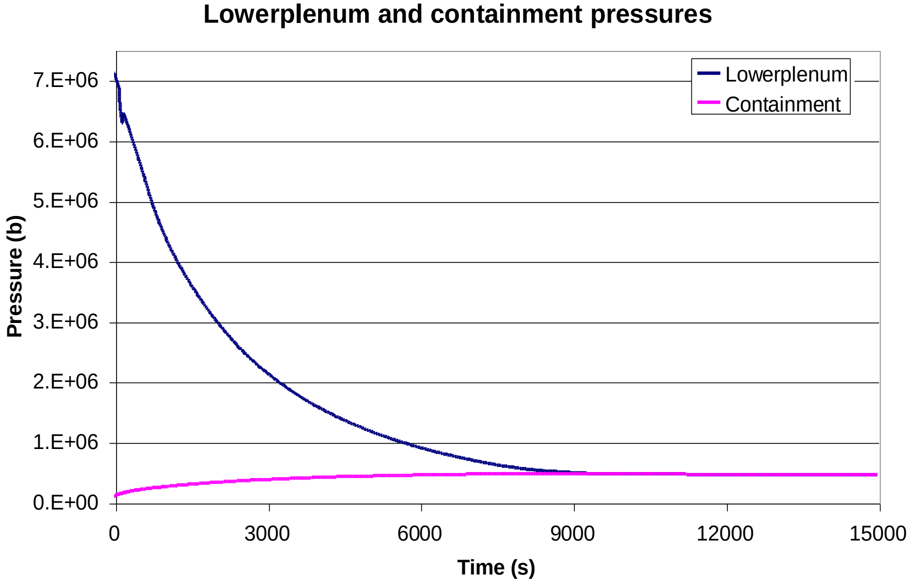
Situations considered :

- DBAs : 100 % PN + EI + single aggravating failure
  - Intermediate states still to be addressed
- DEC : → 100 % PN + EI (DEC)
  → Complex sequences → 100 % PN + EI (DBA) + multiple failures

DETERMINISTIC ANALYSIS (2/3)

CATHARE2 calculation of a 1 inch break (category 3)

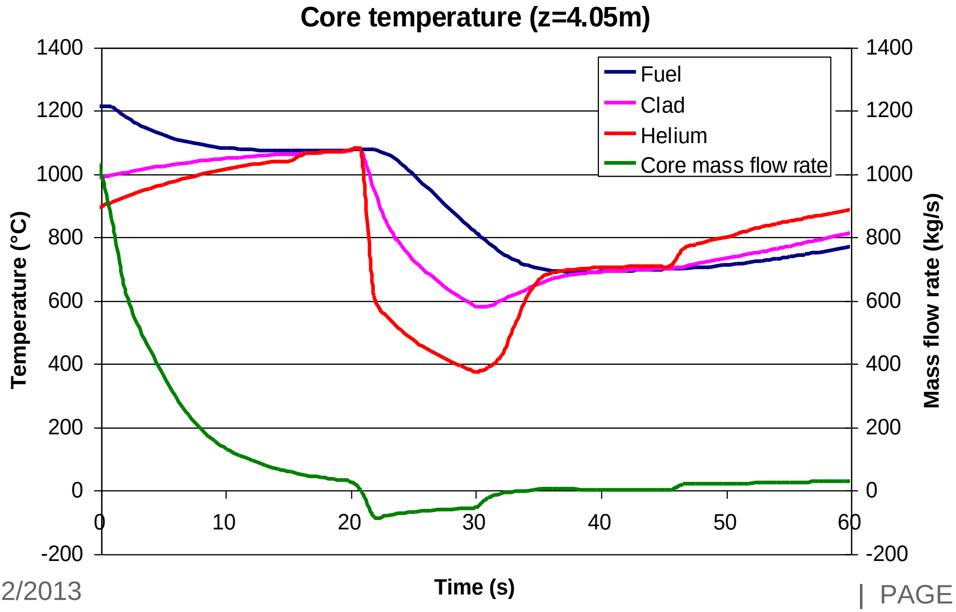
pressure transient



CATHARE2 calculation of a 10 inches break (category 4)

temperature

& flow rate transient

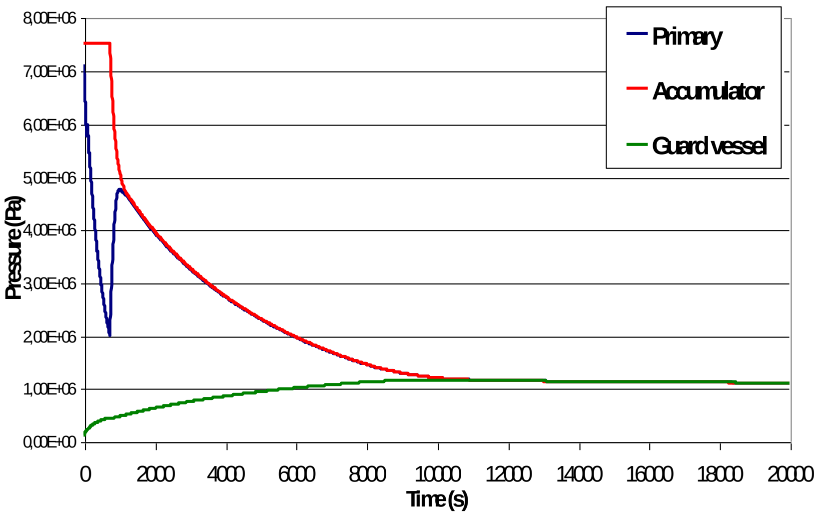


DETERMINISTIC ANALYSIS (3/3)

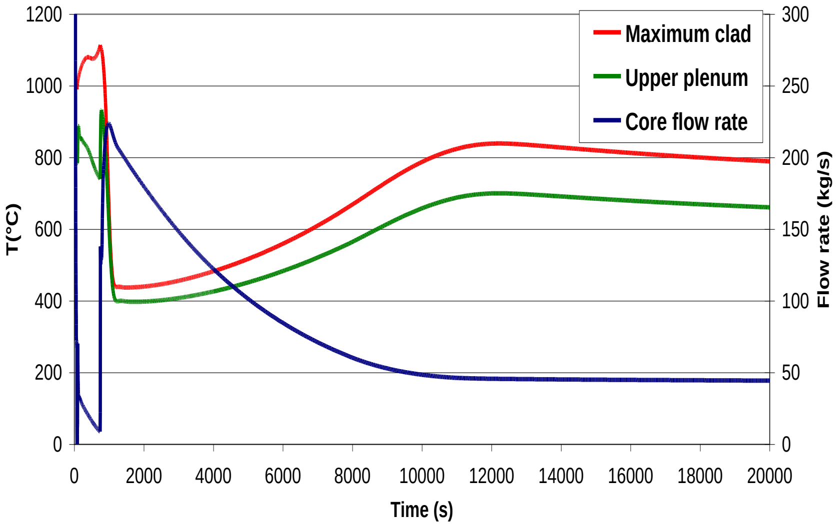
➢ SB-LOCA with failure of blowers at demand (cat.4 <= 4)

- Tests are foreseen to assess nitriding process (→ the objective is to keep a coolable geometry)
- Argon is also an acceptable heavy gas candidate

Pressure history in the accumulators, the guard vessel and the primary circuit



Cladding and upper plenum temperature, core flow rate



Pressure transient

Thermal transient

➢ LB-LOCA with failure at 24 h (DEC) → envelopped by the previous situation

PRELIMINARY SAFETY ANALYSIS

Evaluation

≅ 50 Initiating Events considered, ≅ 30 transient situations calculated, using combined **deterministic and probabilistic analyses**

An **encouraging safety potential**, based on systems with moderate pumping power and natural convection capabilities

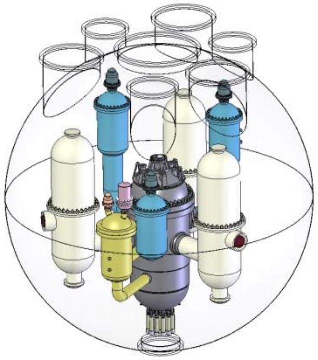
Checking of the capabilities of the normal and dedicated DHR systems

- **In case of primary circuit integrity:** only one DHR loop (forced or natural convection) can cool the core (even combining with the failure of a primary circuit isolating valve); only one normal loop could be used to extract the decay heat

DBA: significant T° margins* (decoupling criteria 3th or 4th cat.): > 300°C

- **In case of primary depressurization:** only one DHR loop (forced convection) can cool the core; in case of loss of all DHR blowers, two DHR loops operating under natural convection can cool the core for LOCA up to 3 inches, thanks to heavy gas injection

(*: with best estimate calculations)

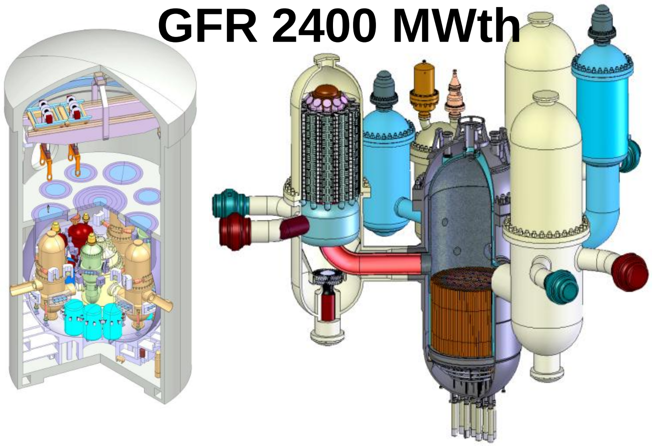


DBA: T° margins* (4th cat.) at least : > 100°C

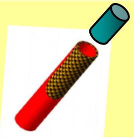
Decay Heat Removal strategy: close containment enclosing the primary circuit, valorization of the 3 normal loops, blower as normal dedicated system, natural convection capabilities

GFR PRELIMINARY VIABILITY – PRESENT CONCLUSION

No showstopper was identified, global confidence in the viability of the concept, based on innovative pin-type fuel element: (U, Pu)C & SiC-SiCf clad



Challenging fuel technology, difficulties to be overcome:
fuel element manufacturing and **in pile behaviour**



FIN

GFR 2400 MWTH, OVERALL PLANT LAYOUT