Innovative and inherently safe small SFR as a response to the dilemma 'safety vs cost'

SMR-CADOR

DE LA RECHERCHE À L'INDUSTRIE

AIEA Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR type

Milano – 24-27 september 2019

P. Gauthé, A. Pantano

OUTLINE

- Context for GenIV SMR development
- Objectives of the SMR CADOR design
- Passive Decay Heat Removal calculations
- Predesign options
- Conclusions & Prospects

CONTEXT FOR GENIV SMR DEVELOPMENT

- Competitiveness and safety of future reactors must improve in order to be acceptable by the population and decision-makers.
- Unfortunately, for now, safety means costs and the safer the reactor is, the more expensive it is.
- Research in advanced reactors must tackle this dilemma by promoting inherent safety and simplified design.

➡ SMRs can be a response to this challenge : simplification, intrinsic safety, reduced capital cost, flexibility, passive systems

➡ **SMRs have key features to improve the acceptability of reactors : can they be economically competitive ?**

CONTEXT FOR GENIV SMR DEVELOPMENT

- Sustainability is still a key issue, so we must still promote the development of fast reactors.
- SFR have interesting features for promoting intrinsic safety : no coolant pressure, resilient natural core behavior, efficient natural convection, thermal inertia providing grace time & autonomy.

➡ **Mixing the ambitious objectives of SFR GenIV designs and the benefits of SMRs could be a game-changing choice for the future of nuclear industry.**

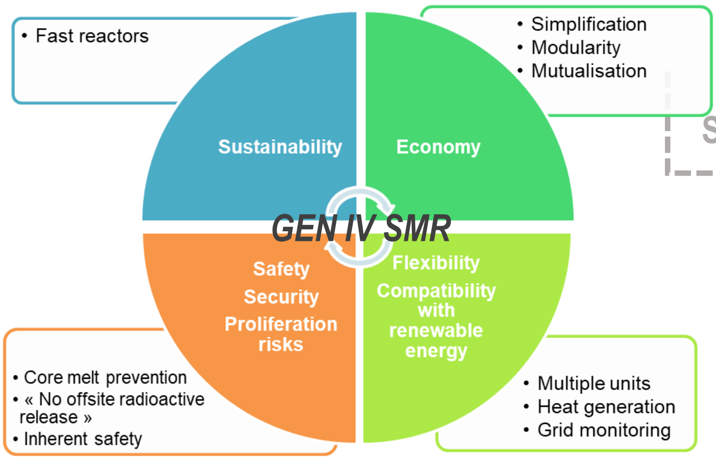
➡ **Rather than oppose SAFETY and ECONOMY, bring them together in a breakthrough design approach, aimed at a shock of simplification**

SAFETY + ECONOMY = ACCEPTABILITY

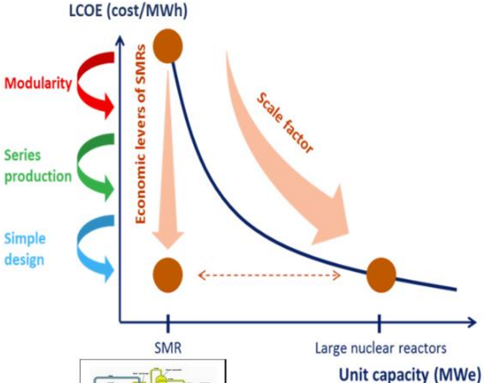
Objectives of GenIV reactors

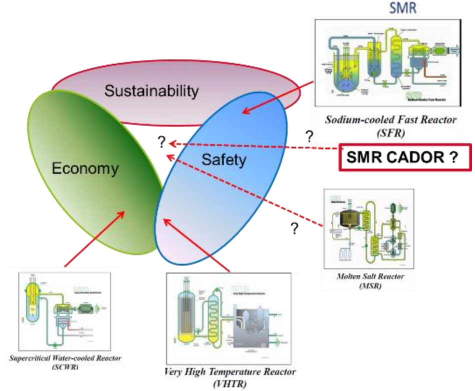
The perfect GenIV reactor is safe, cheap, resistant to proliferation, sustainable, flexible and compatible with the intermittency of renewable energies

➔ everyone is trying to square the circle

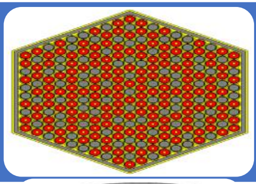


SMR approach



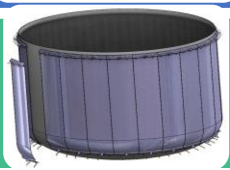


What scale effects can simplify the design of a sodium SMR and make it economically viable ?
➔ SMRs allow more easily the implementation of technological breakthrough



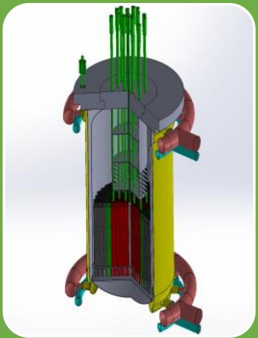
Intrinsic safety core design

- CADOR core type relying on a sufficiently large Doppler reactivity feedback effect able to prevent core melting during unprotected reactivity insertion
- ➔ Practical elimination of the whole core melting ?



Passive Decay Heat Removal through the primary vessel

>> Breakthrough in the diversification & reliability in comparison of classical systems



Simplifications

- Less safety systems (no core catcher)
- No secondary circuit
- Simplified fuel handling (low decay heat of on subassembly)
- Less sodium circuits
- Vessel diameter sufficiently small to allow factory fabrication
- No safety vessel
- Modularity

- Safety
- Two strong main objectives are the guidelines of the design :
  - Avoid the total meltdown of the core for all situations, including unprotected reactivity insertions. The CADOR core is selected for this purpose.
  - Allow to remove the decay heat in natural convection with one system through the Primary Vessel (PV) without sodium circuit.
    - **This objective has clearly the most impact on the design and is the main topic of the paper.**

CADOR CORE (1/2)

CADOR CORE (1/2)

We need to demonstrate that ULOF, ULOHS, UTOP, SAF and all other transients cannot lead to total core meltdown

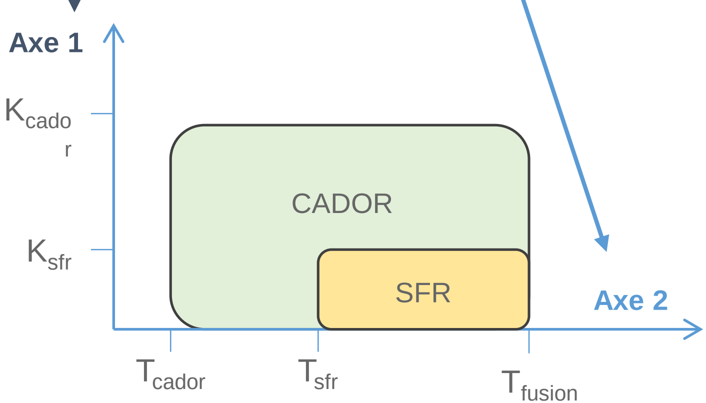
Prevention objectives	Design options	Interest of SMR
No boiling for all ULOF	Passive devices (hydraulic rods, SASS…), core design (CFV…), enhanced natural convection	Yes
No subassembly melt for TIB (Total Instantaneous Blockage)	Subassembly design (hexagonal tube with holes…)	Yes
No fuel melting for all UTOP	Biggest challenge ! >> CADOR core	No
No total loss of DHR safety function	Passive DHR through the vault	Yes

CADOR: Core with reinforced Doppler effect

CADOR CORE (2/2)

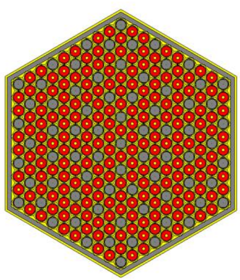
How to enhance the Doppler effect ?

$$\Delta\rho_{Doppler} = K_{Doppler} * \ln\left(\frac{T^{Fusion\,Combustible}}{T^{Nominale}}\right)$$



Lower lineic power (more pins, larger core) Or higher fuel melting temperature (carbide fuels)

Introduction of Beryllium pins as moderator to soften the neutronic spectrum and favorize the U8 captures



- Economy
  - Vessel diameter less than 6m to allow road transportation of the vessel
    - **LOOP-type reactor to reduce the size of the vessel.**
  - Suppression of the secondary circuit. One of the overcosts of SFR in comparison of PWR is the need of an intermediate circuit, to prevent the damage to the core in case of sodium-water (or gas) reaction. **Considering that the CADOR core can cope with reactivity insertion due to an unprotected gas flow through the core**, the design option of the suppression of the intermediate loop can be envisaged. That implies to design appropriate a sodium/gas heat exchangers and means of leakage detection.
  - **Simplified fuel handling systems**, due to a low decay heat per subassembly for a SMR.
  - Supercritical CO2 Brayton conversion system to increase the efficiency of the energy conversion system. The feasibility of this type of cycle is not guaranteed for large power unit but can be envisaged for a SMR. **The choice of the fluid of the conversion system has not been made yet.**
  - **Suppression of the safety vessel**. A liner directly in the reactor pit is a design option suitable for a SMR. This option is also investigated in the ESFR-SMART project (see paper 280 – Joel Guidez – ESFR SMART Organization of a pit justifying the option of safety vessel suppression >> Tuesday afternoon)

- **DHR system through the primary vessel and the primary circuit must operate in natural convection during station black-out**
  - High degree of DHR systems diversification
  - Better acceptability of the design in a post-Fukushima context

Design criteria

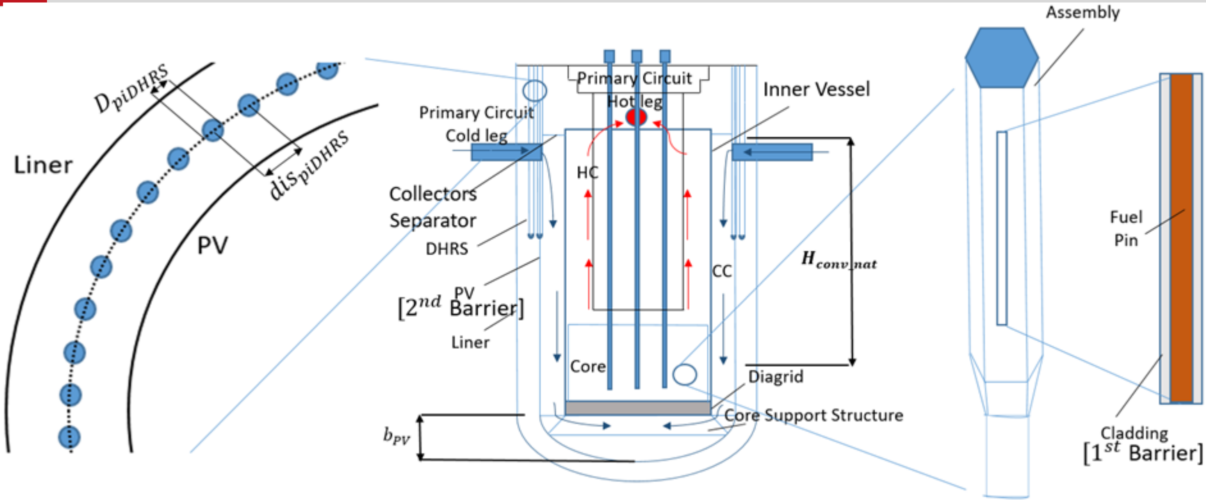
1^{st} *barrier integrity*	$T_{clad} <= 825°C,$
2^{nd} *barrier integrity*	$T_{PV} <= 700°C,$
Natural circulation	$\Delta p_{net} = \Delta p_{nat\_conv} - \Delta p_{tot} > 0$ $\Delta p_{nat\_conv} = g\, H_{nat\_conv}\, (\rho_c - \rho_h)$

- **Main design parameters to reach the criteria**
  - Capability of the DHR system
  - Height between the core and the barycenter of the DHR system
  - Temperature difference between the cold and hot pool
  - Core pressure drop
  - Primary circuit pressure drop

(first three) To maximize

(last two) To minimize

PASSIVE DECAY HEAT REMOVAL CALCULATIONS



Three ways to improve the design

$\Delta p_{conv\ nat}$		$\Delta p_{primary\_circuit}$	DHR-PV perfromances
$\rho_f - \rho_c$	H_{utile}		
Isolation between the cold and hot pool (double inner vessel)	Higher primary vessel height Higher position of the DHR-PV exchange tubes	Decrease the primary loops length Designing a bypass between the hot pool and the cold pool Lower core pressure drop	Localisation of exchange tubes Type of fluide Exchange surface of the vessel Emissivity

- **Pre-design COPERNIC code has been use, complemented with Matlab routines**
- **Main equations**
  - Ensuring the Na level in case of primary vessel leakage

$$V_{PV_{Na}} = \frac{D_{int\ PV}^{2}\ \pi}{4}\ (H_{PV} - b_{PV}) + V_{int\ Ellip\ PV},$$

  - Temperatures calculation in the primary circuit and for the reactor pit

$$\frac{dT_{hc}}{dt} I_{hc} = [P_{res} - (K_{cond\ IV} + (Q_{tot}\, c_p))\ (T_{hc} - T_{cc})];$$

$$\frac{dT_{cc}}{dt} I_{cc} = [\,(K_{cond\ IV})\,(T_{hc} - T_{cc}) + (Q_{tot}\, c_p)(T_{hc} - T_{cc}) - K_{conv\ Na}\ (T_{cc} - T_{PV})];$$

$$\frac{dT_{PV}}{dt} I_{PV} = \left[\, K_{conv\ Na}\ (T_{cc} - T_{PV}) - K_{conv\ _{N2}}(T_{PV} - T_{N_2}) - P_{PV} \right];$$

$$\frac{dT_{pit}}{dt} I_{pit} = [\, K_{cond\ Li}\ (T_{Li} - T_{pit}) - P_w\,].$$

  - Power extracted through the primary vessel

$$P_{PV} = A_{PV}\ \frac{\varepsilon_{PV}}{1 - \varepsilon_{PV}} (\sigma T_{PV}^{4} - J_{PV})$$

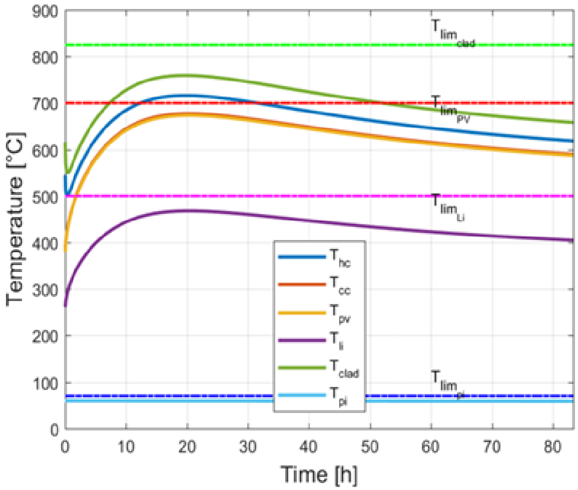
  - Natural convection calculation

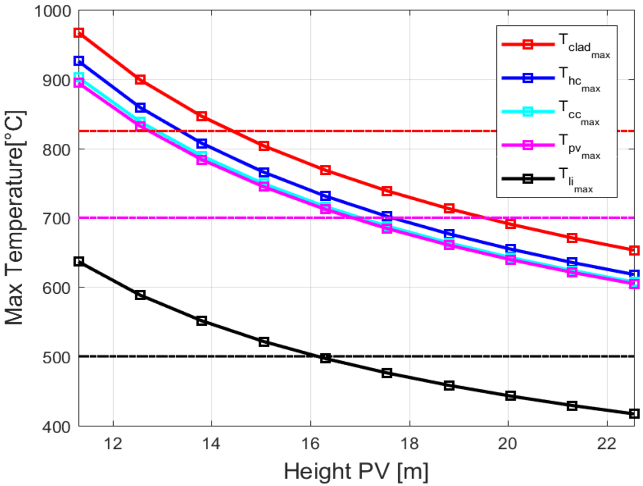
$$Q_{nat\ \_conv} = Q_0 \left(\frac{\rho_m \beta_m p_{res}\, \Delta T_0\, Cp_0\, g H_{nat\ \_conv}}{2\Delta p_0\, Cp_m}\right)^{4/11}$$

  - 13 equations and 13 unknowns (see paper)

- **Main design options are :**
  - Target power is between **200MWth to 400MWth**, meaning a range of [75MWe - 150MWe]. Another design track is to investigate the design of SMR-CADOR **only for heat production, operating in natural convection** for normal operation. In this case, the target power is 50MWth.
  - **CADOR** core
  - **LOOP** type reactor : 2 or 3 loops
  - **EMP** on the primary circuit
  - Water/steam, gas or supercritical CO2 PCS
  - Main DHR system : **DRACS** with active or passive operation
  - Vessel diameter **less than 6m**
  - Vessel height **less than 23m**
  - **DHR-PV fluid** : oil, salt, Nak, Pb-Bi
  - Vessel **emissivity** higher than 0,5

PRE-DESIGN OPTIONS

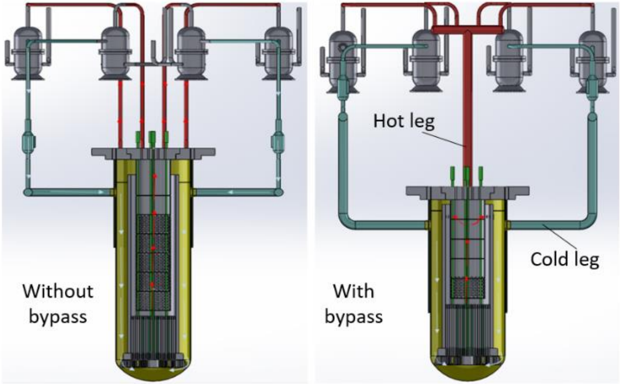




- **Vessel height should be sufficient to allow the natural convection in the primary circuit using the DHR-PV as the cold sink**
- **Structures maximal temperature is the limiting parameter (not the core)**

PRE-DESIGN OPTIONS

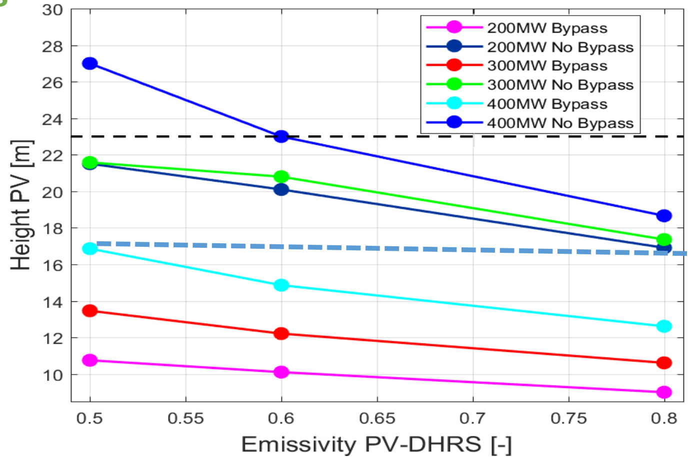
- **Sketch exemples**
  - 2 LOOPS and modular HX
  - With or without by-pass

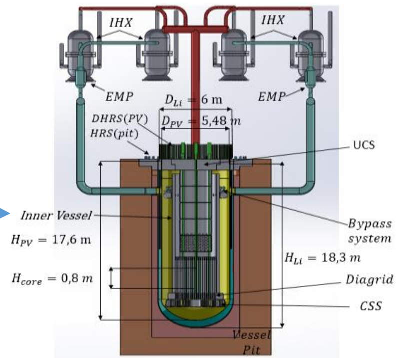


Main parameters are :

- **nominal power**
- **circuit pressure drop (by-pass benefit)**
- **vessel emissivity**
- **vessel height**

Synthesis abaqus





DHR through the primary vessel

100% after the scram

Fully passive

CADOR core

Resistant ot unprotected reactivity insertions

➔ **Towards practical elimination of the whole core melting**

Simplifications

Less safety systems

Secondary circuit suppression

Simplified fuel handling

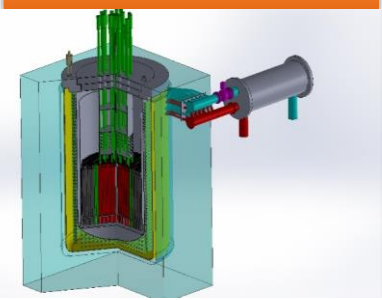
Small diameter vessel

No safety vessel

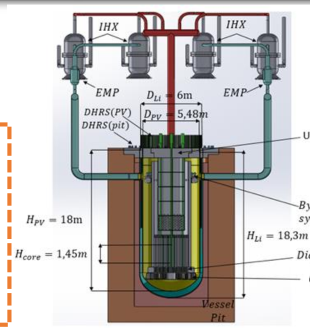
All these innovating design options are allowed by the small power of the reactor

SMR CADOR

Heat production 50MWth



Electricity production 150MWé



D=~6m

H=~18m

- **Prospects**

Finish the design for a 400Mwth

Evaluate the safety (natural convection & unprotected transients) and economy

THANK YOU FOR YOUR ATTENTION