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R&D in support to the ALLEGRO project

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Outline

- Existing ALLEGRO concepts
- Main characteristics of ALLEGRO safety
- Topic 1: Core and Fuel
- Topic 2: Design and Thermalhydraulics
- Topic 3: Materials and Coolant technology
- Topic 4: Energy Conversion Systems
- Topic 5: Safety and Instrumentation
- Summary

Existing ALLEGRO concepts

- **ETDR 50 MWt (2008)**
  - **I. He, II. Water, III. Air**
  - FP6 GCFR STREP
- **ALLEGRO CEA 75 MWt (2009)**
  - **I. He, II. Water, III. Air**
  - C. Poette: ALLEGRO Preliminary viability report.
- **ALLEGRO CEA 75 MWt (2010)**
  - **I. He, II. He, III. Air**
  - N. Tauveron: Innovative option (turbomachinery).patented by CEA
- **ALLEGRO V4G4 xx MWt (20xx)**
  - **I. He, II. Gas, III. ?**
  - Under development within V4G4
  - Based on ALLEGRO CEA 2009 but being under deep revision (power, …)

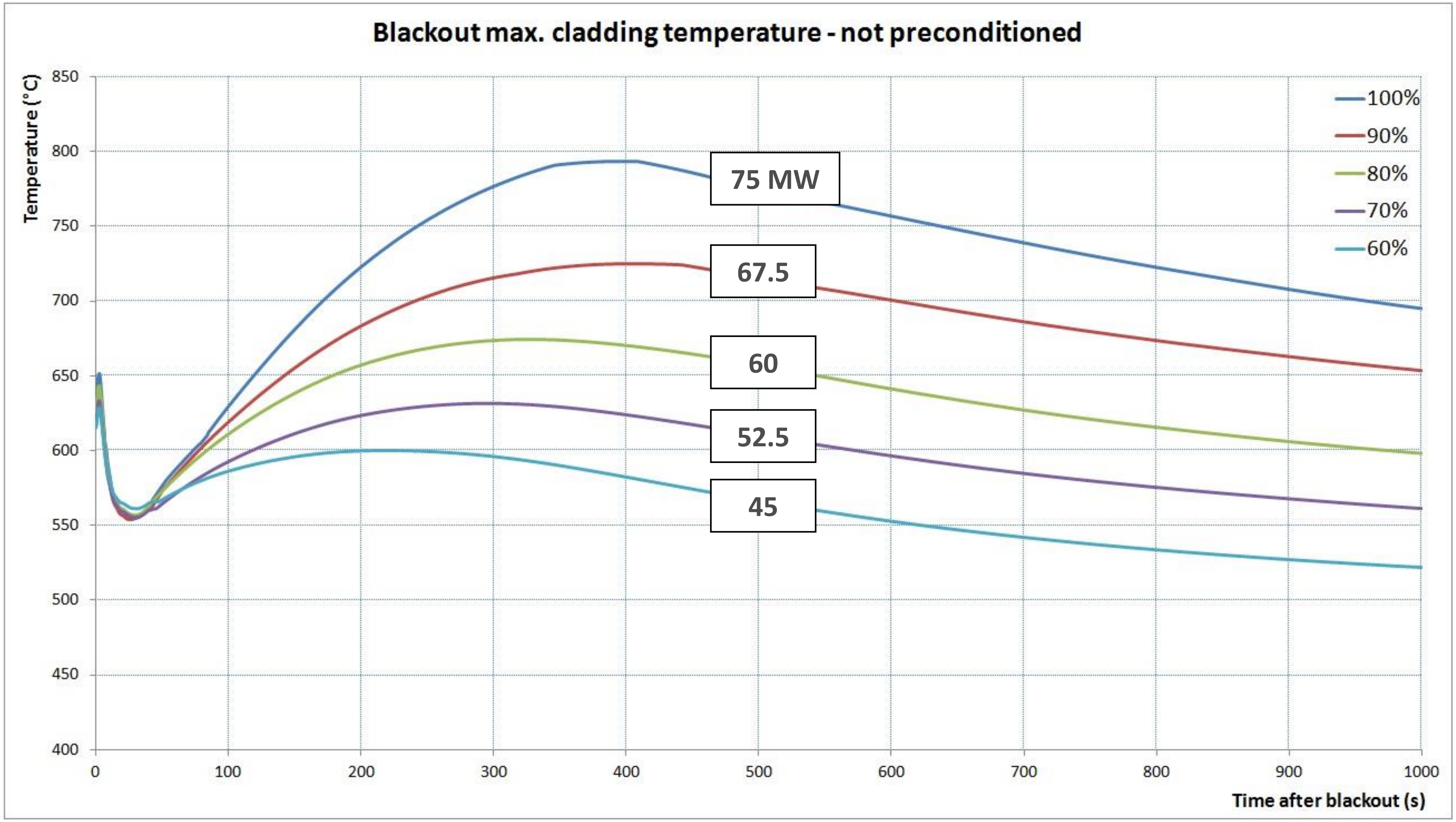
Safety issues in ALLEGRO

- **ALLEGRO is coolable, when active systems are available**
- **Pressurized transients (LOFA, blackout): Natural convection might be OK**
- **Depressurized transients (LOCA): Natural convection is not sufficient**
  (Except the promising Innovative option by CEA from 2010)
- **Fuel assembly blockage or ATWS may lead to rapid fuel/core overheating**
- **Massive water ingress into I. circuit: Loss of subcriticality and/or investment**

- **Feasibility studies to be performed on design:**
  - **Reduced power (power density) in current geometry** (by 10-40 %) **- underway**
  - **Innovative solution by CEA (turbomachinery) using suitable gas in II. circuit** (He, N_2, Ar, … ?)

Coolability of ALLEGRO with reduced power (density)

- Station blackout by MELCOR



Remark

- The R&D topics will be influenced by:
  - Design Requirements & Objectives (Basis of Design), e.g.:
    - **Is the full refractory core the target for ALLEGRO ?**
    - **What is the target core outlet temperature ? 850 ºC ?**
    - **What is the required degree of similarity with the large GFR(2400) ?**
    - **…**
  - Safety Requirements & Objectives, e.g.:
    - **Is a robust decay heat removal (DHR) system without external power input, even in depressurized conditions, a requirement also for ALLEGRO ?**
    - **…**
- R&D can restart only after having fixed reasonable design options

Topic 1: Core and Fuel

- **First ALLEGRO core: Based on fuel from the sodium program**
  - **MOX** (or UOX) **pellets in wire-wrapped SS claddings in tight hex lattice**
    - Some experience is transmissible from the sodium program (fuel)
    - Limits of the SS claddings may be reached easier in gas than in sodium
    - No experience available with such fuel bundles in prototypic helium, where unexpected phenomena may occur.
  - **Is there an alternative to the MOX / wire-wrapped SS type fuel ?**

- **Refractory core: Target for ALLEGRO & large GFR**
  - **Development at CEA is interrupted for this moment**
    - First the viability of ALLEGRO must be demonstrated
  - **Design / technology / material limitations to be overcome**
    - Out of scope of this document

Main priorities for GFR Topic 1 (Fuel & Core)

- **1- Heat transfer & friction coefficient from wire-wrapped MOX (UOX) SS rods into helium**
  - **To check the ability of this type of fuel design to effectively transfer heat into GFR-prototypic He (p, T, v).**
    - Validation of system & CFD codes.
    - Best-estimate Nu number & friction factor correlations for bundles.
    - Temperature non-uniformities (hot spots) in nominal & accident conditions.
    - Feasibility of cladding surface roughening for wire-wrapped claddings.
    - Wear & erosion of rib profiles during operation ?
    - Natural convection cooling capability as function of system pressure.
  - **Test train for bundle tests in He to be built**
    - ESTHEL was not built at CEA
    - ESTHAIR in CEA Grenoble for air only
    - Test data for nominal plant & accident conditions.

Main priorities for GFR Topic 1 (Fuel & Core) continued

- **2- Effects of He flow-induced vibrations (rod / assembly / core)**
  - **High gas velocities may cause unexpected effects**
  - **Potential local wear (wire/rod) to be estimated experimentally**
- **3- SS cladding acceptance criteria for safety analyses** (LOCA, RIA …)
  - **Mechanical: Creep-down / ballooning / burst phenomena, …**
  - **Chemical: Oxidation / nitridation (embrittlement) at high T, …**
- **4- Fuel rod design criteria (nominal conditions)**
  - **SS cladding** (behavior under pressure difference)
    - Mechanical: Creep-down, PCMI, bowing, …
    - Chemical: Corrosion & He-induced embrittlement
  - **Fuel pellets** (know-how applicable from the sodium program ?)
    - Irradiation effects (fragmentation, swelling, densification, FG release, …)
    - Treatment of minor actinides: Cross-cutting issue with SFR
  - **Validation of fuel codes against fuel rod out-of pile / in-pile data is needed**

Topic 2: Design and Thermalhydraulics

- **Coolant in the secondary circuit**
  - **Water: Danger of water ingression into I. circuit**
  - **Gas: Potential use of turbomachinery** (request for patent by CEA in 2010) **to prolong the rundown time of the primary blowers**
- **Performance of the DHR system in operational conditions**
  - **Water-cooled HXs 12-15m above the core to remove decay heat**
  - **Disc check valves in the HX vessel (closed)**
  - **Temperature & He flow field in the DHR loops**
- **Layout of the primary circuit of ALLEGRO**
  - **Symmetry / Non-symmetry versus number of loops (2 or 3)**
- **Guard vessel shape**
  - **Cylinder, sphere**

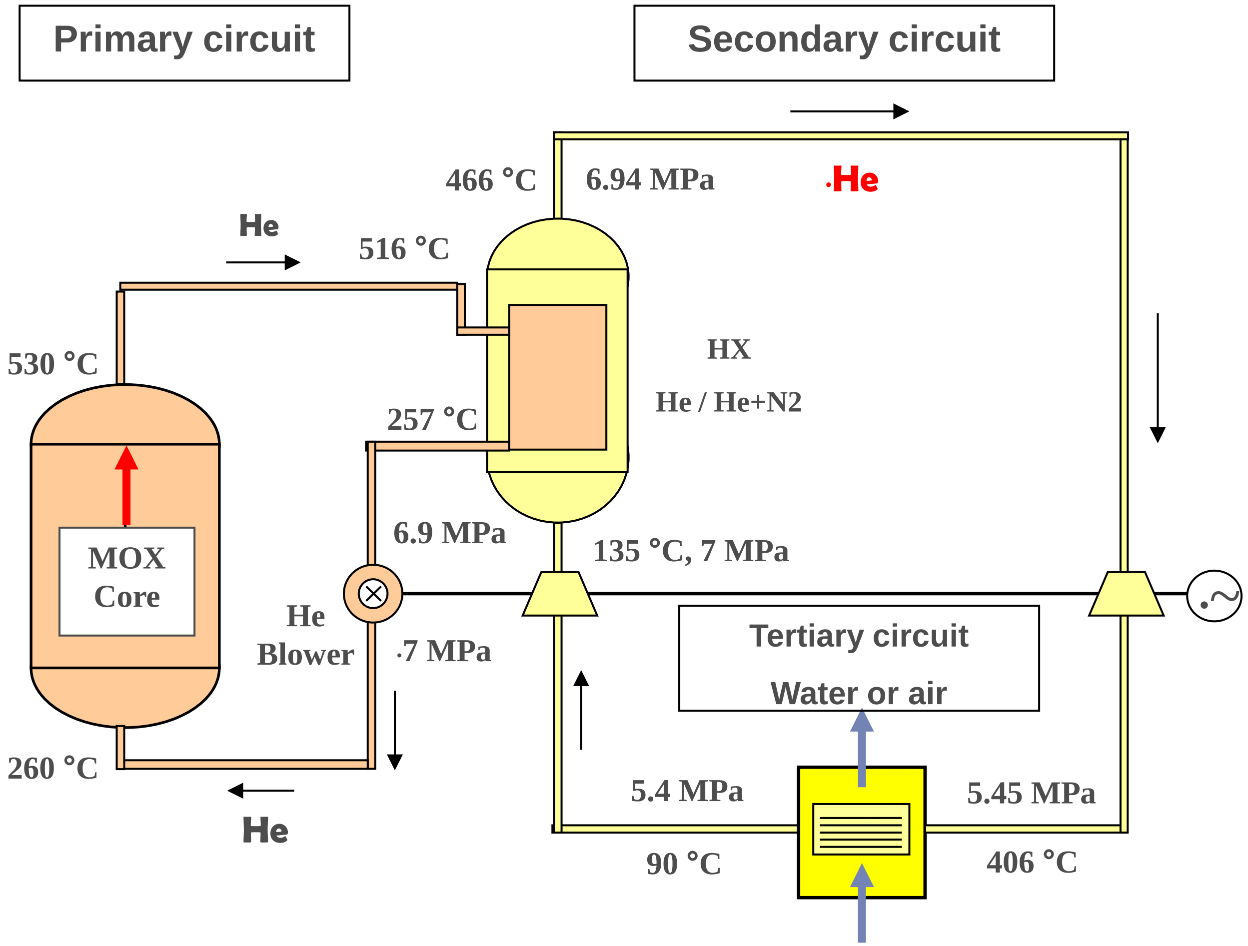
Main priorities for GFR Topic 2 (Design & TH)

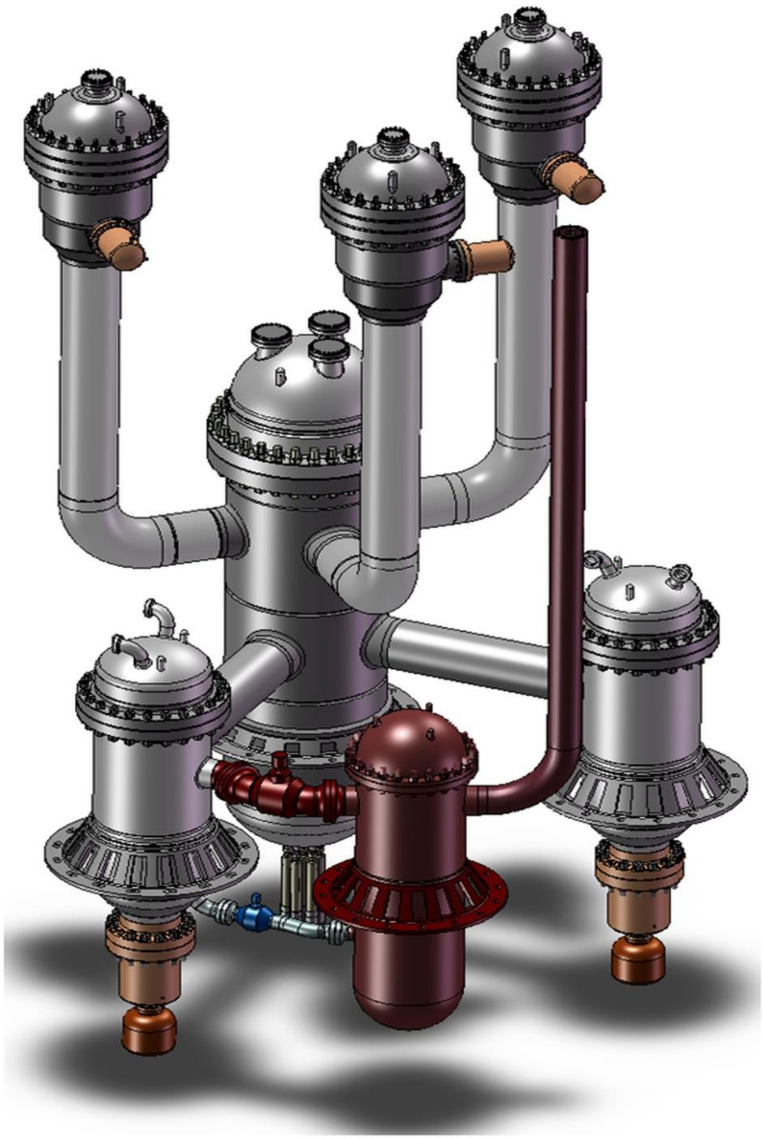
- **1- Suitable gas for the secondary circuit**
  - **Choice between He, N_2, He-N_2, Ar, …**
    - **He**: Difficult to limit the leakage rate. Question of **costs**.
    - **N_2**: Feasible for low temperatures. Experiments to get **temperature limit**.
    - **Ar**: Inert gas but low heat capacity. Feasibility of the **high** pumping power.

- **2- Turbomachinery in the secondary circuit**
  - **Very sensitive machinery (… must be safety qualified !)**
  - **Efficiency & feasibility depends on the type of the secondary gas**
  - **Feasibility of the mechanical / electrical connection with the primary blower**
    - Mechanical: - Very difficult direct connection turbomachinery / prim. blower
      - Unknown characteristics outside the nominal point
    - Electrical: - El. generator provides current for the prim/second blowers
      - Unknown characteristics outside the nominal point

ALLEGRO CEA (2010) Innovative option

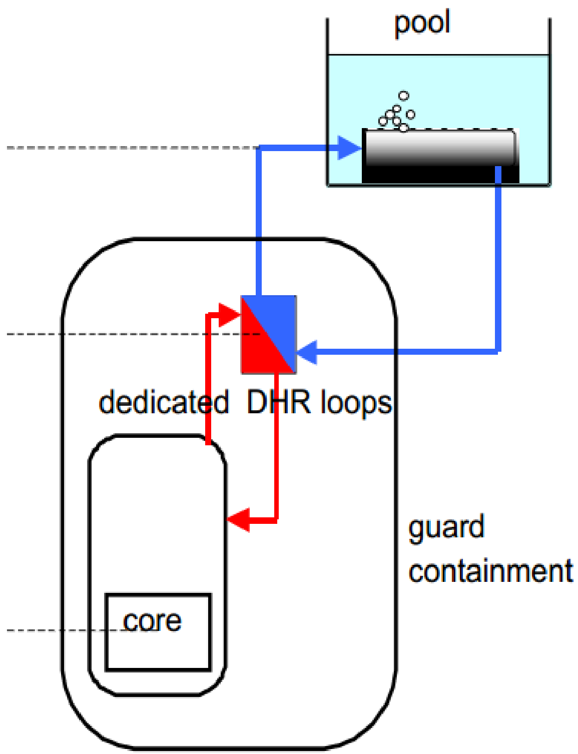
ALLEGRO CEA (2009)





Main priorities for GFR Topic 2 (Design & TH) continued

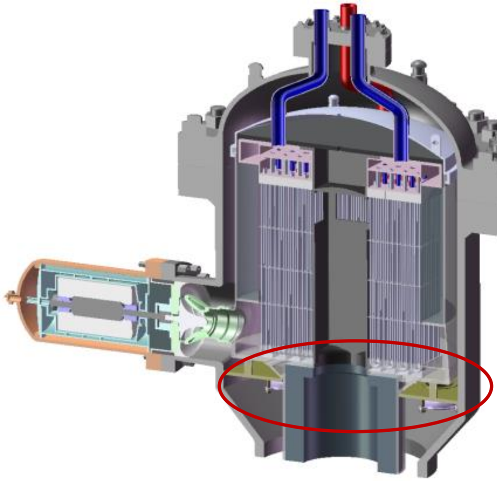
- **3- Phenomena associated with DHR HX tube failure**
  - **At full system pressure**
    - 1. He ingress into the intermediate water circuit: Loss of heat removal ability ?
    - 2. **Potential** water ingress into the primary circuit.
  - **At low system pressure**
    - Water ingress into primary circuit.
  - **Code validation needed.**
- **4- Isolation of the DHR loop from the RPV**
  - **DHR loop isolation is needed, when:**
    - DHR HX tube fails
    - DHR loop exhibits a gas leakage into guard vessel
  - **Isolation valve needs to be:**
    - Designed
    - Tested

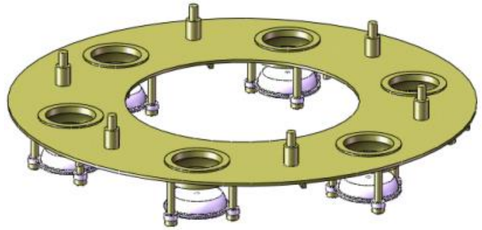


Main priorities for GFR Topic 2 (Design & TH) continued

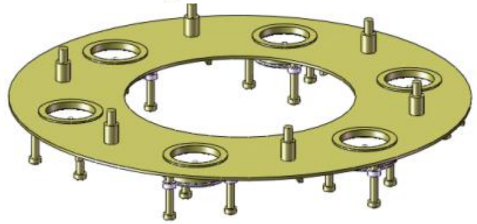
- **5- Conditioning of the DHR loops**
  - **Conditioning = permanent presence of ΔT between hot and cold DHR leg**
    - Promotes the natural convection, when the DHR loop is open
    - DHR loops in ALLEGRO CEA 2009 are not conditioned
  - **The conditioning of DHR loop must be:**
    - Designed
    - Tested.
- **6- DHR passive disc check valves**
  - **The Δp on the disc valve is approx. equal to the Δp along the whole core**
    - Δp < 1 bar (sufficient to keep the valve closed)
  - **Question: Is such Δp able to close the valve (to lift the disc) ?**
    - Aerodynamic analysis of the closing process is needed
    - If necessary, experimental mockup of a DHR disc check valve is needed

DHR check valves & Main isolation valves





OPEN
When main blowers are OFF



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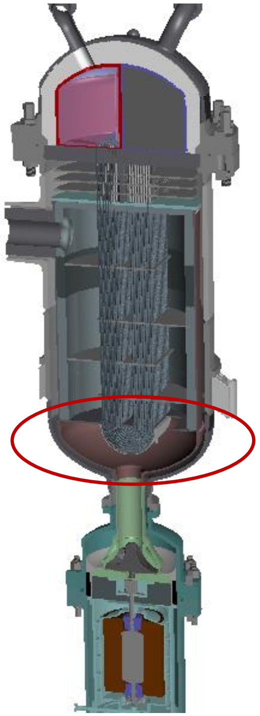
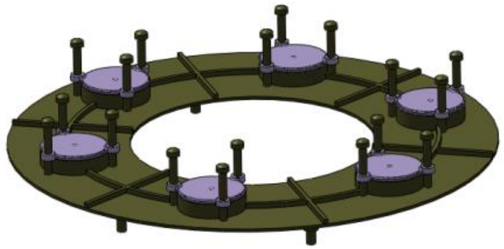
When main blowers are ON





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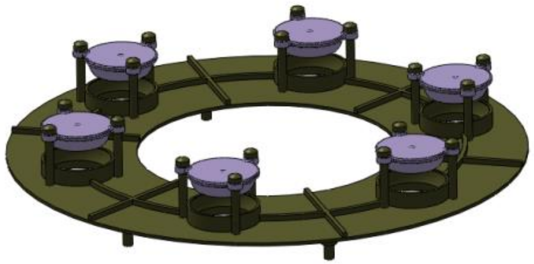
When main blowers are OFF



OPEN
When main blowers are ON

Main priorities for GFR Topic 2 (Design & TH) continued

- **7- Asymmetry of connection of main loops to the RPV**
  - **Non-symmetrical connection of I. loops to RPV risks to generate non-symmetry in the RPV cooling**
    - The non-symmetry equally influences the thermal barrier inside RPV
  - **Current design: Connection to RPV under 90 º**
    - Does such asymmetry generate excessive T non-uniformities in RPV through insufficient cooling symmetry ? What are the design criteria for the RPV ?
  - **If yes, what layout is more acceptable:**
    - 2 loops under 180 º (requires more space)
    - 3 loops under 120 º (GFR2400)

Main priorities for GFR Topic 2 (Design & TH) continued

- **8- Battery backup of DHR blowers** (blackout & LOCA)
  - **3x DHR blowers during LOCA require ~0.5 MW power (1-2 days)**
    - Revision of the maximum power from batteries is needed.
  - **Question: Is such a requirement feasible by batteries ?**
    - Large & Expensive battery field
    - Expensive maintenance
- **9- Dilatation of components fixed to both DHR and guard vessel**
  - **Water inlet/outlet pipings of the DHR system exhibit important displacement in space due to dilatation of DHR loops.**
    - Assessment of such dilatations is needed before suitable solution is proposed.

Main priorities for GFR Topic 2 (Design & TH) continued

- **10- Guard vessel shape optimization (cylinder or sphere)**
  - **Free volume is given by the required backpressure**
  - **Maximization of the backpressure for LOCA may reduce the battery power needed by DHR blowers**
  - **The shape must be resistant to overpressure & feasible to be fabricated**
    - The optimum shape for ALLEGRO may be determined after the technology inside guard vessel has been defined.
  - **Questions:**
    - What is the required similarity with GFR(2400) ?
    - What technology must be located inside the GV ?
    - What are the requirements for inspections ?
    - …

Topic 3: Materials and Coolant technology

- Pressure vessel & other structural materials
  - Solved case by case
- Gas management systems
  - Primary helium, Secondary gas, Guard vessel, Containment
- Thermal barrier & Insulation
  - Inside RPV protecting the RPV wall
  - Inside both the main & DHR coaxial piping
  - Selected external parts of the primary & secondary circuit
- Heat exchangers
  - Gas/water (DHR)
  - Gas/gas (main HX)

Topic 3: Materials and Coolant technology continued

- Sealing technology
  - Vessels, Valves, Bushings at elevated T
- Blowers
  - Main & DHR He blowers characteristics & cooling
  - Wide pressure range, pressure drop on a stopped blower
- Valves
  - Various types, active, passive, elevated T
- Wear resistance at elevated temperatures
  - Surface to surface friction
  - Surface wear due to flowing impure gas
  - Prevention of self-welding

Main priorities for GFR Topic 3

- **1- Removal of radioactivity from primary helium**
  - **FPs leaked from fuel rods to coolant & Activated corrosion products**
    - Quantification of leaked Noble gases, Iodine, Cesium, Strontium, …, Dust.
    - Little information on purification methods is available in literature.
    - Experimental facility for removal of active isotopes is expensive.
  - **Well dimensioned system is needed for ALLEGRO**
  - **Maintenance of filters & Waste management to be formulated**
- **2- Management of O potential in the primary He**
  - **Optimum controlled oxygen level is needed to generate protective oxide layer on Ni and Fe base alloys.**
    - Depends on temperature.
    - Sampling, evaluation & dosing system to be developed

Main priorities for GFR Topic 3

- **3- Thick-walls vessel materials (e.g. RPV)**
  - **Technological properties**
    - Manufacturability & weldability
  - **Material properties**
    - Effects of neutron irradiation (embrittlement, swelling, ageing)
    - Corrosion, fatigue, creep
    - Large thermal emissivity required (>0.8)
- **4- Reactor internals**
  - **Core barrel, support plate, reflector, shielding**
    - Alloy 800 ?
- **5- Heat exchangers & Sealing technology & Blowers**
  - **Cross-cutting issue with VHTR**

Main priorities for GFR Topic 3

- **6- Thermal barriers**
  - **Al_2O_3 & SiO_2 mixed ceramic fiber materials contained between metallic or ceramic-ceramic cover plates**
    - Components to be tested and optimized
  - **Thermal barrier of the hot duct in the curved part of DHR coaxial piping**
    - Revision of feasibility of this component is required
- **7- Valves**
  - **See the Topic 2**

Topic 4: Energy Conversion Systems

- **Turbomachinery in the secondary circuit**
  - **See Topic 2**

Topic 5: Safety and Instrumentation

- **Severe accident mitigation provisions**
  - **Need to be part of the design**
    - Prevention of recriticality & massive FP release outside containment
    - Long-term coolability of degraded core materials
  - **Different severe accident phenomena in:**
    - First MOX/SS core (large amount of steel – T_M ~1320 ºC)
    - Refractory core (large amount of ceramics – T_M ~2200 ºC)
- **Core catcher**
  - **Must be part of the ALLEGRO design**
- **Instrumentation**
  - **Not an issue for this moment**

Main priorities for GFR Topic 5 (Safety & Instrum.)

- **1- Core catcher**
  - **One design required for both the MOX/SS & Refractory cores ?**
    - If yes, is such a design feasible for the given materials ?
  - **Feasibility of various core catcher designs:**
    - Internal CC (in-vessel)
    - External CC (ex-vessel) inside guard vessel
  - **Identification of missing models in severe accident codes**
    - Development of new models
    - Validation of SA codes against SET and/or integral tests (feasibility ?)
- **2- DHR HX (He/water) performance at design limit**
  - **Requirement to survive 1250 ºC during 30 minutes ? (at 7 MPa ?)**
    - Gas flow & temperature field inside the DHR HX
    - Assessment of integrity of the DHR HX pressure vessel
    - Assessment of resistance to water boiling & resistance of HX tubes to failure
  - **Revision of the current DHR HX design is necessary**

Main priorities for GFR Topic 5 (Safety & Instrum.)

- **3- Passive mode (natural convection) under various flow resistances**
  - **Flow restrictors (DHR blower, …) may reduce or prevent the performance of the natural convection**
    - Analysis of all potential flow resistances (pressure losses) is needed
    - Some pressure losses will have to be measured experimentally (DHR HX, …)
  - **Validation of system thermalhydraulic codes on mockup will be needed**

- **4- Transition of the core cooling from main to DHR loops**
  - **Reduced performance (or stop & restart) of main blowers may need to opening of DHR loop(s)**
    - What will be the interference of main & DHR loops under such conditions ?
    - What will be the heat removal from the core under such conditions ?
  - **ALLEGRO mockup will be needed for experimental studis of such phenomena.**

Main priorities for GFR Topic 5 (Safety & Instrum.)

- **5- Potential core bypass under LOCA conditions**
  - **Assessment of potential core bypass scenarios**
    - Location of potential breach(es) in the primary circuit
    - May multiple breaches occur (deterministic & probabilistic assessment) ?
  - **Core bypass to be studied experimentally using ALLEGRO mockup**
- **6- Failure of the pressure boundary inside the DHR system**
  - **Setting of design & safety criteria for the DHR system**
  - **When failure occurs (e.g. tube failure):**
    - What is the degradation of the heat removal through the DHR system ?
    - What is the water (steam) ingress into the primary system ?

Summary

- **The R&D for ALLEGRO currently focuses onto issues related to:**
  - **Feasibility** (robust & foolproof)
  - **Safety** (coolability, negative reactivity coefficients, …)
- **Once ALLEGRO is felt to be "feasible & safe":**
  - **First core fuel & Refractory fuel development must restart**
  - **Irradiation programmes in fast neutron flux must start on:**
    - First core fuel
    - Refractory fuel
    - Structural materials