ADVANCED LEAD FAST REACTOR EUROPEAN DEMONSTRATOR – ALFRED PROJECT

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Meet the Presenter

Dr. Alessandro Alemberti is the Nuclear Science Development Manager of ANSALDO NUCLEARE (Italy) and in this position takes care of the Research & Development activities of the company. He coordinated the ELSY and LEADER projects in the frame of 6th and 7th Framework Program of the European Community, projects devoted to Lead cooled Fast Reactors development and participated as well to the main EU projects related to Lead and Lead Bismuth Eutectic (LBE) coolant technologies in recent years.

Since 2012, he has served as the chairman of the Generation IV International Forum (GIF) Lead Fast Reactor provisional System Steering Committee representing EURATOM.

After earning his doctoral degree in Physics at the University of Genoa (Italy) in 1979 and joining Ansaldo in 1981, Dr. Alemberti dedicated his efforts to thermal-hydraulic simulations for Light Water Reactors safety and licensing and participated in research programs like OECD-LOFT as well as AP600 and SBWR activities.

He is the author of a number of papers and patents devoted to the development of passive safety systems. In 2017 he was awarded the title of "Maestro del Lavoro" (Master of Work) by the President of Italian Republic.

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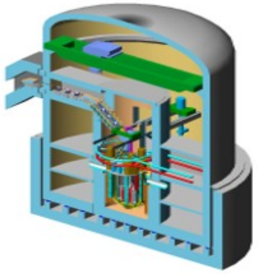
Presentation Outline

- History of lead coolant development in Europe
- The European context and the FALCON consortium
- ALFRED conceptual design from the LEADER project
- ALFRED status
- LFR technology development and awareness
- The ALFRED strategy

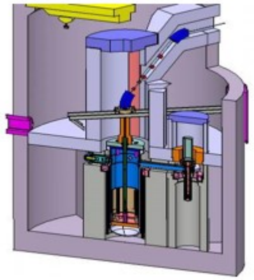
A Little Bit of History ….

Heavy Liquid Metal Technology Development in Europe

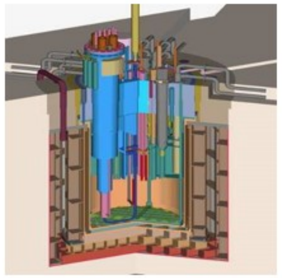
PDS-XADS project 5th FWP (2002-2004)



80 MW LBE-cooled XADS

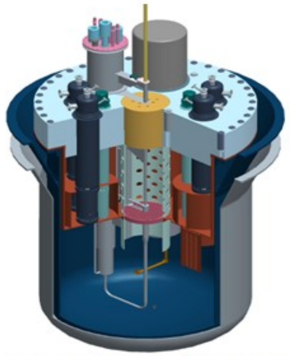


80 MW Gas-cooled XADS

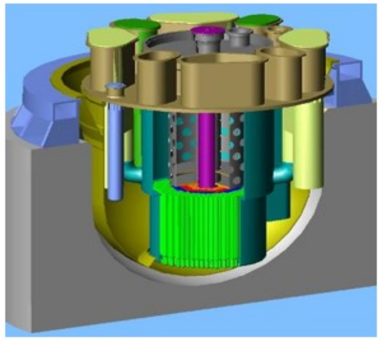


50 MW LBE-cooled XADS *(MYRRHA)*

IP-EUROTRANS project 6th FWP (2005-2010)

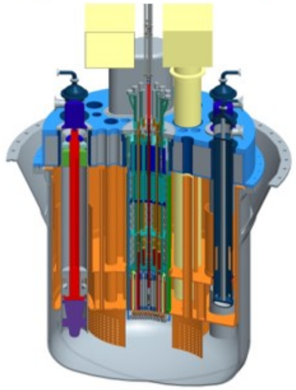


60 MW XT-ADS/MYRRHA



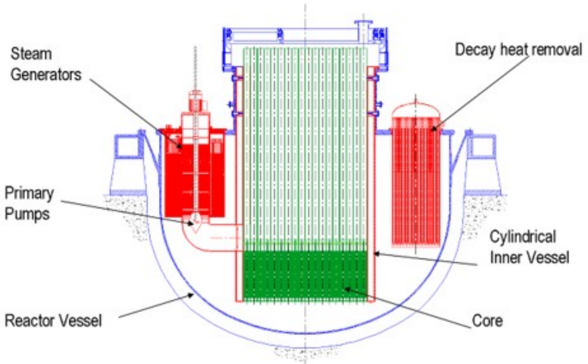
400 MW EFIT

CDT project 7th FWP (2009-2012)



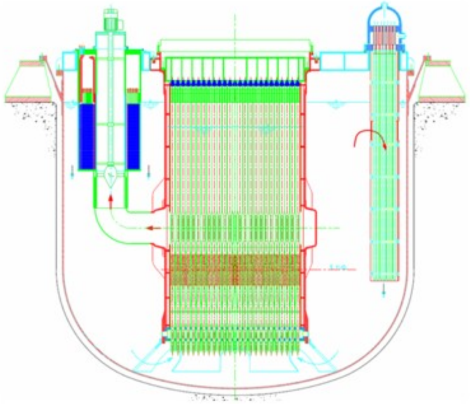
100 MW FASTEF/MYRRHA

ELSY project 6th FWP (2006-2010)

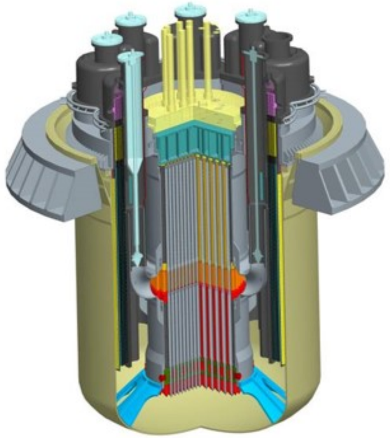


1500 MW ELSY

LEADER project 7th FWP (2010-2013)



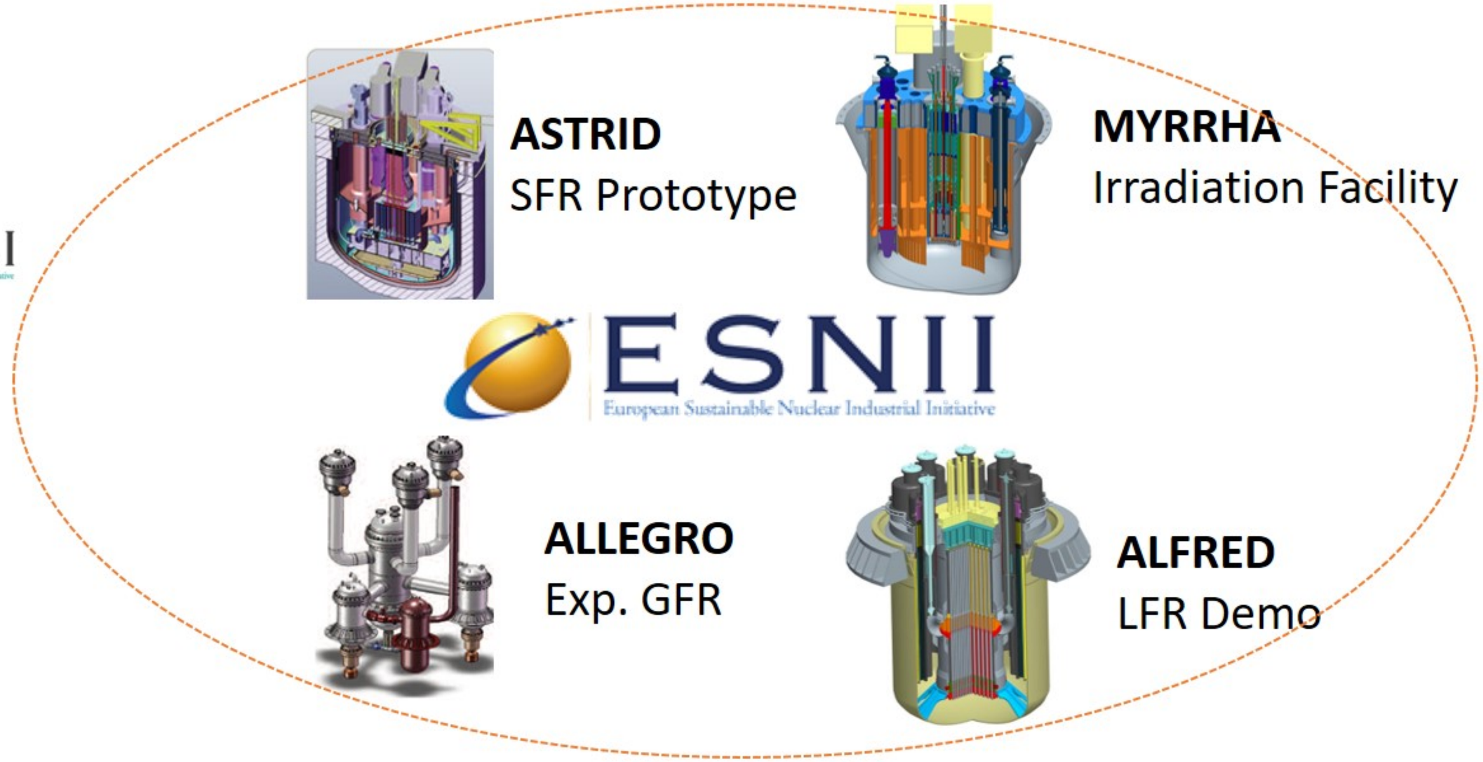
1500 MW ELFR



300 MW ALFRED

The European Context
Sustainable Nuclear Energy Technology Platform

4 ESNII initiatives



LFR technology can offer a **safe**, **sustainable** and **competitive** alternative to address market opportunities

More than **200 M€** invested in LFR technology in the last **10 years**

(From the report: Euratom contribution to the GIF Systems in the period 2005-2014 and future outlook, JRC)

ALFRED SUPPORT:
The FALCON* Consortium

- **FALCON** Consortium Agreement was established in 2013 to bring LFR technology to industrial maturity
- **FALCON** recently evolved to better cope with European context.
- Main **objectives** are:
  - Firm **commitment** to ALFRED as a Major Project in **Romania**
  - **Finalization** of ALFRED feasibility study
  - Initiation of **construction** of supporting R&D facilities
- **New** members sharing the **objective** of a rapid deployment of an LFR demonstrator, interested in the R&D supporting infrastructure and in the ALFRED industrial outcomes are **welcome** to join.

*__FALCON__ – **F**ostering **AL**fred **CON**struction

ROMANIA SUPPORT

- **2011 - Availability of Romania to host ALFRED**
- 2014 - Decision to implementation of ALFRED on the **Mioveni nuclear platform**
  Commitment to support the Project by covering **5 to 20% of the total cost**
- **2015 - Inclusion of ALFRED in the Smart Specialization Strategy of the South-Muntenia (high technology industry field)**
- May 2016 - Letter from ANCSI acknowledging ALFRED as a major project
- **Dec 2016 - ALFRED was included as a priority in the National Energy Strategy**
- 2017 - Government Programmes
  supporting the **European** partnership and
  financing the implementation of ALFRED at RATEN ICN
- Feb 2017 - New **sub-programme** specifically dedicated to **ALFRED** (National Plan for RDI 2015-2020
- **May 2017 - Commitment to support a share of 20% of the total cost**
- Sep 2017 - ALFRED included as an **emergent research infrastructure** (National Roadmap for Major Research Infrastructures)

- **Feb 2018 - Romanian position paper on ALFRED**
- **Mar 2018 - ALFRED included in the demonstrator fast track by ESNII**

LEADER

Lead-cooled European Advanced DEmonstration Reactor

GEN IV International Forum

A Technical overview from the LEADER project - Back to 2010

Project Partners:

ANSALDO NUCLEARE Ansaldo Energia Group

ENEA

KIT Karlsruhe Institute of Technology

Cirten

SCK•CEN STUDIECENTRUM VOOR KERNENERGIE CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

RATEN ICN PITEŞTI

PAUL SCHERRER INSTITUT PSI

EMPRESARIOS AGRUPADOS

cea

KTH VETENSKAP OCH KONST

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

AGH

ÚJV

JRC

NRG

Development of a New Concept

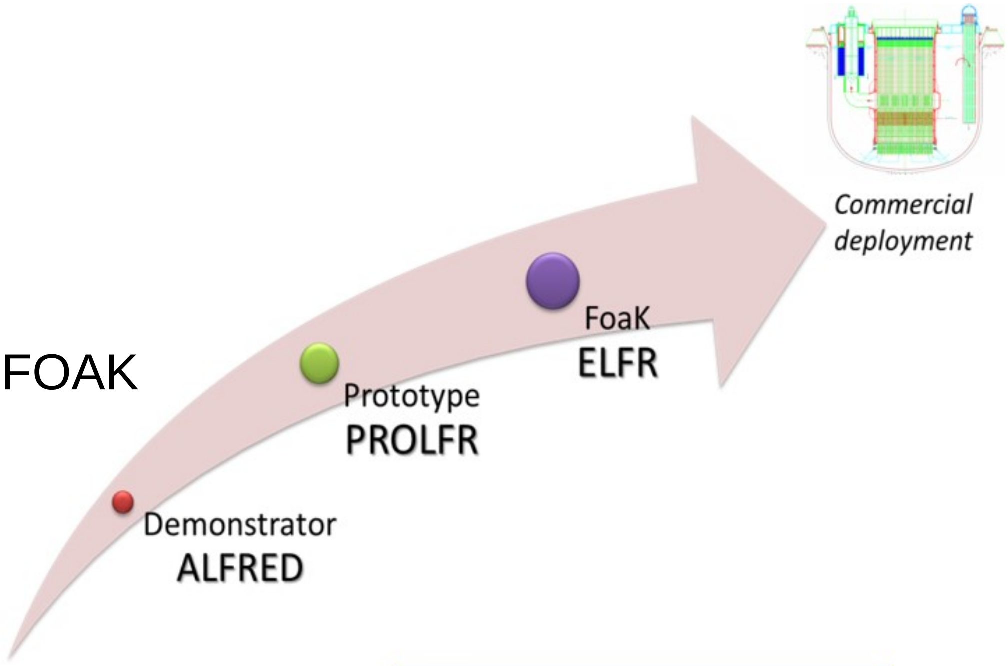
Development of a new reactor technology must follow a chain of gradual and progressive steps to reach maturity

- Identification of main adavntages/issues related to the technology
- Small scale to Large scale experimental facilities
- Irradiation tests, fuel and materials development

and try to:

- Exploit full potential of the coolant
- Include from the beginning Safety in the Design
- Show sustainability of the fuel cycle
- Define and evolve a reference conceptual design of the FOAK

ELFR roadmap is based on the progressive up-scaling from a zero power facility to the commercial Deployment of the first-of-a kind plant



LEADER
Lead-cooled European Advanced DEmonstration Reactor

Design can take into account the coolant potential…..

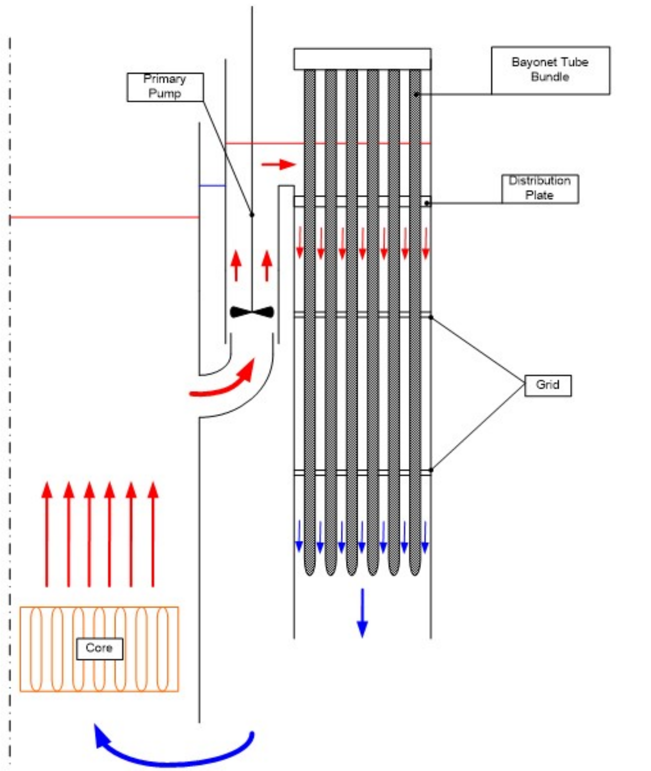
- Lead does not react with water or air
  Steam Generators installed inside the Reactor Vessel

- Very high boiling point (**1745°C**), very low vapor pressure (3 10^{-5} Pa @ 400 °C)
  Reduced core voiding reactivity risk, practically no lead deposition on cold surfaces

- Lead has a high density
  Dispersion of breached fuel favored

- Lead is a low moderating medium and has low absorption cross-section
  No need of compact fuel rods (large p/d defined by T/H)
  → Very low pressure losses (1 bar for core, 1.5 bar for primary loop)
  →Very high primary natural circulation capability → natural circulation DHR

LEAD COOLANT ⟷ ***PASSIVE SAFETY***



Sketch of the primary configuration presented at LEADER kick – off meeting – Genova, April 21st, 2010

….but also take care of the issues

High Lead melting point (~ 327 °C) –Lead Temperature above 340-350 °C

Heating system, design and operating procedures

Overcooling transient (secondary side) may cause Lead freezing

FW and DHR requirement – Really a safety issue?

Corrosion / erosion of structural materials - Slugging of primary coolant

Coatings, oxygen control, limit flow velocity

Strategy at low oxygen content, Lead chemistry

Seismic risk due to large mass of lead

2-D seismic isolators, vessel hanged, specific design

In-service inspection of core support structures

Similar to other HLM reactors but high T, all components replaceable

Fuel loading/unloading by remote handling

Develop appropriate cooling system (active → passive back-up)

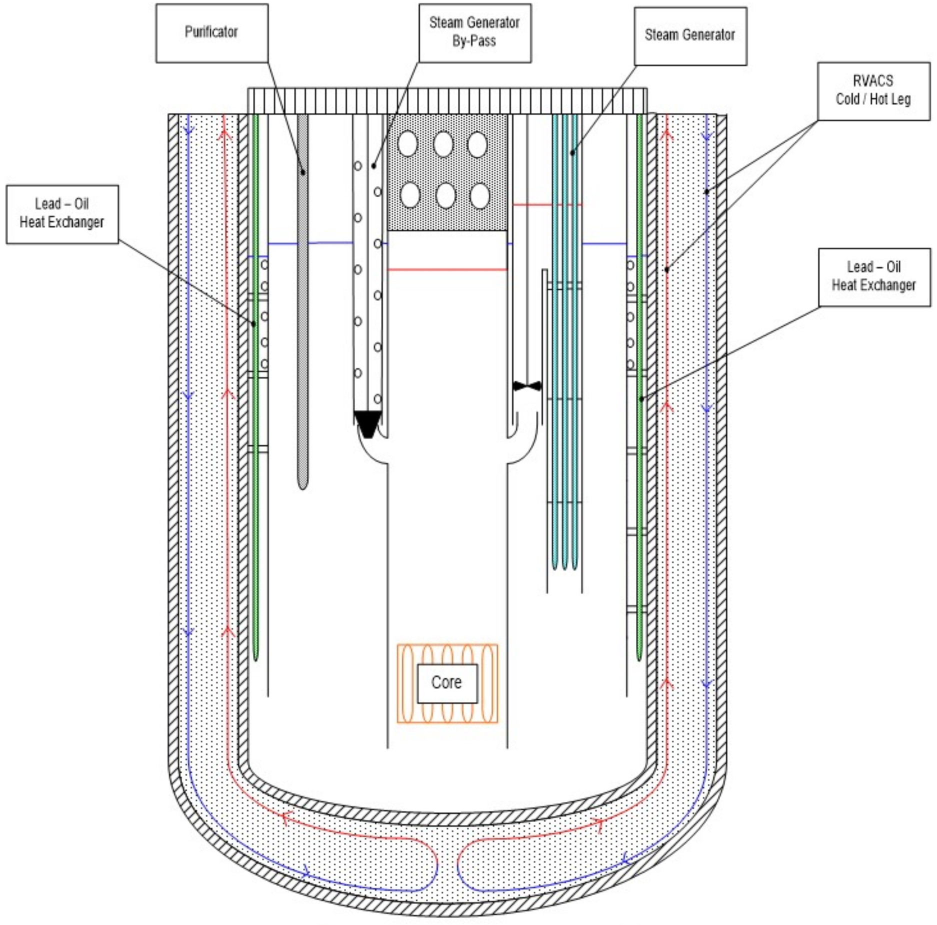
Steam Generator Tube rupture inside the primary system

Show no effect on core, rupture disks/Safety valves on reactor cover limit max pressure, double walls SG tubes

Flow blockage and mitigation of core consequences

Hexagonal wrapped Fuel Assemblies

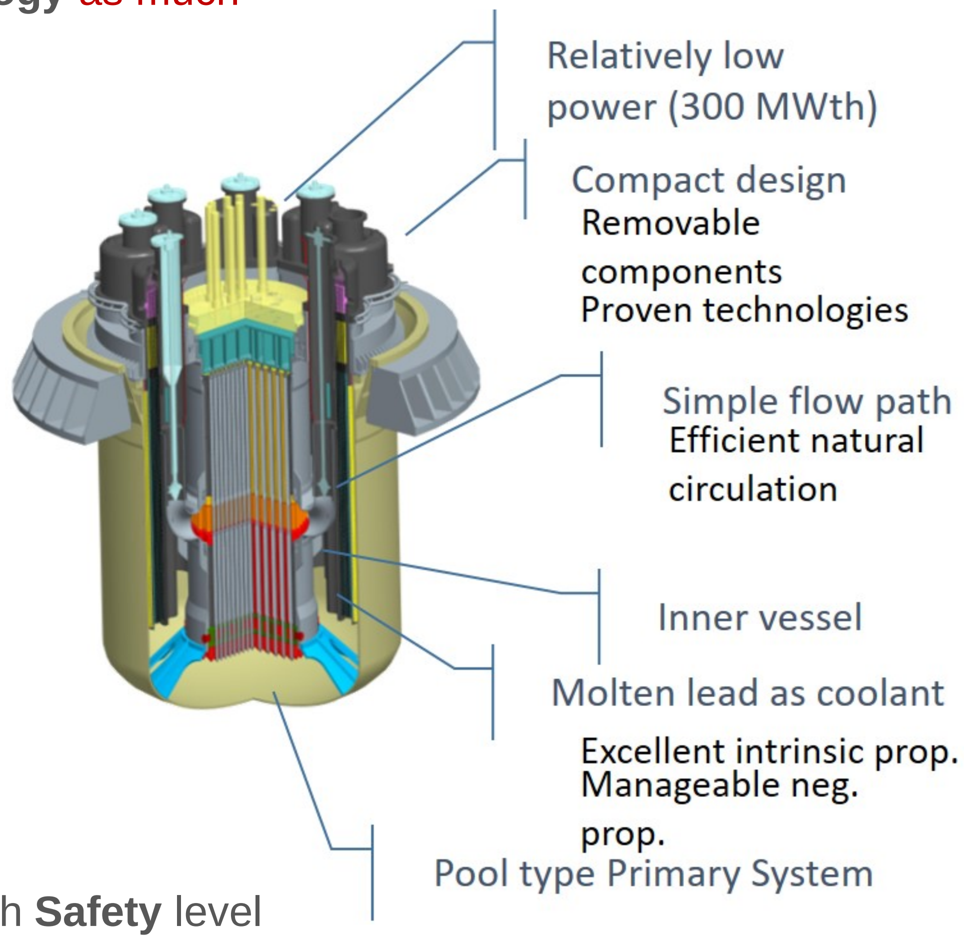
Outlet temperature continuous monitoring - Multiple FA flow inlet



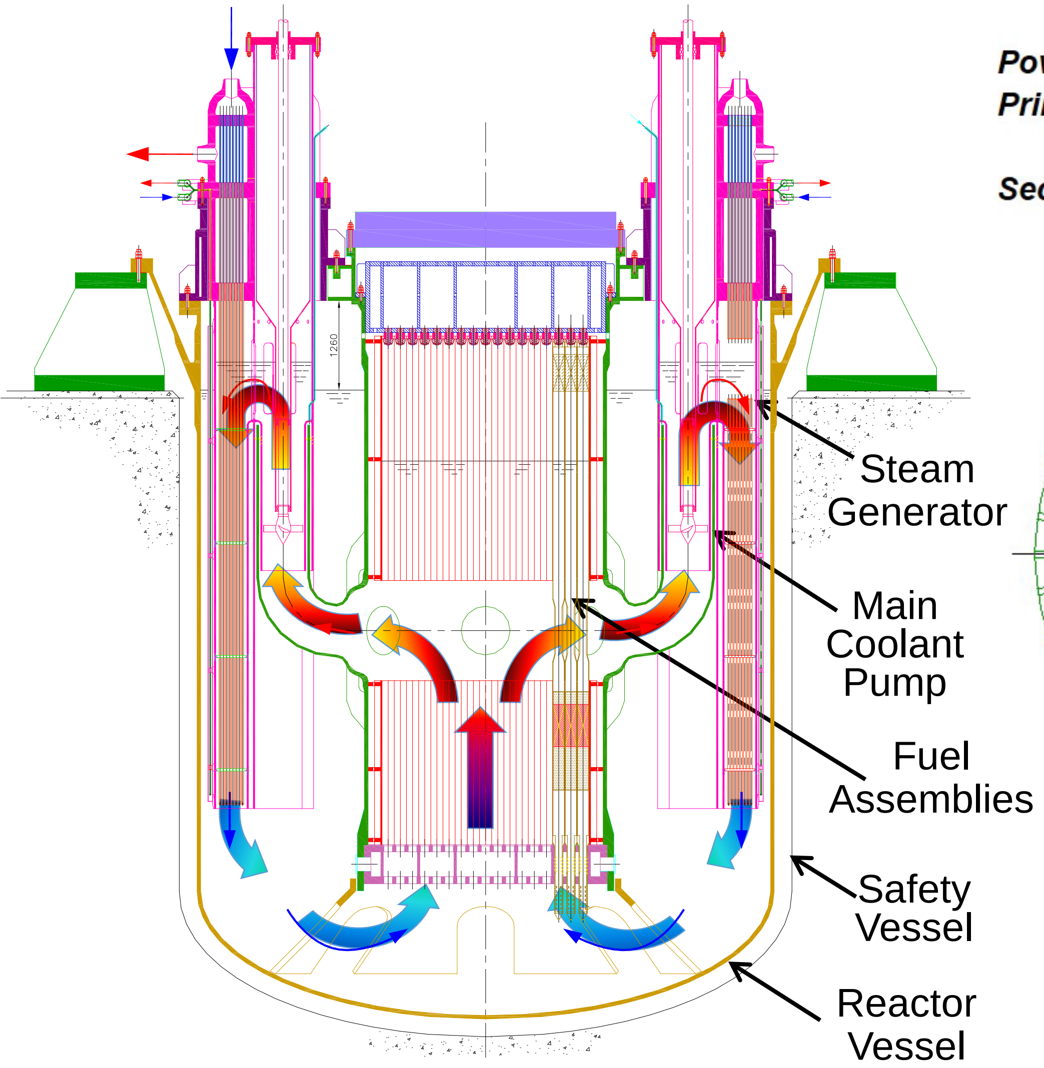
Sketch of the primary configuration presented at LEADER kick – off meeting – Genova , April 21st, 2010

ALFRED – Design Guidelines

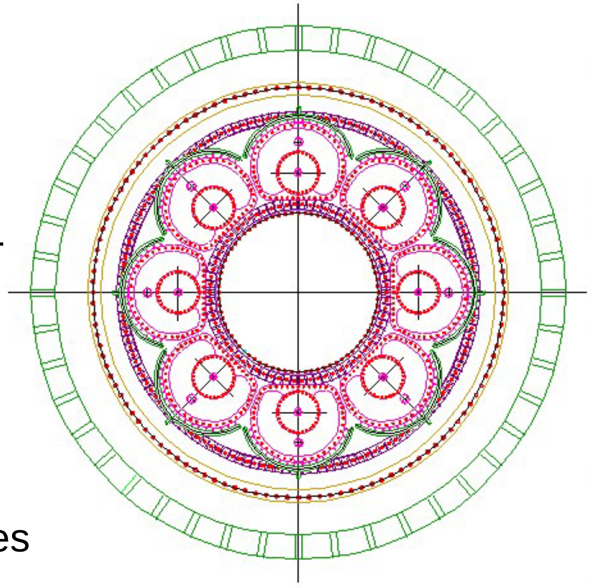
- ALFRED shall be connected to the **electrical grid** (Reactor Power ~125 MWe)
- ALFRED design should be based on **available technology** as much as possible, in order to speed up the **construction** time
- ALFRED shall use structural **materials** compatible with the **corrosive** Lead used as coolant (selected candidate materials AISI 316LN, 15-15/Ti)
- ALFRED design shall **limit** coolant flow velocity to values compatible with the **erosive** Lead used as coolant
- ALFRED design solutions shall allow components to be **removed** from the Reactor Vessel to facilitate inspection, maintenance, replacement
- ALFRED design solutions (especially for Safety and Decay Heat Removal function) shall be characterized by very **robust** and **reliable** choices to smooth the **licensing** process
- ALFRED Decay Heat Removal Systems shall be based on **passive** technology to reach the expected high **Safety** level (low primary system pressure drops to enhance natural circulation)



ALFRED – the Primary System



Power:	***300 MWth***
Primary cycle	***Atmospheric***
	400-480 °C
Secondary cycle	***1.8 Mpa***
	335-450 °C

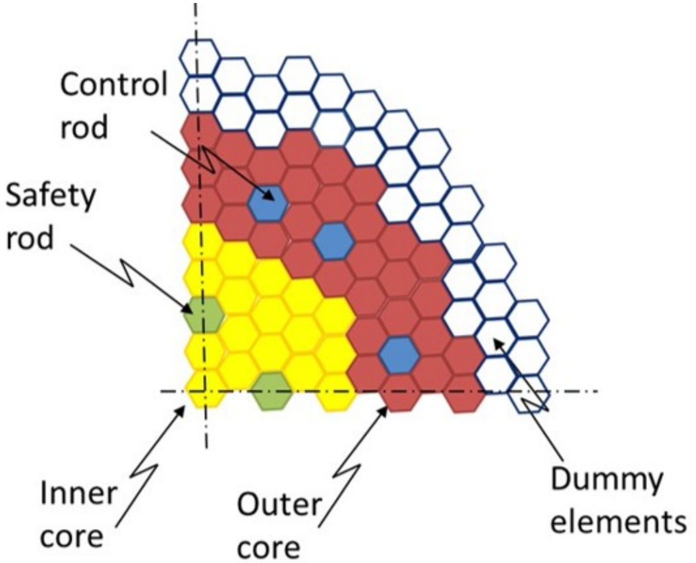


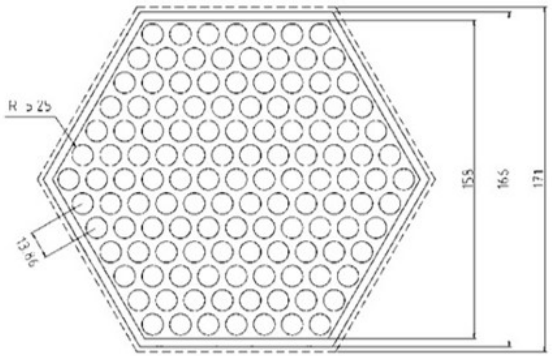
TOP VIEW

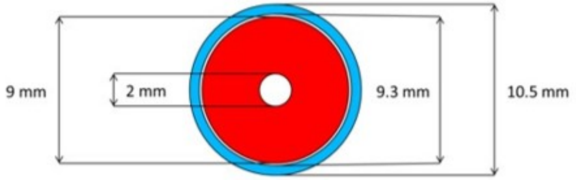
Primary system	Pool-type, compact
Coolant circulation	
Normal operation	Forced (8 pumps)
Accident conditions	Natural (pressure drop 0.15 MPa)
Pressure	< 0.1 Mpa
Temparature	400-480°C
Flowrate	26 000 kg/s
Reactor vessel	Austenitic SS, hung
Safety vessel	Anchored to the pit
Inner vessel (Removable)	Cylindrical, Integral with the core support grid and the hot collectors
Steam generators	8, bayonet type with double walls,
Primary pumps	8, integrated with the SGs, in hot leg
Fuel assembly	Closed (with wrapper), Hexagonal, forced in position by springs
Control/Shutdown Systems	2 diverse and redundant systems concept derived from MYRRHA
Decay Heat Removal	2 separate and redundant systems of 4 Isolation Condensers connected to the Steam Generator (actively actuated, passively operated)
Refuelling System	No refuelling machine stored inside the Reactor Vessel

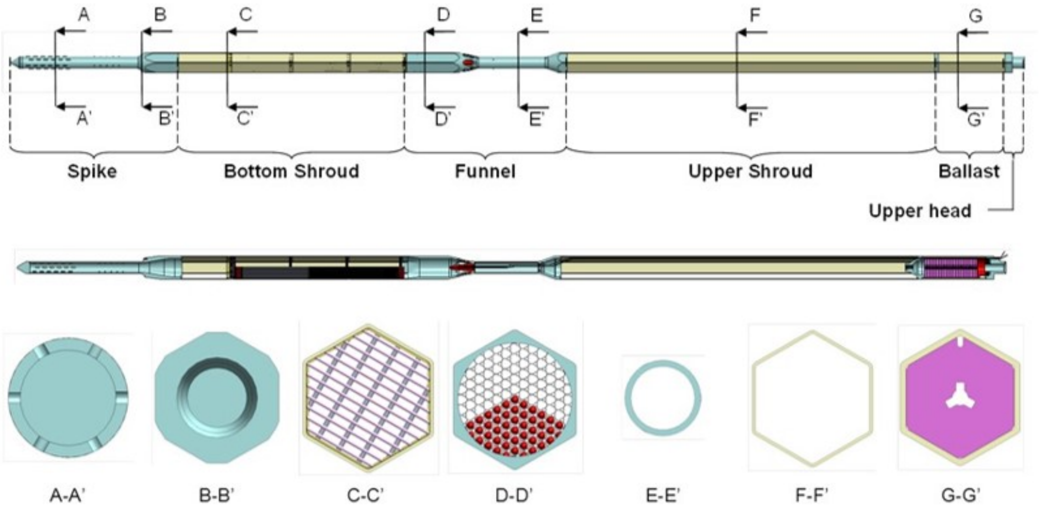
Reactor Core

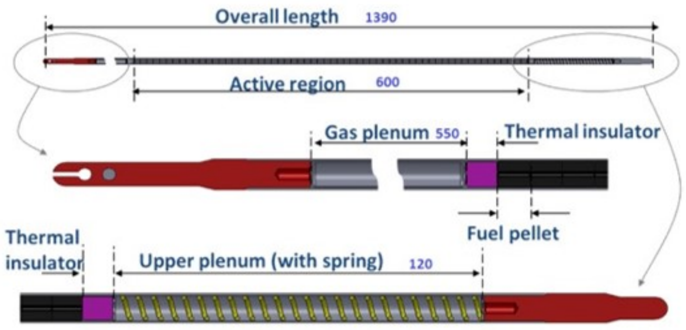
FA	171, hexagonal, wrapped
Inner	57 (21,7 at.%)
Outer	114 (27,8 at.%)
Dummy	108 (ZrO_2-Y_2O_3)
FA lattice	Triangular (127 pins)
Pins p/d	1,32
Cladding	15-15 Ti
Fuel	MOX, 25.77 at% (avg)
Residence	5 years



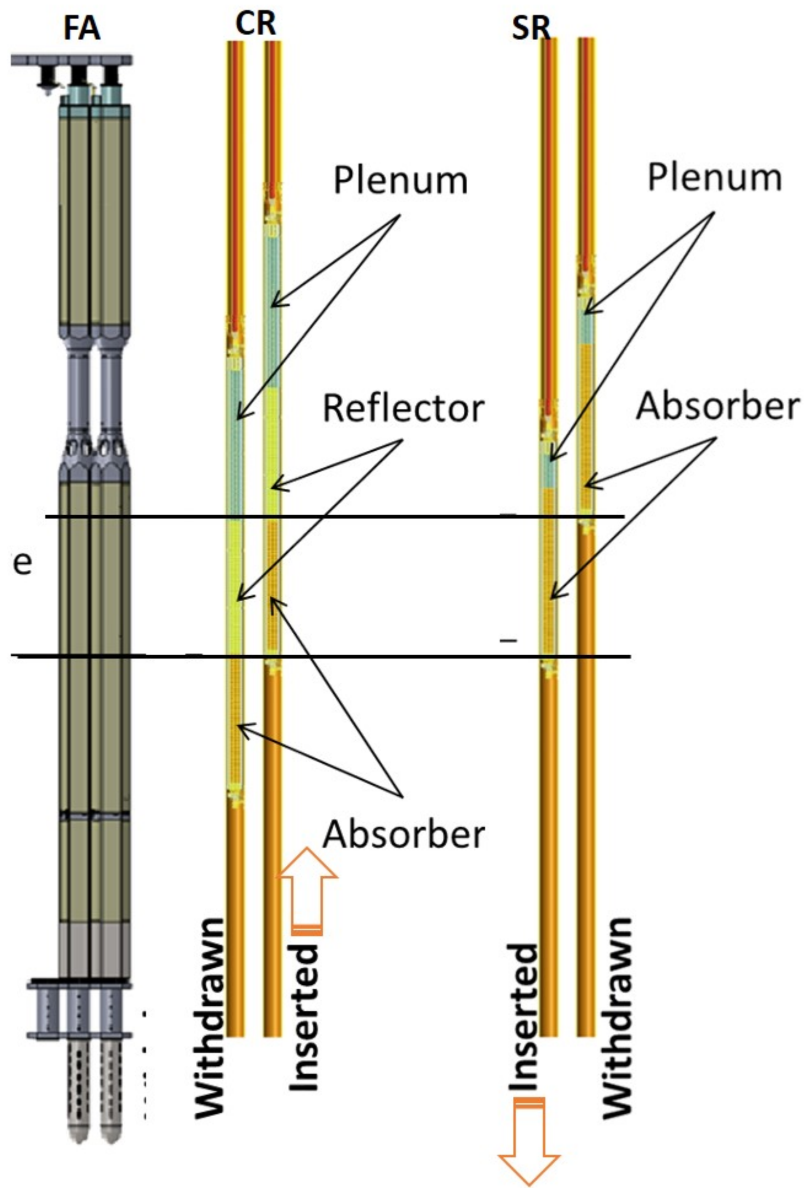








Control and Safety Rods



- Control rods (12)
  - bundle of 19 absorber pins
  - B_4C with 90 at.% ^{10}B
  - absorber length: 68 cm
  - reflector follower
  - actuation logic:
    - **withdrawn** below the core
    - moved by motors for (CZP to HZP, reactivity swing, power transients, commanded shutdown)
    - **passively** inserted by buoyancy for SCRAM
- Safety rods (4)
  - bundle of 12 absorber pins
  - B_4C with 90 at.% ^{10}B
  - absorber length: 80 cm
  - actuation logic:
    - **withdrawn** above the core
    - only for SCRAM
    - **passively** inserted by a pneumatic mechanism
    - forced insertion (backup) by **tungsten ballast**

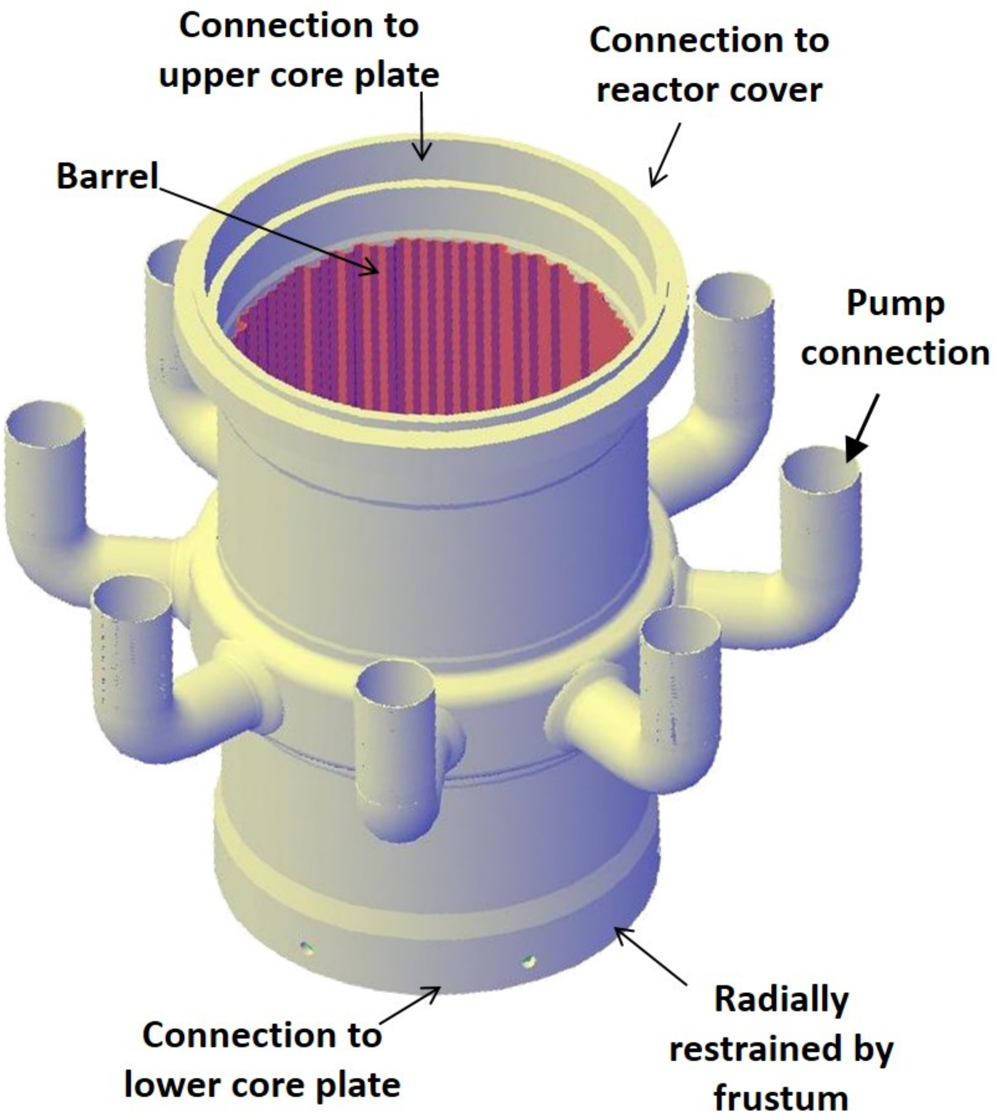
Each system designed against most reactive rod stuck / Both inserted during **refueling**

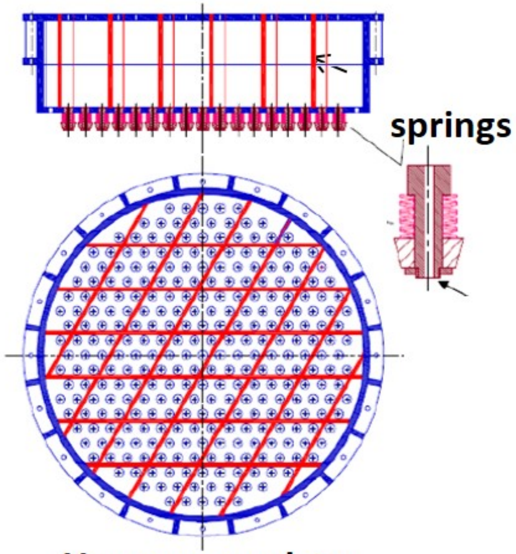
Reactor Vessel

Material	AISI 316LN
Design temperature	400°C
Height	10.13 m
Inner diameter	8 m
Wall thickness	50 mm

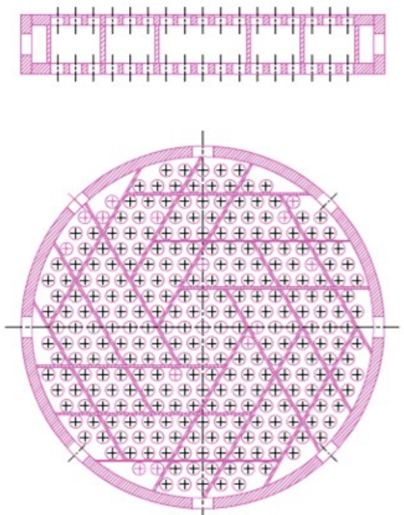
- Cylindrical with a torospherical bottom head **anchored** to reactor pit from top
- RV closed by a **roof** supporting core and all primary components
- RV upper part divided in two branches by a "**Y**" junction: the conical skirt (cold) supporting weight and the cylindrical (hot) supporting the Reactor Cover
- Cone **frustum** welded to the bottom head as radial restraint of Inner Vessel

Inner Vessel





Upper core plate

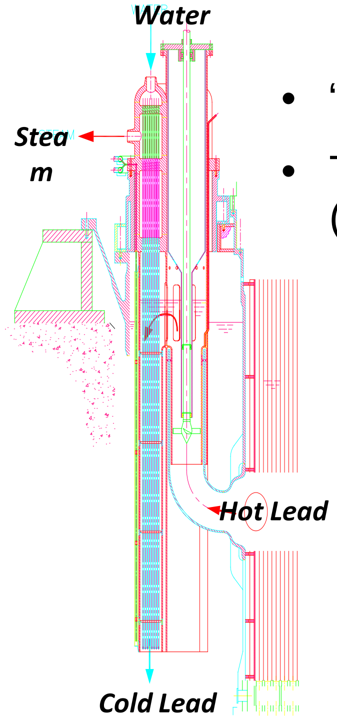


Lower core plate

- Double wall shell:
  - outer thick cylindrical wall with a **structural** function
  - inner thin wall (core barrel) **constraining** the core
- Fixed to the cover by bolts
- Radially restrained at the bottom, axially **free** to expand downwards
- 8 tubes connecting to the PP/SG units

Material	AISI 316LN
Height	9,7 m
Inner diameter	3,3 m
Wall thickness	50 mm
Core barrell thickness	20 mm

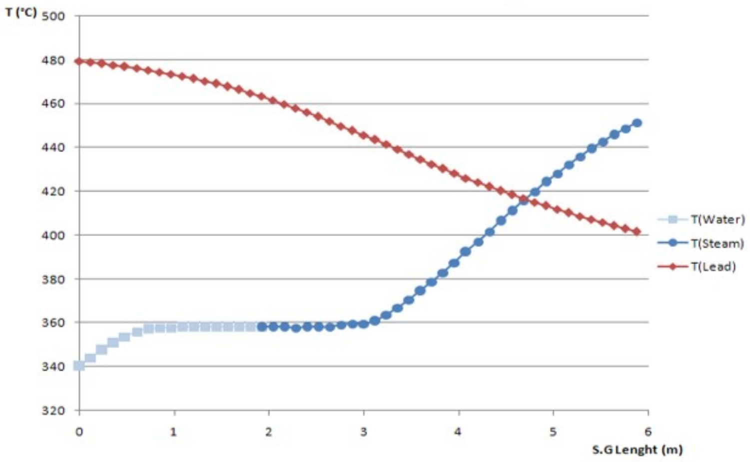
Steam Generator & Pump

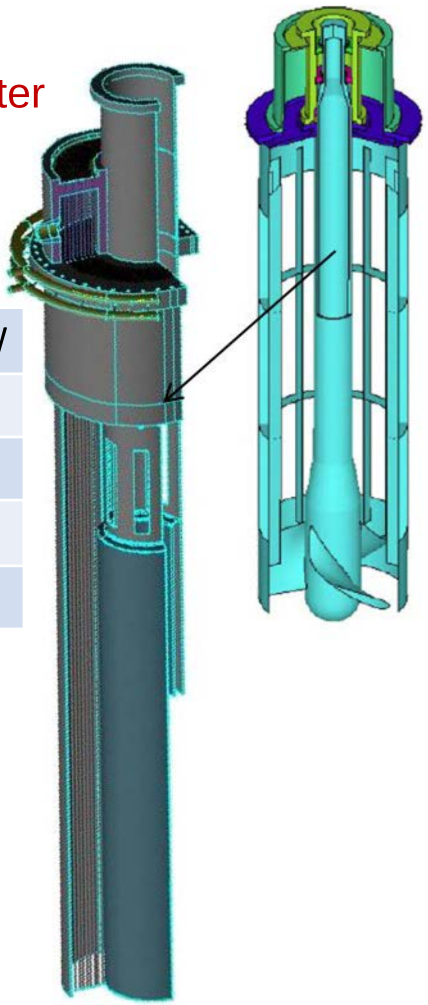


- "**C**" shell with **PP** at the center
- Tubes in triangular lattice (p/d=1.42)

Removed Power	37.5 MW
Core outlet Lead T	480 °C
Core inlet Lead T	400 °C
Feedwater T	335 °C
Steam outlet T	450 °C

SG performances



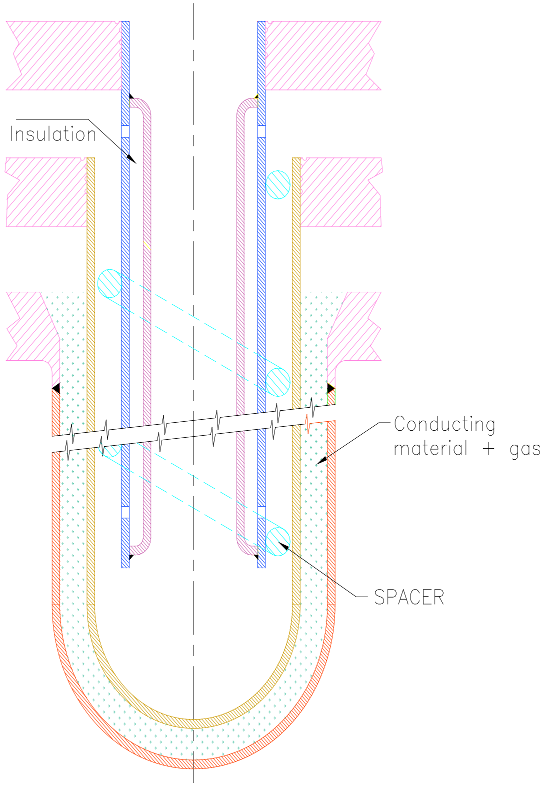


Primary Pump

Flow rate	3247.5 kg/s
Head	1.5 m
Impeller diameter	0.59 m
Hub diameter	0.39 m
Impeller speed	315 rpm
Number of vanes	5
Suction pipe vel.	1.12 m/s
Vanes tip vel.	9.8 m/s

Bayonet Tube Concept

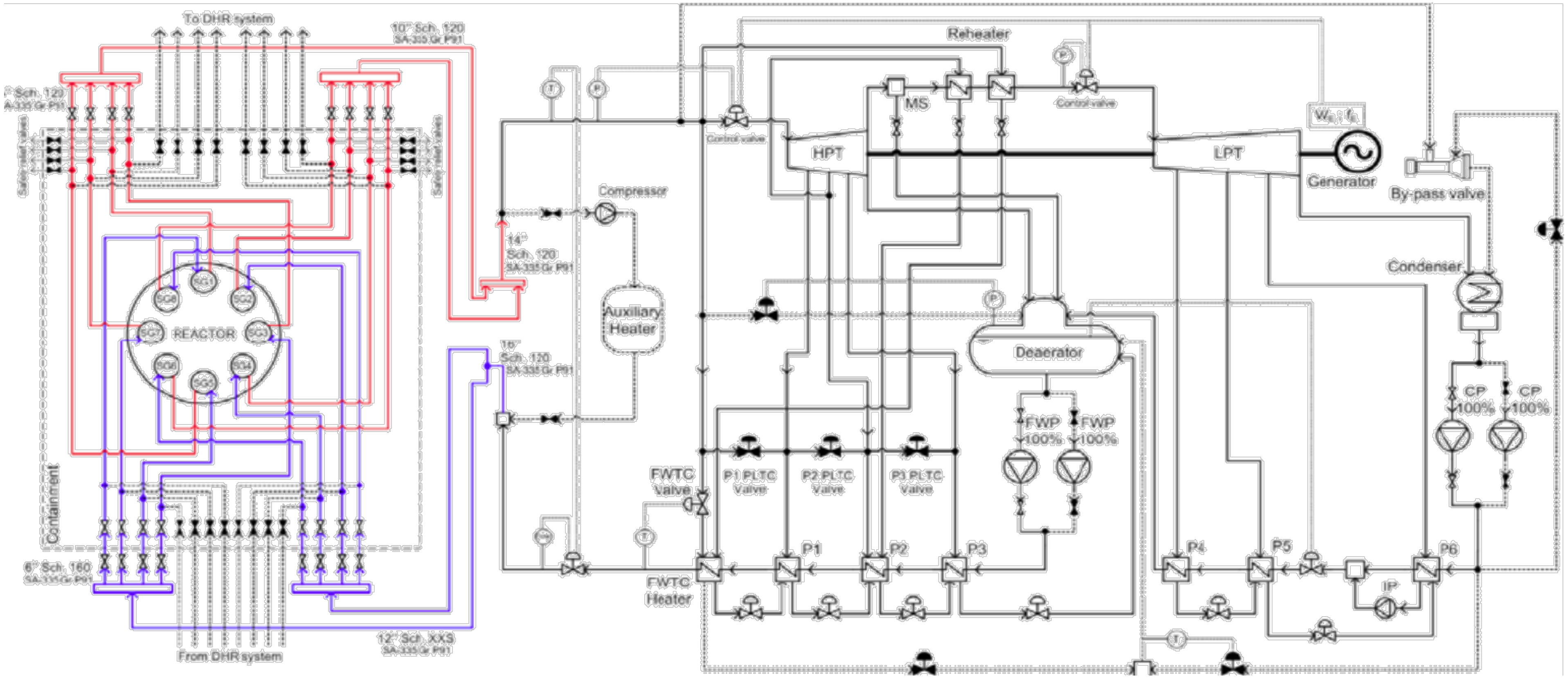
Exchange length	6 m
Number of tubes	510
Number of tubes	4 coaxial
Slave tube	9.52 mm
Inner tube	19.05 mm
Outer tube	25.4 mm
Outermost tube	31.73 mm



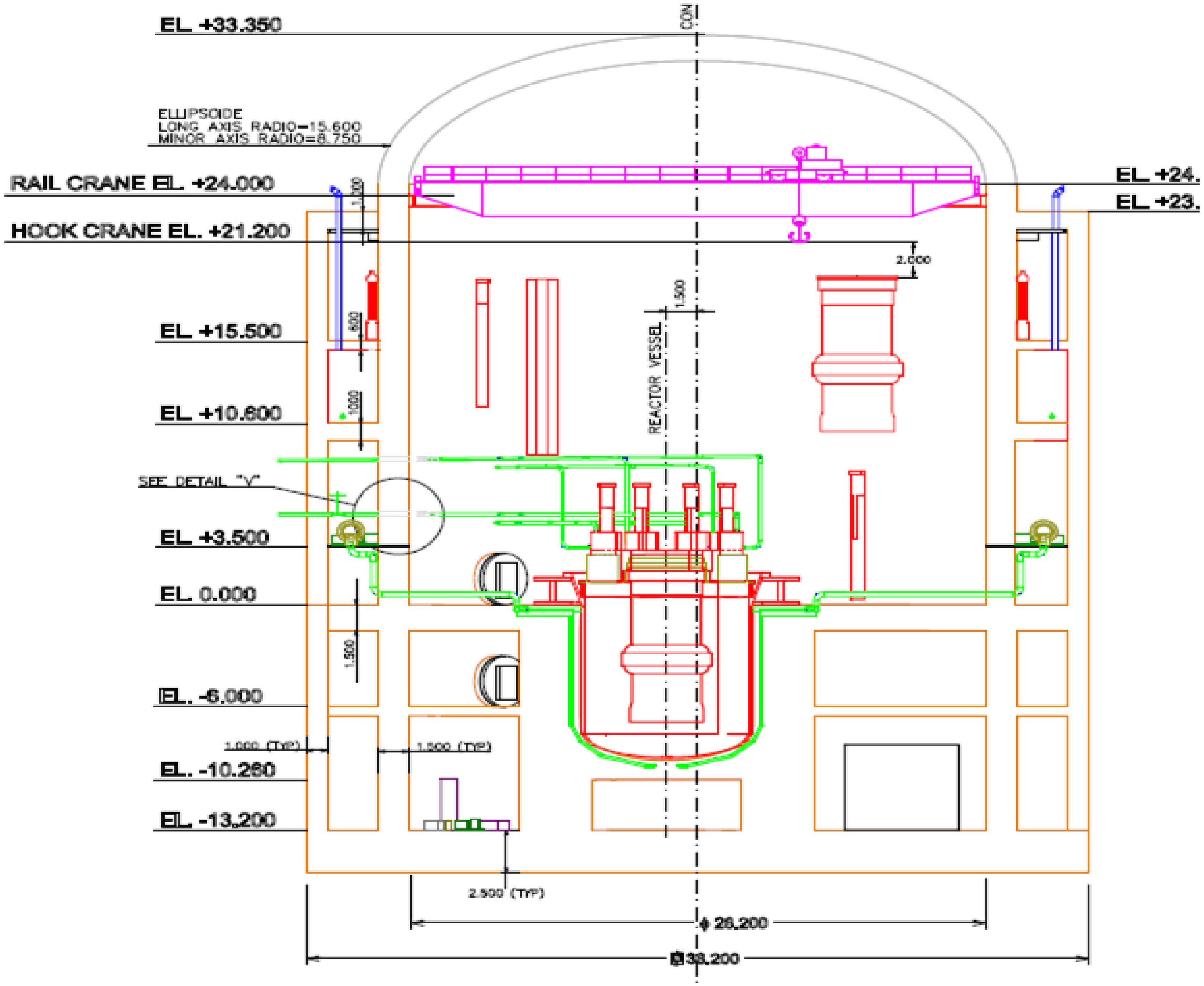
ALFRED - Secondary System

Plant net output	125 MWe
Cycle Net Efficiency	41%
SG Mass Flow	192.7 kg/s
SG Pressure outlet	18.2 Mpa
SG Pressure inlet	18.8 Mpa

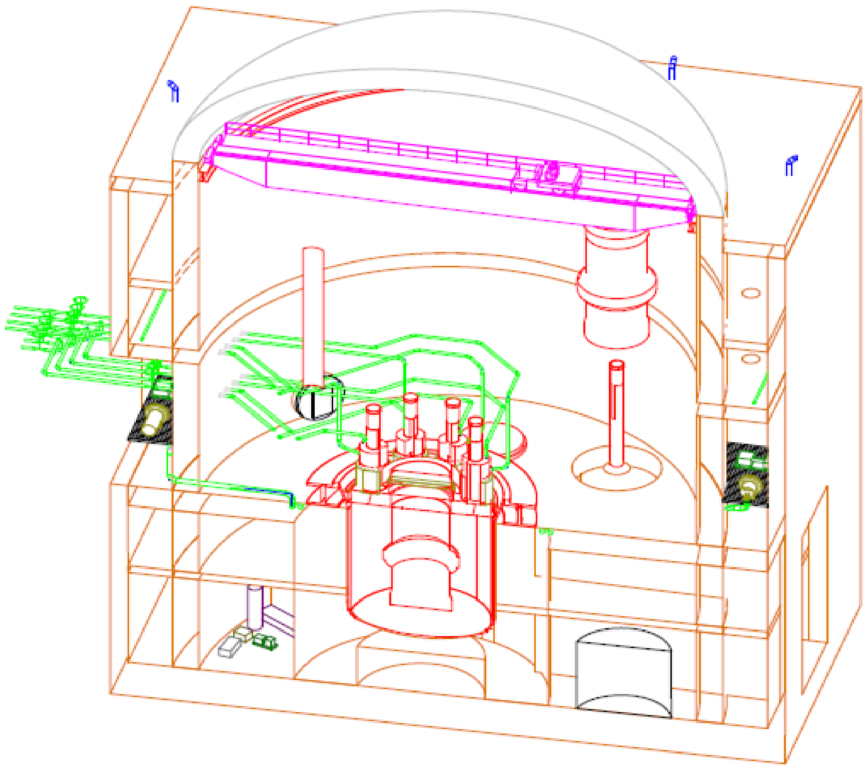
- Superheated cycle
- Dual turbine configuration
- 3 extractions in HP and in LP



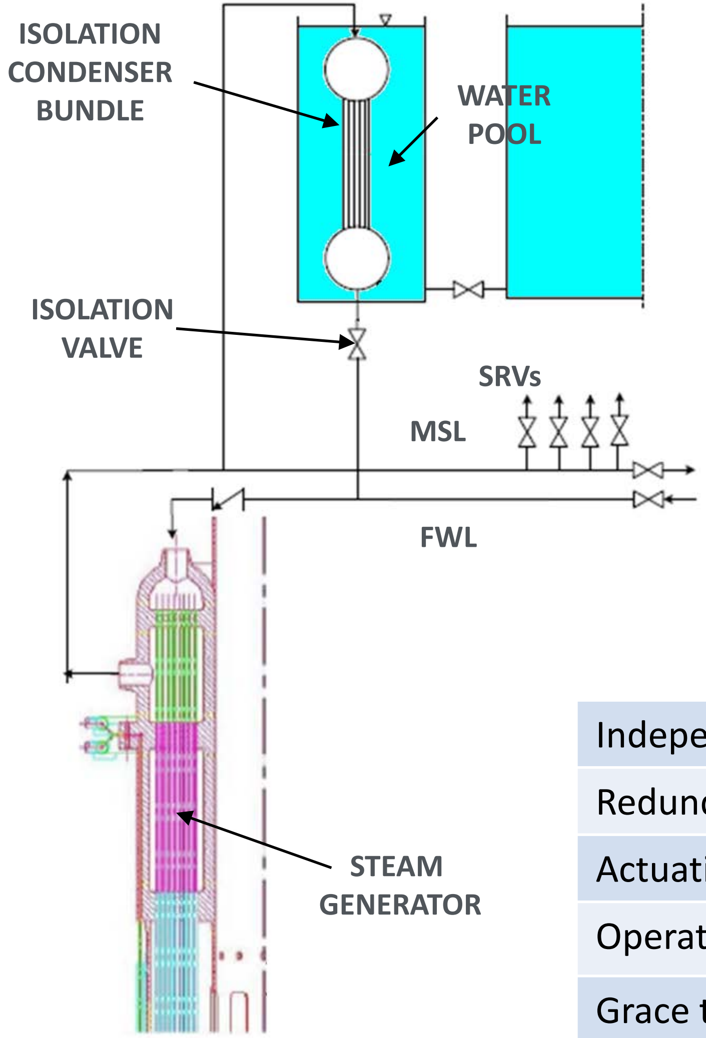
ALFRED - Reactor Building



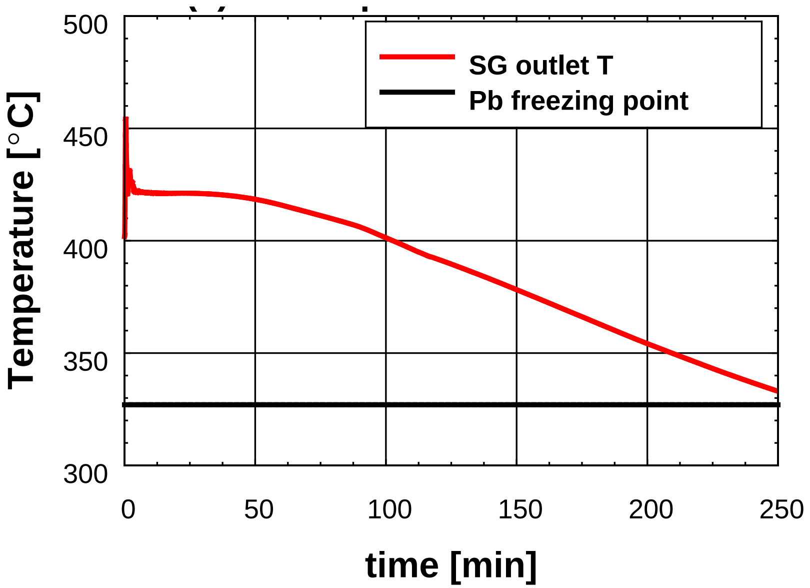
- Seismic isolation of ALFRED (SILER project)
- Strong reduction of ground accelerations
- Help design standardization



Safety: ALFRED decay heat removal



SBWR experience



Independence	2 systems (4 SGs, 4 loops)
Redundancy	3 out of 4 loops
Actuation	active (condensate valve)
Operation	passive (no need of AC power)
Grace time	3 days (water inventory)
Safety Relief Valves	195 bar

Description of working principle

System called in operation by:

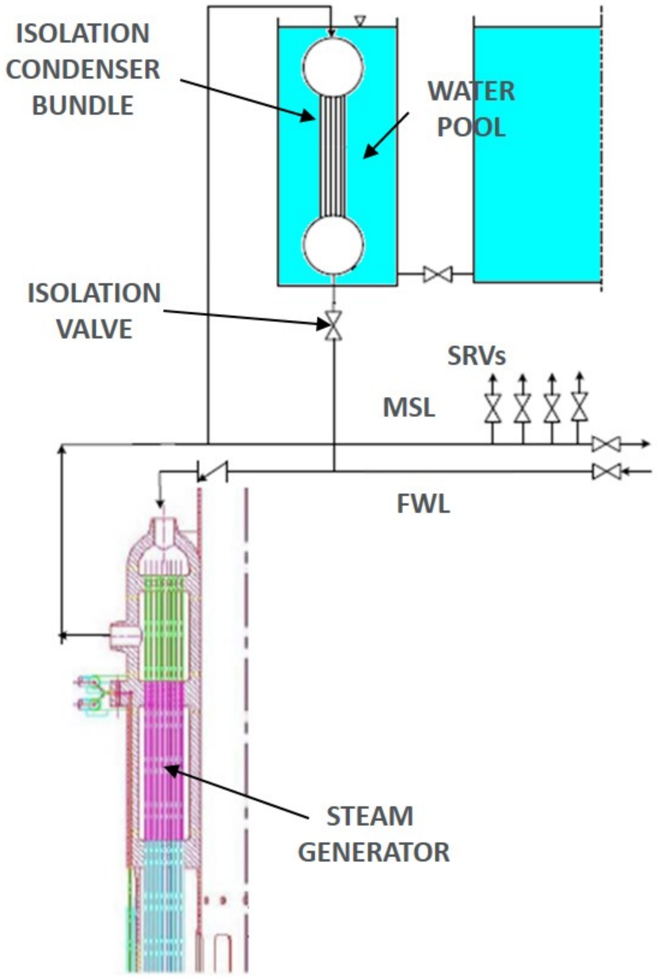
Closing MSIV and MFWIV

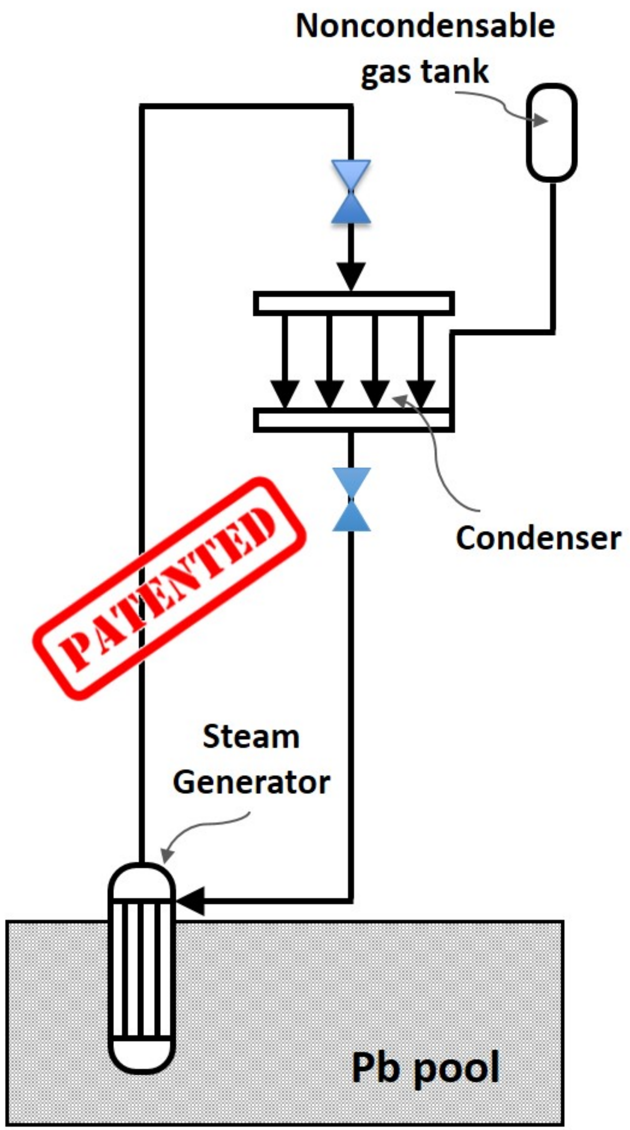
Opening Isolation Valve

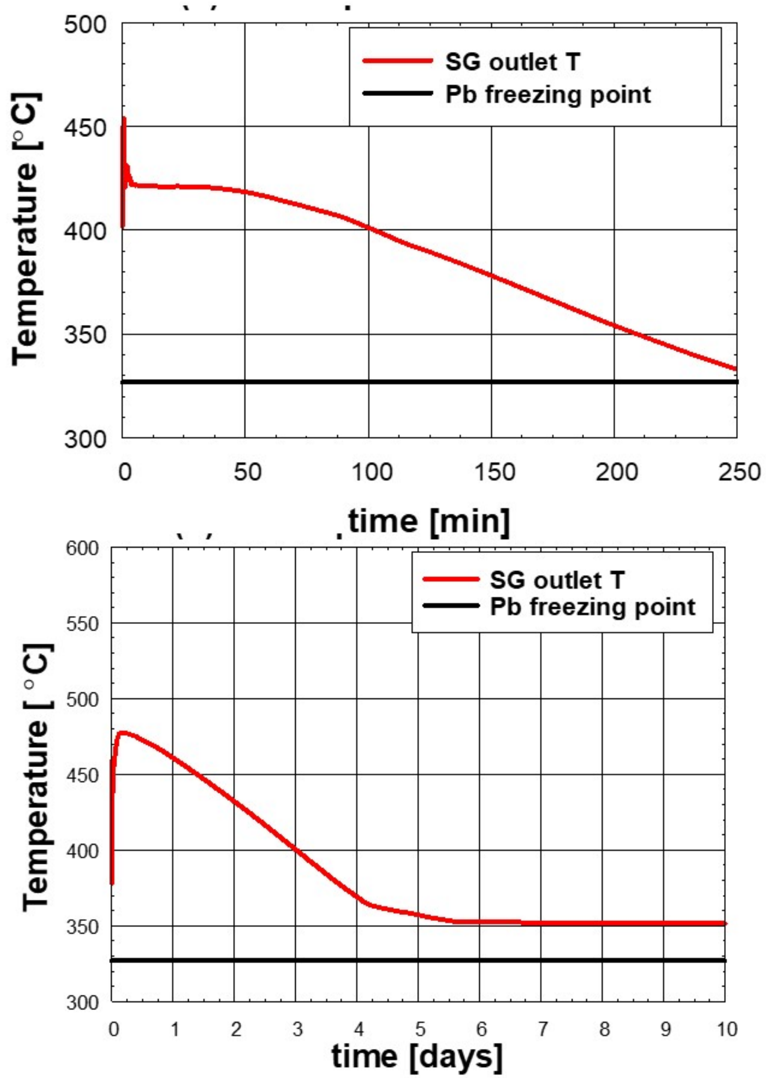
Water inside IC injected to SG

SG-Evaporation/ IC-condensation

Safety: ALFRED decay heat removal



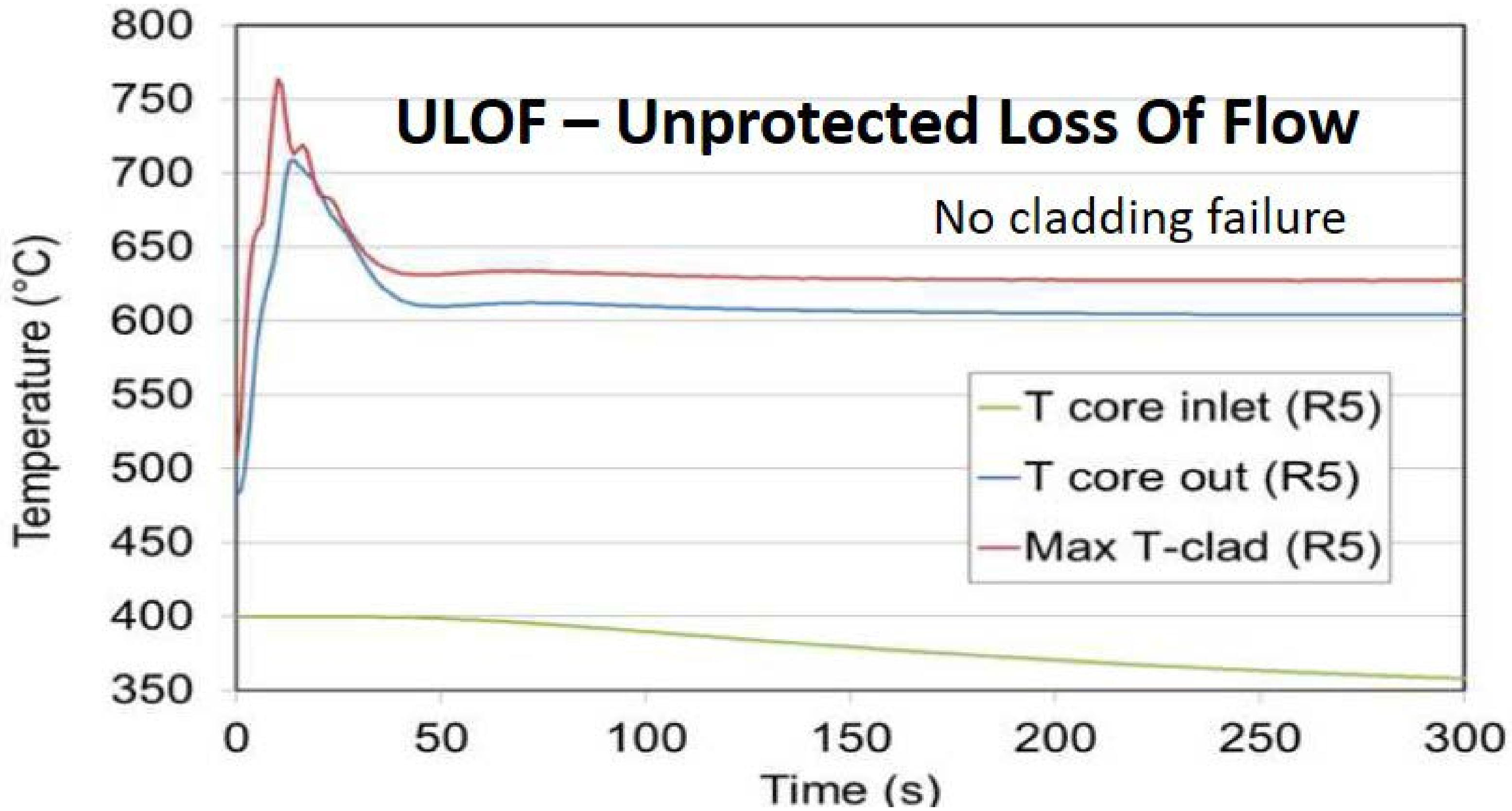




Safety: Transients without SCRAM

Unprotected Transients are very unfavourable scenarios with no SCRAM actuation (both CRs and SRs systems are not actuated) - System response determined by natural characteristics (reactivity feedbacks) of the core

- Reactivity Feedback coefficients decrease power
- Temperatures tend to increase slowly or stabilize
- No major degradation for fuel, cladding or vessel

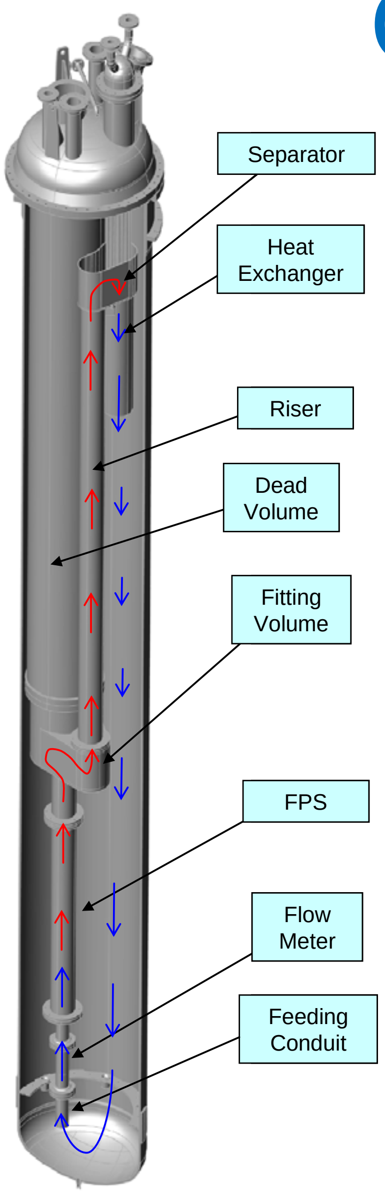


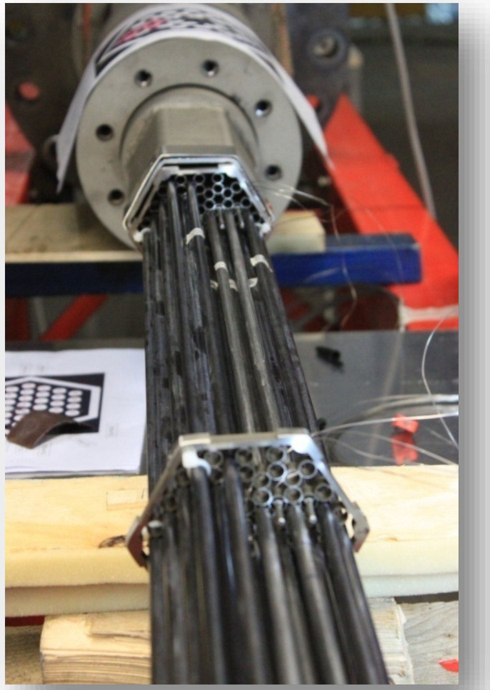
ALFRED Status

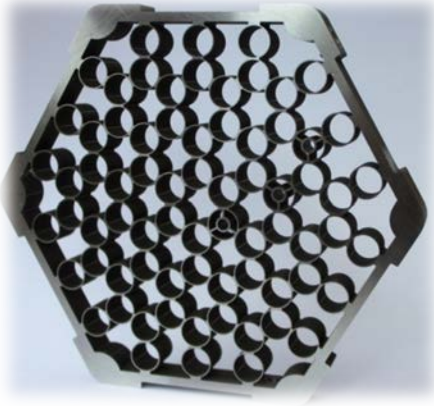
- Design review on-going
- Main options confirmed
- Diversification of decay removal systems
- Working on aspects not directly addressed in **LEADER** project
- Construction of facilities and experiments
- Technology developments (chemistry and materials)
- Operation strategy
- Experimental facilities support on going….

Integral Test & Component Qualification

GEN IV International Forum





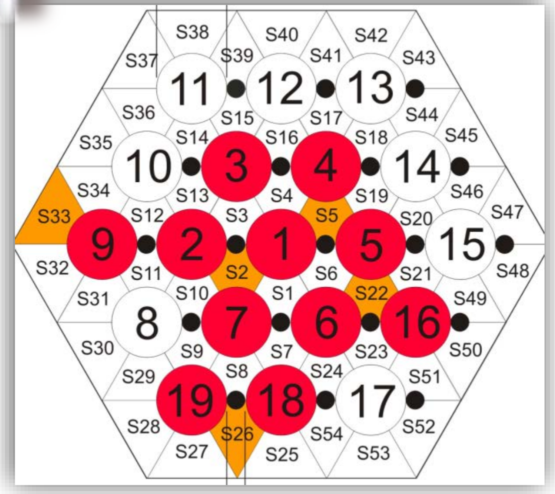


- Integral Experiments (1 MW)
- OCS testing in large pool
- Component qualification
- SGTR Experiments
- SG & Pump Unit Test

Courtesy of ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

CIRCE – CIRCulation Eutectic

Fuel Pin Bundle



- Experiments @ 250 kW
- OCS testing in loop
- Component qualification
- Instrumentation Test

Courtesy of ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

NACIE – Natural CIrculation Experiment

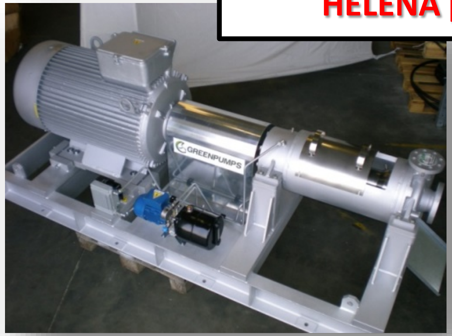
Material Characterization

LECOR loop

HELENA pump impeller

HELENA loop

HELENA pump



- Corrosion test in flowing lead
- OCS testing in loop
- Component qualification
- Instrumentation Test
- Pump Unit Test

Courtesy of ENEA

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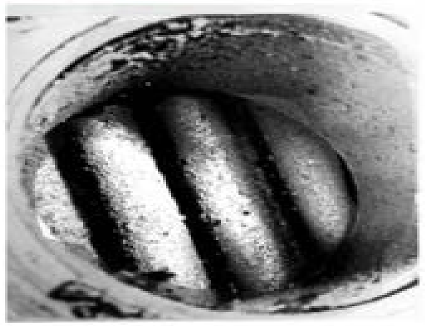
CHEMISTRY OF HLM (LEAD AND LBE)

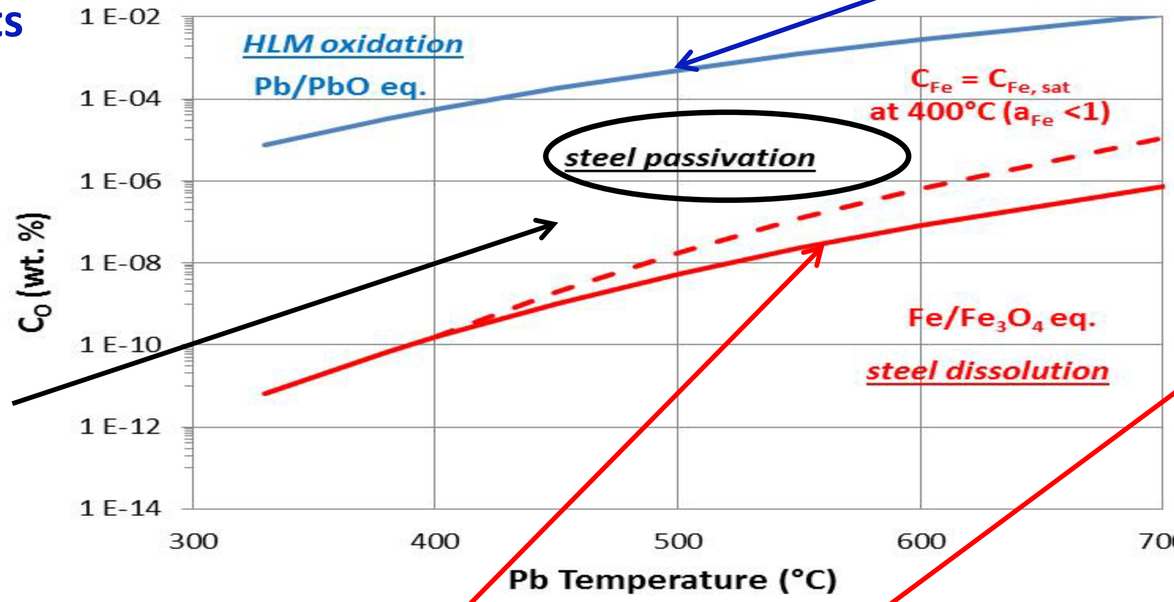


High Oxygen → slug deposits

$$Pb_{liq} + O_{diss} \leftrightarrow PbO_{diss}$$

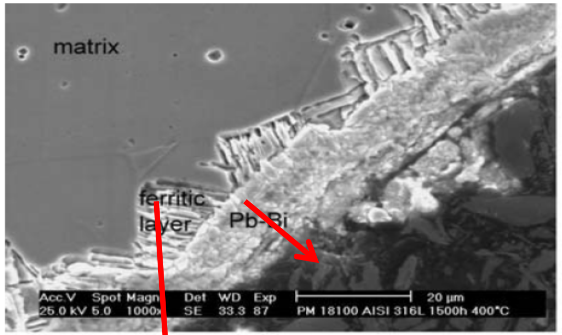
Oxygen saturation and PbO deposition

oxygen balancing for steel passivation and to avoid PbO formation:
need of <u>oxygen sensors</u> and <u>oxygen control devices</u>



Steel corrosion at low oxygen content

Ni and Cr dissolution in 316L steel. Flowing LBE, 400◦C , low C_O, 1500 h.



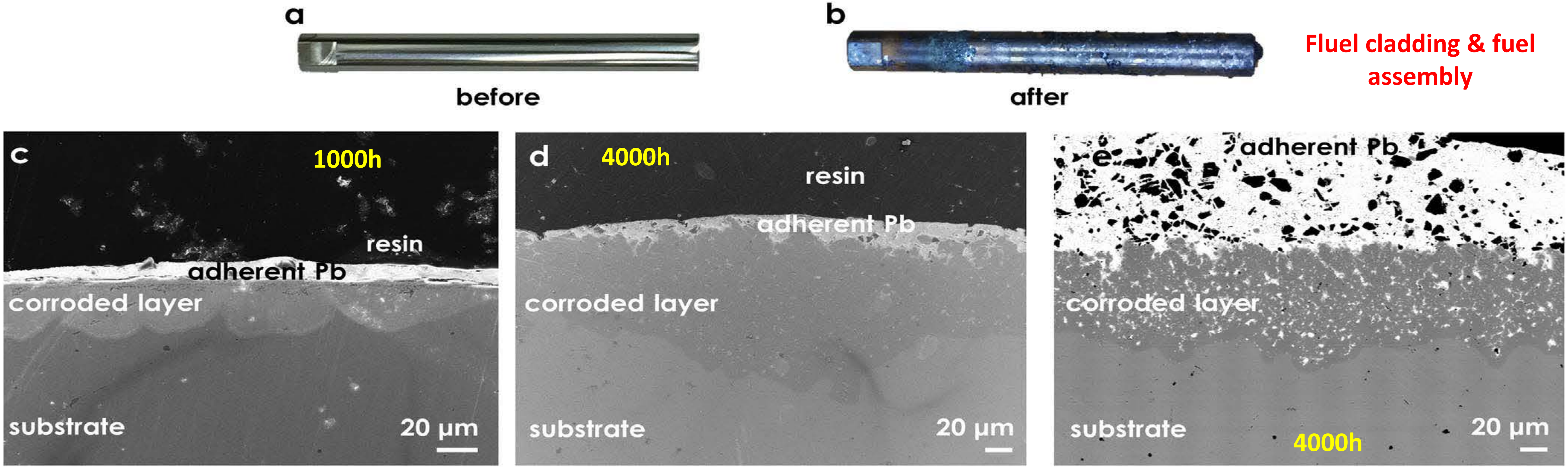
Benamati et al., J Nucl Mater 335 (2004) 169-173.

Low Oxygen → Dissolution

Courtesy of ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

15-15Ti cold worked steel, static Pb, 550°C, 1000-4000h, [O] = 10^{-8} % wt.

Fluel cladding & fuel assembly



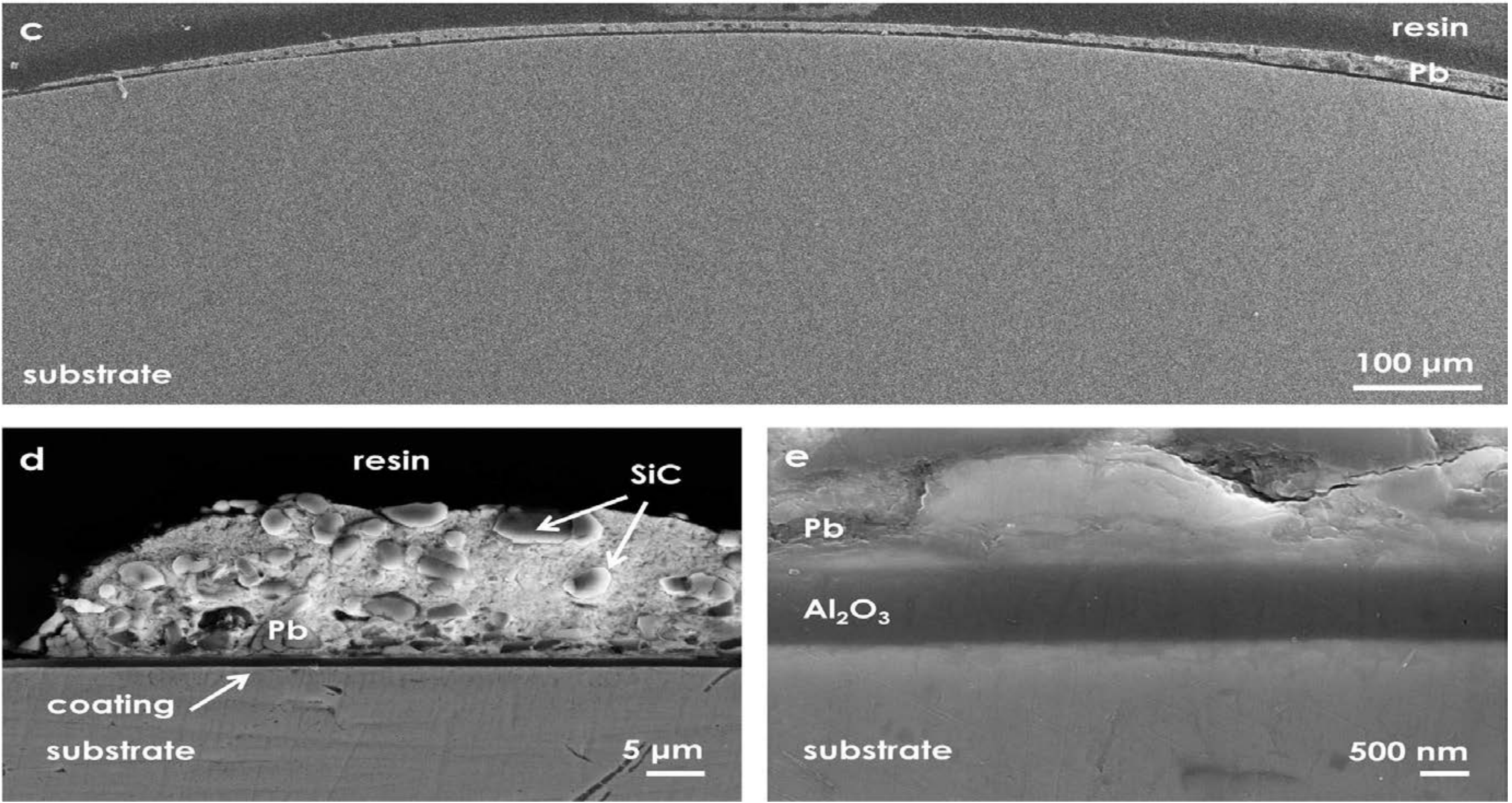
Cross-sectional micrograph in (c) reveals the presence of a corroded layer (depth of ≈ 25 µm) underneath the adherent solidified Pb after 1000 h.
After 4000 h, the depth of the corroded layer increases to approximately 85 µm and occasionally exceeds 150 µm (d). The micrograph in (e) shows that the corroded layer contains considerable amounts of Pb.

F. García Ferré et al., Corr. Sci. 124 (2017) 80-92.

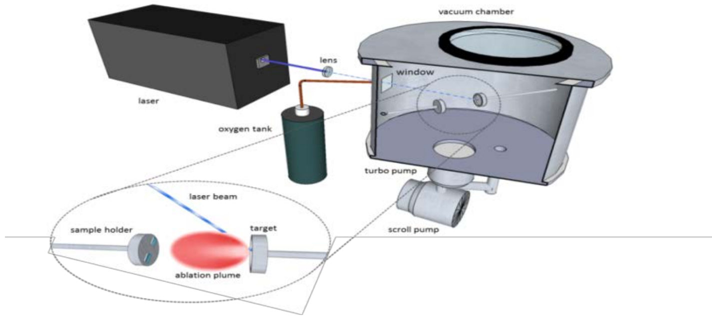
Courtesy of ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

PLD-Al_2O_3 coating (IIT), static Pb, 550°C, 4000h, [O] = 10^{-8} % wt.

amorphous alumina with nano-crystalline inclusions



Coated 15-15Ti with PLD-Al_2O_3 for fuel cladding & fuel assembly



Pulsed Laser Deposition

No evidence of Pb corrosion neither at the macroscopic scale (c) nor at the microscopic scale (d and e).

F. García Ferré et al., Corr. Sci. 124 (2017) 80-92.

Courtesy of ENEA

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A long way walked…

- Many relevant activities performed at national and European level
- Relevant evidences collected to target the horizon objective
  - significant extension of the technological base
  - identification of solutions for the main issues, no longer seen as show-stoppers

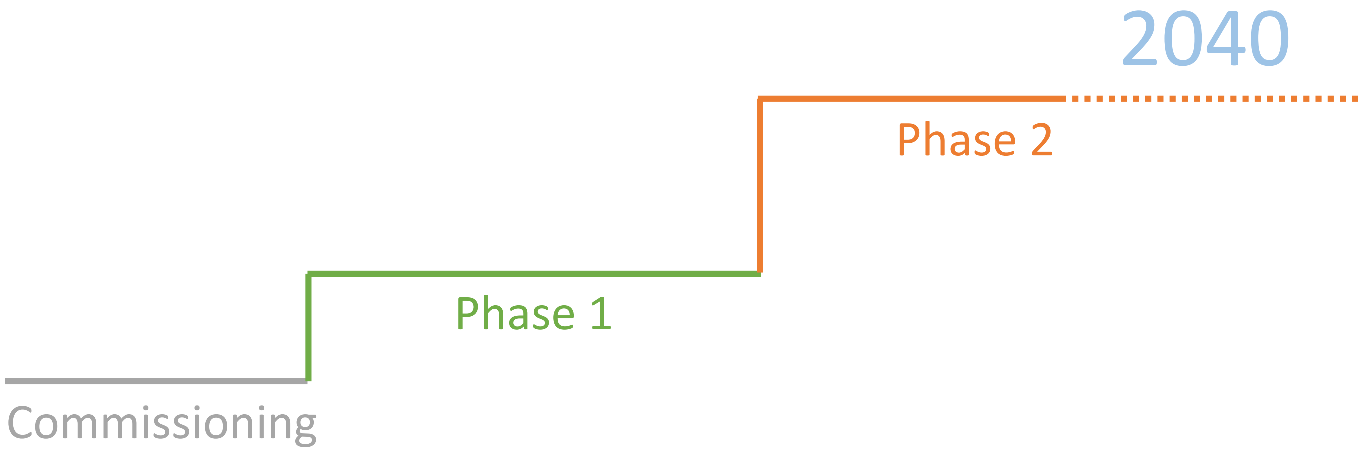
Awareness of a much higher technology readiness

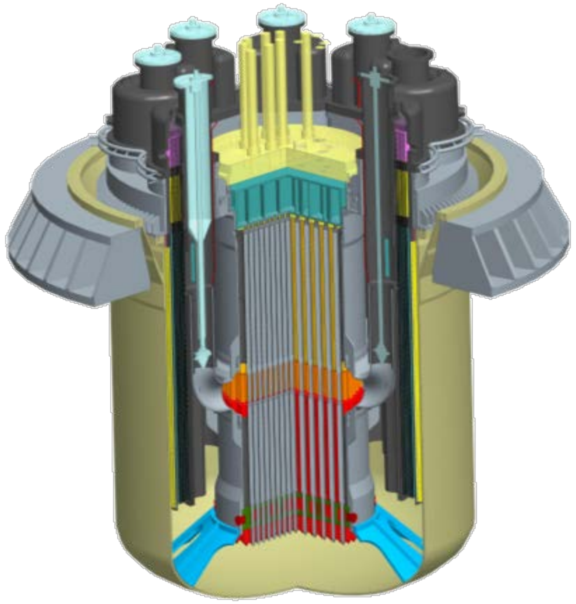
2035-2040

- proper time window to exploit this market segment
- shortened perspective raising industrial interest

J.M. Folon

ALFRED DEMONSTRATOR
a way to achieve technology maturity



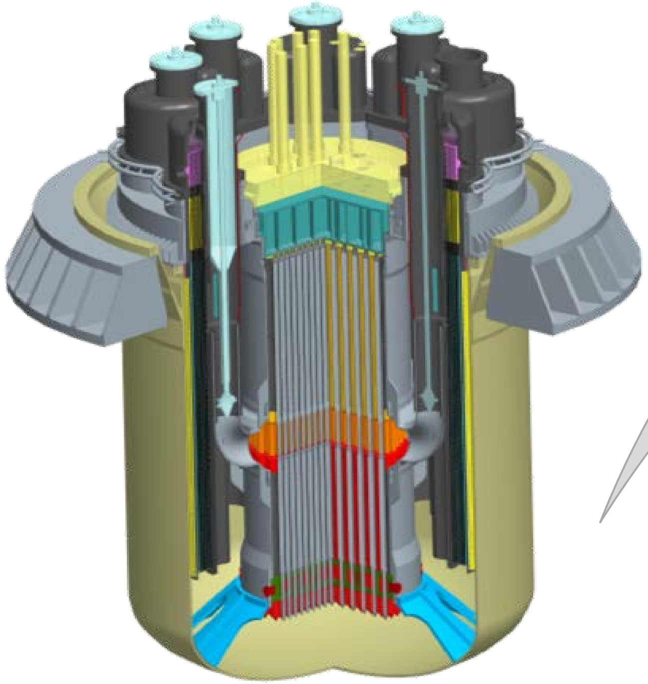


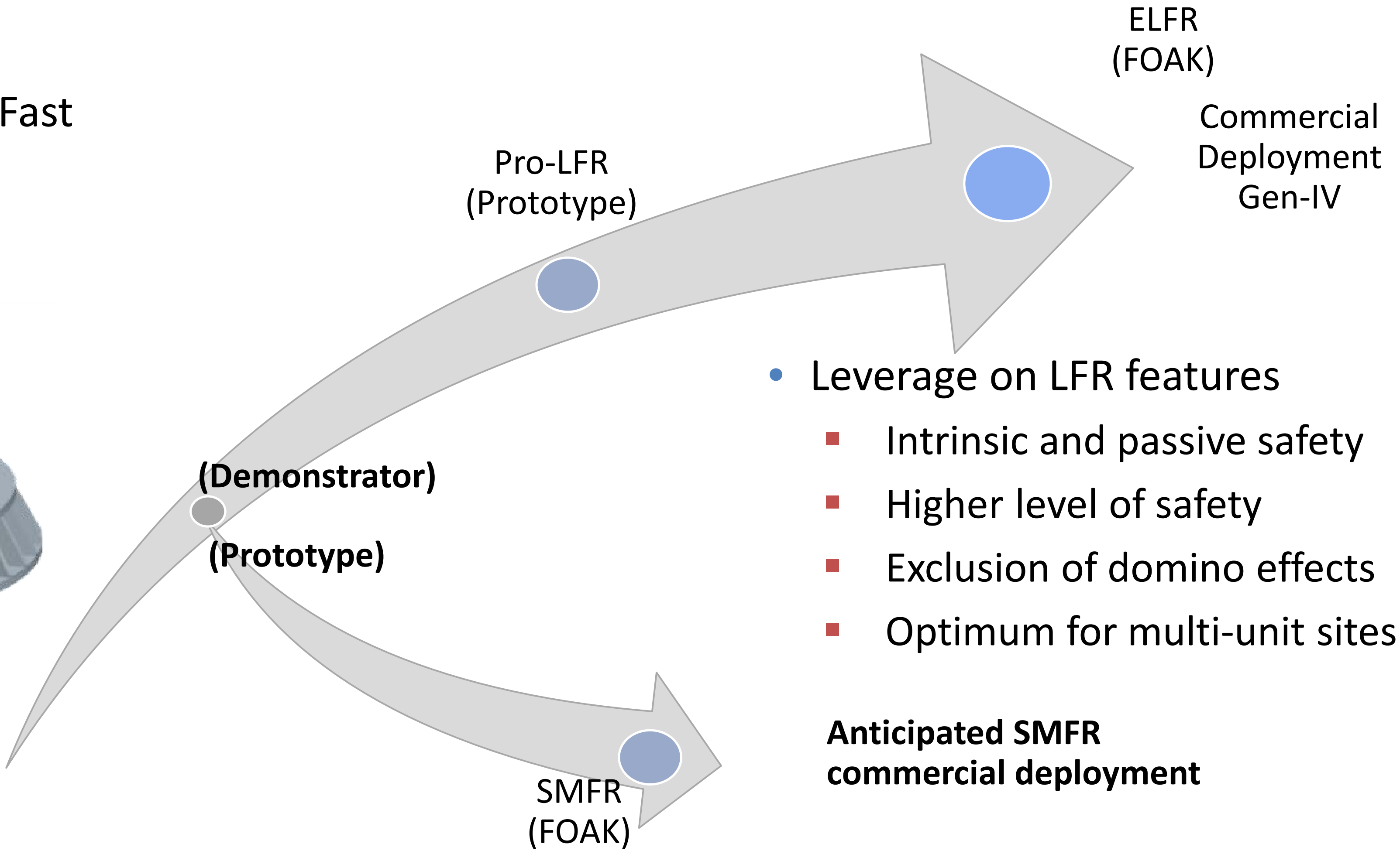
The operation of ALFRED will be based on a stepwise approach:

- phase 1: operation at low power in low-temperature range
  - presently existing proven materials working without corrosion protection
- phase 2: operation at full power in high-temperature range
  - coated materials fully qualified during phase 1

ALFRED: a LFR Demo with SMR-oriented features

ALFRED
Advanced Lead-cooled Fast Reactor European Demonstrator





- Leverage on LFR features
  - Intrinsic and passive safety
  - Higher level of safety
  - Exclusion of domino effects
  - Optimum for multi-unit sites

Anticipated SMFR commercial deployment

TIME WINDOW TARGET – 2035 - 2040

Thank you for your attention

Upcoming Webinars

24 October 2018	Safety of Gen IV Reactors	Dr. Luca Ammirabile, European Commission
28 November 2018	The Allegro Experimental Gas Cooled Fast Reactor Project	Dr. Ladislav Belovsky, UJV a.c., Czech Republic
19 December 2018	Russia BN 600 and BN 800	Dr. Iiuri Ashurko, IPPE, Russia