



THE ALLEGRO EXPERIMENTAL GAS-COOLED FAST REACTOR PROJECT

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Meet the Presenter



Dr. Ladislav Bělovský works at the ÚJV Řež, a. s., Husinec-Řež close to Prague, Czech republic as a senior engineer and has over 30 years experience in nuclear energy research. He graduated from the Czech Technical University of Prague (Czech Republic) in 1988 as M.Sc. in Mechanical Engineering for Nuclear Industry, and earned his PhD in 1993 at the same university for “Modelling of LWR Fuel Behavior in Severe Accidents.” Since 2011, the main area of his research activities has focused on development of Generation IV Reactors. At ÚJV Řež, Dr. Bělovský participates in the development of the helium-cooled demonstration Fast Reactor ALLEGRO in the frame of the international association “V4G4 Centre of Excellence” in the following areas: 1) design & safety of the reactor, 2) related R&D focused on safety, helium technology and material research. His background in the Czech republic and France in the period from 1988 to 2011 is mainly characterized by activities in the development and application of computer codes for modelling of LWR fuel behavior in design basis and severe accident conditions.



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Outline

- Motivation & Philosophy of ALLEGRO
- History of ALLEGRO
 - **CEA** (ETDR, ALLEGRO)
 - **V4G4** Centre of Excellence (ALLEGRO V4G4)
- V4G4 Recent Developments
- R & D for ALLEGRO
- Perspectives & Conclusions

Reasons for the First Ever GFR Demonstrator ALLEGRO



- To establish **confidence** in the GFR technology with the following objectives:
 - A) To **demonstrate the viability** in pilot scale & **qualify specific GFR technologies** such as:
 - Core behavior & control including fuel
 - Safety systems (decay heat removal, ...)
 - Gas reactor technologies (He purification, refueling machine ...)
 - Integration of the individual features into a representative system
 - B) To contribute (by fast flux irradiation) to the **development of future fuels** (innovative or heavily loaded in Minor Actinides)
 - C) To provide test capacity for high-temp components or heat processes
 - D) To dispose of a first validated safety reference framework
- Power conversion system is currently not required in ALLEGRO.

ALLEGRO Faces Main Technical Challenges of CEA GFR2400



- High-temperature resistant (refractory) fuel (tolerant to overheating)
 - (U,Pu)C in SiCf-SiC tubes
- Safety systems – Reliable shutdown and decay heat removal (DHR)
 - With use of natural circulation
- Fuel handling machine
 - Under He flow to cool the fuel
- He/gas main heat exchanger
 - Large (?) dimensions
- Materials & components & helium-related technology
 - Heat shielding, He sealing, He purification, He recovery, ...
- **One challenge related to ALLEGRO only:**
 - Driver core based on the **existing SFR** technology

Philosophy for the ALLEGRO Core Design (Unique Feature)

■ **Three** distinct phases of operation ⇒ **three** different core configurations:

■ STARTING MOX (or UOX) CORE

- Oxide fuel in SS (MOX ~25% Pu) – Phenix-based hex. Fuel Assemblies
- Core outlet temperature limited to ~530 °C

Oxide / SS fuel has small safety margin

■ INTERMEDIATE CORE (containing 1 to 6 refractory FAs)

- Exp. refractory FAs: (U,Pu) carbide pellets in SiCf-SiC pins (29-35% Pu) inside thermally insulated metallic hex. wrapper tube.
- Outlet temperature: Test assembly ~800-850 °C (reduced flow rate at FA inlet)
Average core ~530 °C

■ FINAL REFRACTORY CORE

- Average core outlet temperature increased to ~800-850 °C

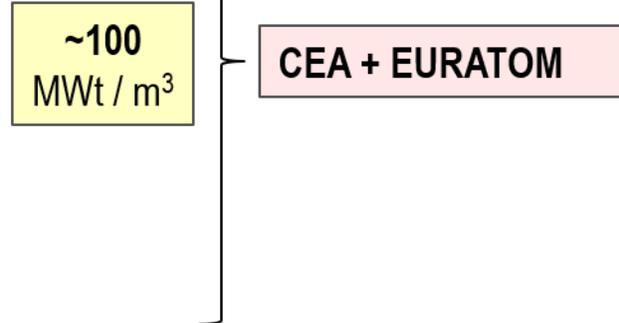
Refractory fuel needs R&D

■ Remark: **ALLEGRO must be designed for the high-temperature option**

History of ALLEGRO concepts

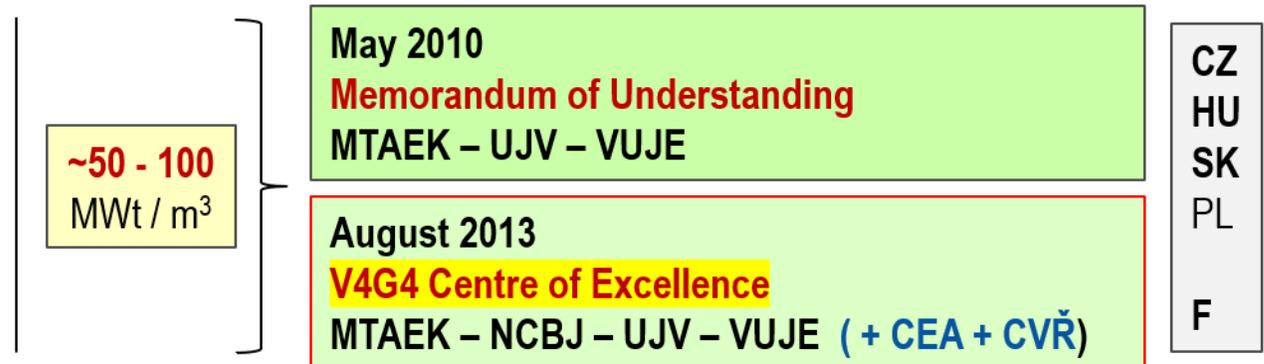
2002

- **ETDR CEA 2008** (Exp. Technology Demonstration Reactor)
50 MWt, 1 loop, He/water (FP6 GCFR STREP)
- **ALLEGRO CEA 2009** (ALLEGRO is not an acronym)
75 MWt, 2 loops, He/water (FP7 GoFastR)
- **ALLEGRO CEA 2010**
75 MWt, 2 loops, He/gas(He), Patented option (turbomachinery)



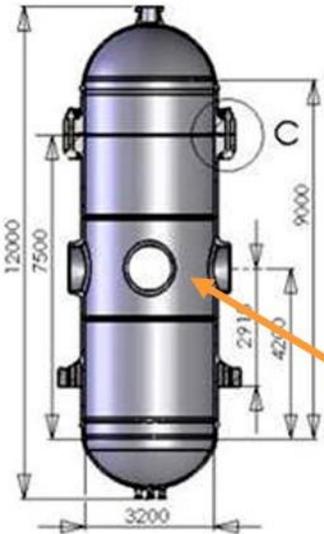
2010

- **ALLEGRO V4G4**
~75 MWt, 2-3 loops, He / (N₂-He)
based on ALLEGRO CEA 2009

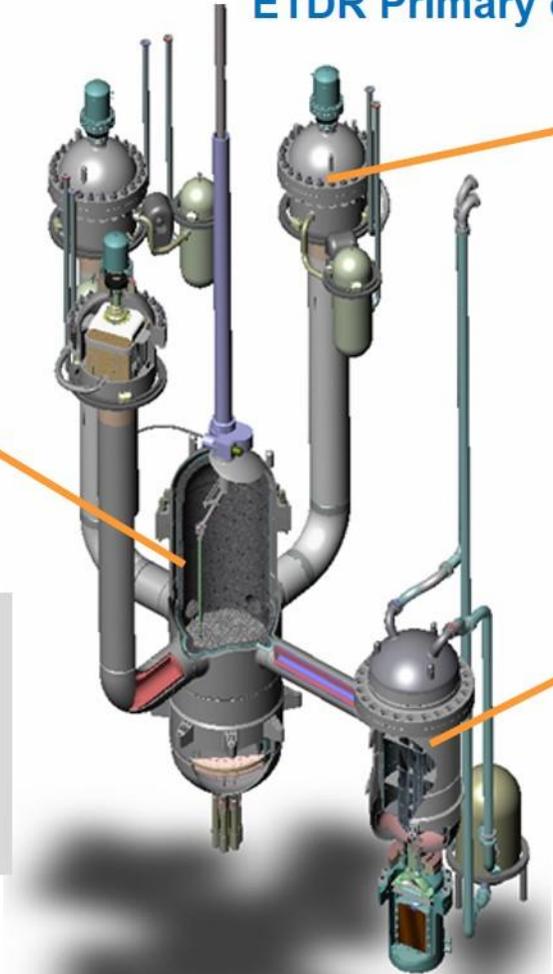


ETDR CEA 2008 (50 MWt): Design of I. Circuit

ETDR Primary circuit



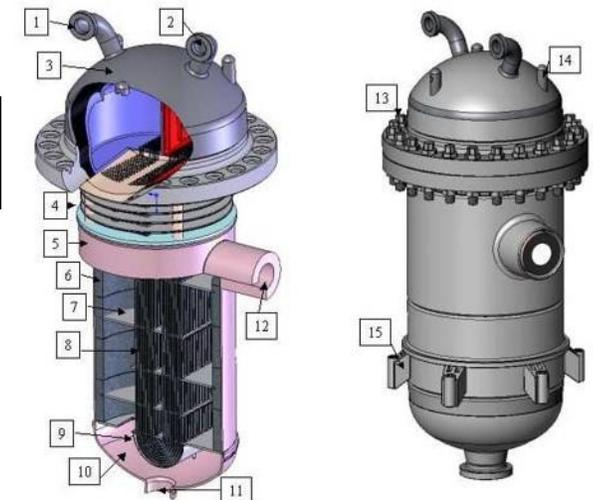
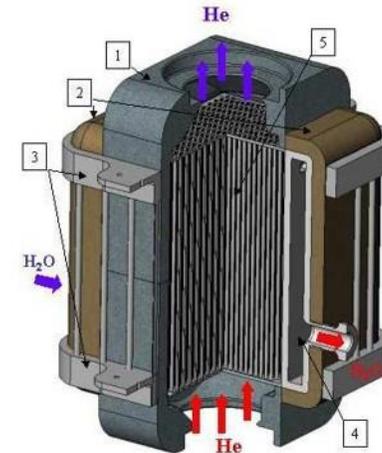
I. circuit is enclosed in a close containment (guard vessel) not shown here



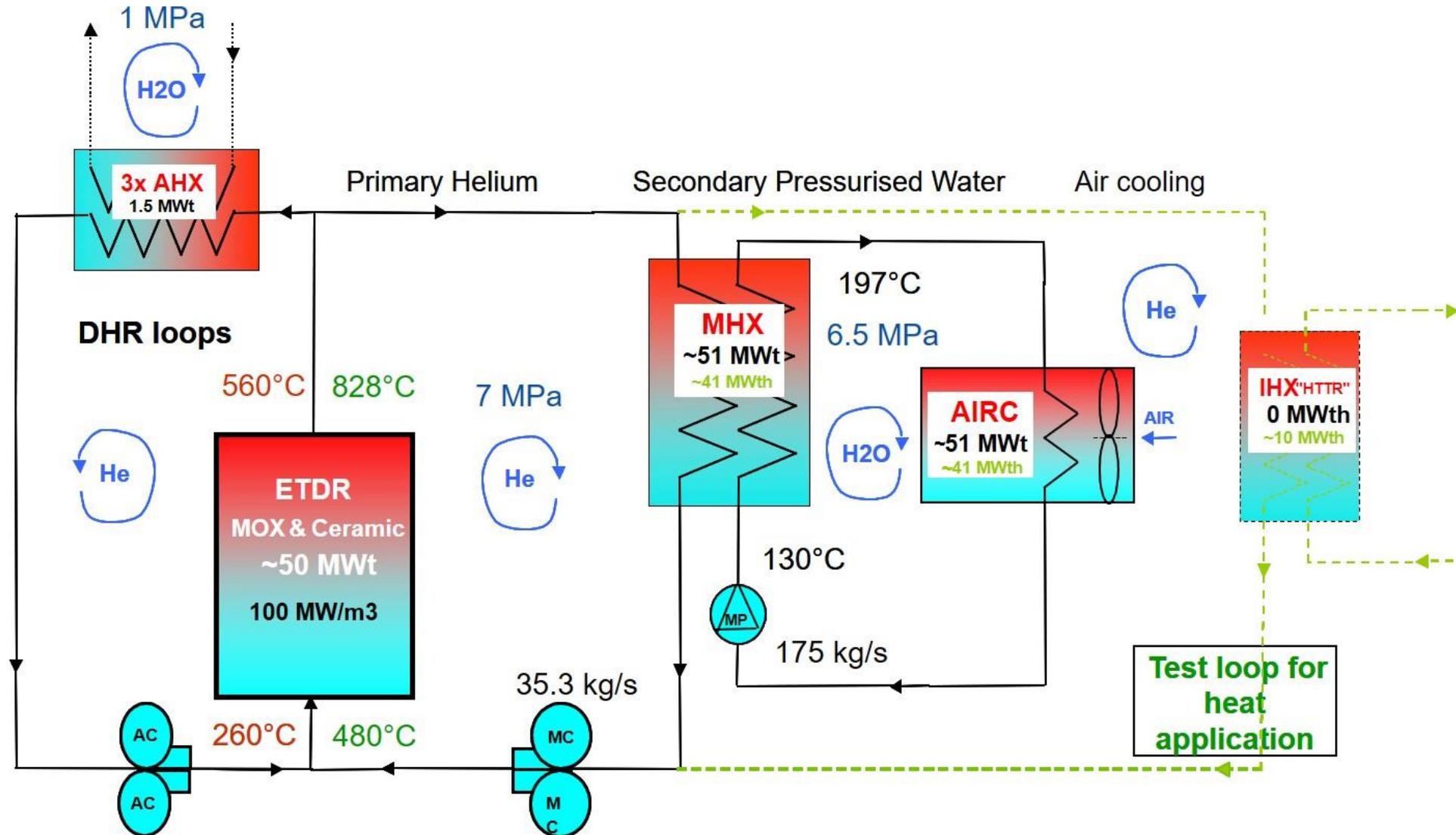
Decay Heat Removal (DHR) Heat Exchanger

Note: This DHR HX does not promote natural convection

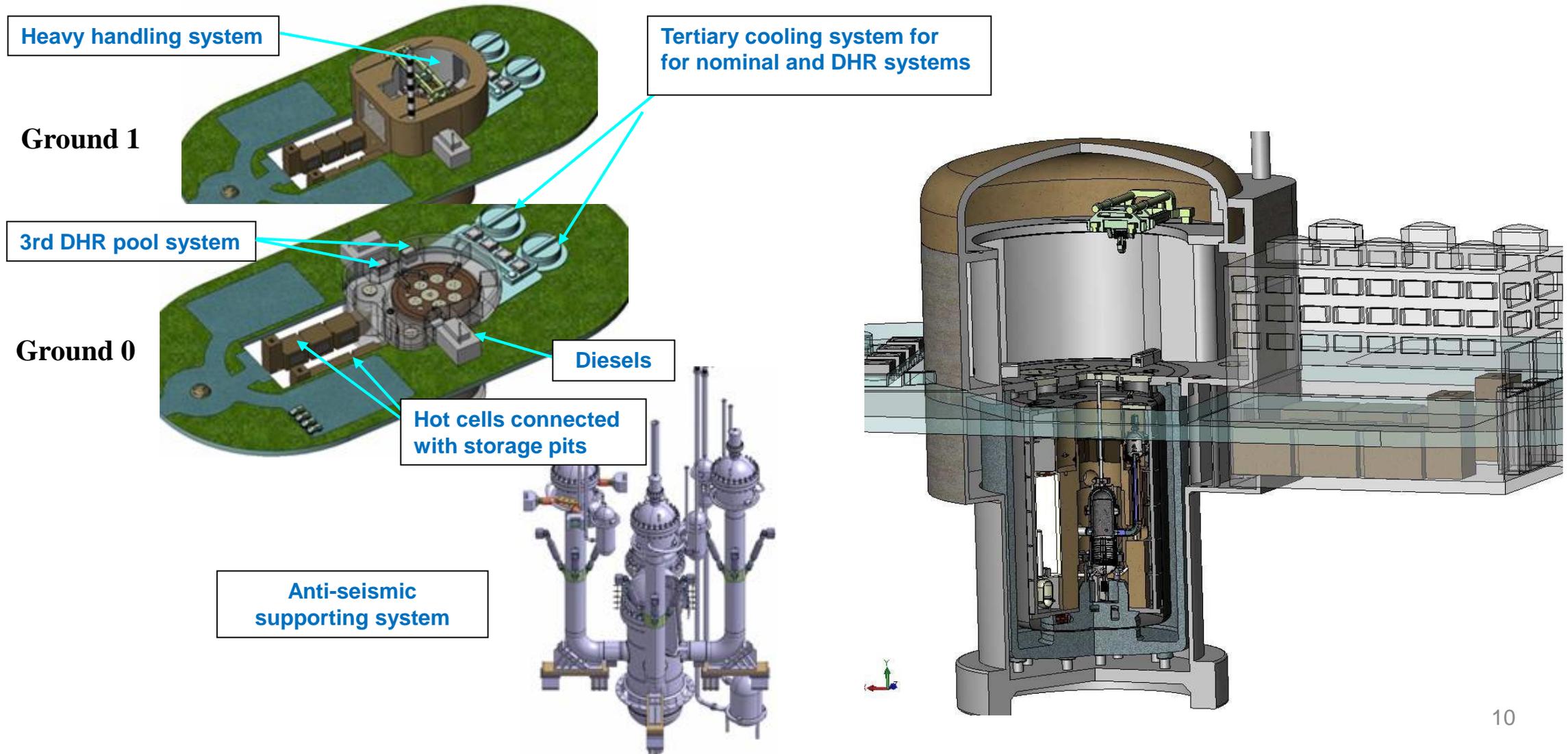
Main HX (gas/water) (similar to IHX in JAEA HTTR)



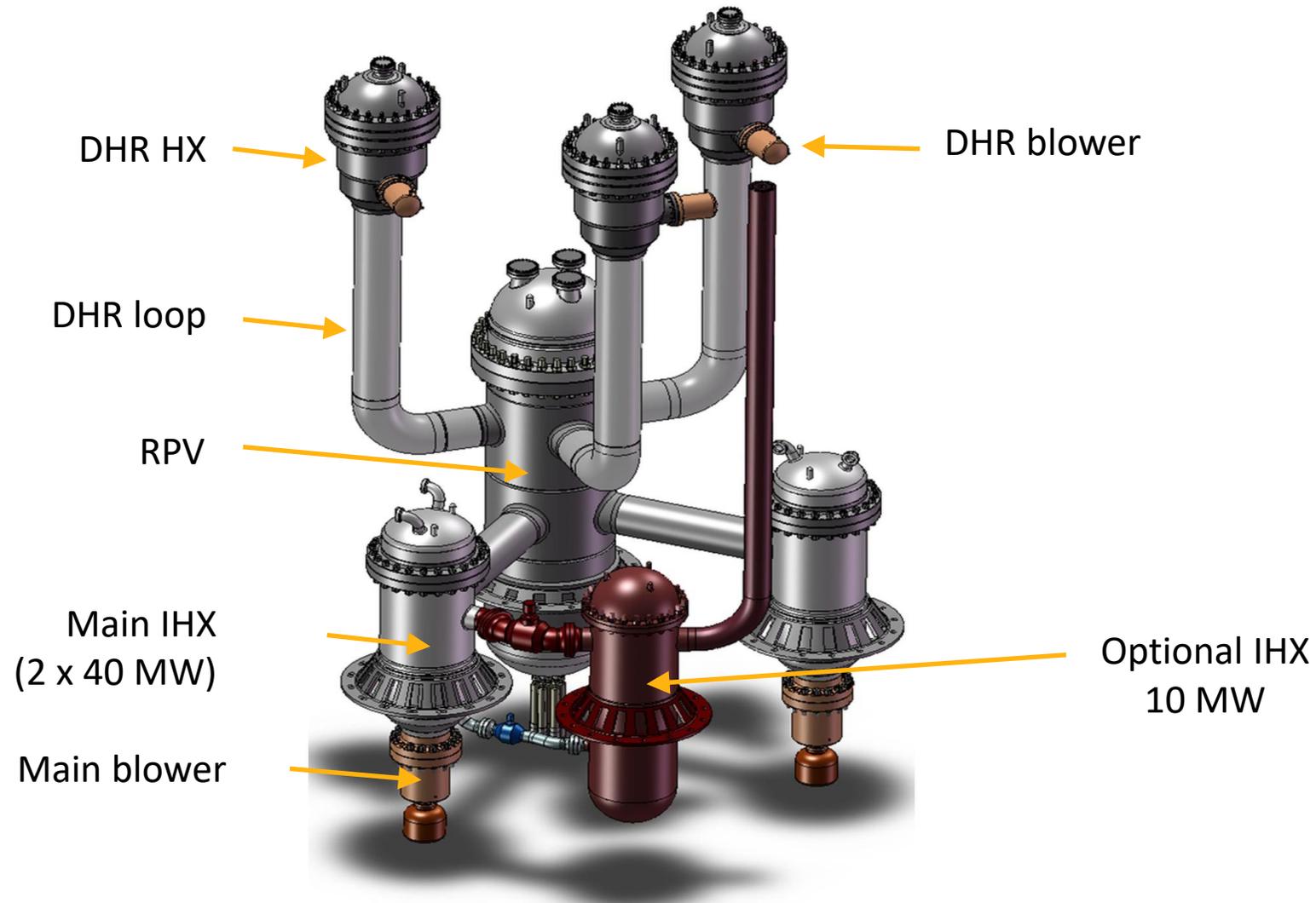
ETDR CEA 2008 (50 MWt): Thermal Scheme



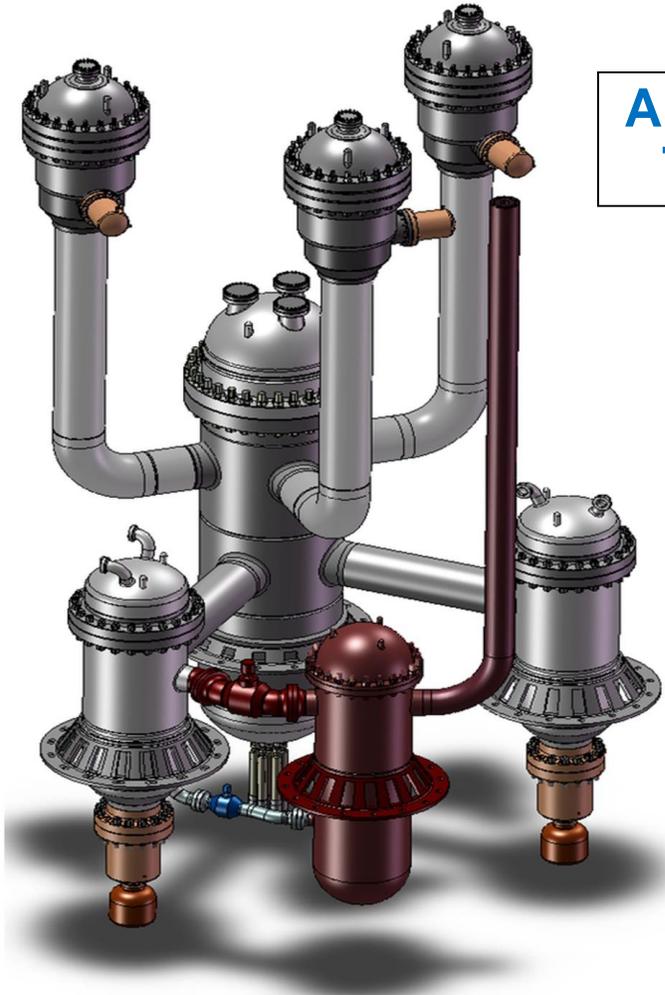
ETDR CEA 2008 (50 MWt): Global View



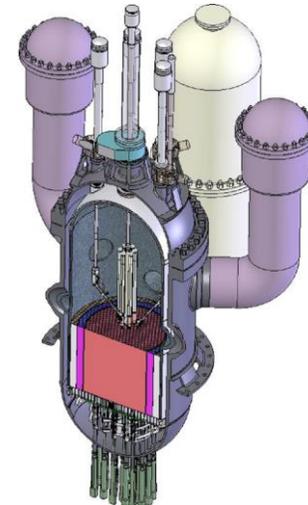
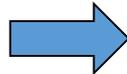
ALLEGRO CEA 2009 (75 MWt): Design of I. Circuit



What after ALLEGRO ?

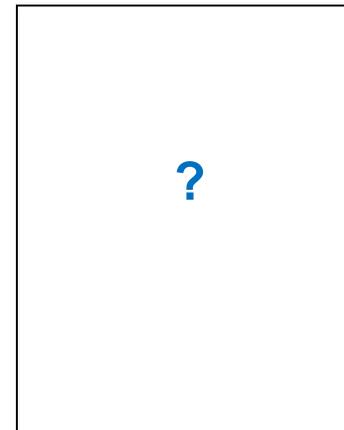


ALLEGRO
75 MWt



CEA
GFR 2400 MWt

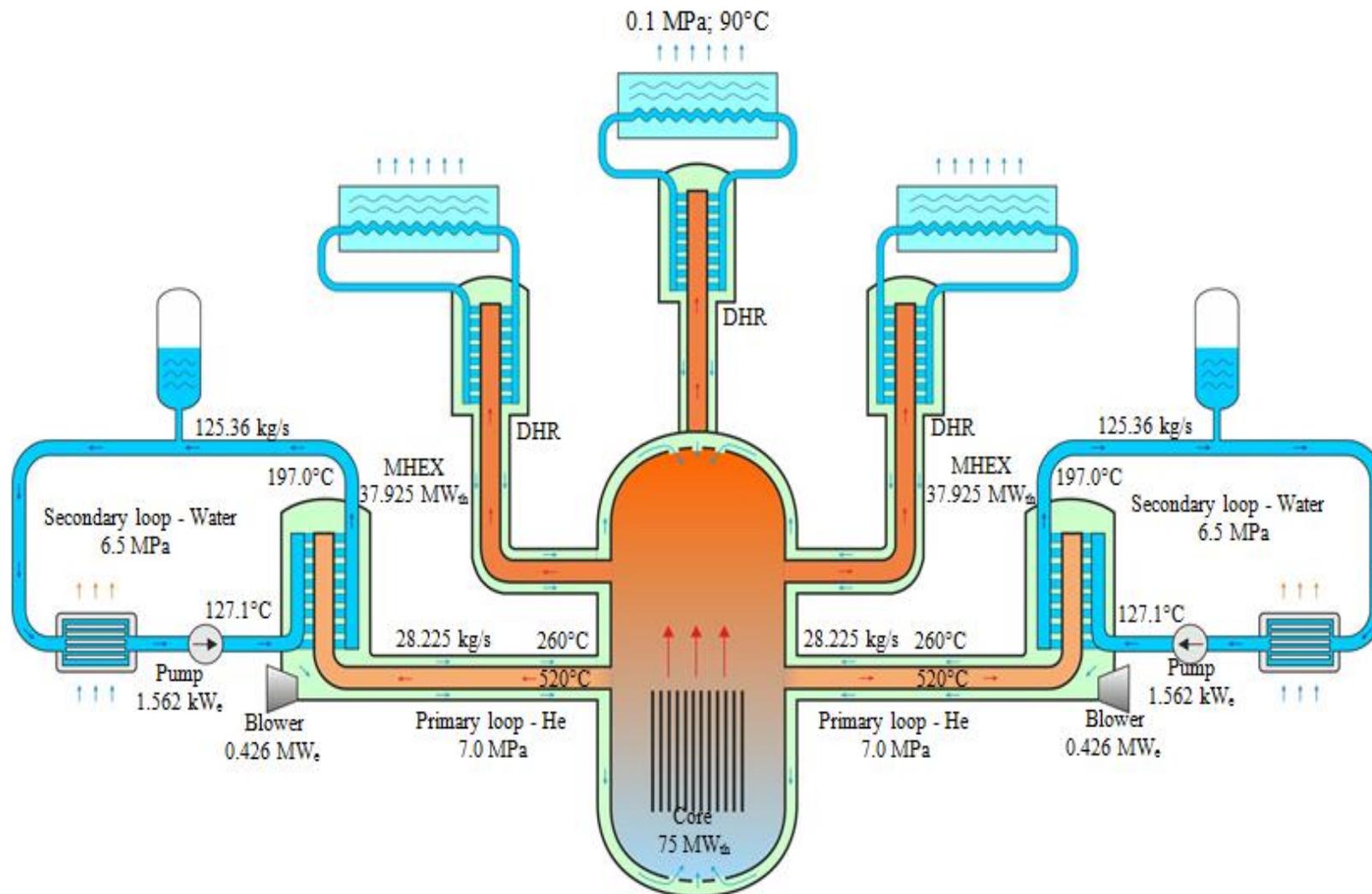
Original demand
by EdF in ~2002



SMR
GFR 200 MWt ?

Smaller units are
preferred today

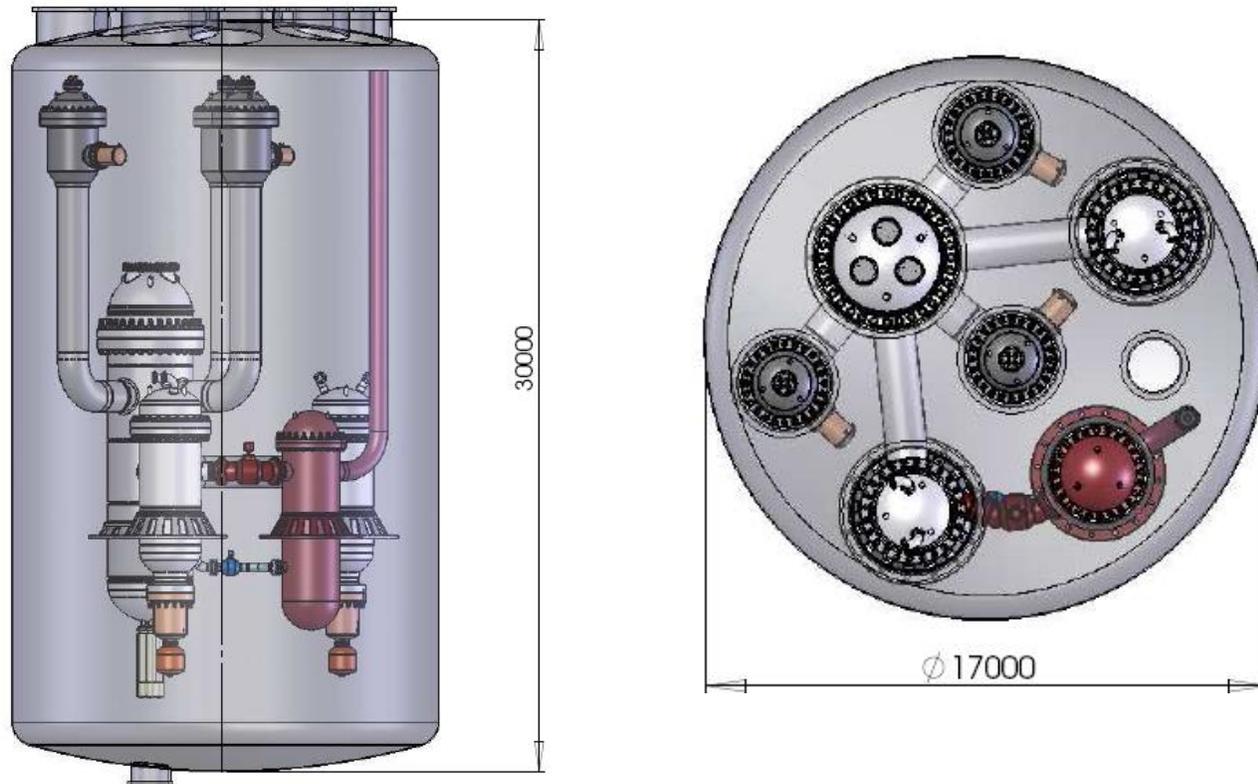
ALLEGRO CEA 2009: Parameters



Core temperatures Inlet/outlet:

- **ALLEGRO with driver core**
(mixed oxide fuel in SS)
260 / 530 °C
- **ALLEGRO with refractory core**
(mixed carbide fuel in SiC_f-SiC)
400 / 850 °C

ALLEGRO CEA 2009: Design of Guard Vessel (GV)



Purpose of the GV:

- Improve core coolability in **LOCA**
- Provide gas backpressure >1 bar
- **Forced convection (3-4 bar):**
Reduce pumping work
- **Natural convection ($>>4$ bar):**
Promote gas circulation

Note: Internal concrete support structures are not shown

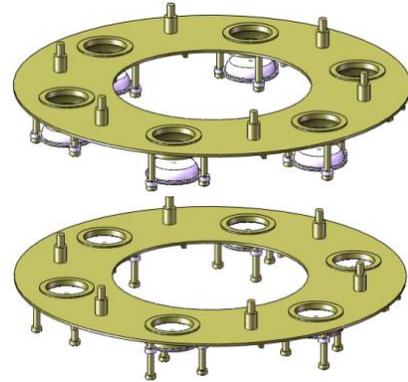
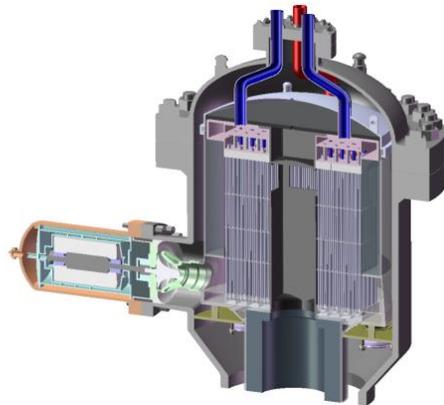
- **Normal operation:** Nitrogen+He (leakages): ~ 1 bar
- **Accident (LOCA):** Nitrogen+He (I. inventory): $\sim 3-4$ bar
+N₂ injection: ~ 10 bar or more

ALLEGRO CEA 2009: Design of DHR HX



- Designed to remove ~2.5 MWt (~3% of 75 MWt)
- Optimized for **forced convection only**
- Susceptible to instabilities, if water boils **in U-tube**

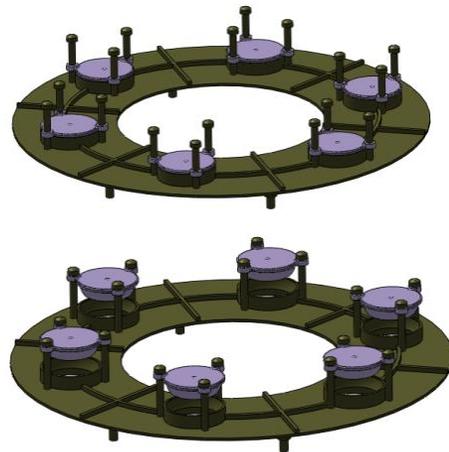
ALLEGRO CEA 2009 – DHR Check Valves & Main Isolation Valves



OPEN
Main blowers OFF

CLOSED
Main blowers ON

DHR Check valves

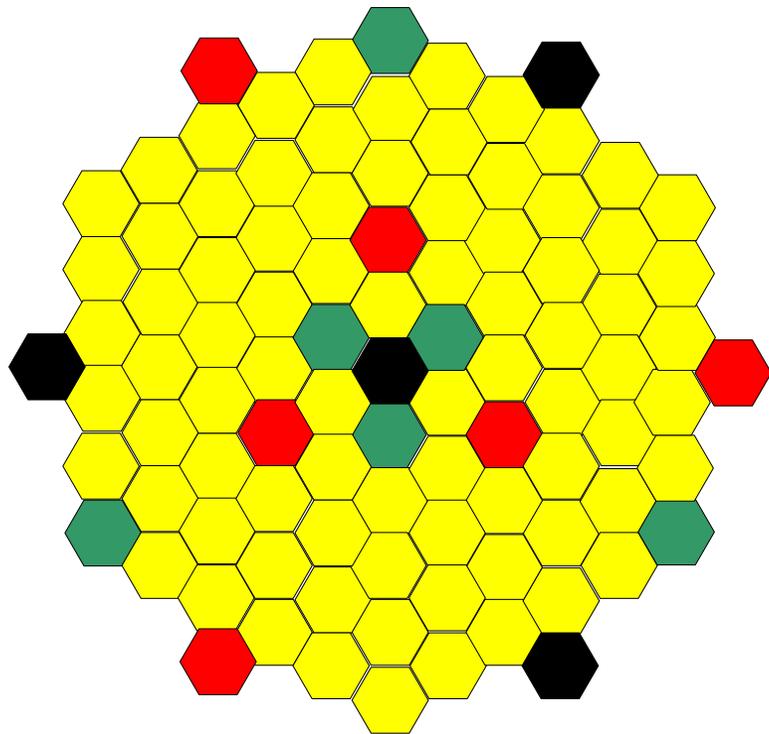


CLOSED
Main blowers OFF

OPEN
Main blowers ON

Main isolation valves

ALLEGRO CEA 2009: First Core Layout



- Experiment
- MOX (Phenix)
- Control
- Shutdown

Remark:

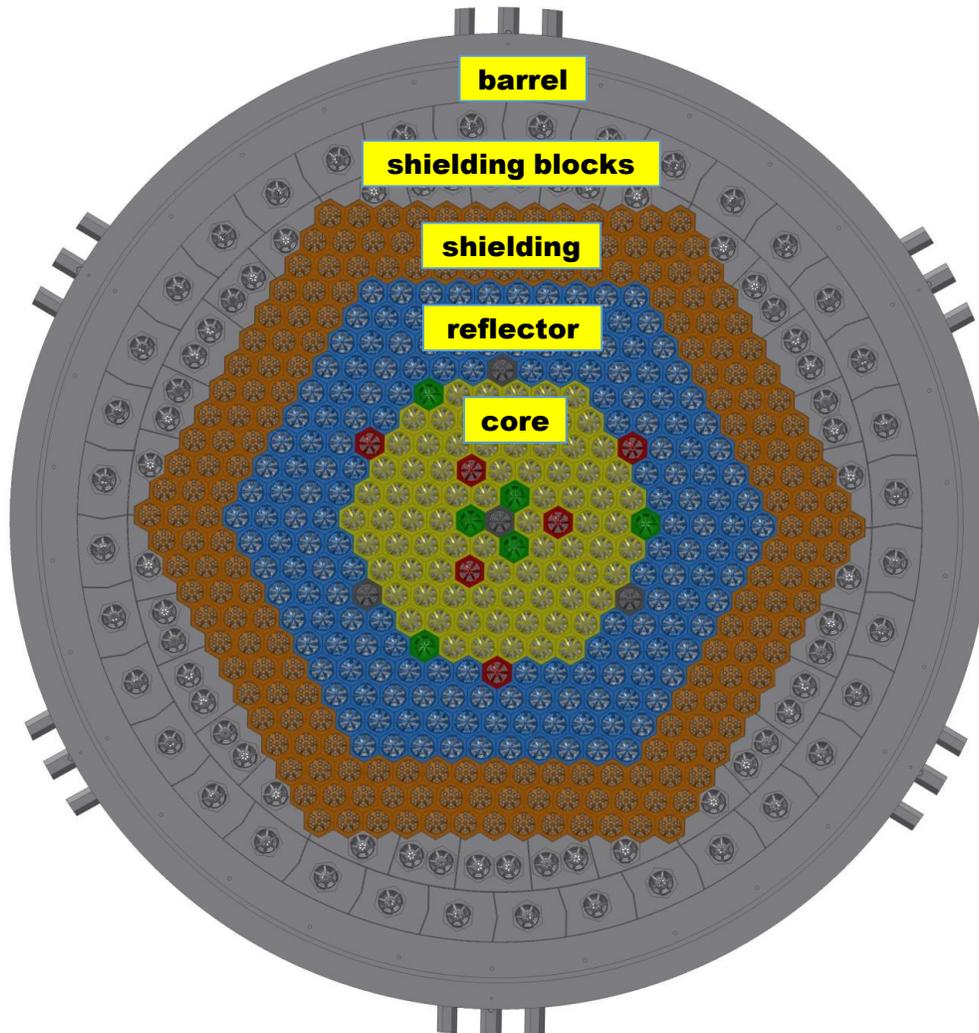
- Cycle length: **660** EFPD
- Frequency 1: No core reload

Number of assemblies:

- 81** MOX
- 10** control & shutdown
- 174** reflector (not shown)

For one GFR (U,Pu)C FA per year (365 FPEd)	GFR2400 F Core	ALLEGRO MOX 75 MW Frequency 1
Pu concentration [%]	17.3	30.5 X 1.8
Fast Φ max [n/cm ² /s], E > 0.1 MeV	12.4·10 ¹⁴	8.4·10 ¹⁴ -32%
Burn-up max	2 at%	1.8 at% -10%
Dose max dpa SiC per year	22	15 -32%
R = Dose/Burn-up. dpa SiC/at%	11	8.3 -25%

ALLEGRO CEA 2009: RPV Internals



- A) Driver core
 - Fuel: MOX in 15-15Ti steel
 - Reflector: 15-15Ti steel
 - Shielding: B₄C in stainless steel

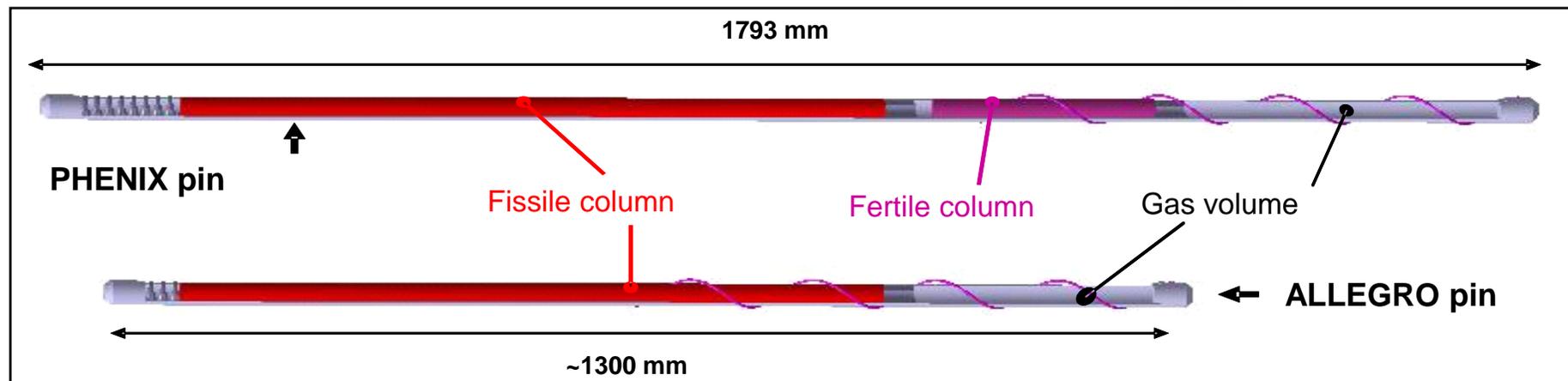
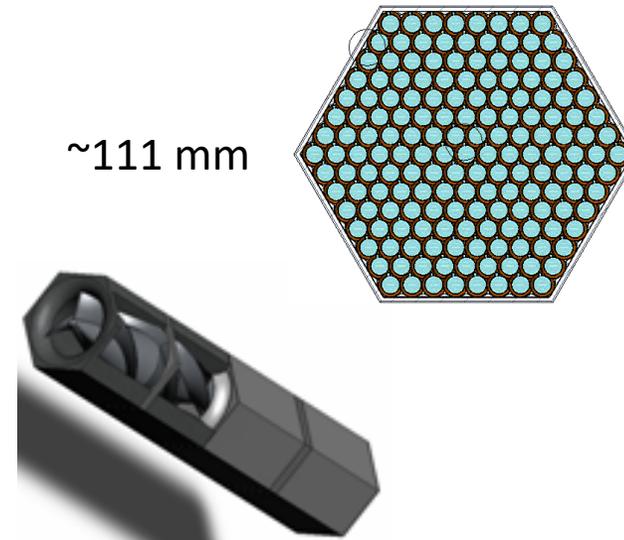
- B) Refractory core
 - Fuel: (U,Pu)C in SiC_f / SiC
 - Reflector: ZrC
 - Shielding: B₄C in stainless steel

- Common structures
 - Shielding blocks: Steel
 - Barrel: Steel

ALLEGRO CEA 2009: MOX Fuel Assembly

- 169 PHENIX-type wire-wrapped SS pins, ϕ 6.55 mm
- Solid MOX pellets ϕ 5.42 mm, ~25% Pu, 86 cm fuel stack
- Stainless steel based fuel assembly in hex. wrapper tube

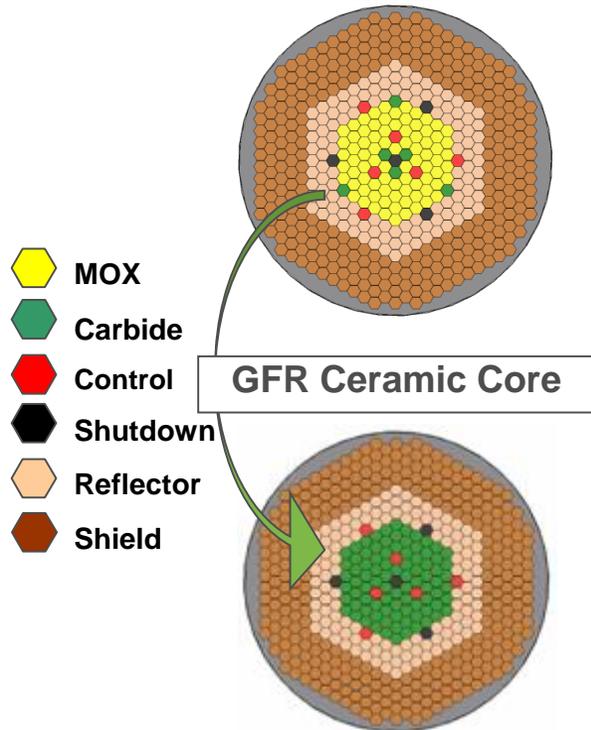
- Neutronic Shields/Reflectors
 - Helium serpentine to avoid neutrons leaks



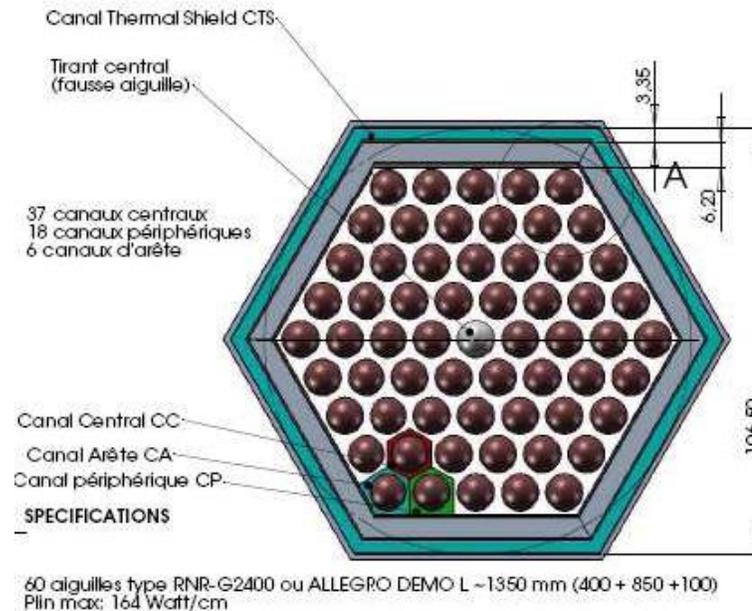
ALLEGRO CEA 2009: Exp. Carbide Fuel Assembly

- The MOX Core of ALLEGRO allows GFR fuel tests with a good scaling
- Switch to a full ceramic (refractory) core will be done with **the same core geometry**, using carbide **(U,Pu)C fuel in SiC_f-SiC tubes** validated in the MOX core

MOX Core + Exp. Fuel Assemblies

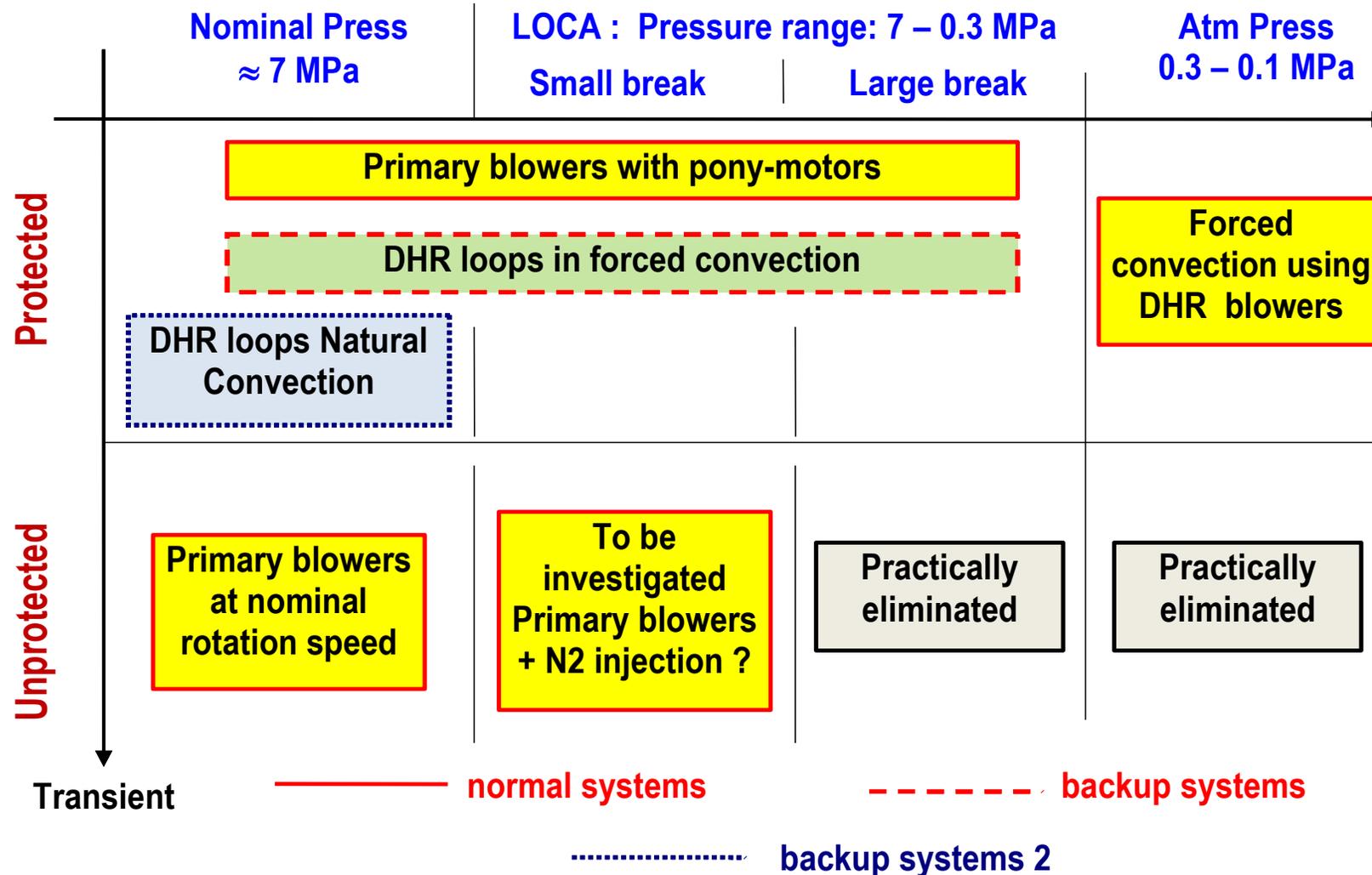


Exp. ceramic fuel assembly
(60 pins, insulated wrapper tube)

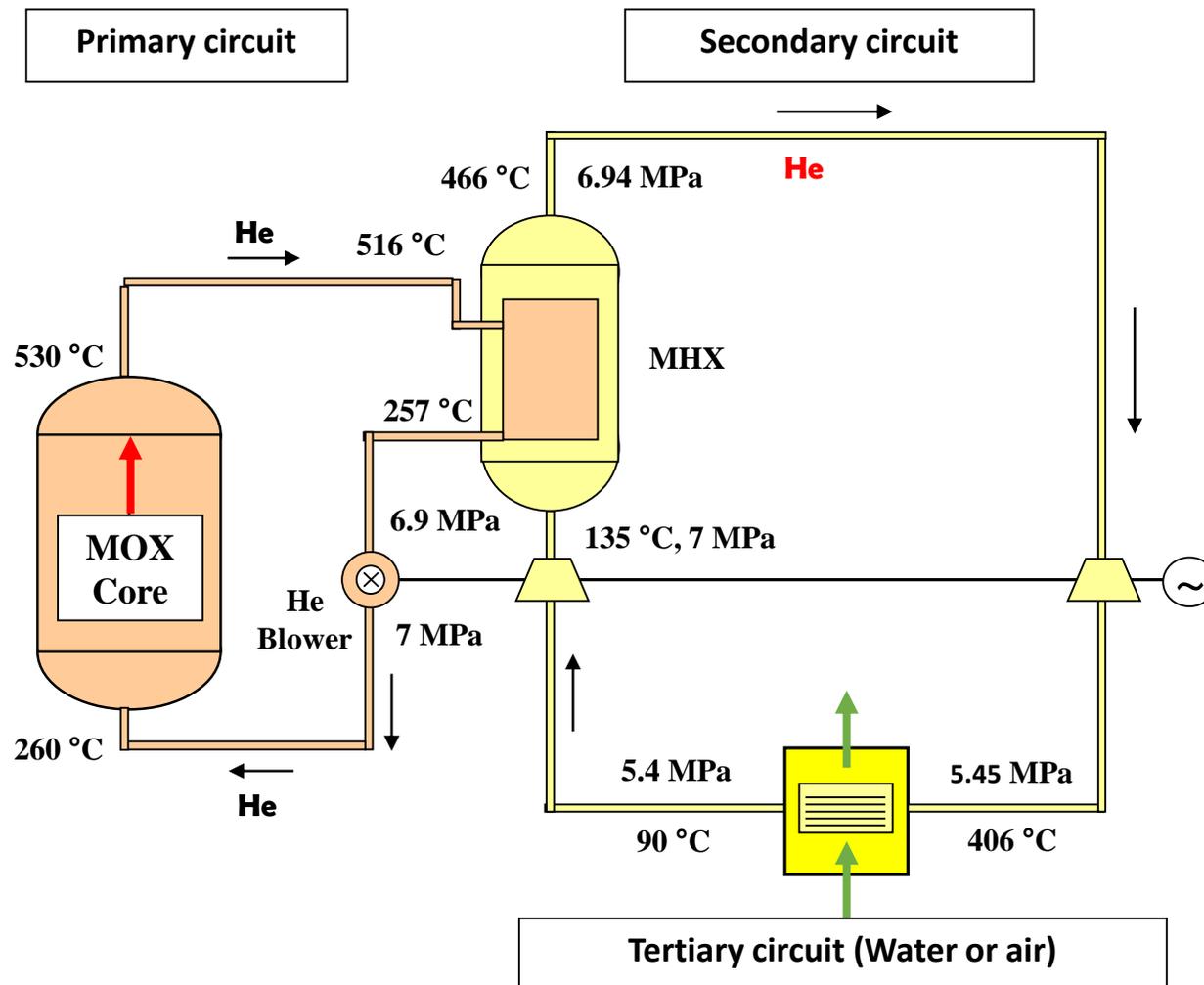


Note: 90 pins in FA without insulation

ALLEGRO CEA 2009 – Safety: DHR Strategy

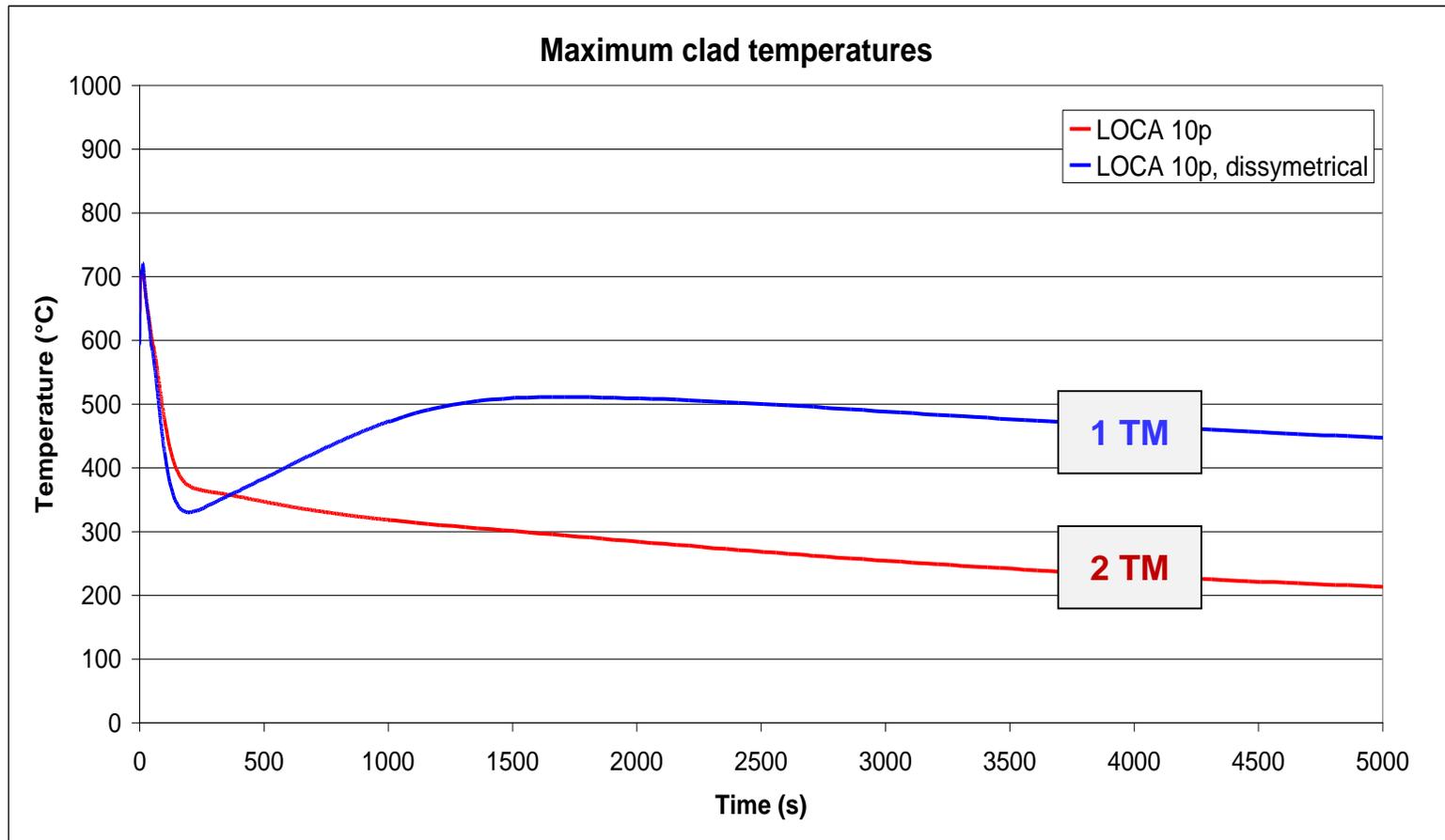


ALLEGRO CEA 2010: Innovative Option 1



- Complete redesign of the II. circuit:
Turbomachinery (TM) & He instead of water
- Decay heat removal in „passive“ way during up to ~50 000 s even in LOCAs

ALLEGRO CEA 2010: Innovative Option 2



- Example of peak cladding temperature during a **10" break LOCA**
- Even **one** TM running is **able** to remove the decay heat

ALLEGRO CEA 2010: Innovative Option 3

■ ADVANTAGES (MOX ALLEGRO 530 °C):

- 1) **Increase of inertia:** Core cooling (few hours) without any active system except the SCRAM actuation and the depressurisation of the secondary circuit (could be passive, and even without depressurization the “grace delay” would be significantly longer than few minutes).
- 2) **No more LOFA transients:** This initiating event is no more possible because the primary blowers are driven by the secondary circuits turbomachinery.
- 3) **Limitation of water ingress risk:** Because of gas in the II. circuit

■ DISADVANTAGES:

- 1) **Operation:** Complex management of the single shaft for start-up and shutdown
- 2) **Technology:** Very complicated to make it feasible (rotating seal in GV)
- 3) Once the TM stops in passive operation it cannot restart

CEA ALLEGRO 2009: Open Issues: Operational Conditions



- Risk of uncontrolled **water ingress** into primary circuit from DHR HX
 - Rupture of one U-tube in water-cooled DHR HX represents a significant risk
 - ... because **DHR loops cannot be isolated** from the RPV
- Risk of uncontrolled **water ingress** into primary circuit from main HX
 - Water in secondary circuit to be replaced with N₂-He mixture (GFR2400)
 - Nitrogen in II. circuit may limit the target T in ALLEGRO to values < 850 °C
- Valves in I. circuit
 - Disc check valves in DHR HX & main HX: Not tested experimentally
 - Isolation valves for coaxial piping (?)
- Other issues
 - Refueling machine, Heat shielding, Asymmetrical I. circuit (2 loops ...), Reactor control, ...
 - He-technologies (space requirements), ...

CEA ALLEGRO 2009: Open Issues: Accident Conditions

- **SS-based FA in driver core (from SFR):** Low safety margin to SS melting (1320 °C)
 - Potential remedy:
 - 1) Very performant & reliable safety systems (**not active, if possible**)
 - 2) Alternative metallic material instead of SS
 - 3) Reduction of power characteristics (≤ 75 MWt - lower decay heat)
- **Decay heat removal in passive mode**
 - Guard vessel resistant to elevated pressure (> 1 MPa)
 - Minimization of flow resistances along the DHR system (bypass of DHR blower, ...)
- **DHR HX resistant to high T**
 - CEA criterion: 1250 °C for >30 min.
 - Low flow resistance required

Keyword:
Core coolability

ALLEGRO V4G4: Background



- 2002-2010: CEA - Development of GFR2400 & **ALLEGRO 50-75 MWt**
- 2010-2025: CZ-HU-SK- PL- Preparatory phase of ALLEGRO:
 - 05/2010: MoU: Prepare documents (pre-conceptual design) for decision makers (ALLEGRO Yes/No)
 - 08/2013: „**V4G4 Centre of Excellence**“ - Association (legal entity) founded in SK

- **VUJE** Trnava (SK): Responsible for Design & Safety (with ÚJV)
- **ÚJV** Řež (CZ): Helium technology, R&D and Experimental support
- **MTAEK** Budapest (HU): Fuel & Core
- **NCBJ** Swierk (PL): Materials (?)

Industry

Research

- Associated members: CEA (FR) 2017, CV Rez (CZ) 2018

■ ALLEGRO Preparatory phase by **V4G4 CoE**:

- Pre-conceptual Design: Revision of ALLEGRO CEA 2009 → **New ALLEGRO V4G4 concept (2020-25)**
- Safety: Core coolability (**passive mode**)
- R&D and Exp. support: Under formulation (**helium technologies underway**)

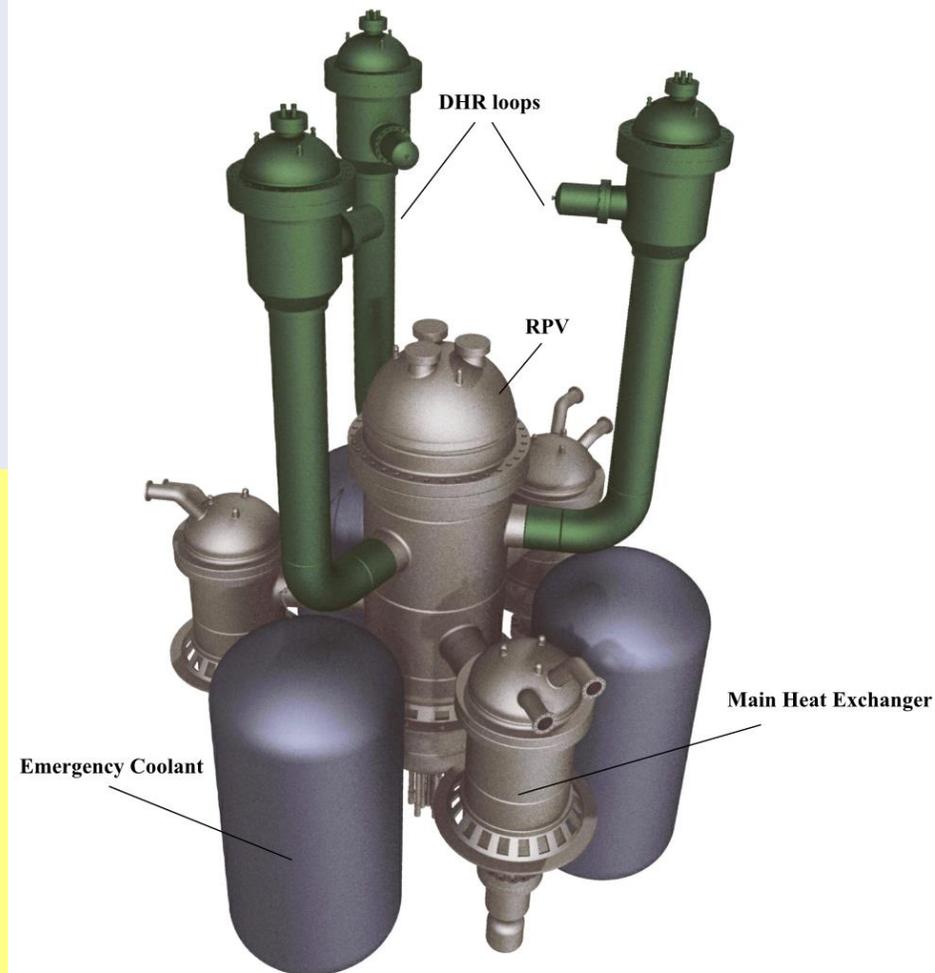
ALLEGRO V4G4: Restart of Development in 2013-2015

■ ALLEGRO CEA 2009: Status

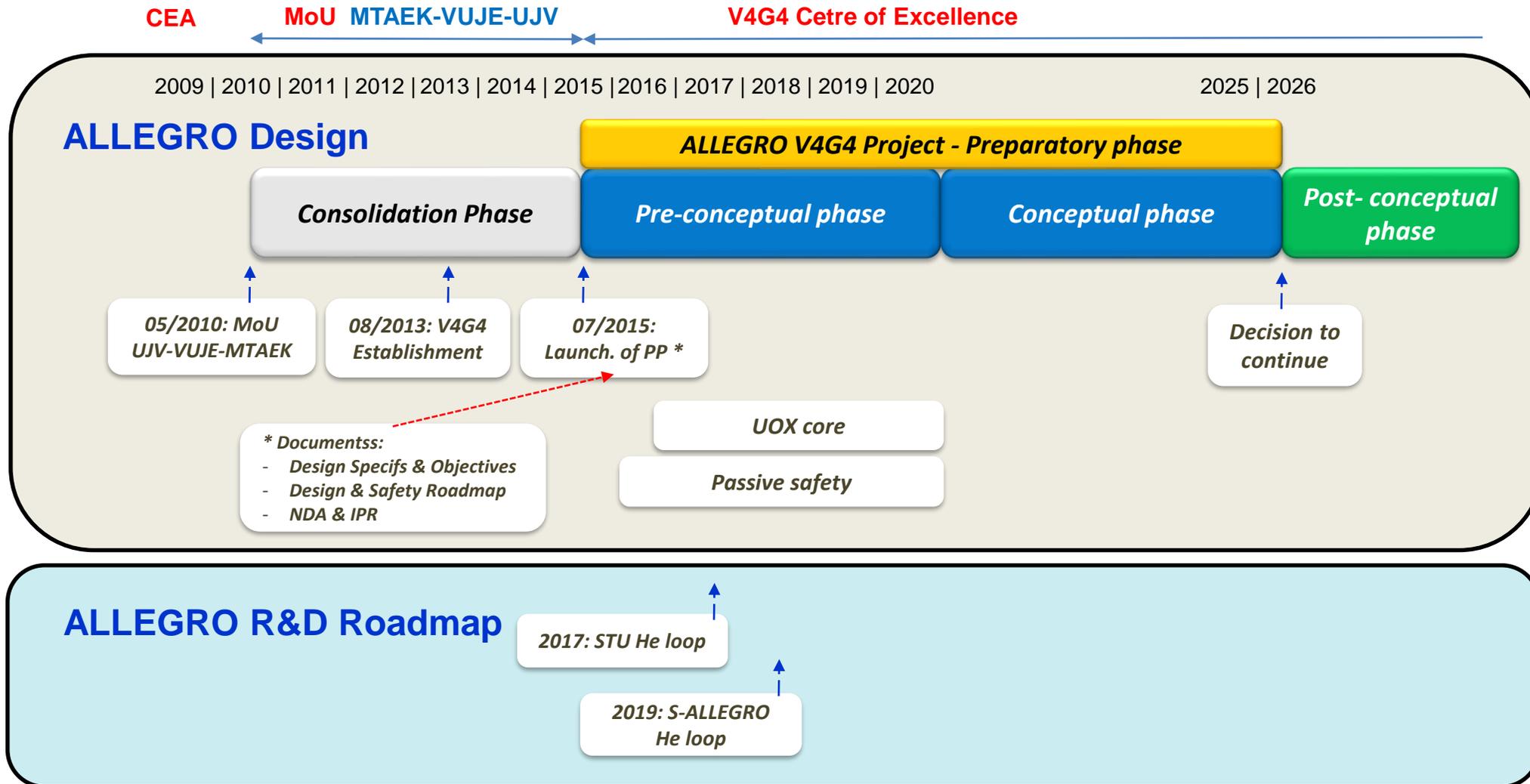
- **Design:** Mainly fuel & I. circuit (Neutronics & fuel in detail)
- **Fuel:** MOX (small compact core)
- **Safety:** Core coolability by using **active** systems mainly
- Auxiliary systems addressed marginally

■ ALLEGRO V4G4 Goal: Make it feasible & safe

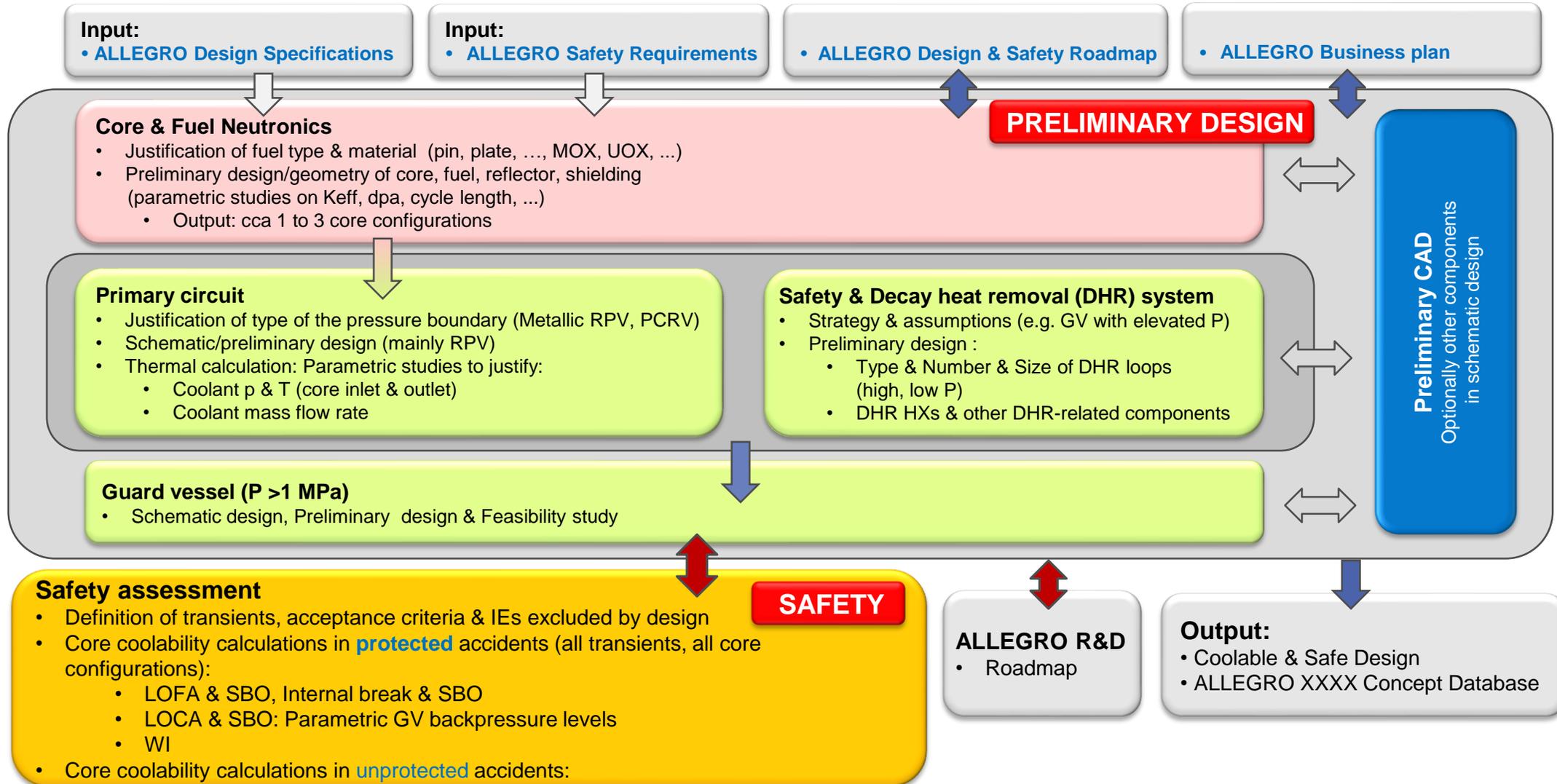
- **Design:** To be closer to GFR 2400
 - **Gas** in the II. circuit (possibly including turbomachinery)
- **Safety:** Core to be coolable using (semi)**passive** systems
- **Fuel:** **UOX** fuel (<20% U235) instead of MOX (**feasible ?**)
 - Option to be viable for Central Europe
- Technology also in focus (He-related technology, ...)



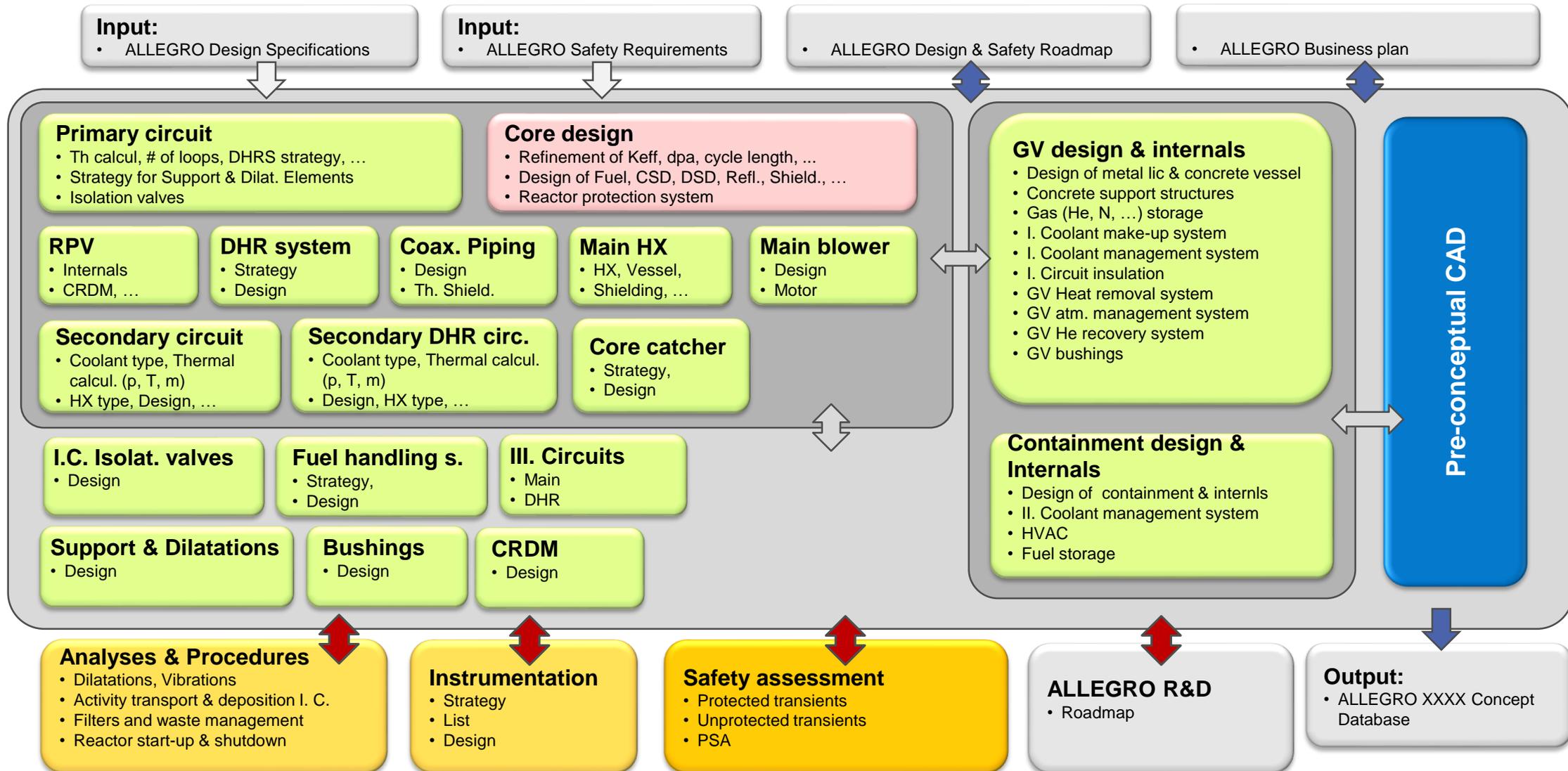
ALLEGRO Time Schedule: Overview



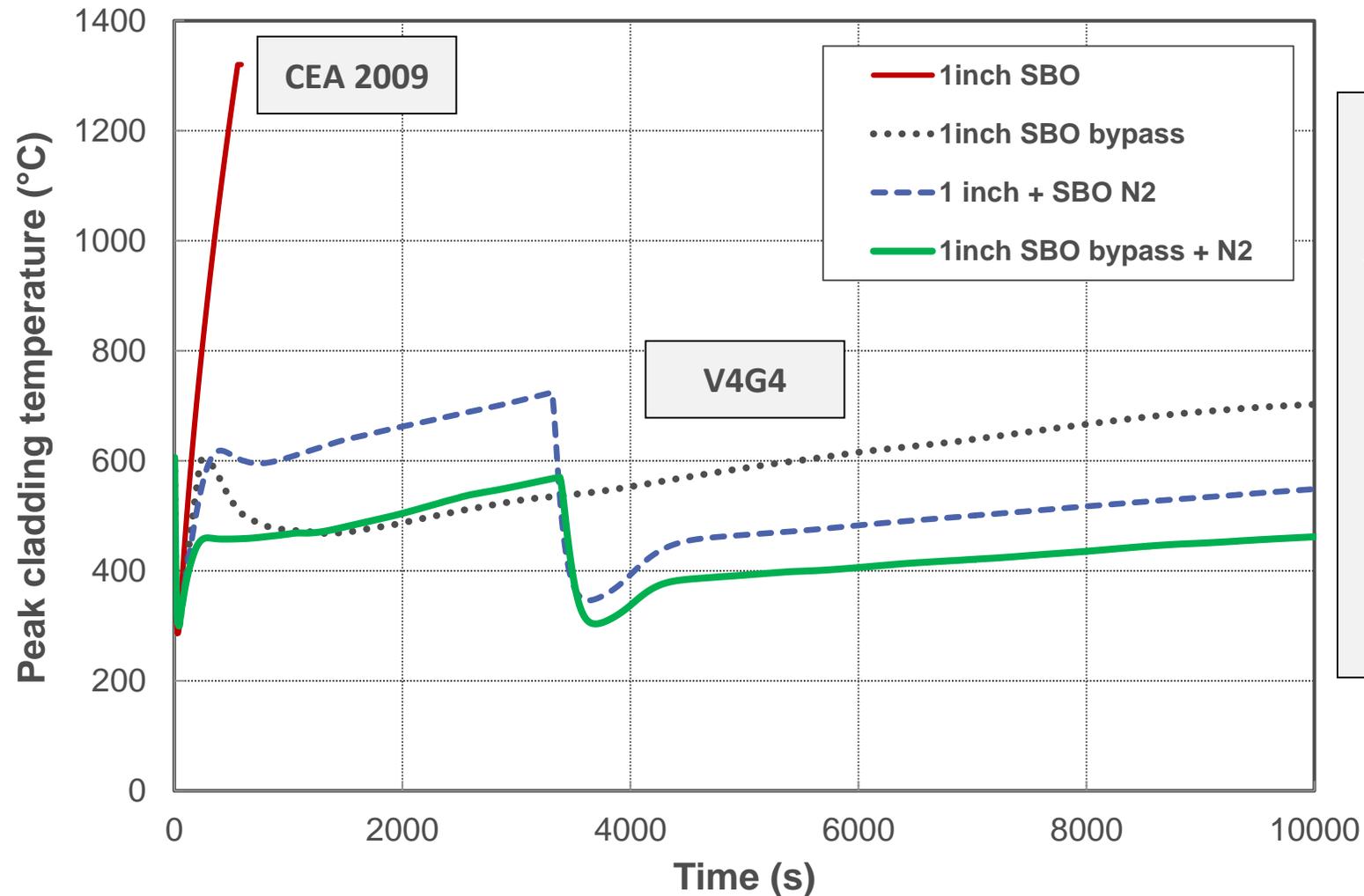
ALLEGRO V4G4: Pre-conceptual Design Process 1



ALLEGRO V4G4: Pre-conceptual Design Process 2



Recent V4G4 Developments: MOX Core 75 MWt (1)

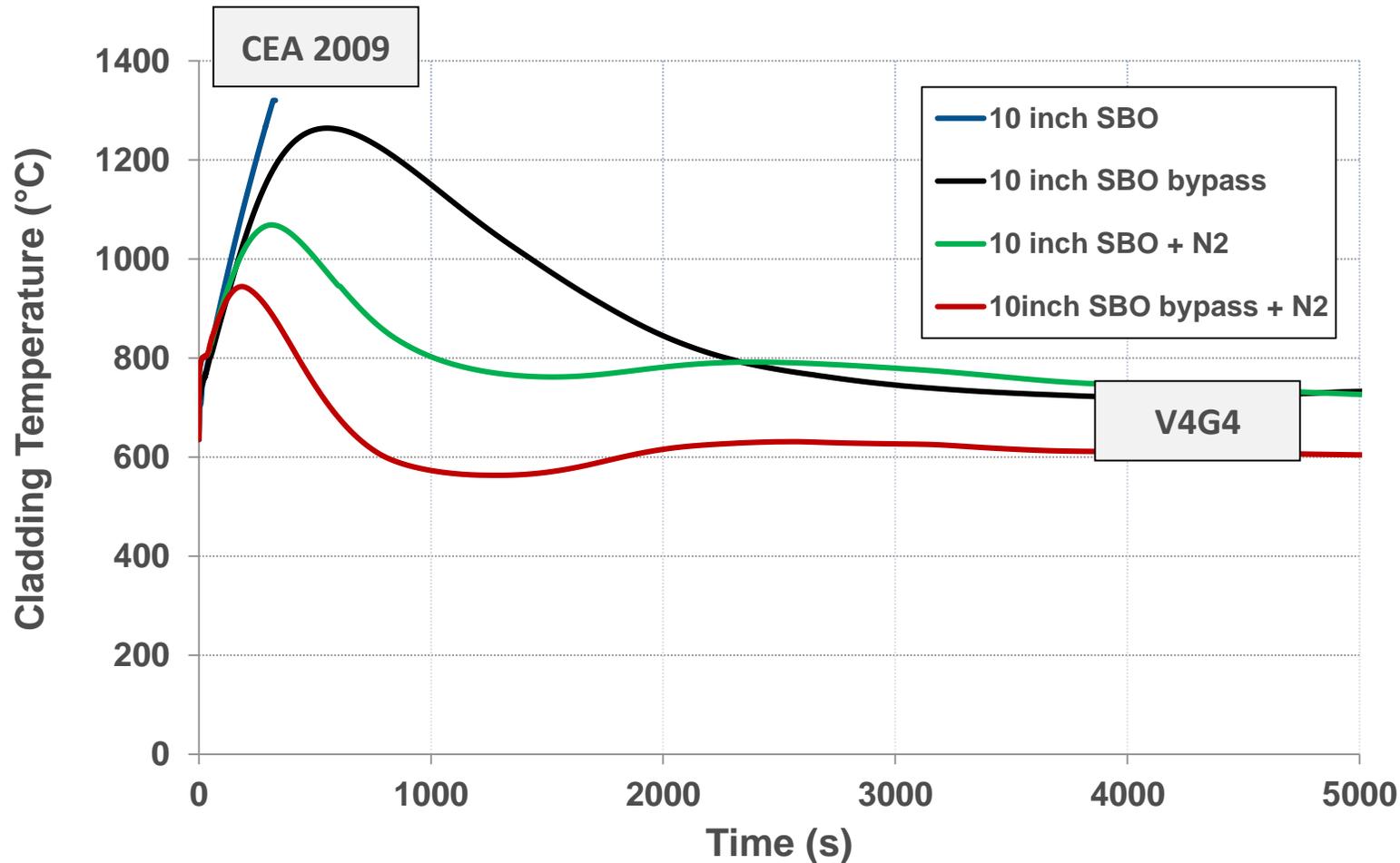


Protected SB-LOCA (1") aggravated with SBO (passive mode)

Better core coolability thanks to design improvements:

- DHR blower bypass
- GV pressurization using N2 (>10 bar)

Recent V4G4 Developments: MOX Core 75 MWt (2)



Protected LB-LOCA (10") aggravated with SBO (passive mode)

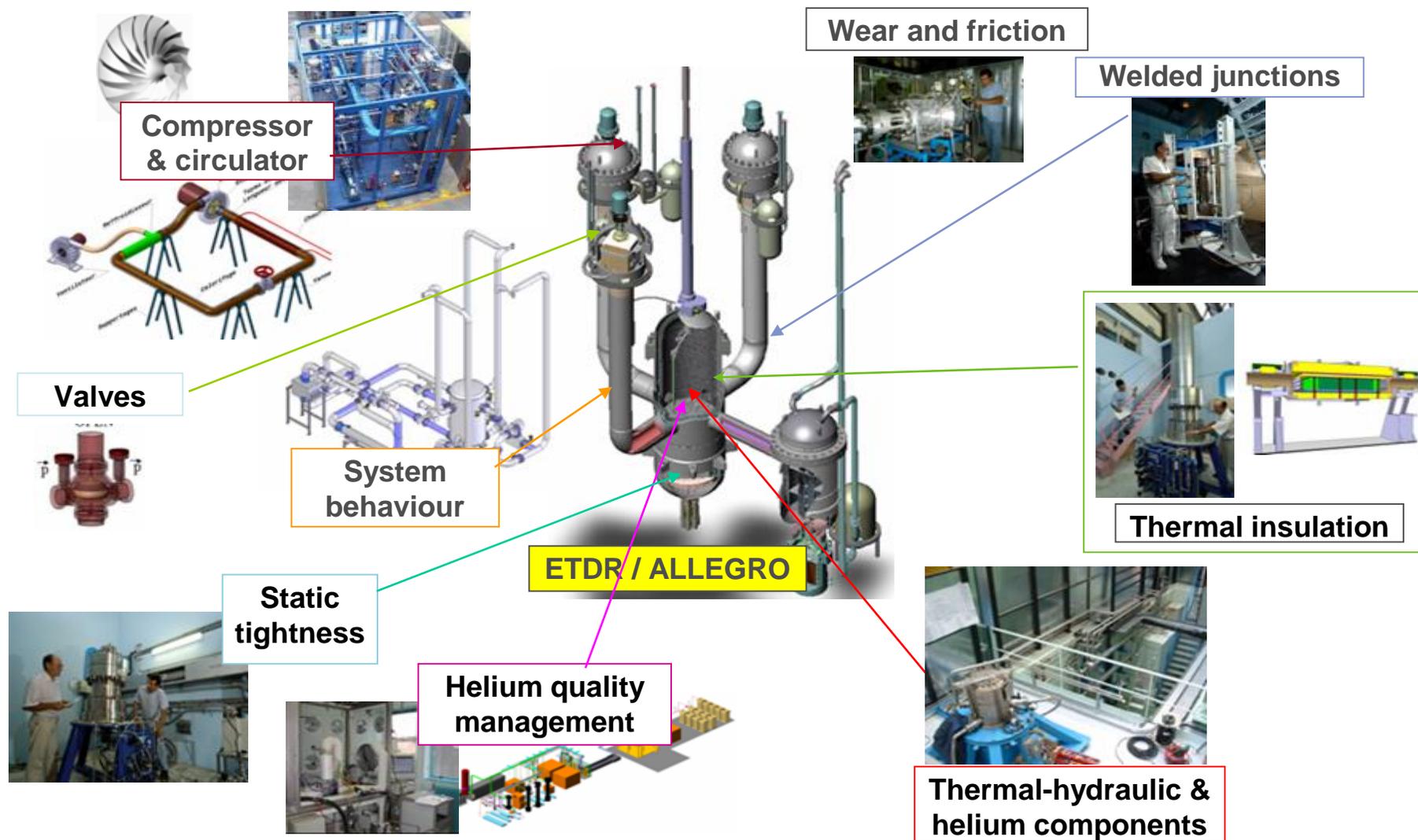
Better core coolability thanks to design improvements:

- DHR blower bypass
- GV pressurization using N2 (>10 bar)

R&D Needs in Support to ALLEGRO

- **Safety of oxide cores (MOX or UO₂)**
 - System thermohydraulics (core coolability), GV (& core catcher) issues
- Helium technology
 - He quality management, recovery, tightness, components (valves, HXx)
 - Subassembly TH, Insulation, fuel handling, instrumentation, ...
- Computer codes:
 - **Benchmark** activities: ERANOS, MCNP, SERPENT, KIKO, HELIOS, SCALE, CATHARE2, RELAP5, MELCOR 2.1
- Materials qualification
 - Composite Matrix Ceramic clad, Metallic clad for oxide core
 - Control rods & elements, S/A structural materials
 - **Thermal barriers**, Other structures (**core catcher**, structural materials)
- Fuel qualification
 - Oxide fuel, Carbide fuel

R & D for ALLEGRO at CEA (2002-2009)



R & D for ALLEGRO: Main Priorities After 2015 (1)

- **Exp. validation of the DHR approach**

- Natural circulation He loop STU, Trnava (SK) – Commissioned in 2016
- He-loop S-ALLEGRO (I. phase), CV Rez (CZ) – Commissioned 2017, in use ~2019

- **Guard vessel resistant to elevated pressure (> 1 MPa)**

- Key structure to promote natural circulation in accident conditions
- Feasibility of such a large structure (metal, concrete)

- **Heat transfer from wire-wrapped rods bundle into prototypic He (7 MPa, up to 850 °C)**

- Validation: System & CFD codes.
- Facilities: - ESTHEL stand (proposed at CEA) has not been built
- ESTHAIR stand using air & low T only (CEA Grenoble)
- Exp. data: - Best-estimate Nu number & friction factor correlations for bundles
- Assessment of temp. non-uniformities (hot spots)
- Design: Feasibility of cladding surface roughening for wire-wrapped claddings

R & D for ALLEGRO: Main Priorities After 2015 (2)

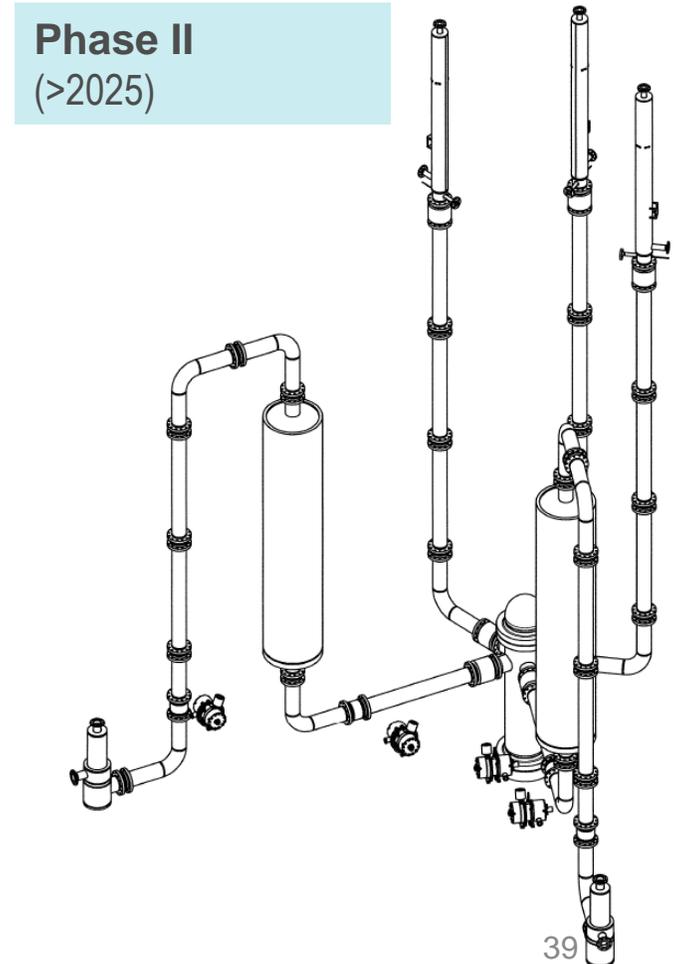
- **Feasibility of safe N₂ injection into RPV**
 - Risk to heavily undercool RPV internals due to N₂ expansion (risk of embrittlement)
- **Feasibility of turbomachinery in II. circuit connected electrically with primary blower**
 - Modification of the CEA Innovative option (shaft replaced with el. motor & el. wires)
- **Core catcher (pre-conceptual design)**
 - Size, shape, materials, cooling, ...
- **DHR heat exchanger**
 - Resistant to high T (1250 °C for 30 min.) & to water boiling at II. side
 - Low flow resistance required
- **Valves for I. circuit**
 - Disc check valves (DHR HX vessel), Main isolation disc valves (Main HX vessel)
 - Possibly isolation valve for coaxial piping (?)

R & D platforms in V4G4 CoE

- **Helium loops: Thermohydraulic phenomena**
Natural circulation studies, code validation, core coolability, ...)
 - **STU He loop** (STU Trnava, SK)
 - **S-ALLEGRO** (CV Rez, Pilsen, CZ)
- **Helium loops: Material research in controlled atmosphere**
 - **HTHL1** (CV Rez, CZ): Out-of-pile
 - **HTHL2** (CV Rez, CZ – SUSEN): In-pile (LVR-15)
- **Helium purification** (Univ. Chemistry & Technology, Praha, CV Rez, CZ)
 - **Individual stands: Mastering of the GFR& VHTR related technology**
- **Helium recovery from N₂+He mixture (CV Rez, CZ)**
 - **Membrane stand: Testing of He separation using membranes technology**
 - **REGNET** (small-scale demonstration facility): **In construction (2020)**
- **Corium interactions (CV Rez, CZ)**
 - **Cold crucible** (CV Rez, CZ – SUSEN): Core catcher related material issues

R & D for ALLEGRO on DHR System: He Loop S-ALLEGRO (CZ)

- **Goal: To study DHR-related phenomena**
(Under commissioning, CV Rez, Plzen, CZ)
- **Mock-up of ALLEGRO:**
1 MWeL., 7 MPa, 260/530 °C, 400/850 °C
- **Configuration:**
 - Primary loop (He/He main HX): 1x / 2x
 - DHR loop (He/water DHR HX): 1x / 3xNote: (Phase 1 / Phase 2)



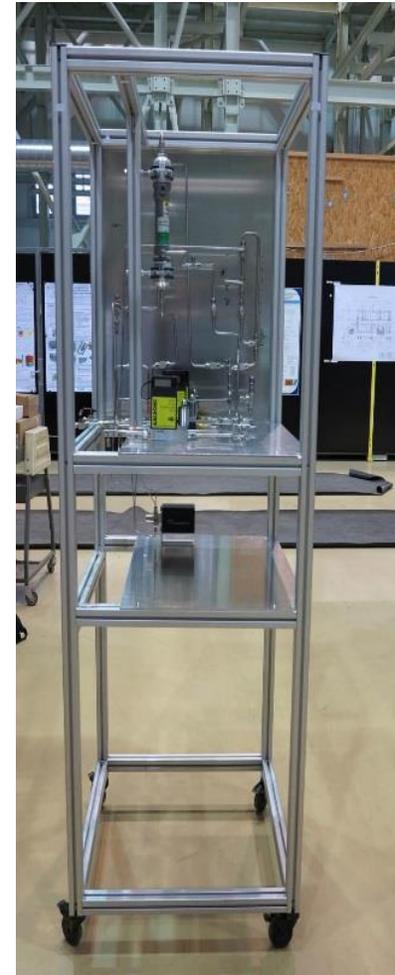
R & D for ALLEGRO on DHR System: STU He Loop Trnava (SK)

- Goal: To study **decay heat** removal phenomenology in **natural circulation**.
- Design: One loop (heating zone & HX)
- Commissioned in 2016
- Owned by Slovak Technology University (STU) Bratislava, located in Trnava (SK)
- Parameters:
 - I. circuit: He 3-7 MPa, 220 kW, ~200 - 520 °C
 - II. circuit: water
 - Vertical distance Core to DHR HX: 10 m



R & D for ALLEGRO: Helium Recovery From GV Atmosphere

- Goal:
To test **membrane** separation of He from N_2+He mixture
- First tests with Polymer PRISM® membrane (for max. 40 °C) in a dedicated stand.
 - Sufficient selectivity for He has been confirmed.
- To be tested: Ceramic membranes
- Underway: Development of a demonstration small-scale facility for testing and verification of **He recovery from GFR guard vessel atmosphere** (N_2+He) using a membrane separation.



R & D for ALLEGRO: Cold Crucible for Severe Accident Research (CV Rez, CZ)

- Project planned for ALLEGRO-related **core catcher** research
- To test UO₂/SS corium interaction with **innovative sacrificial material**

Parameters

Power supply

Transistor generator: Output power 300 kW
Frequency 100 – 800 kHz

Tube generator: Output power 160 kW
Frequency 1.5 – 2.0 MHz

Crucible

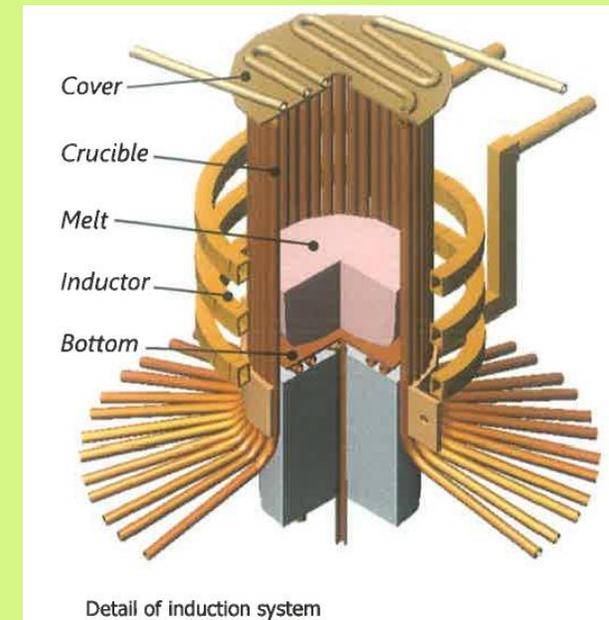
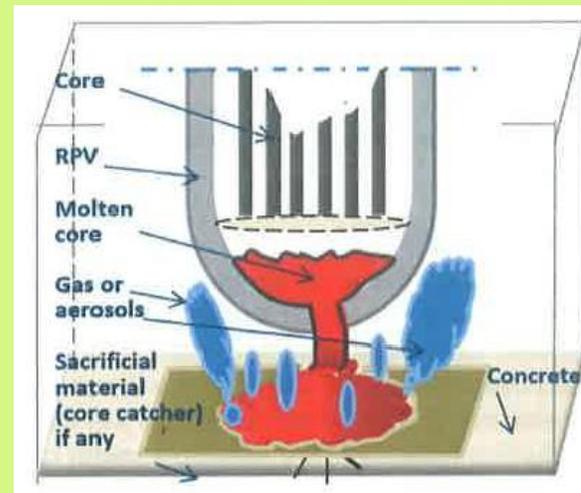
Volume of the melt up to 20 dm³
Up to 50 kg melt with temperature 3000 °C

Pulling system

Pulling rate: 0.1–1.5 mm/min

Vacuum chamber

Melting in any atmosphere
Melting of radioactive materials



Perspectives of ALLEGRO & Conclusions (1)



- ALLEGRO (compared to LMFBR): In the phase of proving feasibility & passive safety
- ALLEGRO CEA 2009: Good **technical** base for further development by V4G4 CoE
 - Under substantial safety improvement while respecting ...
 - 1) Technical feasibility and 2) Target mission of the demonstrator.
- V4G4 CoE (2013) is a good legal base for restarting the development work
- Short-term priorities in the development:
 - Achieve reasonable level of safety using **passive** systems (where possible)
 - Design **UOX**-based driver core

... while maintaining interesting power density & irradiation characteristics (SiC dpa)

Perspectives of ALLEGRO & Conclusions (2)

- Short-term priorities in the R&D (driven by the design requirements)
 - Coolability in protected transients using natural convection
 - Feasibility of Guard vessel **for elevated pressure**
 - Optimization of DHR system (valves, HX, pressure drop, ...)
 - Turbomachinery in II. circuit
 - Potentially alternative cladding material for the driver core

- Simulation tools need additional validation
 - Neutronic & thermohydraulic codes
 - Fuel performance codes



Upcoming Webinars

- | | | |
|---------------|--|--|
| 15 April 2019 | European Sodium Fast Reactor: An Introduction | Dr. Konstantin Mikityuk, PSI, Switzerland |
| 22 May 2019 | Formulation of Alternative Cement Matrix for Solidification/stabilization of Nuclear Waste | Mr. Matthieu De Campos, University Lille 1, France |
| 19 June 2019 | Interaction JOG/Sodium in Case of a Clad Breach in a Sodium Fast Reactor | Mr. Guilhem Kauric, CEA, France |