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LFR Technology for a promising SMR

IAEA TM on "Benefits and Challenges of Fast Reactors of SMR type"
Politecnico di Milano, September 24-27, 2019

ENEA

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Outline

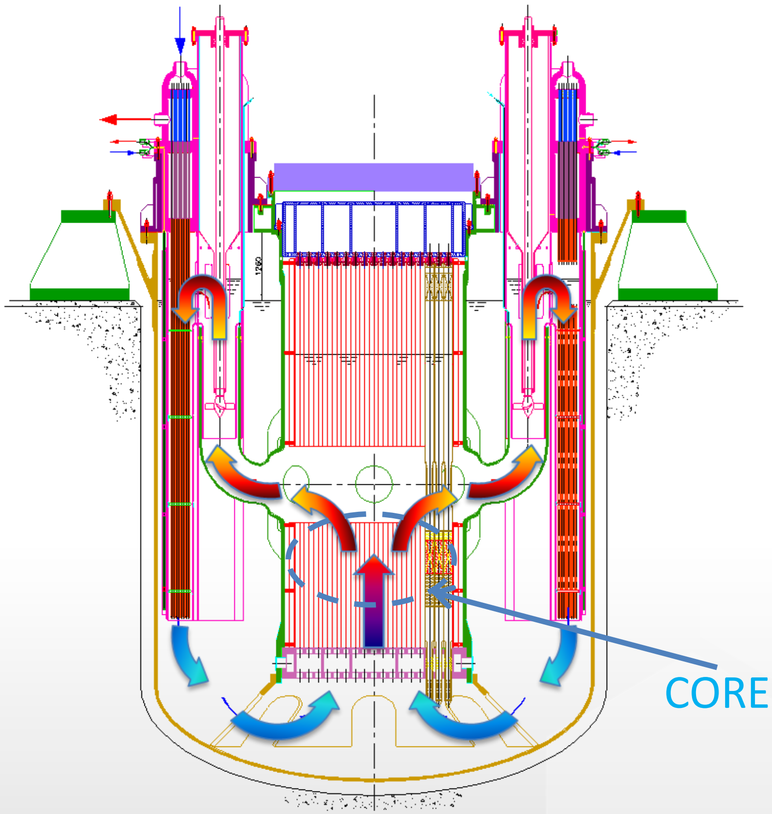
- SMR-enabling features
- A commercial LF-SMR
- RD&Q challenges: ALFRED

Technology-specific features

Neutronics

- Low neutron capture:
  - enhanced breeding
  - higher burnup
  - reduced reactivity swing
  - long-lasting (even cassette) cores
- Low moderation:
  - pins pitch broadening (natural circulation)
  - hard neutron spectrum

Target design

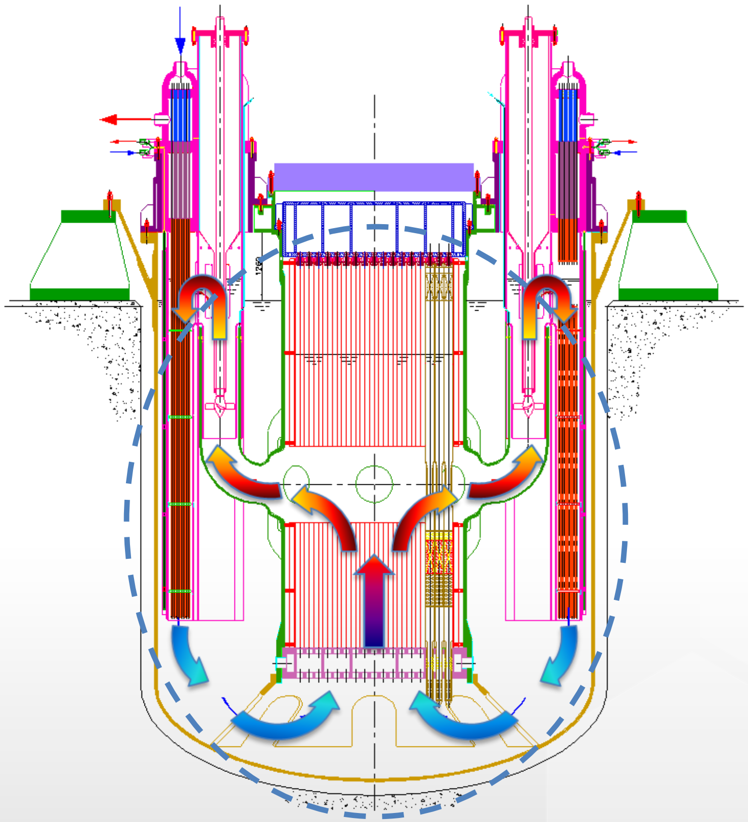


Technology-specific features

Physics

- High boiling point:
  - margins magnifying reactivity feedbacks
- Low relative expansion:
  - low incidence of the coolant density reactivity effect
- High absolute expansion:
  - easy natural circulation without tall chimneys

Target design

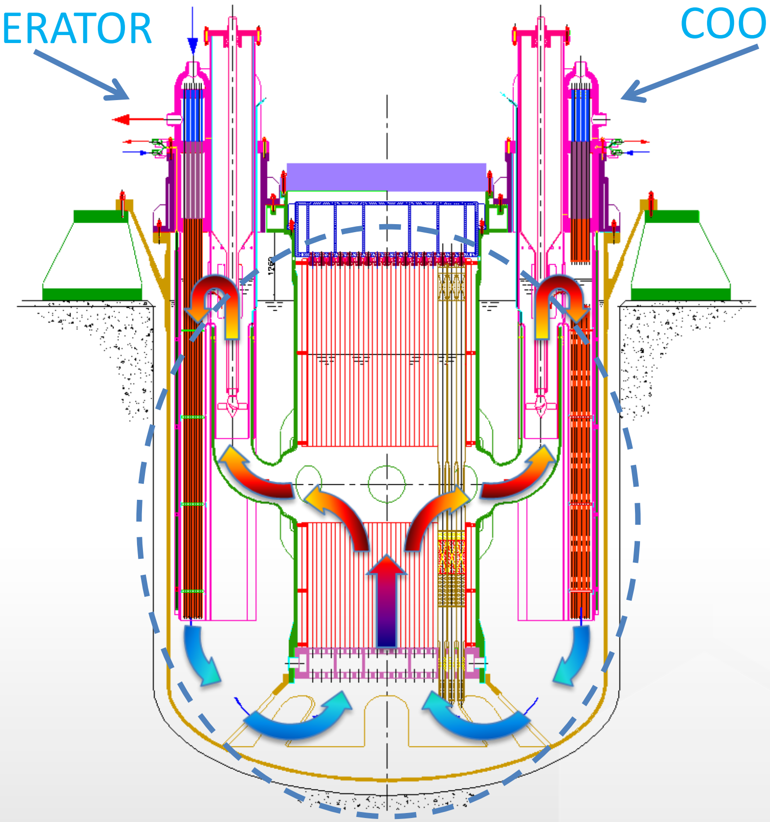


Technology-specific features

Chemistry

- Inert with air and water:
  - steam generators and DHR dip coolers inside primary system
  - minimum of potential energy stored in the primary system
- Ease of chemical bonding:
  - retention of almost all FPs
  - ease of cleaning of removed components

Target design



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SMR-specific features

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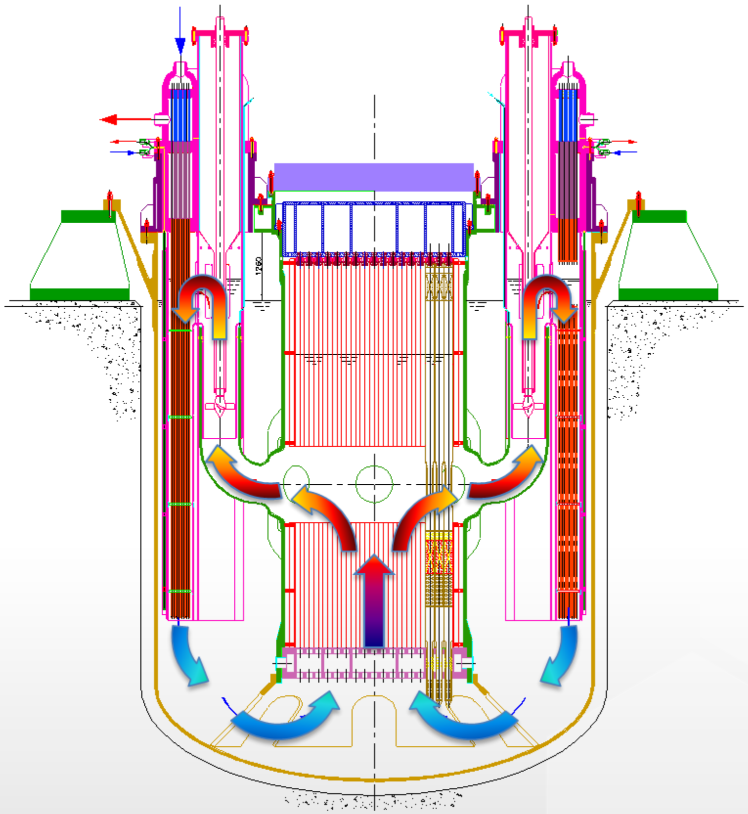
Simplicity and compactness

- Manageable threats:
    - no risk of propagation of accidents from one module to neighboring ones
    - simple implementation of safety strategy (no excess redundancy)
    - simple components
    - compact layout

Target design



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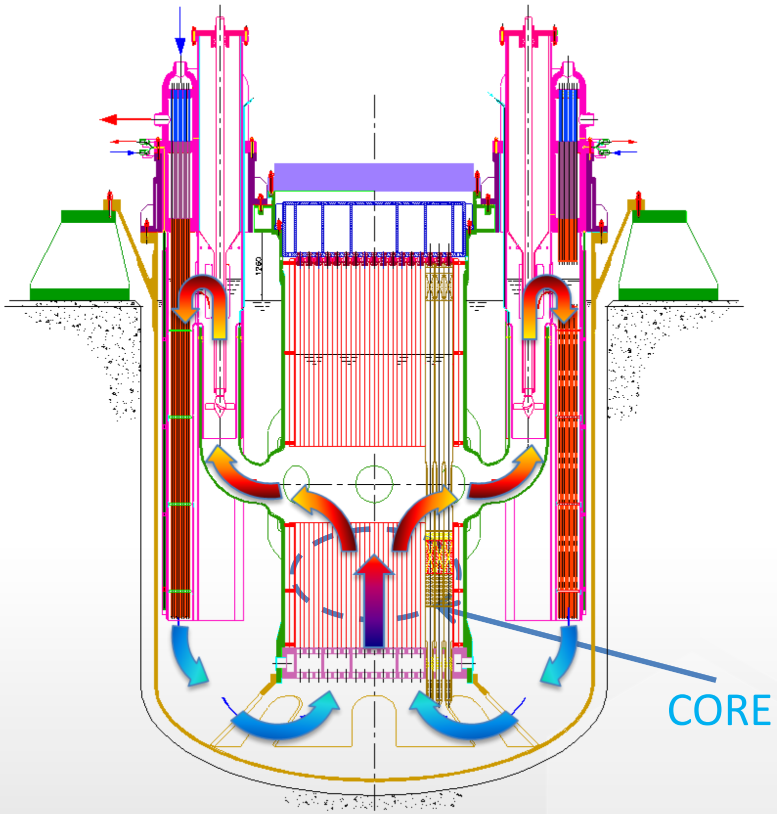
SMR-specific features

Flexibility

- Broad margin to limits:
  - ease to attain systems with very different performances (breeders, burners, batteries, etc.)
- Enhanced reactivity feedbacks:
  - compliance for load following

Target design



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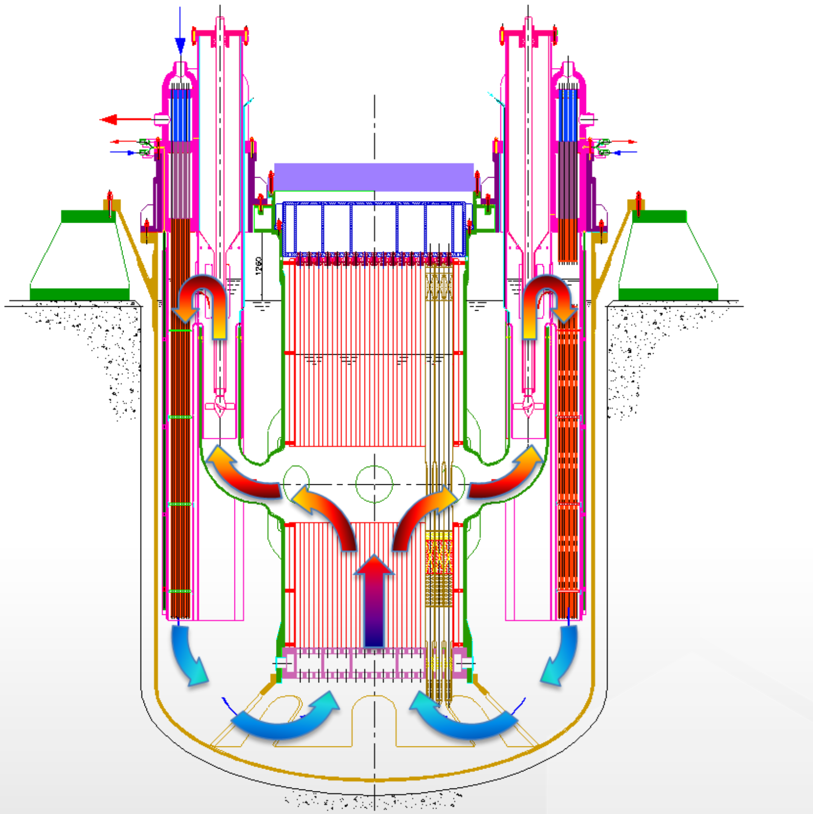
SMR-specific features

Plant Integration

- Elimination of piping:
  - protection from earthquakes
- Simplicity and compactness:
  - reduction of containment building footprint

Target design



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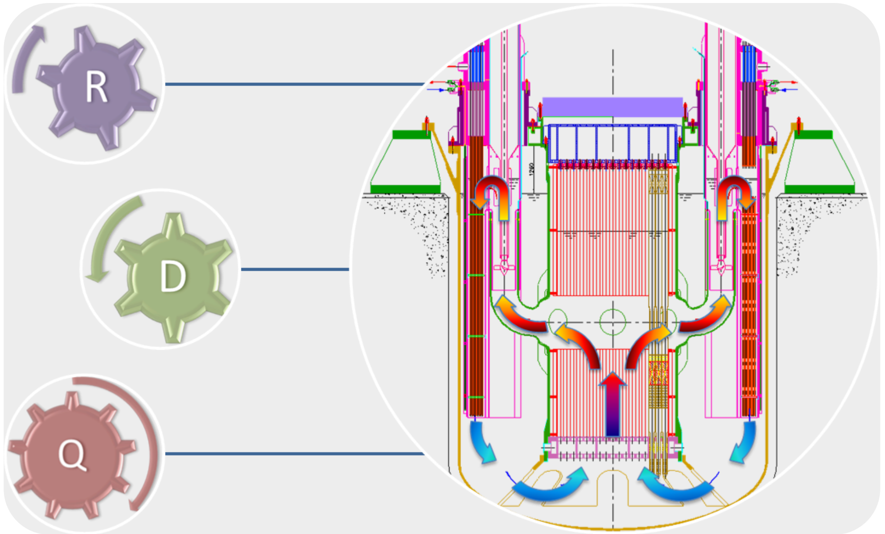

Way to success

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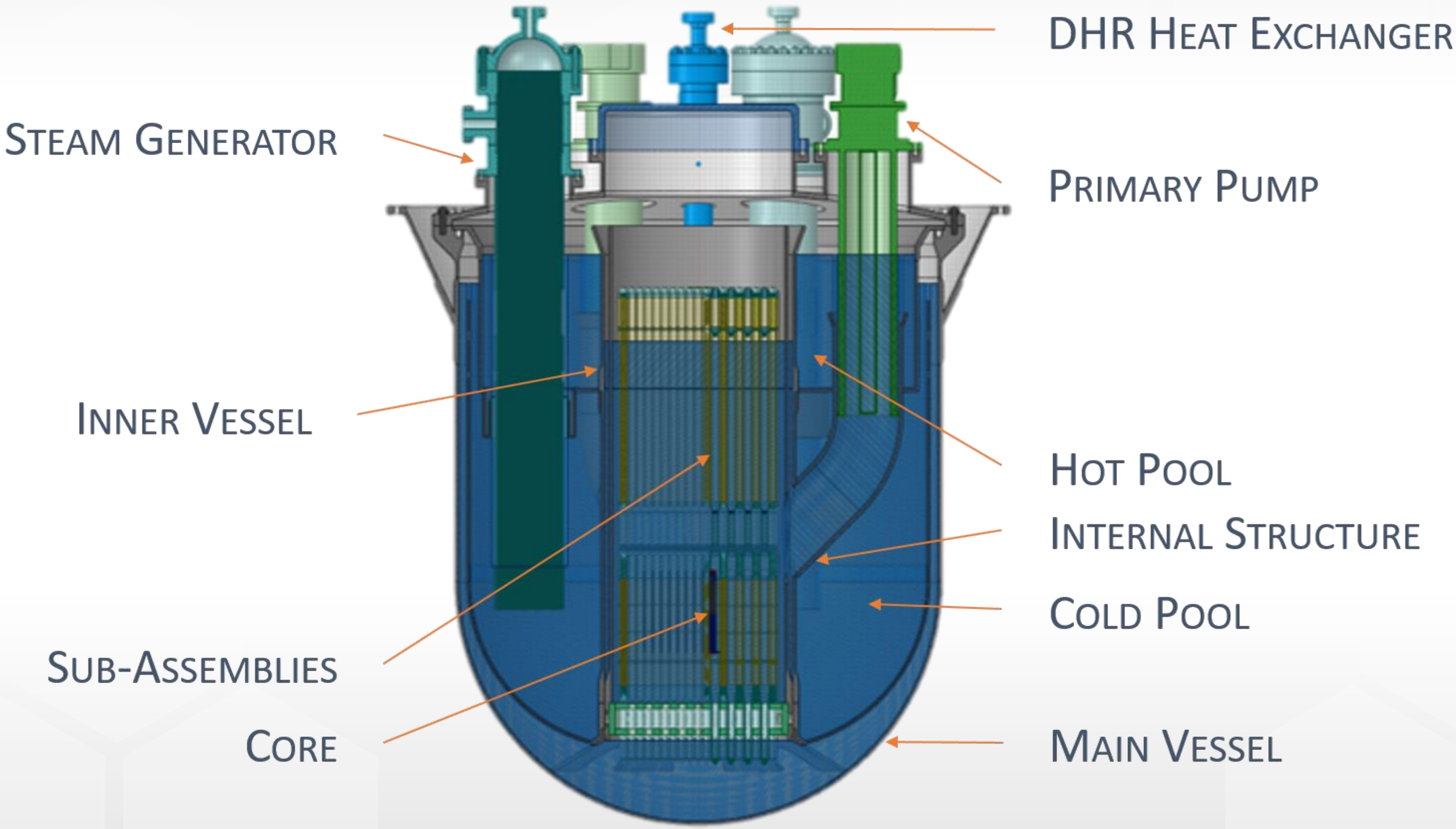
Criteria	Enablers
Economics • the LF-SMR has to be competitive with existing sources	• Simplicity • Compactness • Sharing
Safety • the elimination of the EPZ could be an enabler for large deployment of SMRs	• Inherent/passive behavior • Simplicity • Robustness
Readiness • the product has to be deployable in the next decade	• Simplicity • Inherent features • High TRL

LF-SMR concept layout



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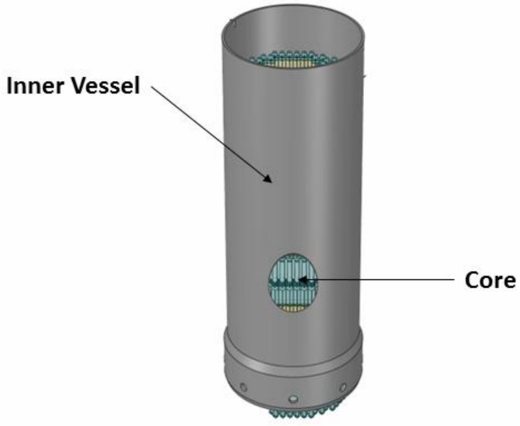
LF-SMR concept layout

Main SSCs

- Core
- Inner Vessel
- Reactor Coolant pumps
- Steam Generators
- DHR Dip-Coolers
- Internal Structure
- Main Vessel
- Safety Vessel

Reference layout



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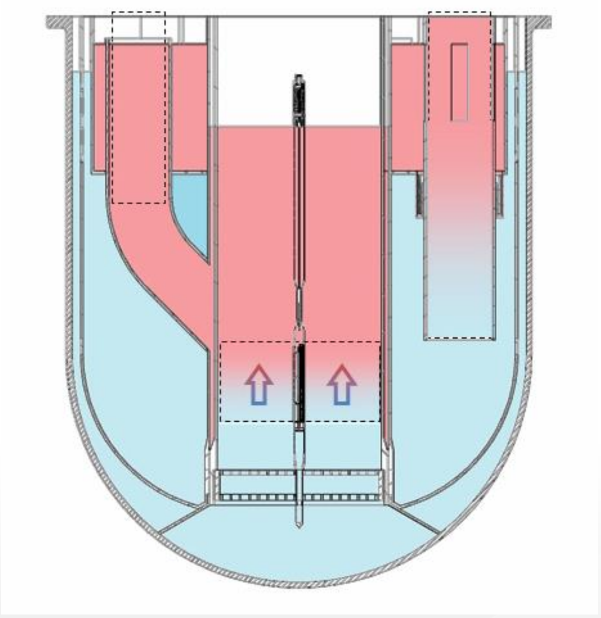
LF-SMR concept layout

Simple flow path

- Internal Structure guides the flow:
  - identifying a Hot Pool and a Cold Pool
  - securing the whole coolant inventory participates, thus preventing stagnant regions, thermal stratification, etc.

Reference layout

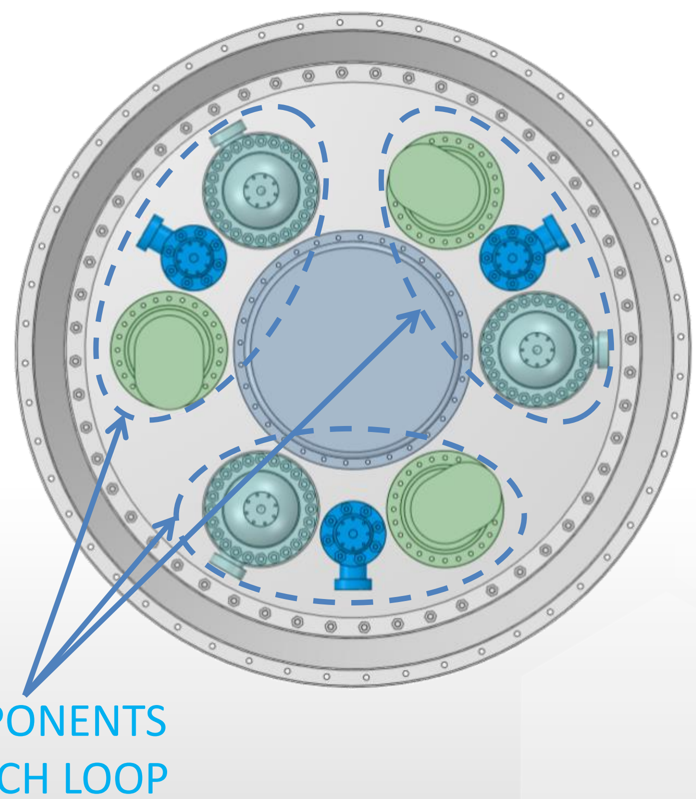


LF-SMR concept layout

Number of loops

- Optimization is possible, compatibly with:
  - size of main vessel (impacting the number of available suppliers and its shop manufacturing - transportability)
  - ease of manufacturability and shipment of components

Reference layout



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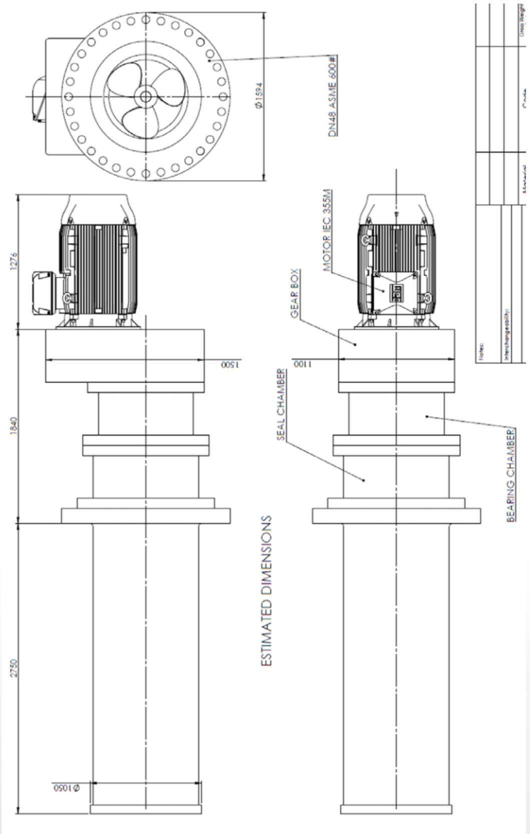
LF-SMR concept layout

Reactor Coolant Pump

- Mechanical
- Axial design
- In hot leg
  - receive coolant from the core
  - release coolant to the hot pool

Reference layout



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LF-SMR concept layout

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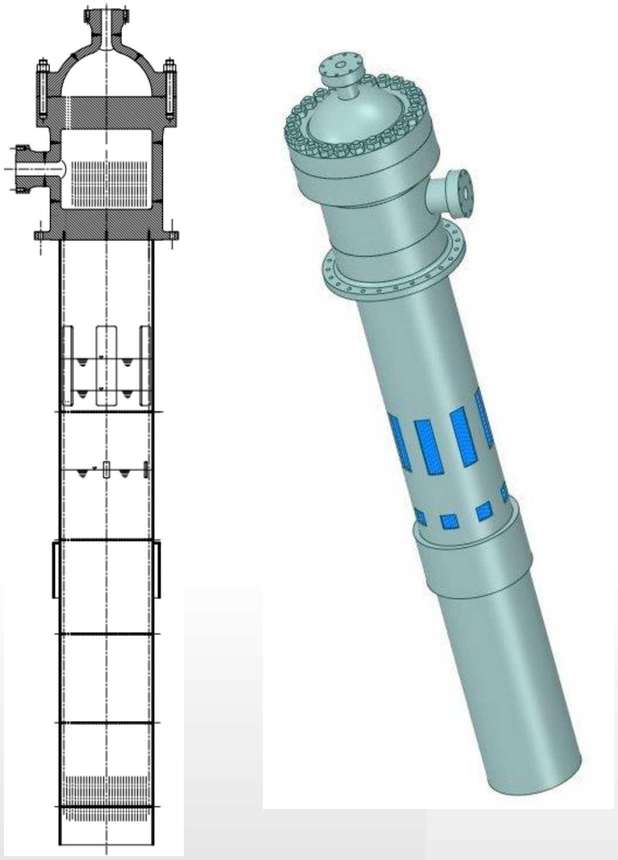
Steam Generator

- Shell-and-tubes
- Single-walled tubes (of either bayonet or helicoidal type)
- Large ports for nominal hot coolant inlet
- Small ports (at lower quote) for coolant inlet in case of MV breach and level drop

Reference layout



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LF-SMR concept layout

DHR Heat Exchanger

- Shell-and-tubes
- Double-walled bayonet tubes; gap to
  - reduce losses in nominal conditions
  - monitor integrity
- Large ports for normal hot coolant inlet
- Small ports (at lower quote) for coolant inlet in case of MV breach and level drop

Reference layout

LF-SMR concept layout

DHR Isolation Condenser

- Immersed in a pool as heat sink
- Provided of a tank of non-condensable gases to
  - regulate autonomously the power it evacuates
  - prevent lead freezing in long-termed transients

Reference layout

LF-SMR concept layout

Fuel Assembly

- Hexagonal and wrapped
- Shortened thanks to lead shielding
- Multiple inlet ports
- Grid-spaced pins bundle
- Extended with a stem till above the lead free level

Reference layout

LF-SMR concept perspectives

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- All design simplifications were brought to
  - enhance safety, effectiveness and compactness
  - pursue economics

System	High-grade steel [kg/kW$_{(e)}$]
GCR	20
Large SFR	5÷10
Gen-III/+ passive LWR	3
Gen-III/+ LWR SMR	>3 (4÷5)
LFR	**2**

Target objective → LFR

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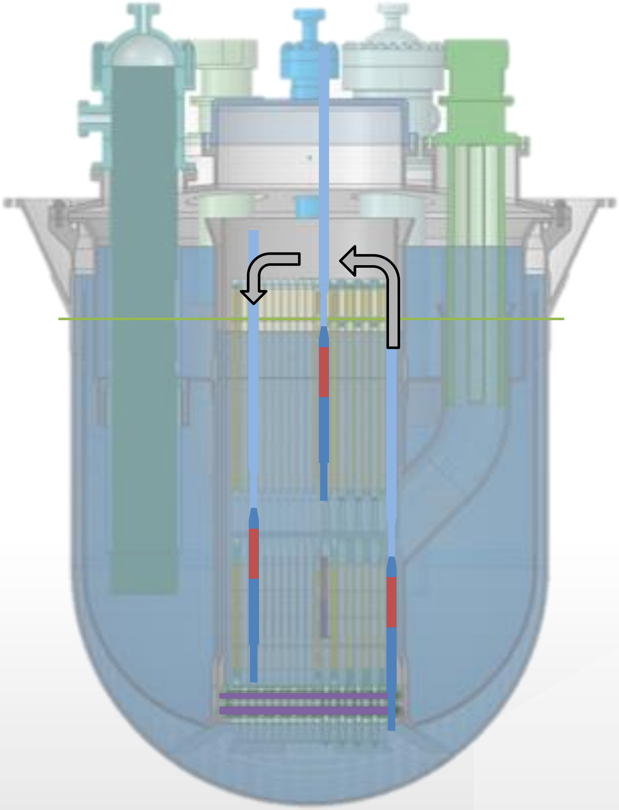
LF-SMR concept layout

Refueling approach

- Opening of MV (in inert containment)
- Use of a Transfer Flask:
  - secures passive cooling by lead inside
  - contributes to shielding during transfer
  - once sealed, represents the unit for storage, allowing to eliminate the spent fuel pool

Reference layout



LF-SMR concept perspectives

- Adding also this innovation, it is possible to preliminarily estimate the potential competitiveness of a LF-SMR.

- Looking at the construction component of the LUEC:
  - for a 125 MWe unit, the FOAK should assess at 46 €/MWh
  - for a 250 MWe unit, the FOAK should assess at 29 €/MWh

- If we project this to the NOAK, it falls to
  less than 18 €/MWh

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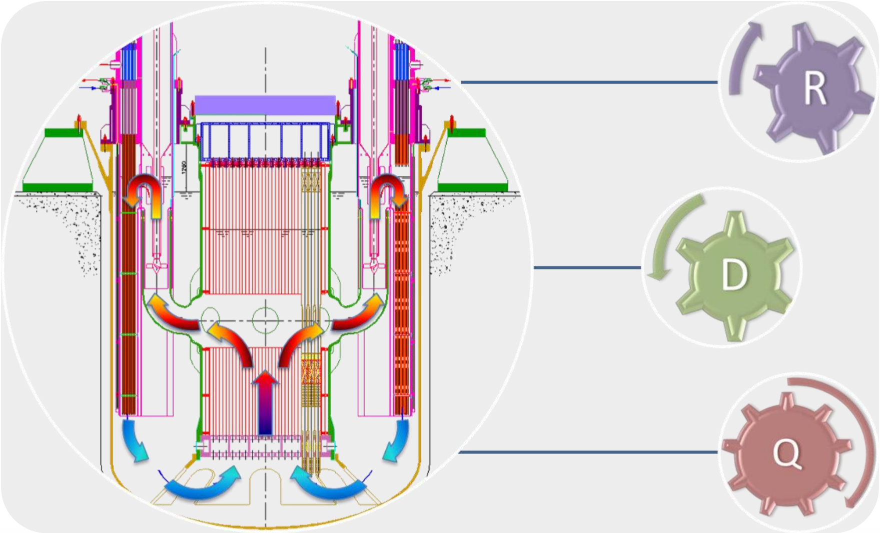
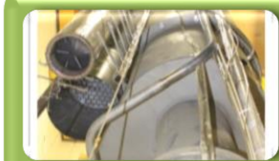


RD&Q Infrastructure: available facilities (ENEA)

LECOR
- Loop facility
- Forced circulation
- Corrosion experiments

TAPIRO
- Zero-power reactor
- Perfectly characterized spectrum
- Lead propagation & calibration experiments



CIRCE
- Large pool facility
- Assisted/forced circulation
- Integral and components test

HELENA-1
- Loop facility
- Forced circulation
- Bundle experiments

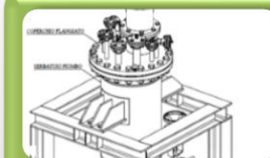
NACIE-UP
- Loop facility
- Natural circulation
- Bundle experiments

RACHEL
- 10 small vessels
- Stagnant lead, controlled environment
- Lead chemistry experiments

LIFUS-5
- Small pool facility
- Stagnant lead
- High-pressure lead/water interaction tests

SOLIDX
- Small vessel facility
- Stagnant lead
- Freezing/re-melting experiments

PLACE
- Large plant
- Controlled environment
- Large components washing



BID1
- Small pool facility
- Stagnant/mixed lead
- Oxygen control experiments

Key challenges

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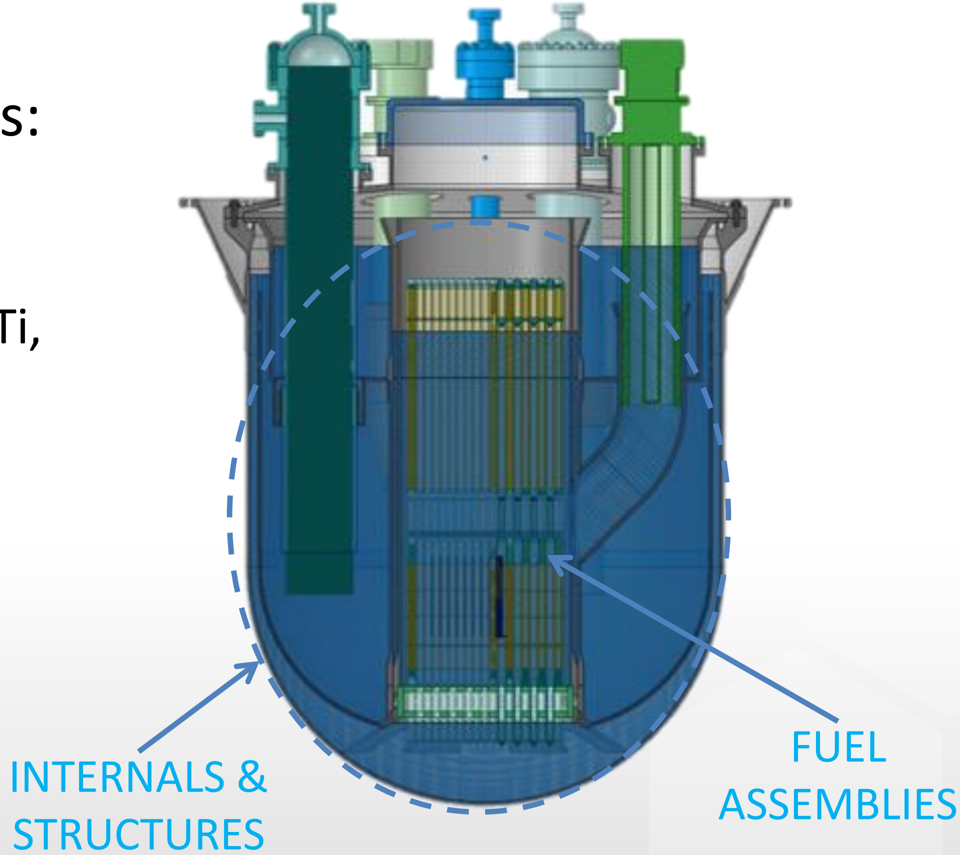
Topics to be addressed

- Material properties/ system thermo-mechanics:
  - assessment of limiting strengths and strains (code cases) for 316LN and 15-15Ti, bare and coated, in lead

Target design

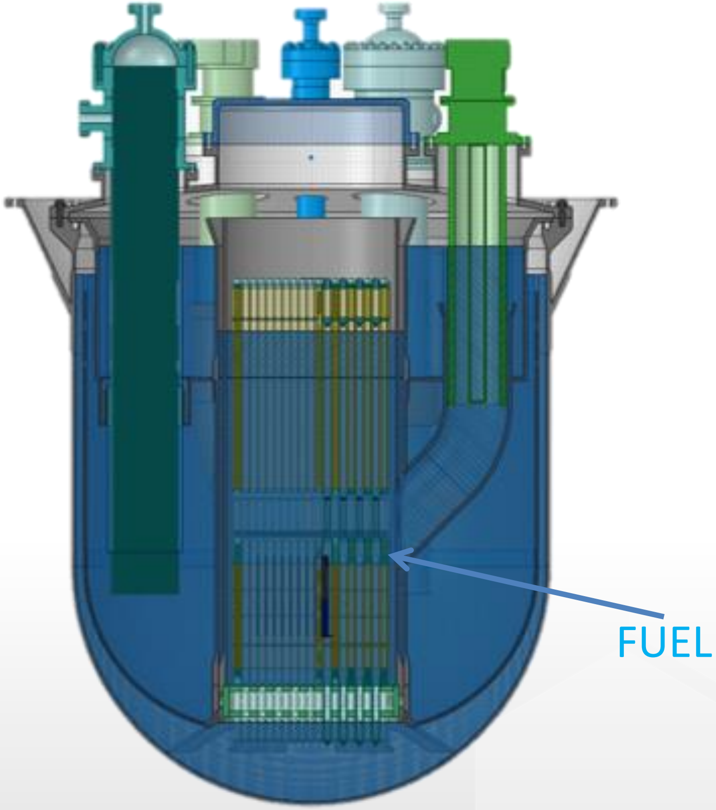


Key challenges

Topics to be addressed

- Lead-fuel interaction:
  - assessment of chemical interaction between coolant and fuel elements
  - assessment of fuel propagation in the coolant (buoyancy/sinking, drag)
  - validation of system thermal-hydraulic codes for severe accidents analysis

Target design

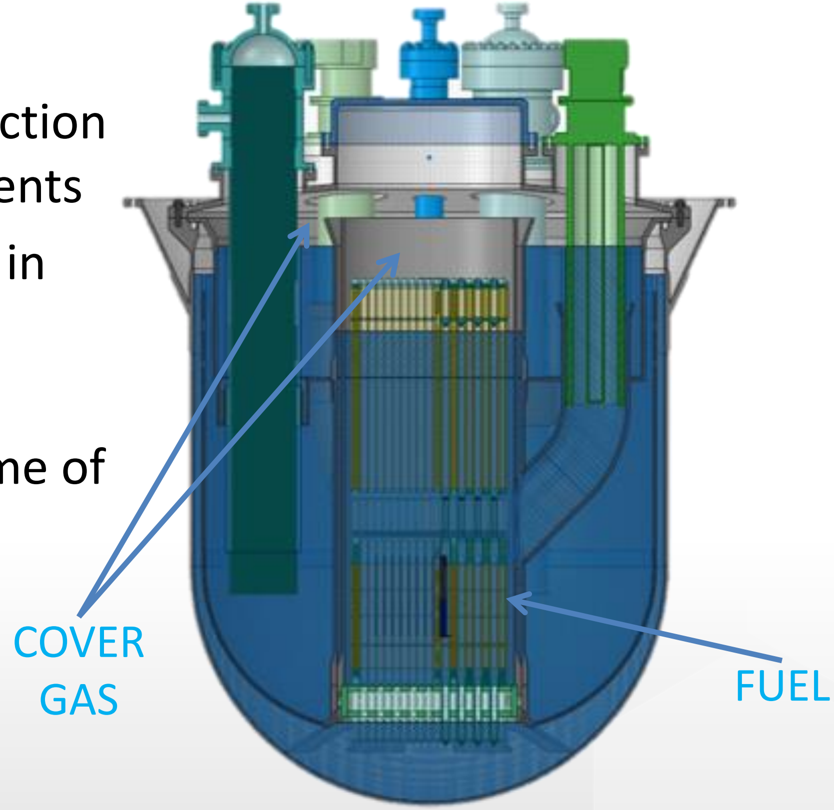


Key challenges

Topics to be addressed

- Fission products retention:
  - assessment of chemical interaction between coolant and FP elements
  - assessment of FP propagation in the coolant (buoyancy, drag)
  - assessment of noble gases propagation in the coolant (time of migration to the cover gas)
  - validation of system thermal-hydraulic codes for severe accidents analysis

Target design



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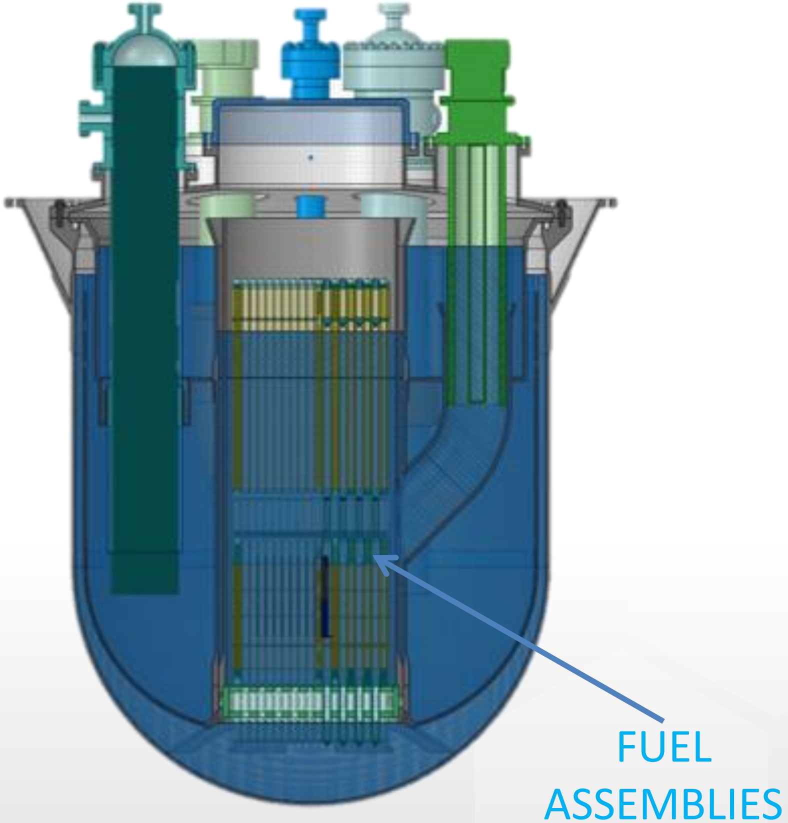
Key challenges

Topics to be addressed

- Fuel assembly:
  - assessment of bundle/ wrapper/core deformations
  - assessment of flow-induced vibrations and related fretting wears (on bare and coated pins, by bare and coated spacers)
  - assessment of manufacturing procedure

Target design

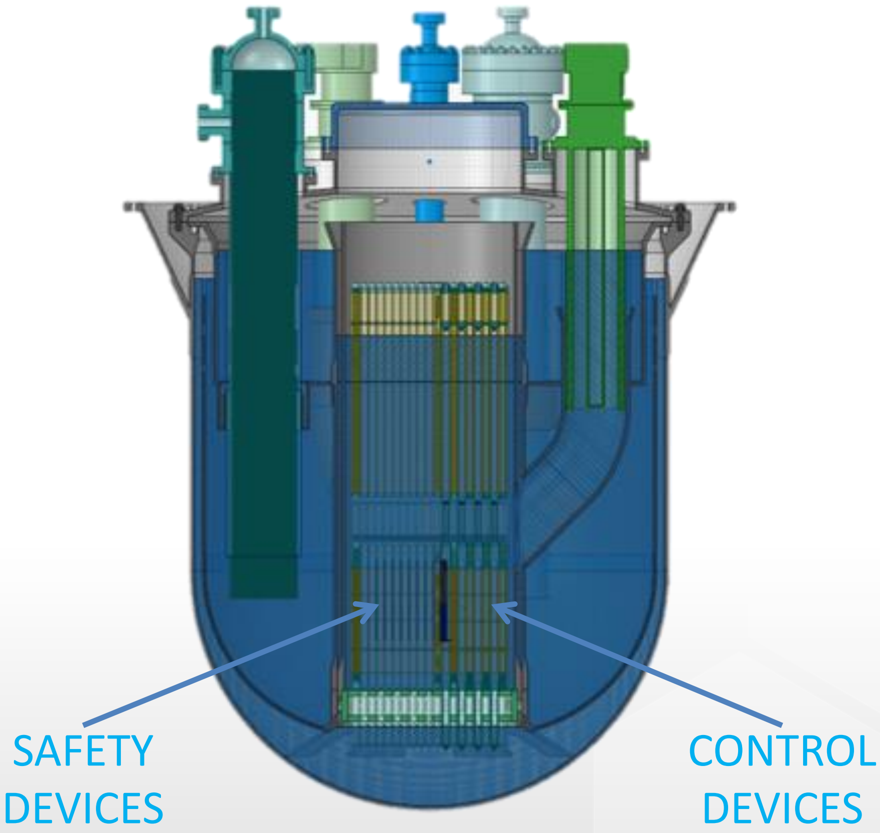


Key challenges

Topics to be addressed

- Control/shutdown devices:
  - assessment of bundle/ wrapper deformations and margin to operability
  - assessment of speed/time of insertion
  - assessment of actuation and operation reliabilities

Target design



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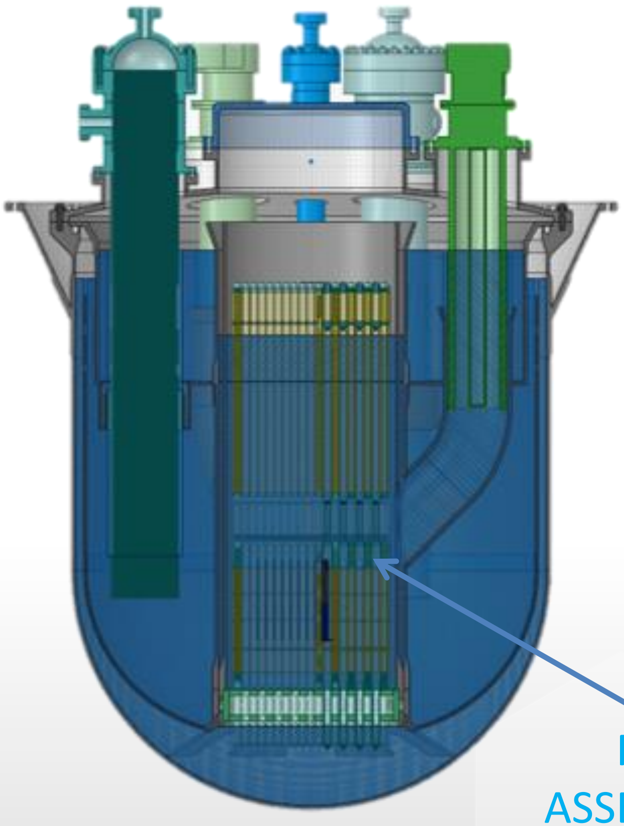
Key challenges

Topics to be addressed

- Fuel handling system:
  - assessment of refueling strategy and sequence
    - reliability of gripping a sub-assembly
    - capability to overcome interference in distorted core
  - assessment of reliability of spent fuel assemblies cooling during transfer

Target design

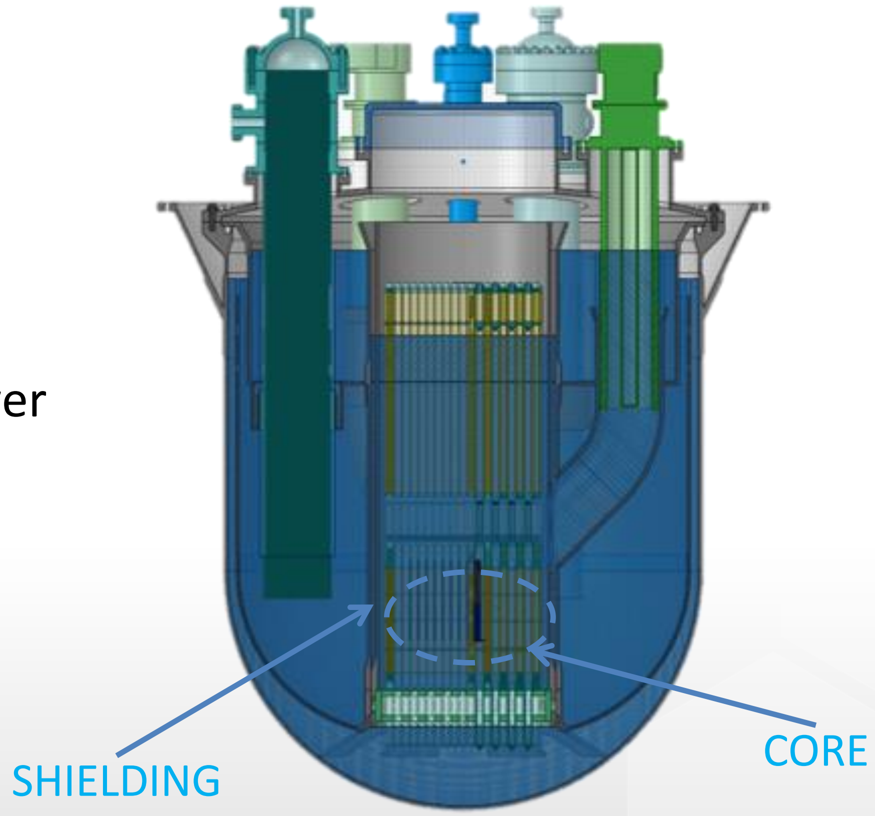


Key challenges

Topics to be addressed

- Neutronics:
  - assessment of safety-related core parameters:
    - reactivity coefficients
  - assessment of local distributions of flux and power
  - qualification of shielding

Target design



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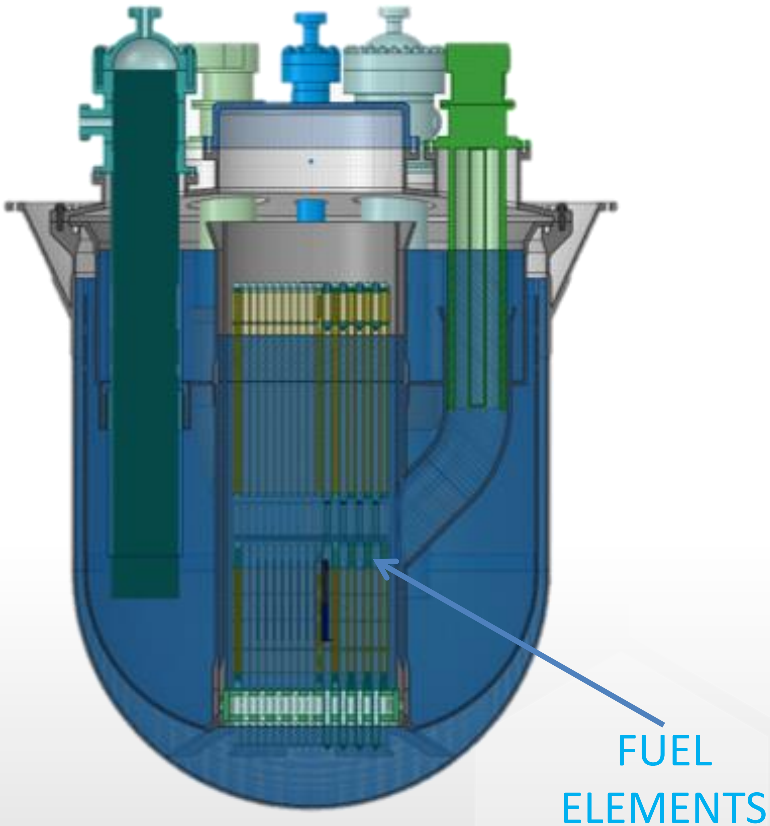
Key challenges

Topics to be addressed

- Fuel thermo-mechanics:
  - predictability of
    - fuel thermal (power distribution, O_2 and Pu migration, restructuring, …)
    - fuel mechanics (swelling, gas release, creep, …)
    - clad mechanics (swelling, creep, internal/external corrosion, …)
  - assessment of confidence

Target design



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RD&Q Landscape: analysis of available resources

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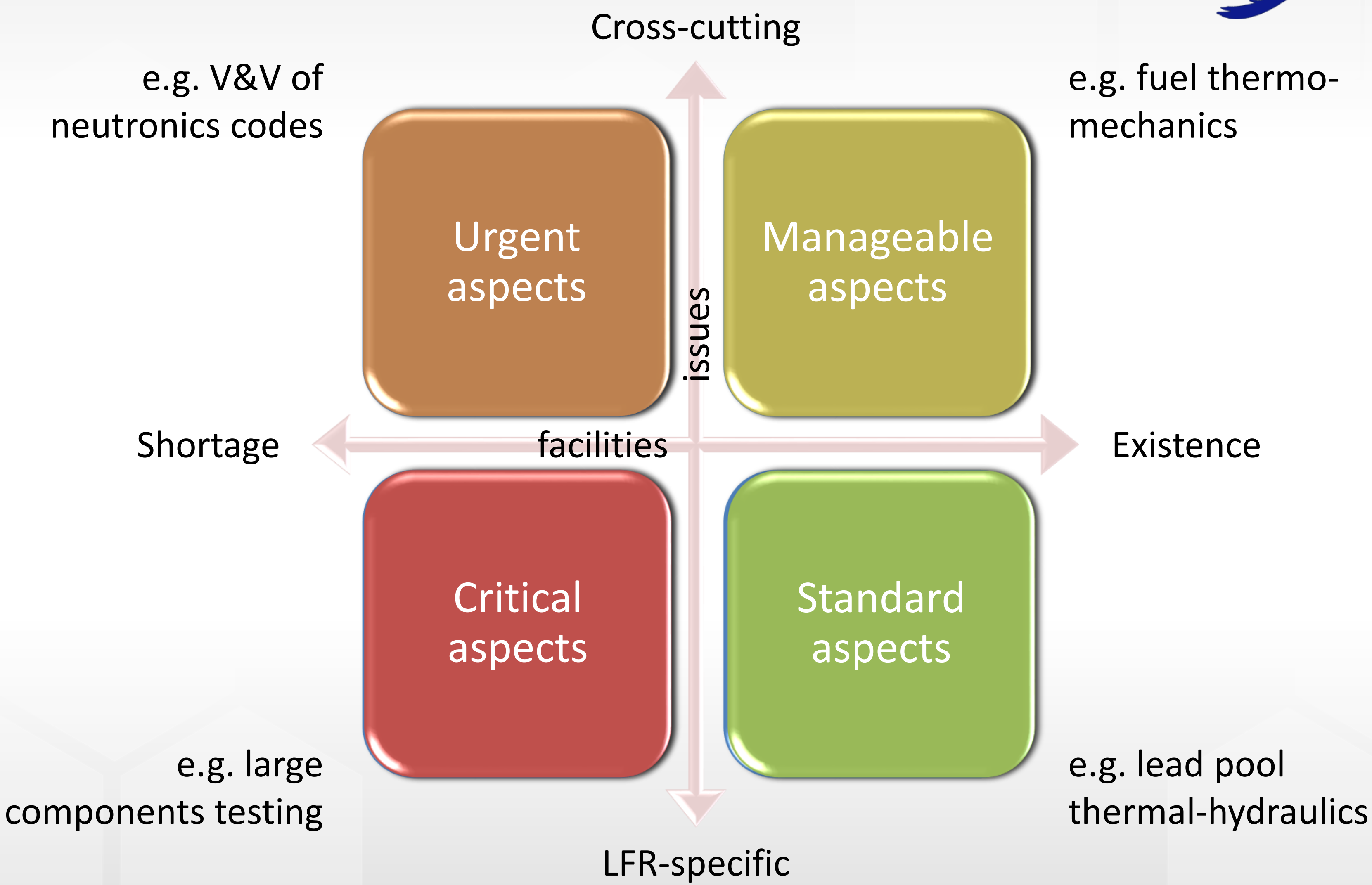
Survey as of IAEA's "Catalogue of Facilities in Support of Liquid Metal-cooled Fast Neutron Systems" (LMFNS Catalogue)

Categories:

- Zero power for V&V and licensing
- Design Basis Accidents (DBA) and Design Extended Conditions (DEC)
- Thermal-hydraulics
- Coolant chemistry
- Materials
- Systems and components
- Instrumentation & ISI&R

EU 49	World 26
BE: 15	CN: 7
CZ: 4	JP: 6
DE: 11	KR: 1
ES: 2	RU: 11
EU: 1	US: 1
FR: 2	
IT: 10	
LV: 1	
RO: 2	
SE: 1	

RD&Q Landscape: identification of gaps



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RD&Q Landscape: definition of the strategy

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Standard aspects

- Optimize use of resources

Manageable aspects

- Extend EU cooperation

Urgent aspects

- Seek for international collaboration

Critical aspects

- Realize new ad-hoc facilities

RD&Q Infrastructure: additional facilities (ICN)

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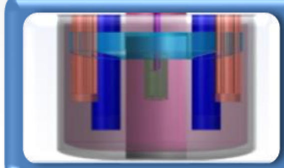
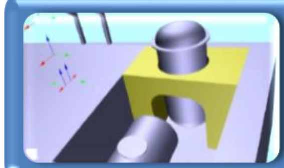
HELENA-2

- Loop facility
- Forced circulation
- Full-scale sub-assembly qualification



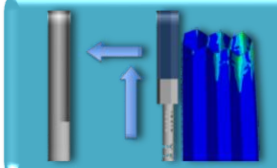
ELF

- Large pool facility
- Forced circulation
- Integral and endurance tests



ATHENA

- Large pool facility
- Forced circulation
- Large components qualification & SGTR tests



Hands-ON

- Vessel with core mechanical mockup
- Nominal and distorted geometries
- Handling system test and qualification

ChemLab

- Vessel and loop facilities
- Stagnant & flowing lead
- Chemistry control system qualification

Meltin'Pot

- Vessel and loop facilities in hot cell
- Stagnant/flowing lead + fresh and burnt fuel
- Fuel-cladding-coolant interaction experiments

Lead School

- Education and Training facilities
- Supercomputing commodities
- Conferencing center

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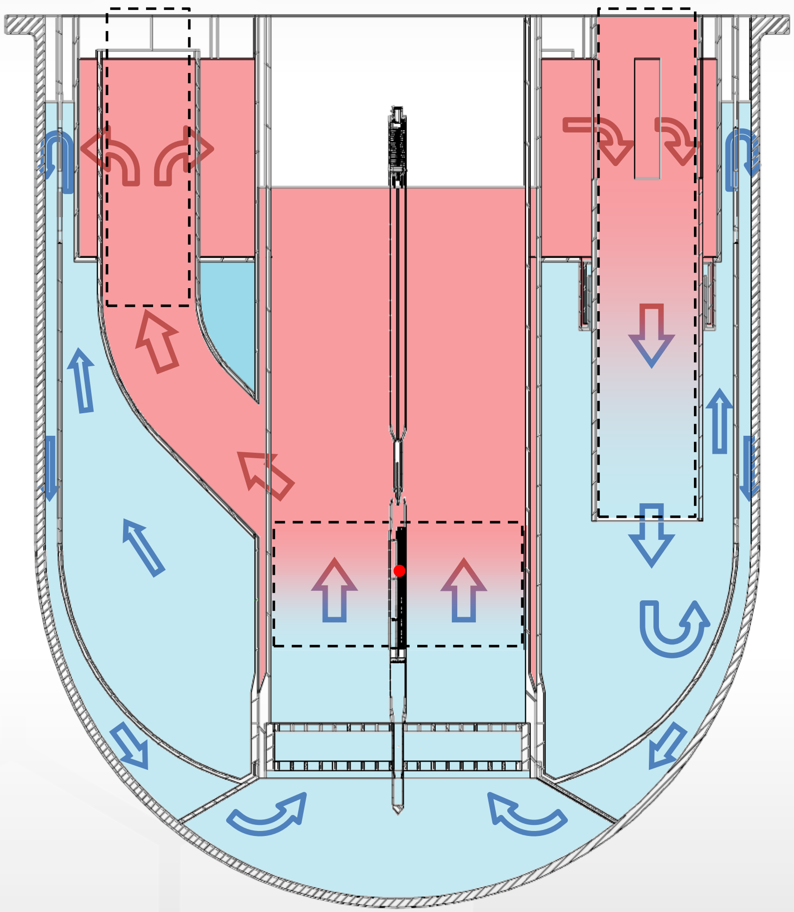
ALFRED relevant regions for component categorization



Hot spot:

- Heated region
- Clad region at highest temperature
- Accounting for uncertainties

Hot pool:

- Region at average core outlet temperature
- Affects also PPs and SGs inlet

Cold pool:

- Region at average core inlet temperature
- High thermal capacity

Corrosion of SSCs under irradiation is the main challenge!

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<table>
<tr><th>Condition</th><th>Parameter</th><th colspan="2">Region</th></tr>
<tr><td rowspan="3">Operation at power</td><td rowspan="3">Maximum Temperature (°C)</td><td>HS</td><td>600 (1)</td></tr>
<tr><td>HP</td><td>520</td></tr>
<tr><td>CP</td><td>400</td></tr>
<tr><td>Shutdown</td><td>Minimum Temperature (°C)</td><td>All</td><td>400</td></tr>
<tr><td rowspan="3">Accident (short-term conditions)</td><td rowspan="3">Maximum Temperature(2) (°C) / Holding time(2) (hours)</td><td>HS</td><td>800 / 0.01</td></tr>
<tr><td>HP (3)</td><td>680 / 2,5</td></tr>
<tr><td>CP</td><td>430 / 1000</td></tr>
<tr><td>Accident (long-term conditions)</td><td>Minimum Temperature (°C)</td><td>All</td><td>330</td></tr>
</table>

(1) Values from preliminary evaluations, to be confirmed.
(2) Preliminary values (extrapolated from LEADER Project), to be confirmed.
(3) Values referred to a different configuration of the HP (different thermal capacity), to be confirmed.

Stages identification

	Stage 0 (Commissioning)	Stage 1 (Low Temp.)	Stage 2 (Medium Temp.)	Stage 3 (High Temp.)
Core inlet temperature (°C)	390	390	400	400
Core outlet temperature (°C)	390	430	480	520
Core thermal power (MW)	≈ 0	100	200	300

- Mitigation against lead corrosion at low/medium temperature:
  - oxide layer working against the diffusion and loss of metal constituents
  - moderate oxygen concentrations in the melt (~10^{-6}-10^{-8} wt.%)
  - fairly stable for temperature below 450-480°C on austenitic stainless steels
  - approximately uniform oxygen content in the whole coolant (sufficiently wide window: 10^{-7} wt.% plus/minus one order of magnitude).
- Optimal oxygen concentration is a function of the minimum and maximum temperatures, in any design condition.

Logic for the selection of protective measures

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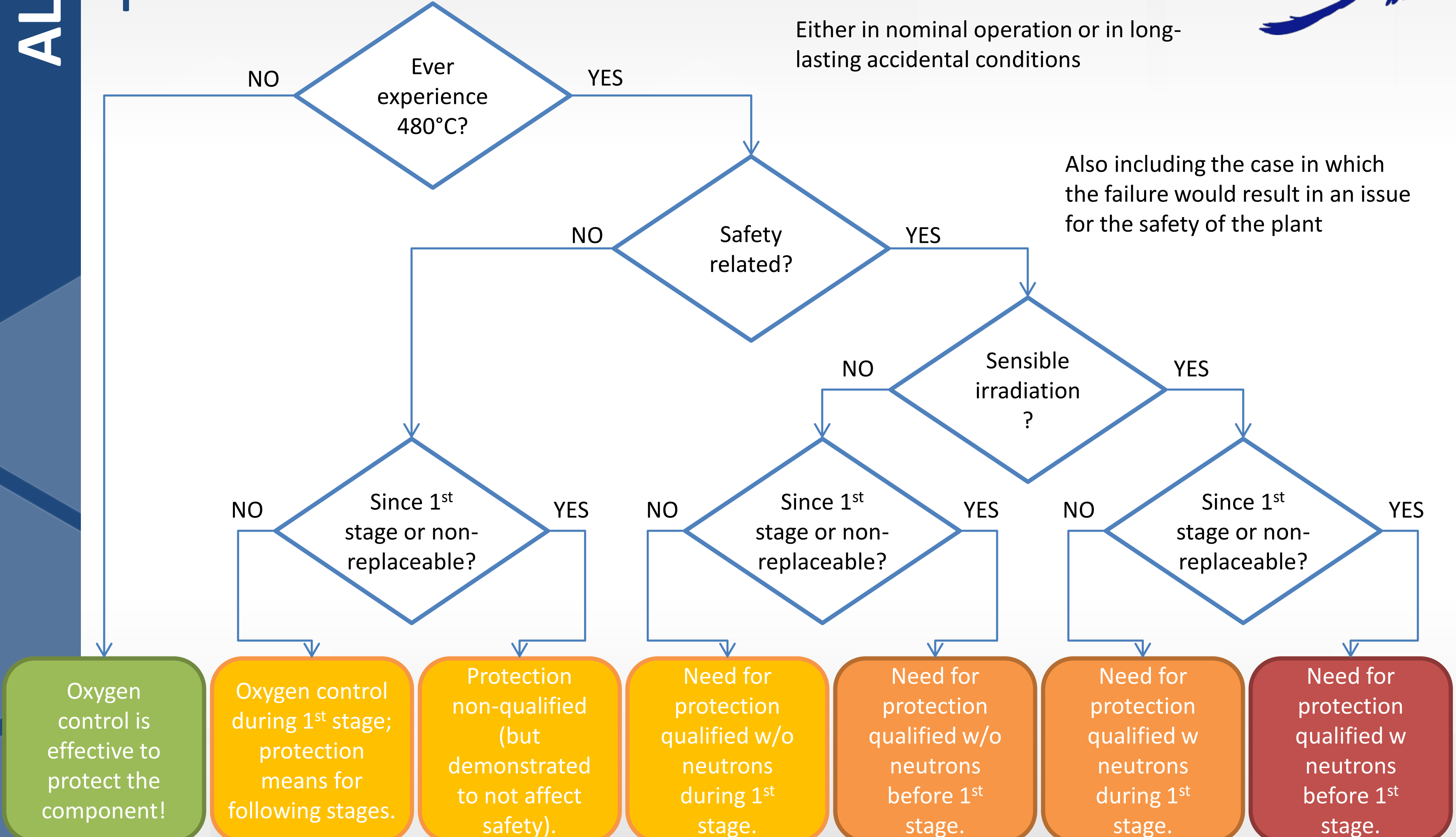

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