



---

# Gas Cooled Fast Reactor

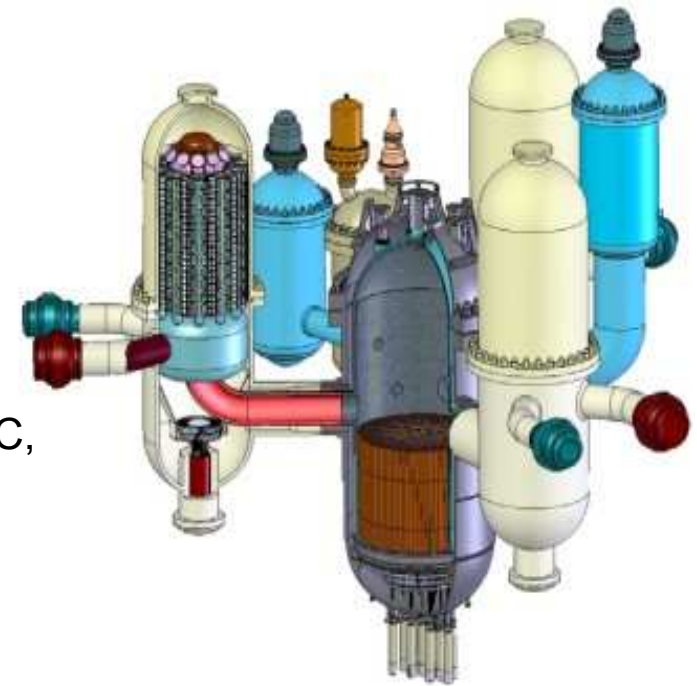
**INPRO Dialogue Forum on Generation IV Nuclear Energy Systems**

IAEA Headquarters, Vienna. 13-15 April 2016

**Branislav Hatala**

**VUJE, a.s., Slovak Republic, (Euratom)**

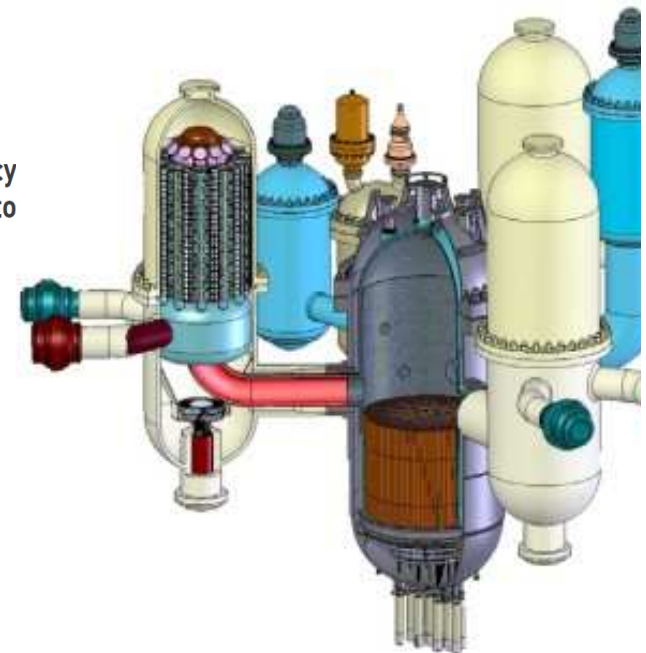
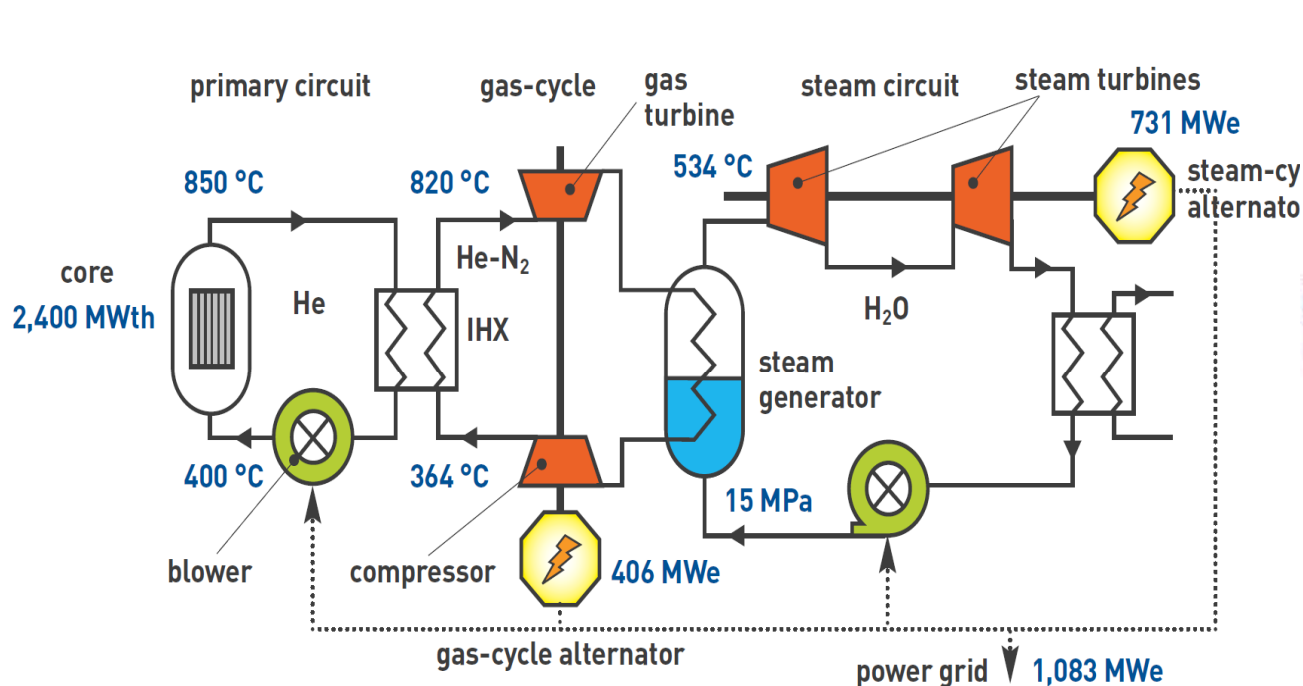
- The GFR system is a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle.
- The reference design for GFR is 2 400 MWth
- The high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency.
- As a one of fast reactor would produce heat about 850° C, which will be able to chemically produce hydrogen
- GFR demonstrator ALLEGRO



# Gas-cooled Fast Reactor

The produced heat (2 400 MWth) will be converted into electricity in the indirect combined cycle with three gas turbines and one steam turbine.

- Primary/secondary arrangement: 3 x 800 MWth (IHX-blower unit) gas turbo-machineries (auxiliary alternators: 3 x 130 MWe)
- Tertiary: 1 steam turbine (main alternator 730 MWe)
- Efficiency (~ 45%) ,



- The choice of coolant is dictated by the desire to introduce the smallest amount of absorption and moderation.
- To obtain the highest breeding potential, the amount of parasitic absorption should be minimized.
  - => The core is very tightly packed.
  - => The volume fractions of structural materials and coolant are kept to a minimum.
- The number of capture reactions producing fissile material per unit time is proportional to the flux level in the reactor. For reasons of economics and fuel cycle characteristics, it is generally desirable to have the highest possible breeding rate, and thus generally the reactor core is designed to have a very high flux level.
- As a result the power density in a fast reactor core is usually very high, typically of the order of 100MW/m<sup>3</sup>.

- Neutronic quasi-transparency  
Gas coolants generally allow a harder neutron spectrum, which increases the breeding potential of the reactor.
- Simple in-service inspection of the primary system and internal vessel components because of the translucent nature of the coolant.
- Helium is chemically inert  
no corrosion products in the primary system are expected.
- No change in phase of the gas coolant.
- The coolant does not become activated by irradiation.
- No decommissioning issues associated with the coolant.
- Helium coolant can be operated under very high temperatures  
no disassociation of Helium allowing very high system efficiencies.  
(CO<sub>2</sub> disassociates ~ 800 ° C)

- Higher pumping power compared to liquid coolants
- Need to maintain high pressure in the system, typically around 7 MPa for helium systems,
- Gas coolant properties generally require artificial roughening of the cladding to maintain acceptable cladding temperature
  - => an increased pressure drop over the core
  - => higher requirement on pumping power
- High coolant flow velocity can lead to significant vibrations of the fuel pins.
- Decay heat extraction from the high power density core is difficult.

- The technology base for the GFR includes a number of thermal spectrum gas reactor plants, as well as a few fast-spectrum gas-cooled reactor designs.
- The GFR may benefit from development of these technologies, as well as development of innovative fuel and very-high-temperature materials for the VHTR.
- It differs from the HTGR design in that the core has a higher fissile fuel content and of course there is no neutron moderator.
- Due to the higher fissile fuel content, the design has a higher power density than the HTGR.

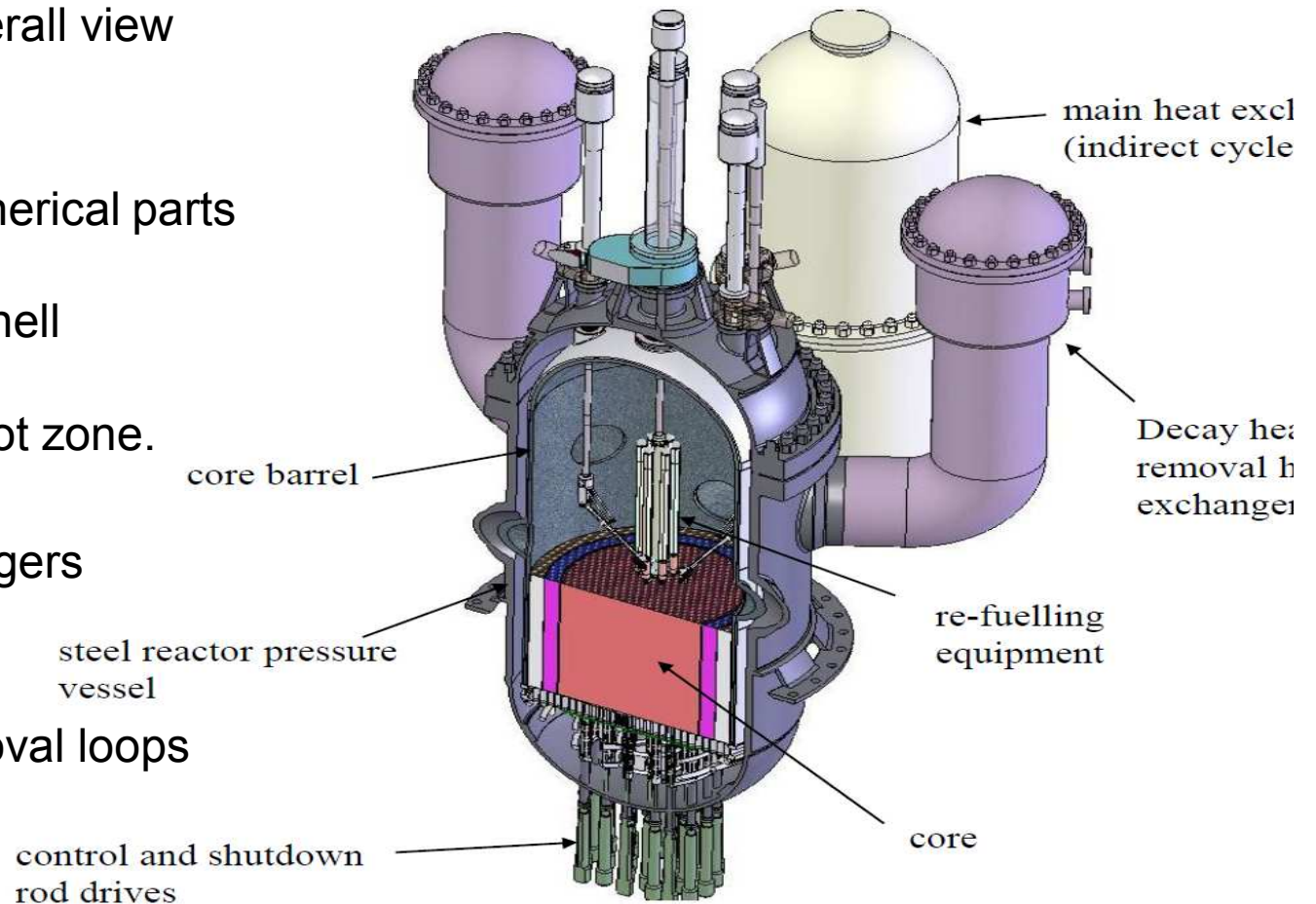
# Gas-cooled Fast Reactor

## GFR primary system overall view

The cylindrical vessel with upper and lower spherical parts contains the core and internal cylindrical shell which separates the cold zone from the hot zone.

Three main heat exchangers with blowers,

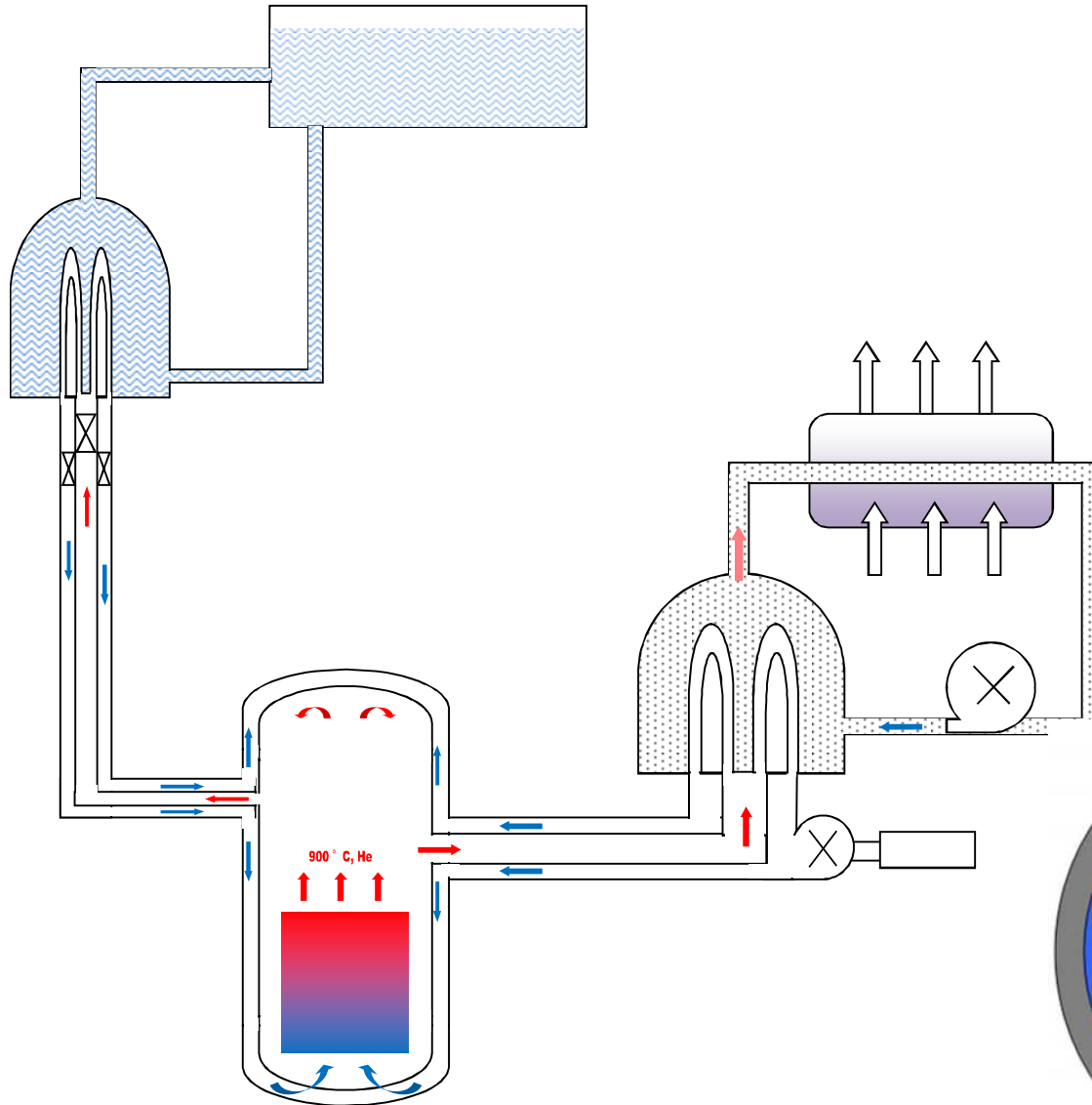
Three Decay Heat Removal loops



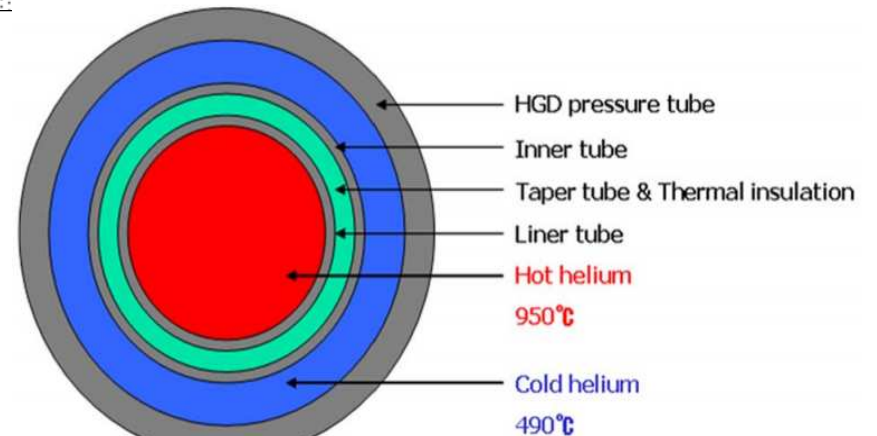


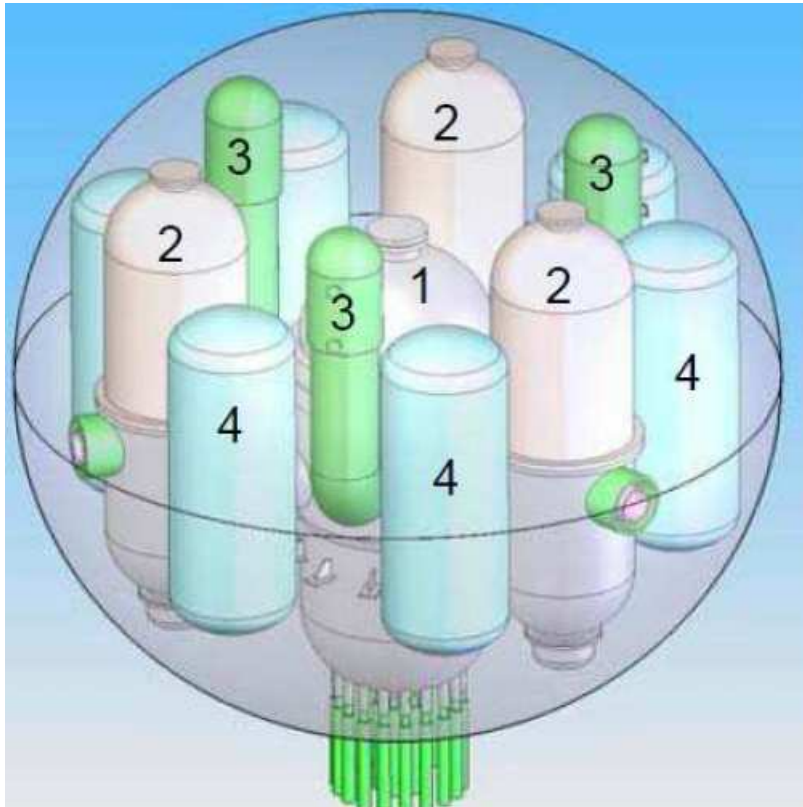
# Gas-cooled Fast Reactor

## ■ Simplified scheme of primary coolant flow



## ■ Cross section of primary pipe





The whole primary system is enclosed in a small pressure guard containment.

1 - vessel

3 - three Decay Heat Removal loops

2 - three Main Heat Exchangers

4 - six gas reservoirs

■ The main parameters of the GFR system

<b>Thermal power, MW</b>	<b>2400</b>
<b>Average core power density MW/m<sup>3</sup></b>	<b>100</b>
<b>Primary coolant</b>	<b>He</b>
<b>Primary coolant pressure, MPa</b>	<b>7</b>
<b>Helium temperature at core inlet, °C</b>	<b>400</b>
<b>Average helium temperature at core outlet, °C</b>	<b>880</b>
<b>Primary flow rate, kg/s</b>	<b>940.1</b>
<b>Core pressure drop, bar</b>	<b>1.43</b>
<b>Fuel pin internal pressure at 20°C, bar</b>	<b>10.0</b>
<b>Secondary coolant</b>	<b>Mixture of 20% He and 80% N<sub>2</sub></b>
<b>Secondary coolant pressure, MPa</b>	<b>6.5</b>
<b>Secondary coolant flow rate in one loop, kg/s</b>	<b>902.0</b>

- To designate Decay Heat Removal (DHR) system, the maximum fuel temperature for accident design basis conditions (DBC) has been set at 1600° C.
- A DHR design has been selected based on depressurization accidents combined with a total loss of power (blackout).
- A fully passive system has been designed: it consists of three loops (3x100% redundancy) in extension of the pressure vessel, equipped with heat exchangers located at a certain elevation above the core, so that the driving height enables the flow circulation.

# GFR - Decay Heat Removal System

3 DHR loops – each 100% decay heat

Dedicated blowers on helium side

Secondary water loop at 10 bar

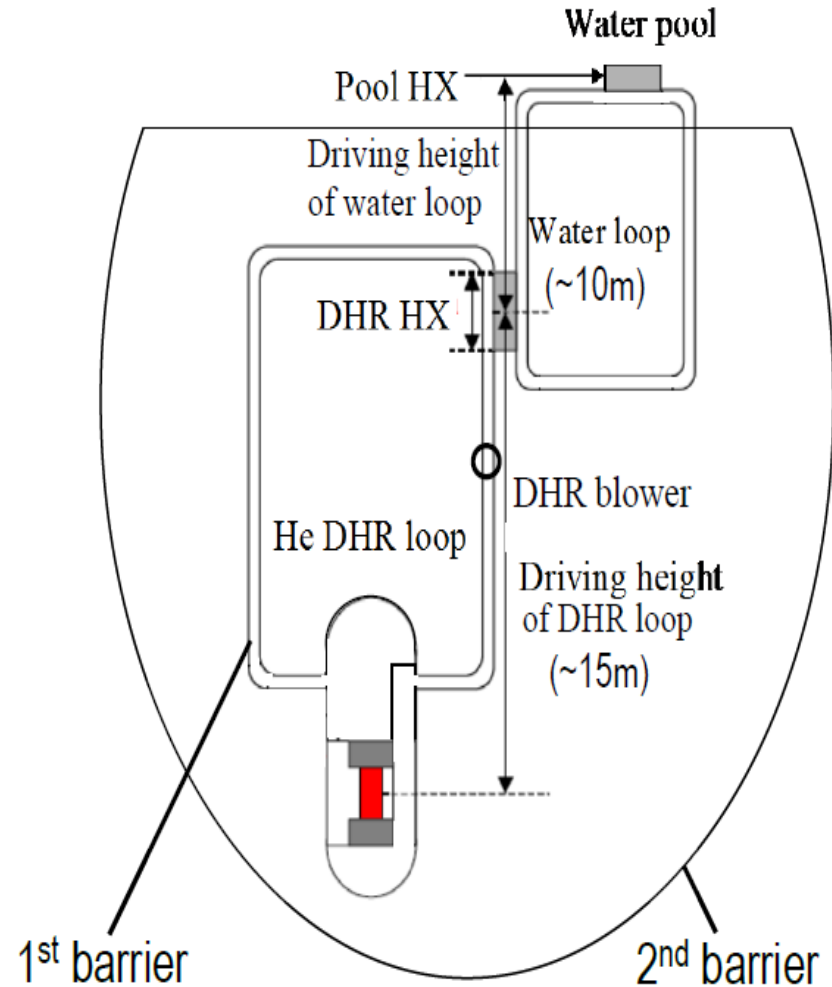
Water loop working in natural convection

Final heat sink: water pools

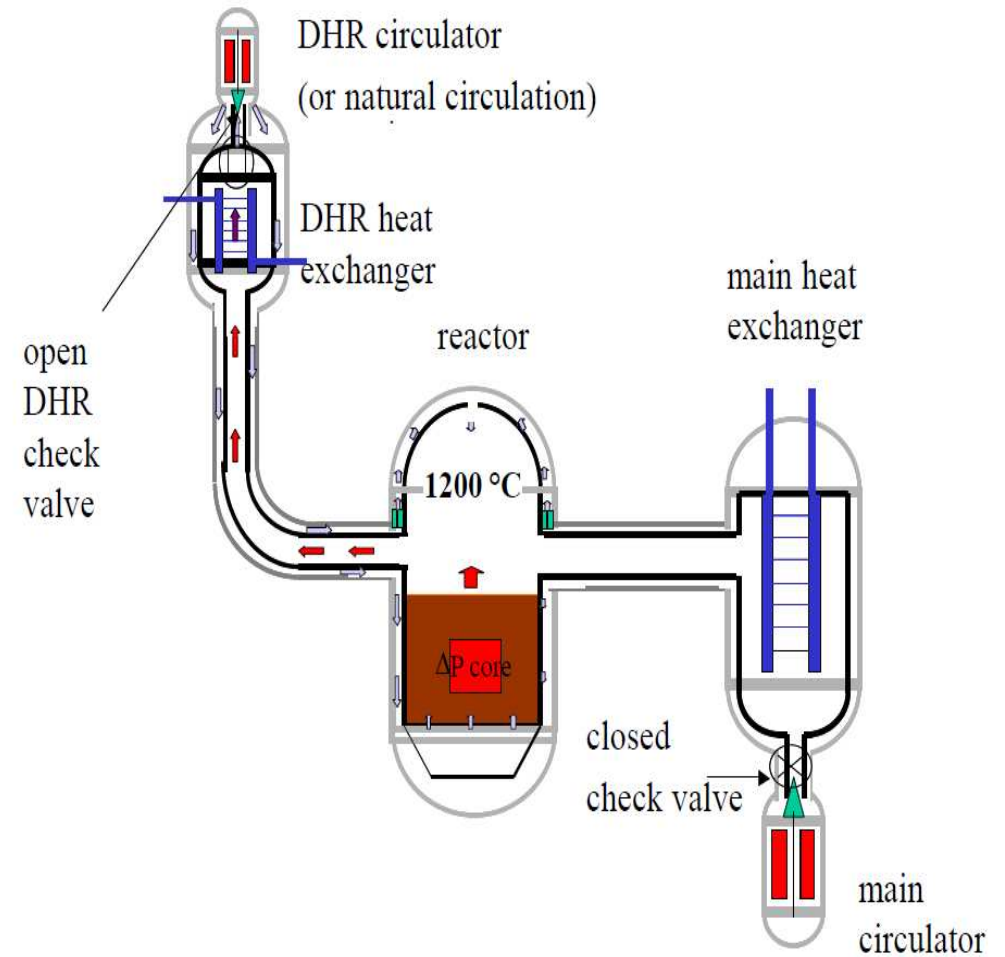
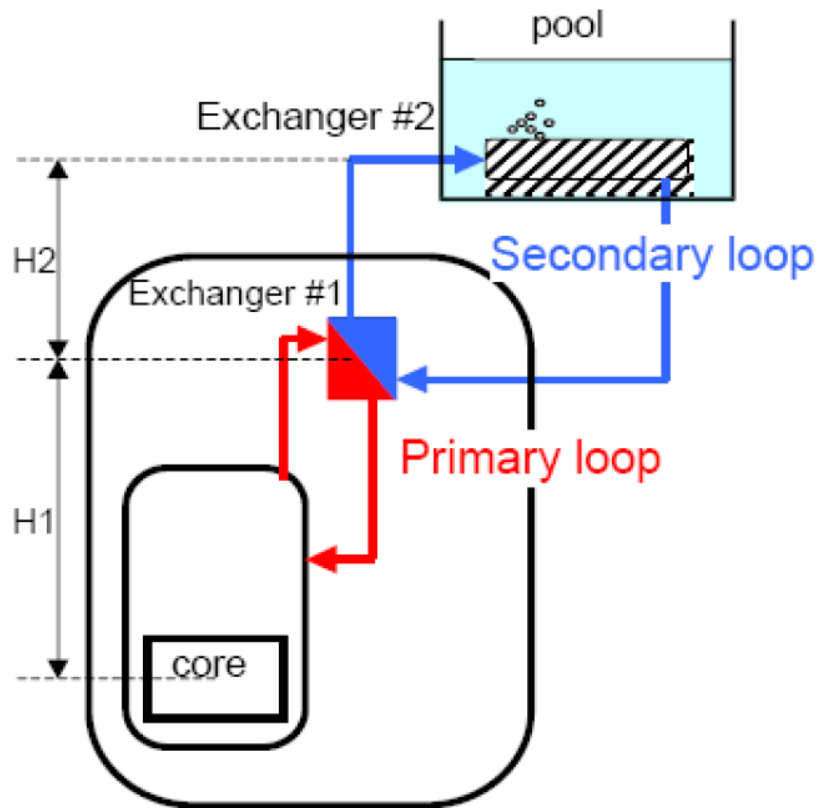
Two barriers

Primary loop

Dedicated small guard containment



# GFR - Decay Heat Removal System

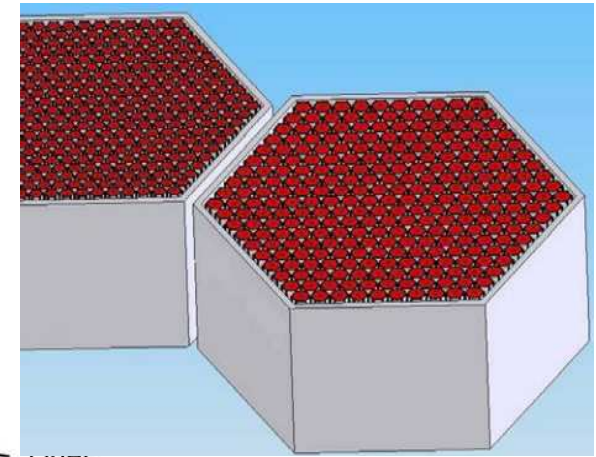
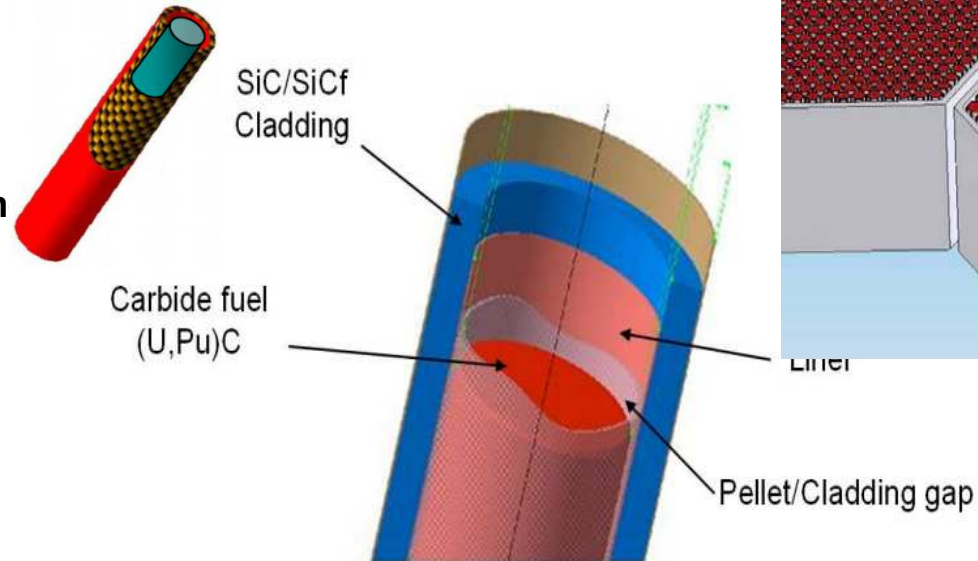


- The greatest challenge facing the GFR is the development of robust high temperature, high power density refractory fuels and core structural materials,
  - Must be capable of withstanding the in-core thermal, mechanical and radiation environment.
  - Safety (and economic) considerations demand a low core pressure drop, which favours high coolant volume fractions.
  - Minimising the plutonium inventory leads to a demand for high fissile material volume fractions.
- Candidate compositions for the fissile compound include carbides, nitrides, as well as oxides.
- Favoured cladding materials include:
  - oxide dispersion strengthened steel (ODS), vanadium and SiC for pin formats
  - ceramic matrices (e.g. SiC, ZrC, TiN) for dispersion fuels in a plate format

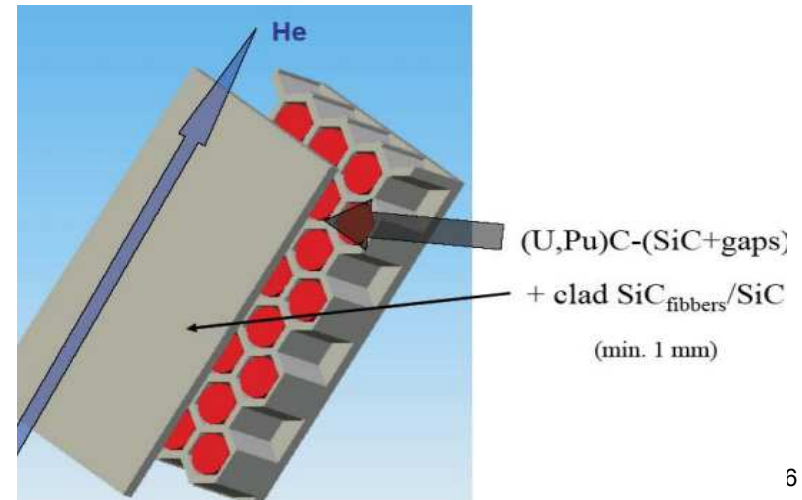
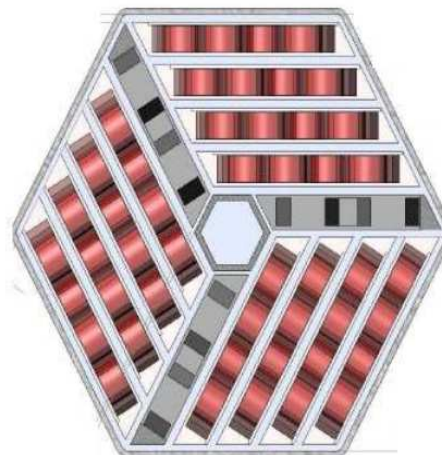
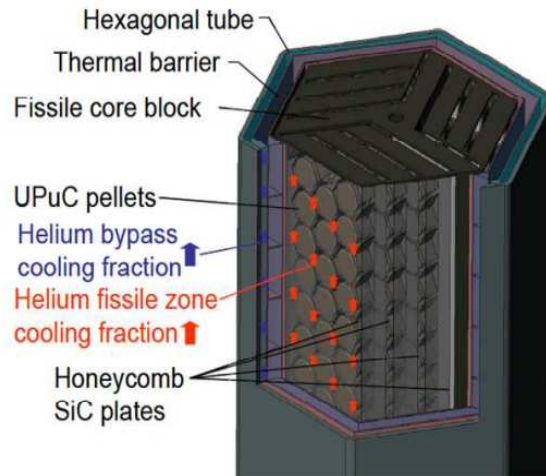
Different types of fuel arrangements are envisaged:

**- pins**

Fuel : (U,Pu)C  
Cladding : SiC/SiCf  
with an internal metallic lin



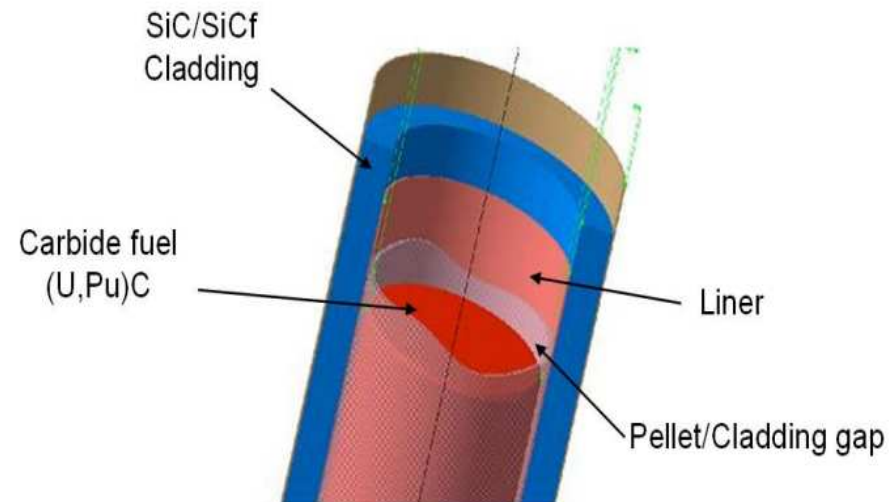
**- plates**





Technology with metal-lined SiC/SiCf pins now being the preferred option.  
The plate fuel concept has been relegated

- Structure is SiC fibre-reinforced SiC.
- An internal refractory metal liner is required prevent diffusion of fission products through the SiC/SiCf structure or flow of fission products through micro-cracks.
- An external refractory metal liner may be required to prevent inward diffusion of reactor coolant (helium) from separating the internal metal liner from the SiC/SiCf structure.



## Two major issues for GFR

The design of a high temperature fuel element,  
able to retain integrity in case of loss of forced cooling accident,  
to withstand high fast neutron fluxes,  
and offering good neutronic performances.

Safety and decay heat removal  
in case of loss of helium pressure.



- The system arrangement was signed at the end of 2006 by Euratom, France, Japan and Switzerland.

France has been very active in the development of the GFR concept, in particular conceptual design, safety assessment and fuel development in the previous years, in 2010 French research priorities were re-focused on sodium-cooled fast reactors, which led to a reduction of effort on the GFR system



- France, Japan and Euratom participants confirm their intention to continue collaborative R&D on the GFR and to sign the Extension to the GFR System Arrangement
- The conceptual Design & Safety project Arrangement was signed in 2009 by Euratom, France and Switzerland,
- Switzerland informed the GFR partners that it is withdrawing from the GFR System Arrangement and the Conceptual Design & Safety Project

- Project on “Fuel & Core Materials” was in preparation.

Project Plan was intended updated,  
no indirect action funding available in Euratom,  
effort re-directed to SFR in France.

Project on “Fuel & Core Materials” arrangement remains unsigned  
and the participants have agreed to continue their collaboration  
on an informal basis.

- On-going work to update the GFR System Research Plan, along 3 axes:
  - Conceptual Design & Safety (existing project)
  - Fuel & Core Materials (provisional project)
  - Technology (new proposal)

### ■ The GFR Conceptual Design and Safety Project

- WP 1 R&D in support of the GFR Design and Safety
- WP 2 R&D in support of the ALLEGRO Design and Safety
- WP 3 Safety Design Criteria and Guidelines

### ■ The GFR Fuel and Materials Project

- WP 1 – UPuC
- WP 2 - Cladding and core materials
- WP 3 - GFR Fuel pin
- WP 4 - GFR Fuel assembly
- WP 5 - ALLEGRO Fuel
- WP 6 - ALLEGRO core materials

### ■ The GFR Technology Project to be created in a later stage, could include the following work packages

- WP1 – Pressure boundaries / Guard containment
- WP2 – Decay Heat Removal Systems
- WP3 – Power Conversion Systems

- France – limited effort dedicated to supporting the “V4G4 Center of Excellence”
- Japan – No national funding for GFR R&D
- Euratom:

**GoFastR** - European Gas Cooled Fast Reactor (FP7)  
project ended in February 2013,

**ALLIANCE** - ALLEGRO Implementing Advanced Nuclear Fuel Cycle (FP7)  
in Central Europe  
coordination and support action

Non-research activities in support of the implementation of the Strategic Research Agenda of Sustainable Nuclear Energy Technology Platform and safety of nuclear systems

project ended in September 2015

**ESNII Plus** – The aim of this cross-cutting project  
is to develop a broad strategic approach to advanced fission systems  
in Europe in support of the European Sustainable Industrial Initiative  
project aims to define strategic orientations for the Horizon 2020 period

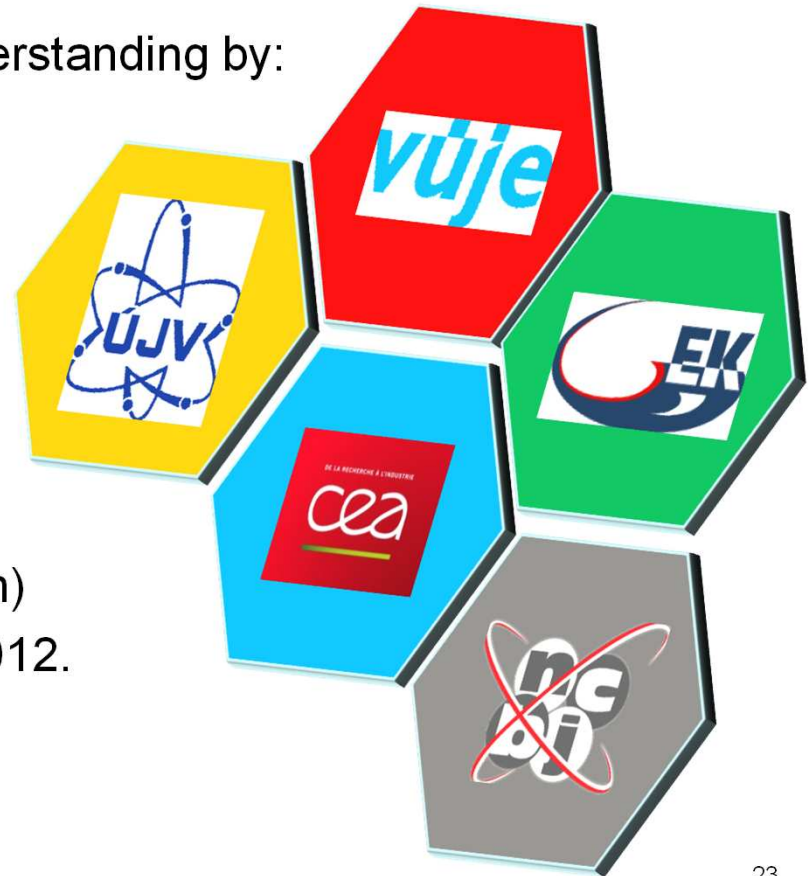
**VINCO** – Visegrad Initiative for Nuclear Cooperation  
coordination and support action

The main objective is to conduct a variety of capacity building activities  
aiming at strengthening the coordinating role  
of the “V4G4 CoE” and supporting its member organizations

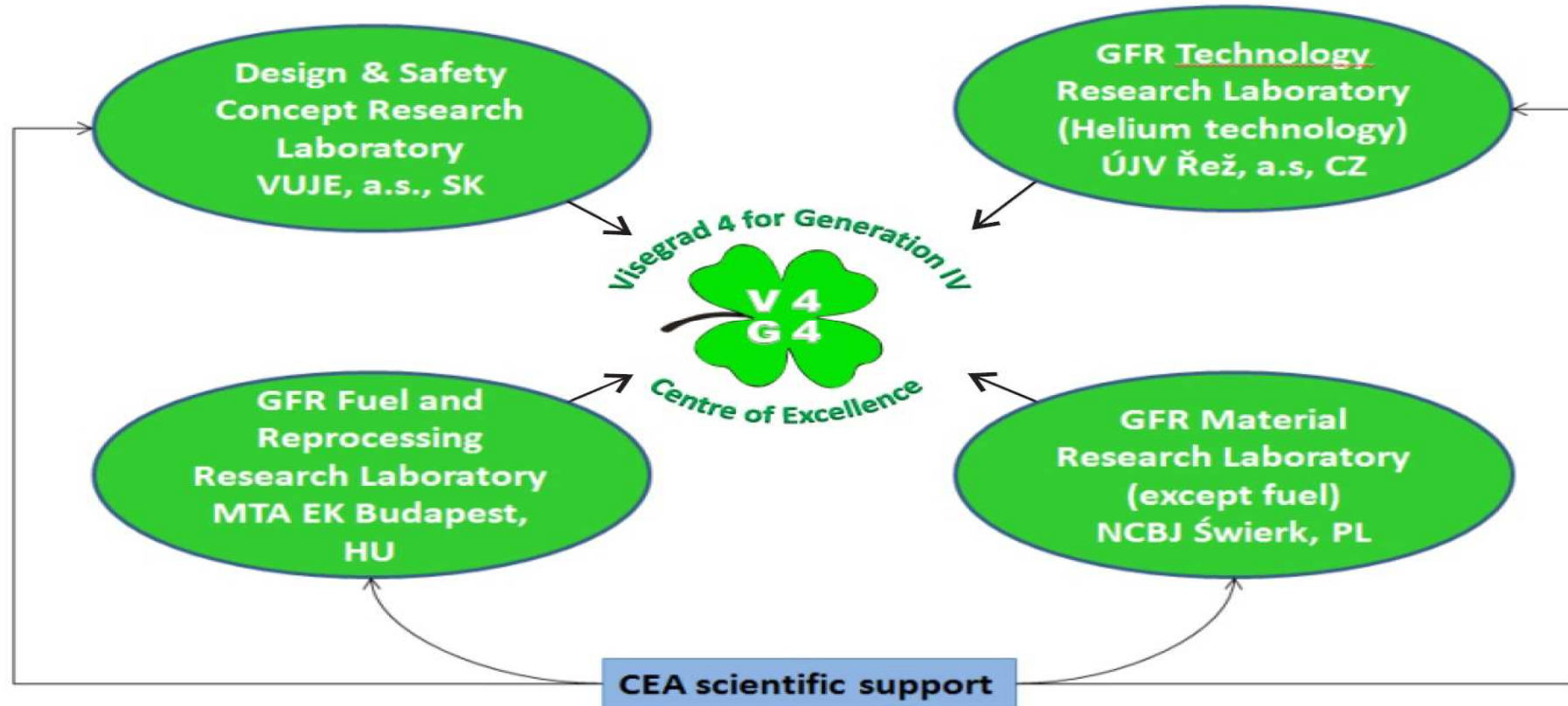
- Joint preparatory work started in 2010 with support of CEA

In May 2010 signature of Memorandum of Understanding by:

- Slovak republic VUJE, a.s.
- Czech Republic UJV Řež, a.s.
- Hungary MTA-EK  
(Magyar Tudományos Akadémia  
Energiatudományi Kutatóközpont )
- Poland NCBJ  
(Narodowe Centrum Badań Jądrowych)  
officially join the consortium in June 2012.



## The V4G4 Centre of Excellence



- Design & Safety Concept Research Laboratory – VUJE, a.s.
- GFR Technology Research Laboratory (Helium technology) – ÚJV Řež, a.s.
- GFR Fuel and Reprocessing Research Laboratory – MTA-EK
- GFR Material Research Laboratory (except fuel) – NCBJ



- investigating crucial aspects, in particular regarding safety, and generating experimental results for the development of Generation 4 nuclear reactors, especially for the innovative concept GFR (Gas Cooled Fast Reactors) for which a demonstrator, ALLEGRO, will be built and operate in the V4 region,
- promoting and popularizing the potential, perspectives, technical, political and environmental issues related to Generation 4 nuclear reactors,
- contributing to the preservation of nuclear qualifications by involving young scientists and engineers into its challenging research and development activities,
- facilitating the integration of nuclear research in Central Europe.



- The Hungarian Nuclear Program  
has been launched in 2015  
including activities **for Allegro safety and core design.**
  
- The members of the Hungarian Allegro Consortium are:
  - MTA EK, (Hungarian Academy of Sciences)
  - Institute of Nuclear Techniques of TU Budapest (BME NTI)
  - NUBIKI Ltd.

## ■ Project SUSEN

Under Operation Programme “Research and Development for Innovations”  
project EU: Sustainable Energy  
Centrum výzkumu Řež s.r.o

## Experimental facility S-ALLEGRO

**Purpose** Verify the basic safety characteristics of helium cooled reactors  
Non-active functional tests, reliability tests, component testing

### Model scales and parameters

Coolant – helium

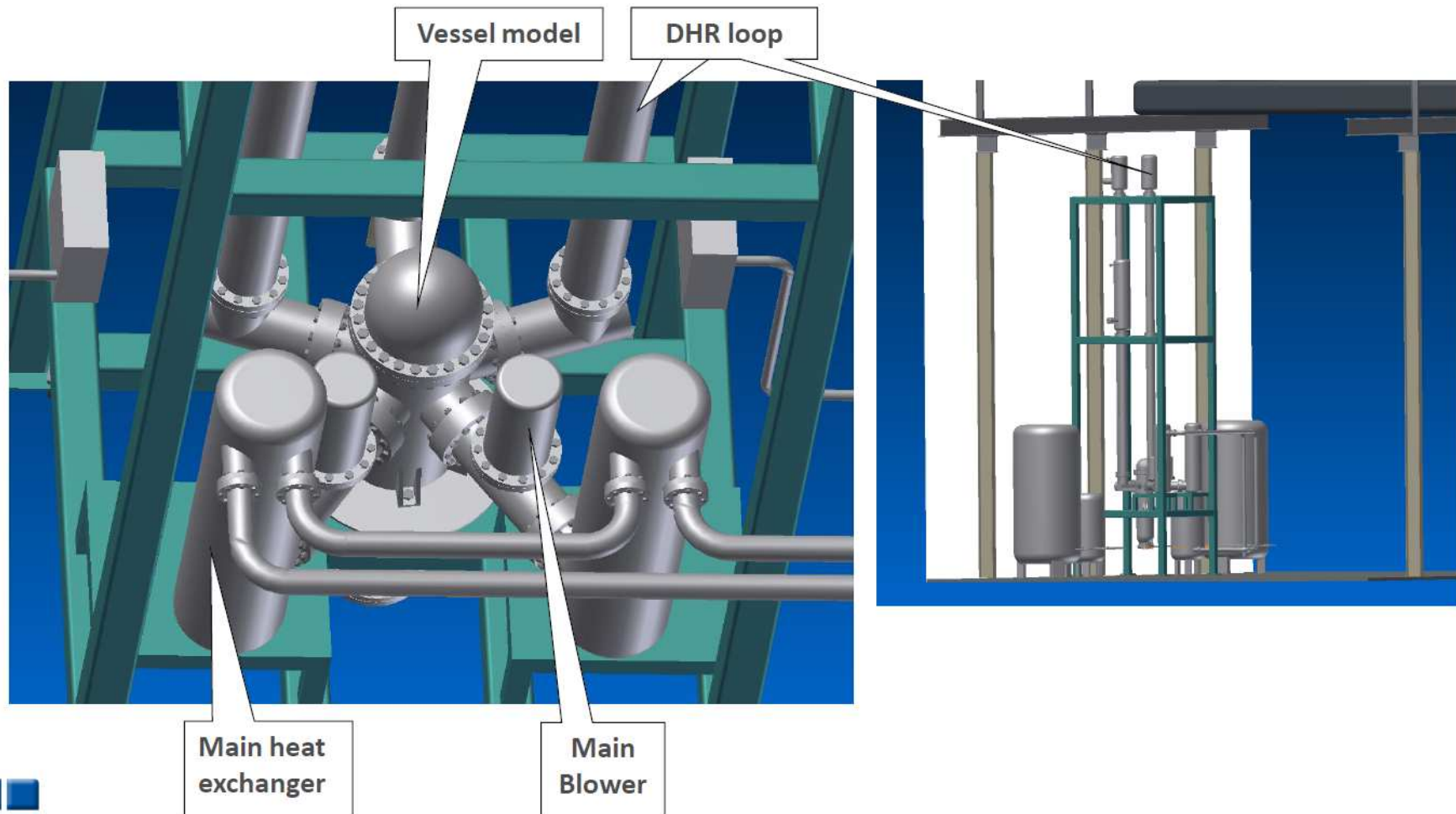
Pressure – 7 MPa

Max. temperature – 900° C

Power – 1 MW

Flow rate – cca 0,5 kg/s

## Experimental facility S-ALLEGRO



### Work packages

#### 1. Establishment and initiation of the ALLEGRO Research Centre

Goal: Development of specialised places of work and laboratories, rooms for employees and technology transfer.

#### 2. Applied research and development

in the area of new materials and technologies

Goal: Realisation of cutting-edge research and development in the area of new materials and technologies, preparation, testing and diagnostics of prototypes

#### 3. Establishment of technology transfer platform

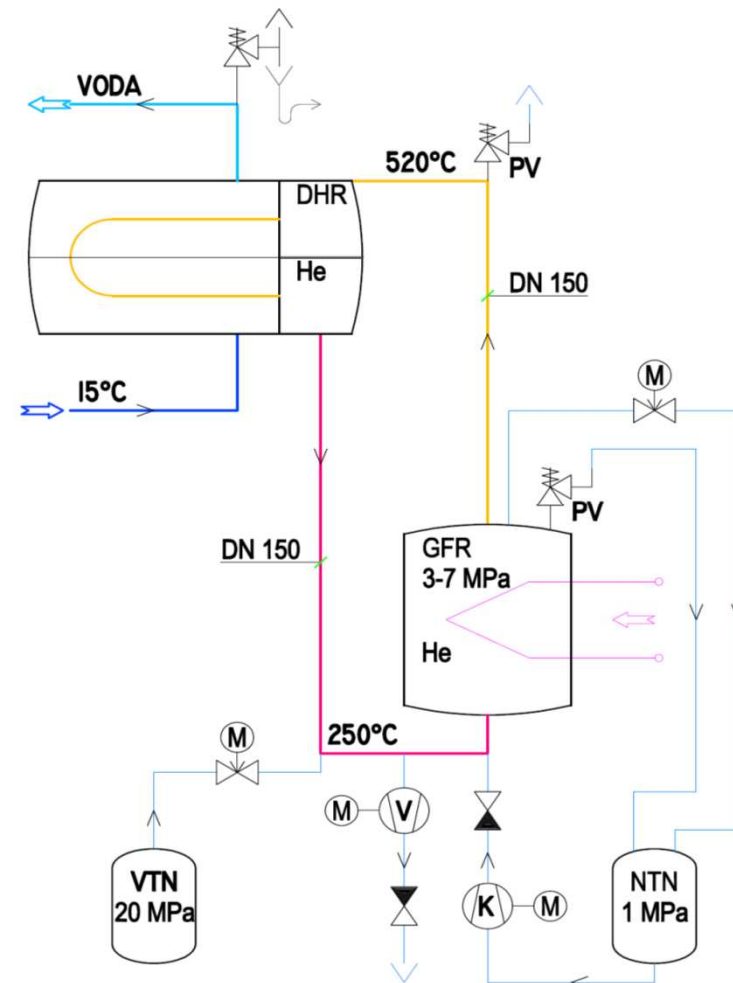
Goal: Establishment of a contact point for communication with entrepreneurial sector in frame of the Office for technology transfer (KTT), establishment of incubator, identification of spin-offs and programme for support of technology transfer and mobilisation of innovations

## Experimental helium loop

Mechanical Engineering  
Slovak University of Technology in  
Bratislava

Facility is determined  
for the testing  
of the decay heat removal.

The natural circulation of helium in  
the cooling loop  
at different temperature  
and pressure of helium  
should be verified on the model.



## Experimental Helium Loop

Helium temperature at the GFR  
output 400°C to 520 °C

Helium temperature at the GFR  
input 150 °C to 250 °C

Helium operational pressure  
3 MPa to 7 MPa

Installed input power of the GFR  
500 kW

Designed heat power of the DHR  
220 kW



# Gas-cooled Fast Reactor ALLEGRO Project

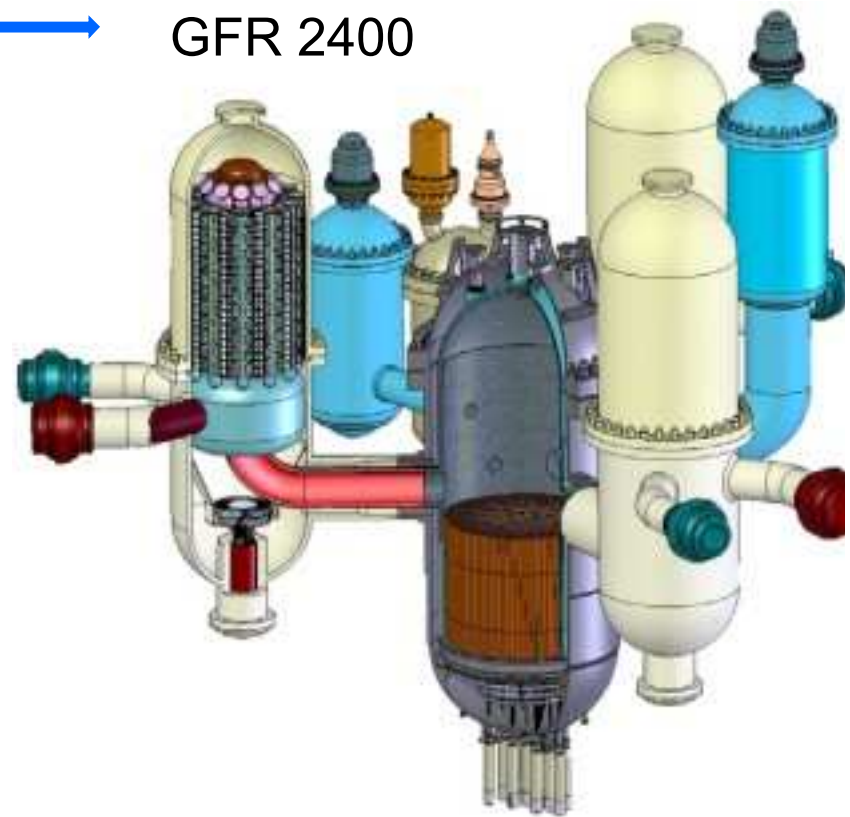
Technology demonstration as a first gas-cooled fast reactor



ALLEGRO



GFR 2400

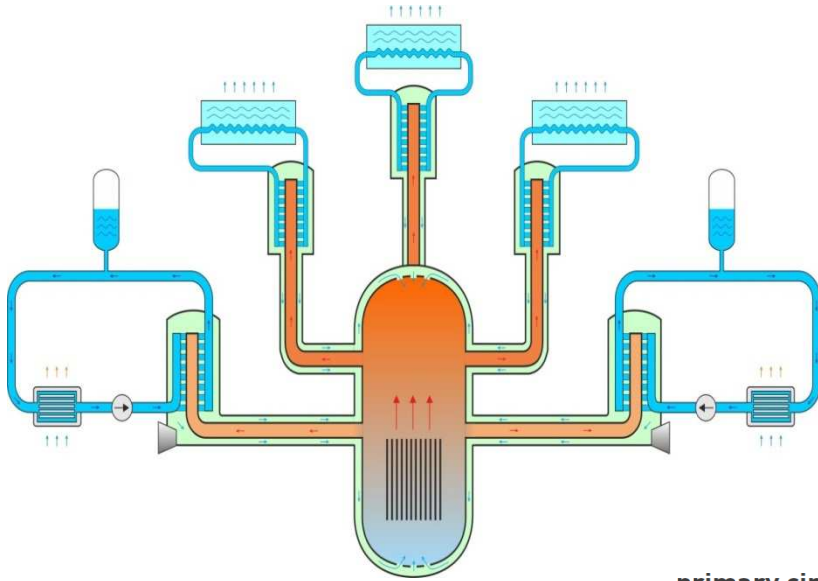




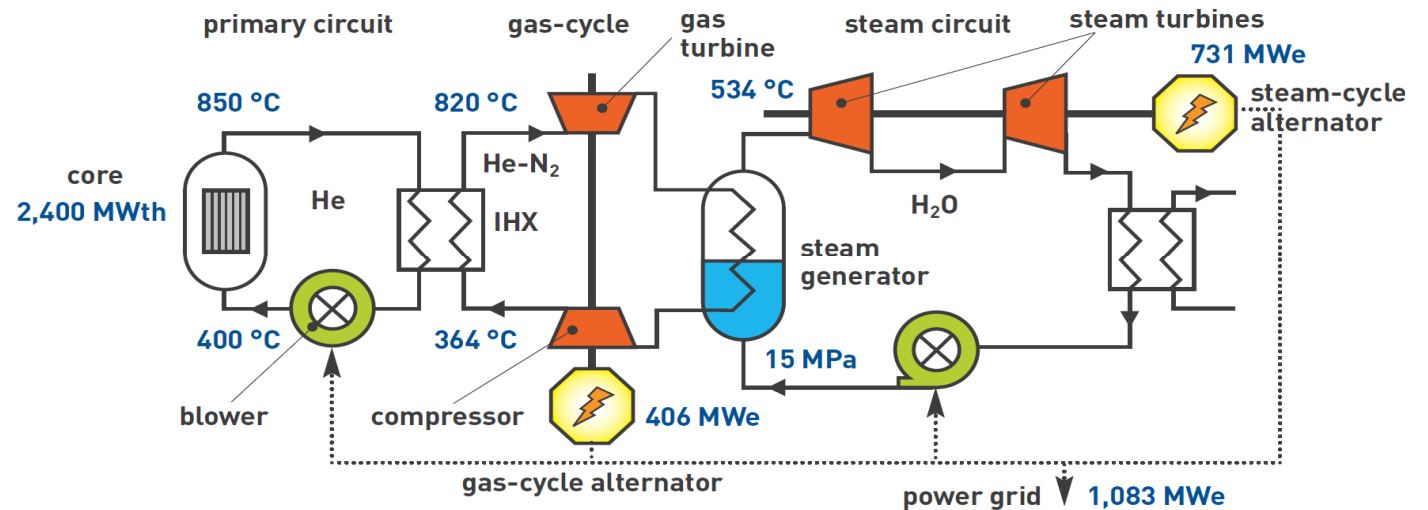
- Demonstration of the GFR gen-4 concept,  
(alternative technology to the reactor cooled by molten sodium)
  - demonstration of the technological feasibility,  
helium cooling and high temperature core,
  - demonstration of the breeding capacity,
  - demonstration of the ability of transmutation of actinides.
  
- Demonstration of heat production at industrial and economic conditions.  
As a one of fast reactor would produce heat about 850° C,  
which will be able to chemically produce hydrogen.  
High temperature heat could be used also for technological purposes.

# ALLEGRO reactor

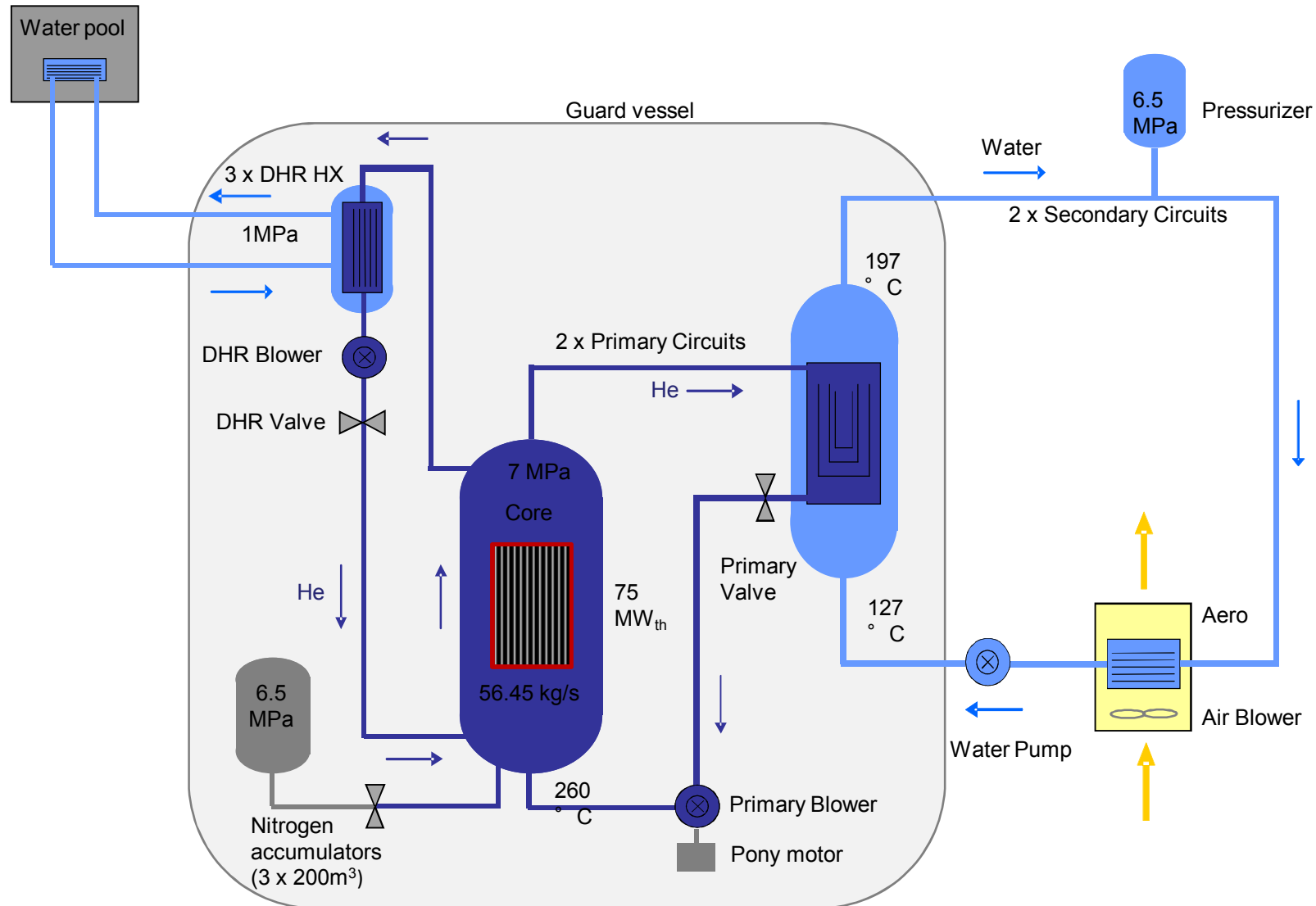
Technology demonstration as a first gas-cooled fast reactor



ALLEGRO → GFR 2400



# ALLEGRO reactor

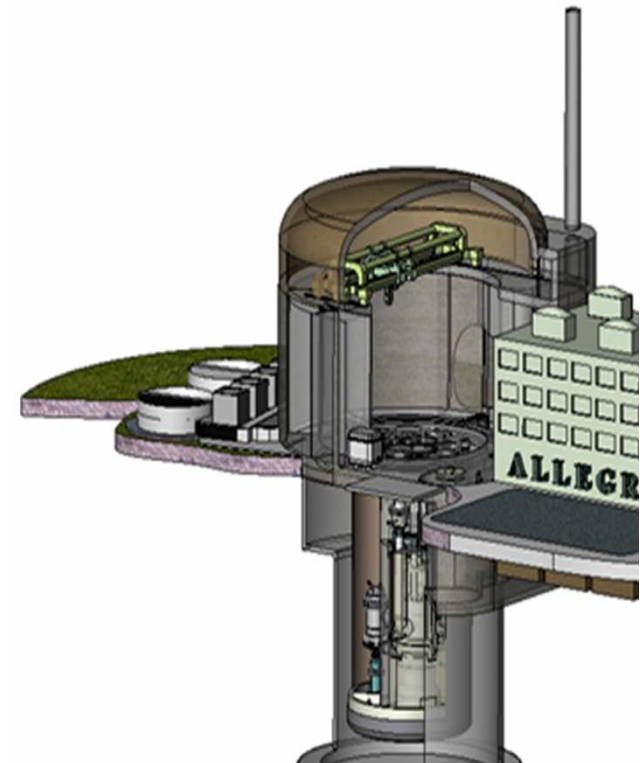
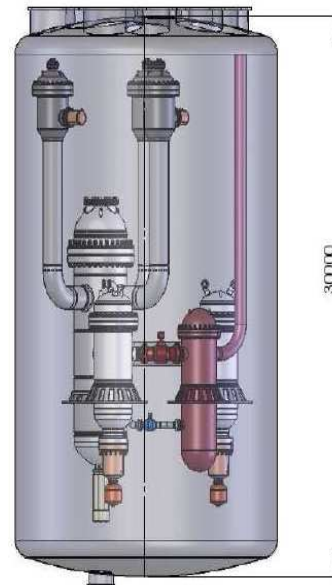


**The guard vessel has two main safety functions:**

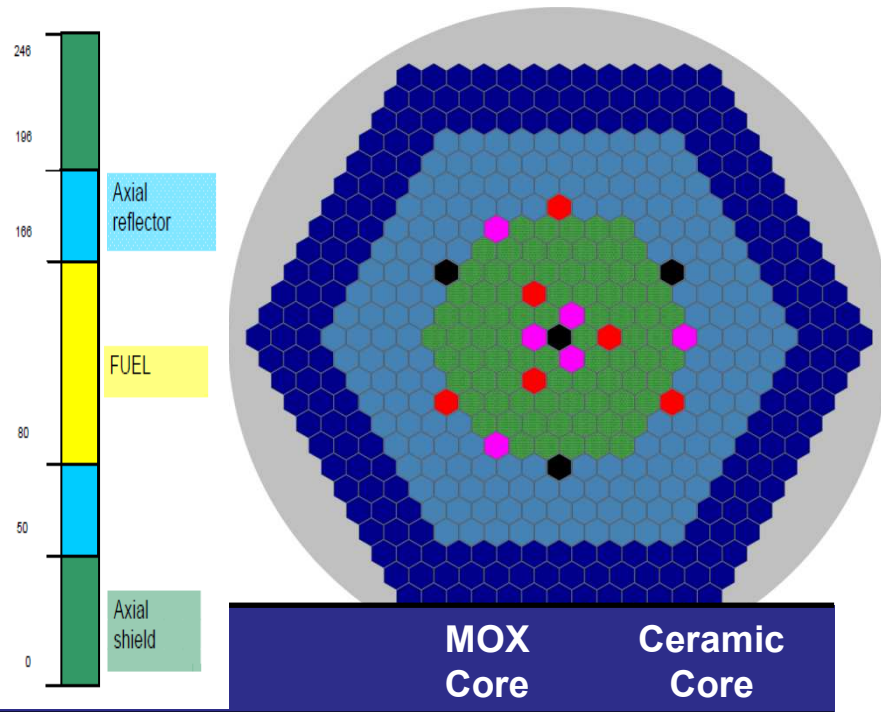
- A contamination barrier function between a possible leakage of primary helium cooling gas and the inside/outside reactor building.
- Maintaining of the back-up pressure in the primary system in the case of a LOCA.

⇒ Helium leaktightness for the guard vessel is required.

- Inner diameter: 18m
- Total height: ~ 32m
- Thickness: 40 mm
- Pressure resistance limit value: 10 bars









# ALLEGRO core



The reactor shall be operated with two different cores: The starting core will serve to test the operation of the gas cooled fast reactor with well established fuel.

The second core using the ceramic fuel will serve for testing the new fuel design.

	MOX Core	Ceramic Core
Core power	75 MWth	
Coolant pressure	7 MPa	
Primary mass flow rate	53 kg/s	36 kg/s
Core inlet temperature	260 °C	400 °C
Core outlet temperature	<b>560 °C</b>	<b>850 °C</b>

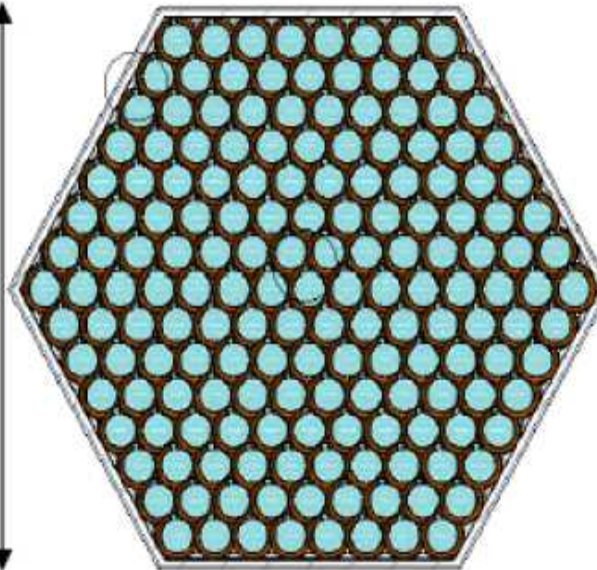
-  Experimental / Steel diluent assembly (6)
-  Fuel (81)
-  Control and Shutdown Devices (CSD) (6)
-  Diverse Shutdown Devices (DSD) (4)
-  Reflector (174)
-  Shielding (198)

# ALLEGRO reactor

The ALLEGRO fuel pins are very similar to the PHENIX Sodium Fast Reactor

169 fuel pins in fuel assembly

110 mm



1793 mm



PHENIX pin

Fissile column

Fertile column

Gas volume

ALLEGRO pin

~ 1300 mm

# V4G4 Center of Excellence ALLEGRO Design and Safety Roadmap

	Specifications	Pre Conceptual Design (Preparatory Phase)	Conceptual Design	Basic Design	Detailed Design
Design	Design Requirements & Objectives (Performance Goals)	Preliminary choice of options	Main design options and justification	Improved Design	Final Design (For fabrication of the components / systems and building)
Safety	Safety Requirements and Objectives (SRO)	Safety Concept (Implementation of the SRO into the design)			
		Introductory Safety Analysis Report (ISAR)	Simplified Preliminary Safety Analysis Report (SPSAR)	Preliminary Safety Analysis Report (PSAR)	Final Safety Analysis Report (FSAR)
Qualification		Qualification background	Qualification needs	Qualification	
Schedule & Cost		First assessment	Updating		

75 tasks identified

- A new strategy for developing the ALLEGRO reactor
  - to reduce ALLEGRO power
  - to find the optimum core configuration;
  
  - to optimize nitrogen injection (launch time, duration)
  - to define backup pressure in guard containment;
  
  - to increase main blowers inertia for the LOCA+ blackout case
  
  - severe accidents mitigation measures in ALLEGRO
- Use UO<sub>2</sub> pellets in AIM1 cladding instead of MOX pellets.



- The GFR concept is attractive as it avoids the coolant handling issues associated with liquid metal-cooled fast reactors:
  - Chemical inertness of helium
  - Excellent nuclear stability avoids activation of the coolant
  - Transparent coolant permits simple inspection and repair
- GFR offers a high temperature heat source for high efficiency electricity generation and high-quality process heat.
- The main technical challenges lie in the development of a high-temperature, high-power density fuel and in the development of robust decay heat removal systems.
- An indirect combined gas/steam cycle has been chosen to be the reference power conversion system as this returns good efficiency with low technological risk and good economics.

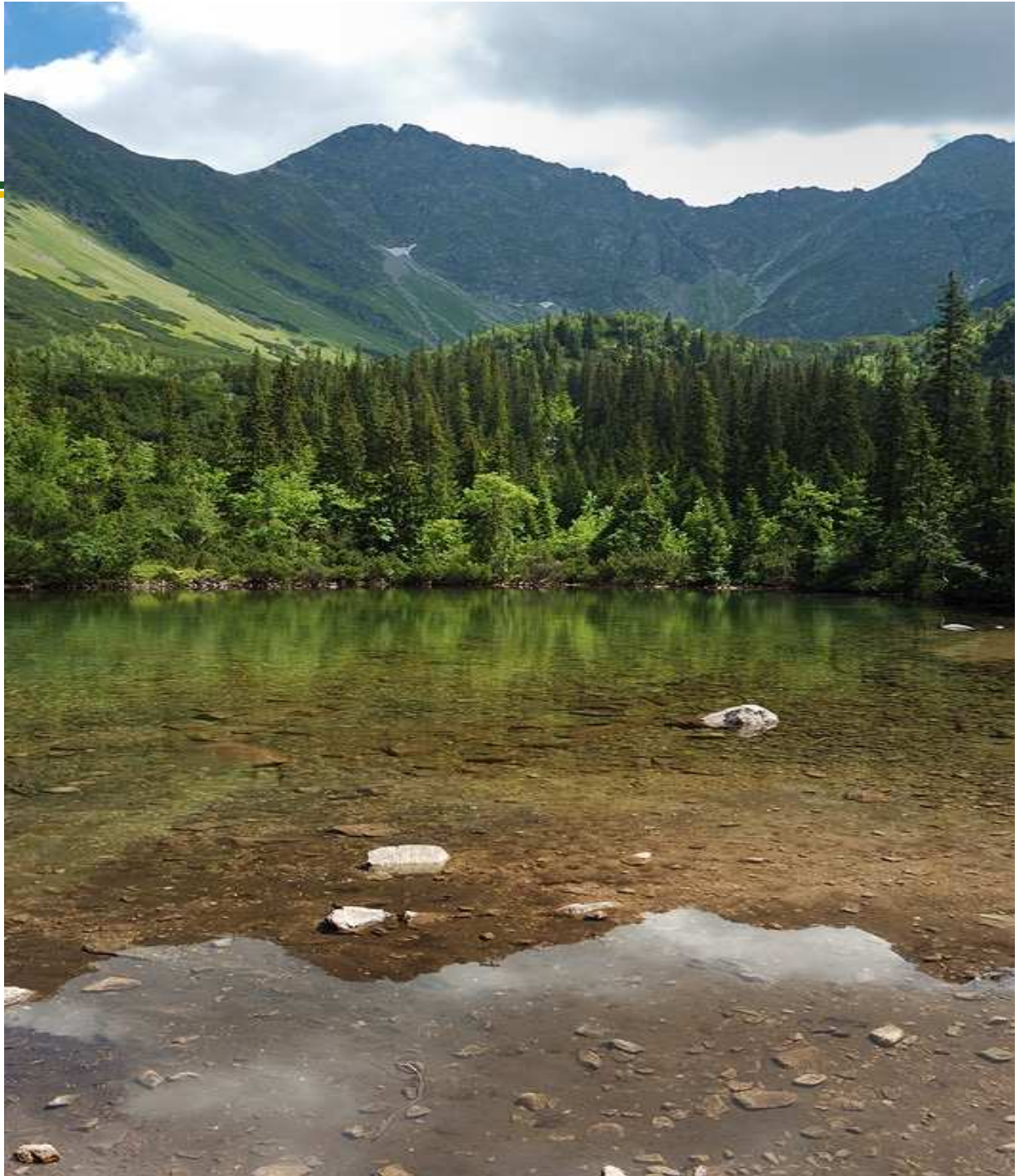
**Thank you  
for your attention**

**VUJE, a.s.**

**Okružná 5  
918 64 Trnava  
Slovak Republic**

**[www.vuje.sk](http://www.vuje.sk)**

**Branislav.Hatala@vuje.sk**



GEN IV International  
Forum

