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Gen-IV Lead-cooled Fast Reactor. Status and Perspectives.

ENEA

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FALCON Objective

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- Deployment of a lead-cooled fast reactor demonstrator having
  - **SMR-oriented features** aimed at being a competitive option for the future Nuclear Power Plants (replacing the old generation NPPs facing retirement or conventional technologies based on fossil fuels), as well as
  - Longer-term potentialities to demonstrate that the **LFR technology can meet the goals set out by GIF for Generation-IV reactors**

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Increased support

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POLITECNICO MILANO 1863

Università di Pisa

Sapienza Università di Roma

Università degli Studi di Palermo

Alma Mater Studiorum Università di Bologna

Politecnico Milano 1863

CIRTEN Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare

Politehnica University of Bucharest UPB 1818

IFIN-HH

Universitatea din Pitești

CITON

C E S I N A

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(*) Bilateral agreeement with ENEA

Supporting organizations (MOA)

CIRTEN Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare

walter tosto

NUCLEARELECTRICA

S.R.S. Servizi di Ricerche e Sviluppo S.r.l.

NRG

CRS4 IDEAS BECOME LIFE

EMPRESARIOS AGRUPADOS

GREENPUMPS (*) MAG - DRIVE SEAL - LESS PUMPS

iit (*) ISTITUTO ITALIANO DI TECNOLOGIA

CHALMERS UNIVERSITY OF TECHNOLOGY

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More Energy…of a new type

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9.7 billion people by 2050

2/3 of the world's people living in urban areas

25% global energy increase by 2040

2 times faster electricity demand increase

1.7% increase of CO_2 in 2018

70% higher than average increase since 2010

2.8% RES increase per year

RES will provide 31% of electricity generation by 2040

Role of nuclear in the «energy transition»

Nuclear to be included in Delegated Act of EU taxonomy

21 April 2021

Share

The European Commission today announced its decision to include nuclear energy in a complementary Delegated Act of the EU Taxonomy Regulation. The decision follows the recent publication of the Joint Research Centre's report confirming nuclear is as sustainable as other taxonomy-compliant energy technologies.

The European Commission building in Brussels (Image: Pixabay)

- **Nuclear energy is the largest (26.7% in 2019) single source of low-carbon energy in the EU**, ahead of hydro (12.3%), wind (13.3%), solar (4.4%) and other (0.5%).
- **Nuclear** energy contributes to **climate mitigation**.
- The technical expert group on Taxonomy concluded that there is clear evidence that **nuclear substantially** contributes to climate mitigation.

Ref.: World Nuclear News

https://world-nuclear-news.org/Articles/Nuclear-to-be-included-in-Delegated-Act-of-EU-taxo

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Ideal Nuclear Power Plants

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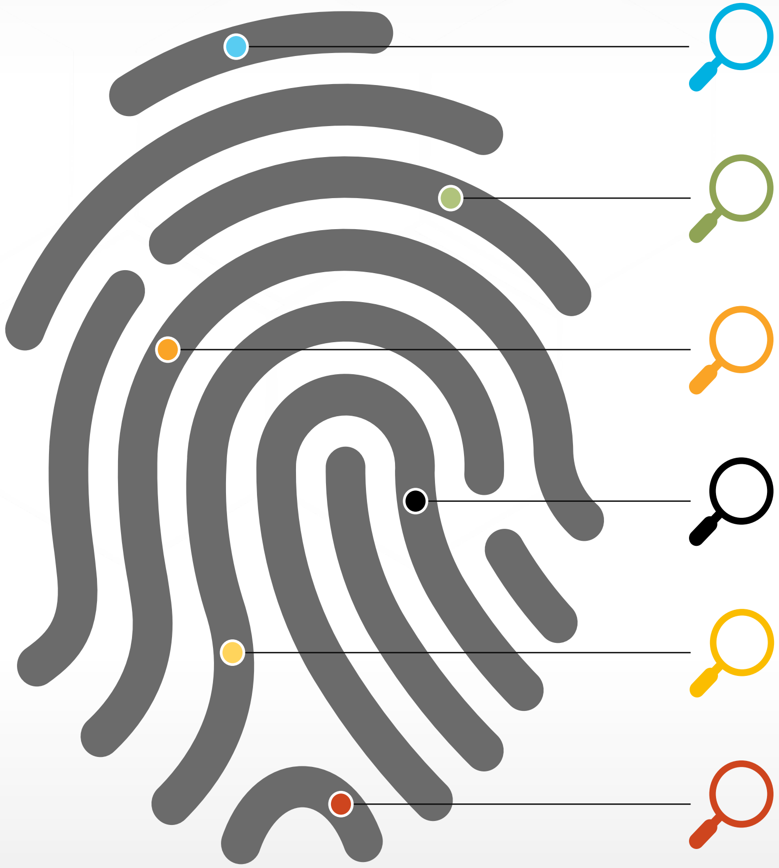
Fission Nuclear Power Plants of a new type are being developed for a short-term deployment (beyond 2030) to replace the current fleet and better integrate future hybrid energy systems: smaller, more flexible, economically competitive, able to produce more than purely electricity.



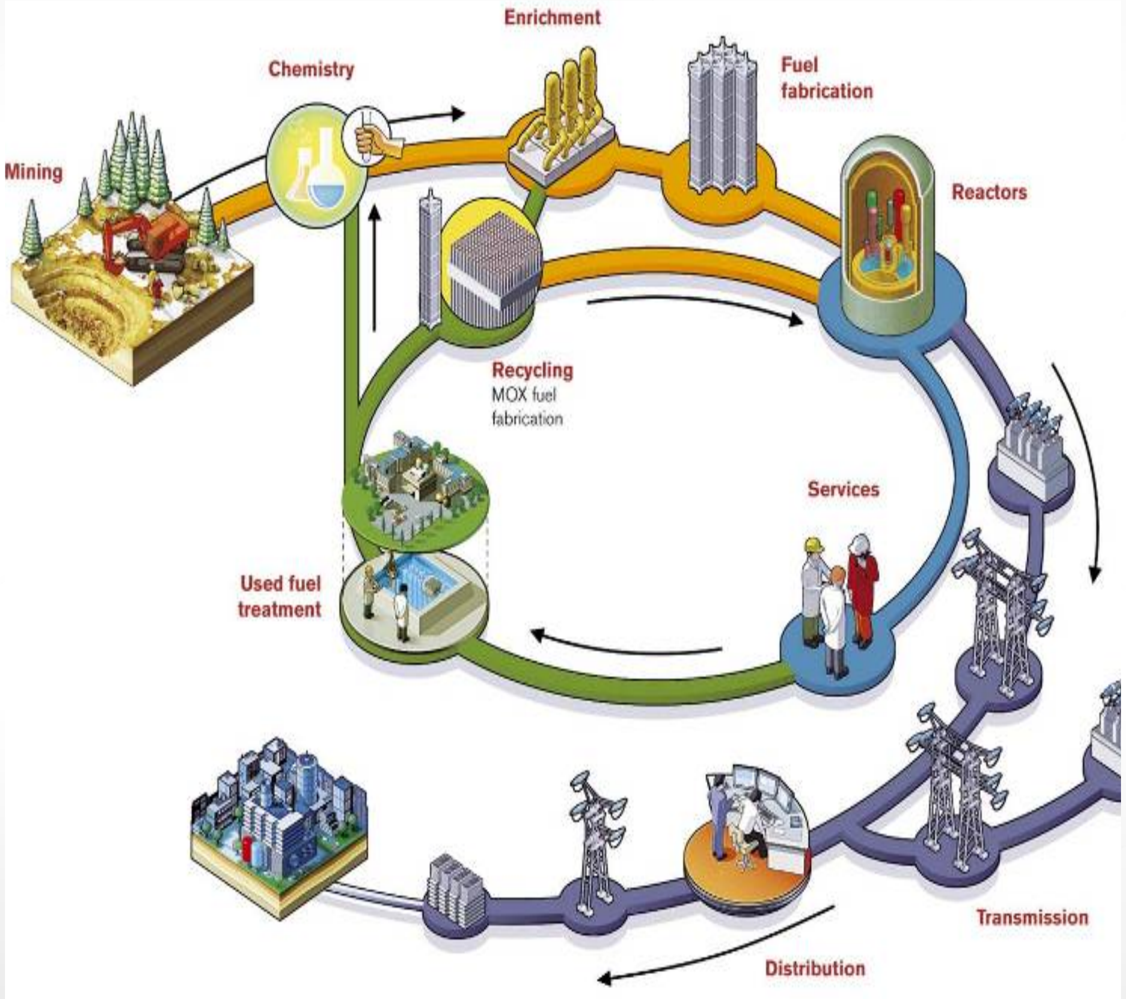
Introduction to Lead-cooled Fast Reactor

- Why Fast Reactor?!
- Why Lead-cooled Fast Reactor?
- International Context
- Some Remarks

Waste Minimization & Economy

The fission process used in nuclear reactors produces a **number of isotopes that can be toxic to human lives and the environment**.

Since the start of the large scale deployment of nuclear energy, **disposal** of the long lived isotopes has been an issue that has had a priority in most nuclear countries.



Source: Phillip Finck and Massimo Salvatores, INL, FUNFI-2, Frascati, October 2016

Waste Minimization & Economy

Reactor and Fuel Cycle Options to Implement P&T

The P&T objectives can be summarized as:

- Minimization of waste mass sent to a repository,
- Reduction of the potential source of radiotoxicity
- Reduction of the heat load in the repository

Strategies making use of P&T can be gathered into three categories:

- Sustainable development of nuclear energy and waste minimization (Pu as a resource)
- Reduction of MA inventory
- Reduction of TRU inventory as unloaded from LWRs

Fast neutron spectrum reactors are the most adapted technology and offer flexible options for implementation.

Source: Phillip Finck and Massimo Salvatores, INL, FUNFI-2, Frascati, October 2016

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Waste Minimization & Economy

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NUCLEAR MATERIALS INVENTORY (TONS) NEEDED TO PRODUCE 100TWH

		1) Present scenario	2) Near term scenario	3) Long term scenario (after 2040)
		Light water reactors	Lead –cooled fast reactors without Minor Actinides recycling.	Lead –cooled fast reactors with Minor Actinides recycling.
Natural Uranium		2100	10,8** *or* a, b, c	10,44** *or* a, b, c, d
Unused uranium,	Depleted Uranium from the enrichment facility.	1900 (a)	–	–
	Uranium from the spent fuel.	184 (b)	–	–
net generated Pu,	Pu	2,6* (c)	Negligible	Negligible
Nuclear waste	Minor Actinides (Np,Am,Cm)	0,38 (d)	0,36	Negligible
	Fission fragments	13	10,43	10,43

- * It is possible to reduce the plutonium inventory with increased production of Minor Actinides.
- ** Reprocessing losses not included

Source: L. Cinotti, "IW on Innovative Nuclear Reactors cooled by HLM: Status and Perspectives, Pisa 2012

Waste Minimization & Economy

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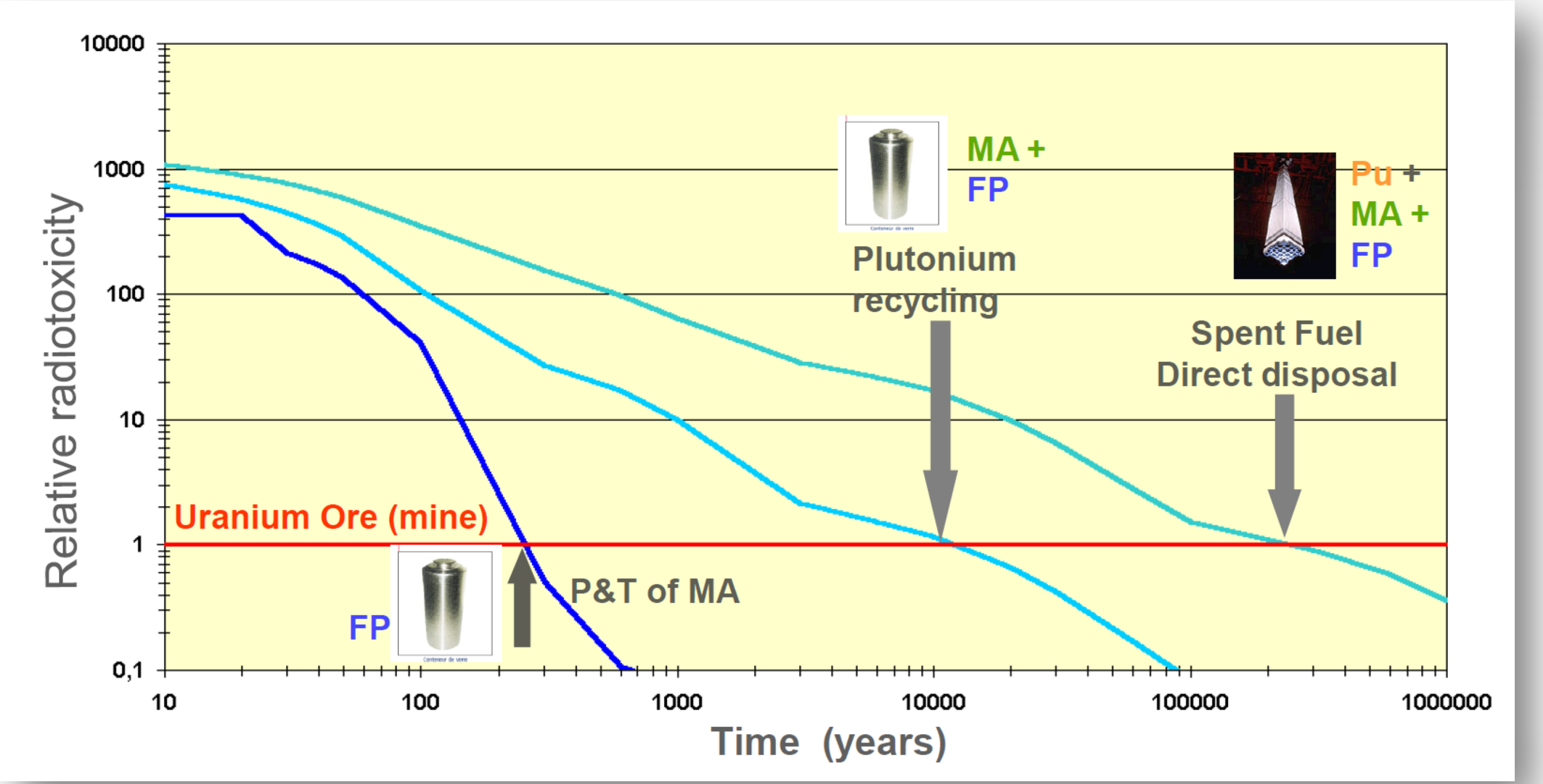

Recycle of all actinides in spent LWR fuel in fast reactors provides a significant reduction in the time required for radiotoxicity to decrease to that of the original natural uranium ore used for the LWR fuel (i.e., man-made impact is eliminated).
From 250,000 years down to about 400 years with 0.1% actinide loss to wastes

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Safety Improvement

Severe Nuclear Accidents. During the historically short period several low probability NPP accidents occurred with significant radioactivity release into environment and considerable economical losses.

Three Mile Island-2
(PWR)
1979

Chernobyl-4
(RBMK)
1986

Fukushima-1
(BWR)
2011

The initial events for these accidents are of extremely low probability

technical failure | **human error** | **extreme external impact**

Safety Improvement

- Severe Nuclear Accidents occurred due to the **release of various types of potential energy accumulated in various materials**, mainly, in the main coolant.
- Radiotoxicity inventory and decay heat amount are mainly independent from the reactor type, being governed by the fission products.
- **Radiotoxicity release into environment depends strongly on the reactor type and is determined by potential (non-nuclear) energy accumulated in various materials**
    - **Coolant compression energy**
    - **Chemical energy.**
- **Potential energy is an inherent coolant property**

Safety Improvement

Coolant	Water	Sodium	Lead, Lead-bismuth
Parameters	P = 16 MPa T = 300 ºC	T = 500 ºC	T = 500 ºC
Maximal potential energy, GJ/m^3, *including:*	~ 21,9	~ 10	~ 1,09
Thermal energy / *including* compression potential energy	~ 0,90 / ~ 0,15	~ 0,6 / None	~ 1,09 / None
Potential chemical energy of interaction	With zirconium ~ 11,4	With water 5,1 With air 9,3	None
Potential chemical energy of interaction of released hydrogen with air	~ 9,6	~ 4,3	None

From ICAPP 2011, Paper 11465 . Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters

G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

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Safety Improvement

- Upgrading the safety level of NPPs with traditional-type reactors, (in which potential energy is stored in large amounts) requires increasing the number of safety systems and defense-in-depth barriers

- **Such measures can only reduce the probability of severe accidents** and mitigate the consequences, **but cannot eliminate them when there is large potential energy**

- Convincing demonstration that future reactors can rule out catastrophic scenarios is necessary to recover public acceptance
  - to exploit to the maximum extent solutions that can deterministically exclude scenarios which are potential initiators of accidents leading to severe core damage;
  - to consider the possibility of managing extreme events in degraded plant conditions.

Lead-cooled Fast Reactor

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- For heavy liquid metal coolants (lead-bismuth alloy, lead) the stored thermal potential energy cannot be converted into kinetic energy.
- There is no significant release of energy and hydrogen in an events of coolant contacting with air, water, structural materials.
- There is no loss of core cooling in an event of tightness failure in the gas system of the primary circuit.
- The way to improve the NPP safety and economic performance is to implement reactor facilities with **the lowest stored potential energy**, where the inherent self-protection and passive safety properties are used to the maximal extent.

Lead-cooled Fast Reactor

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Main advantages and main drawbacks of Lead

Atomic mass	Absorption cross-section	Boiling Point (°C)	Chemical Reactivity (w/Air and Water)	Risk of Hydrogen formation	Heat transfer properties	Retention of fission products	Density (Kg/m^3) @400°C	Melting Point (°C)	Opacity	Compatibility with structural materials
207	Low	1737	Inert	No	Good	High	10580 10580	327	Yes	Corrosive

Lead-cooled Fast Reactor

How lead coolant improves the reactor design?

Lead is a low-moderating medium and has a low-absorption cross section

- Fast neutron spectrum: operation as burner of MA and improve resource utilization (Sustainability)
- Long Life Core: unattractive route for the plutonium procurement (Proliferation resistance and physical protection)
- Large fuel pin lattice (opened/closed): enhanced the passive safety (Safety and Reliability)

Lead does not interact vigorously with air or water

- Improve Simplicity and Compactness of the Plant and reduce the risk of plant damage (Economics)
- Increase the protection against acts of terrorism (Proliferation resistance and physical protection)

Lead-cooled Fast Reactor

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How lead coolant improves the reactor design?

Lead has a high boiling temperature, high shielding capability and very low vapor pressure

- Un-pressurized primary system (Safety and Reliability, Economics)
- Enhancements in passive safety (Safety and Reliability)

Lead has a high heat transfer, specific heat, and thermal expansion coefficients

- Decay heat removal by natural circulation (Safety and Reliability)

Lead has a density close to that of fuel, and retains fission products

- Reduce the risk of re-criticality and vessel damage in the case of core melt (Safety and Reliability)
- No need of off-site emergency response (Safety and Reliability)

How to do it……

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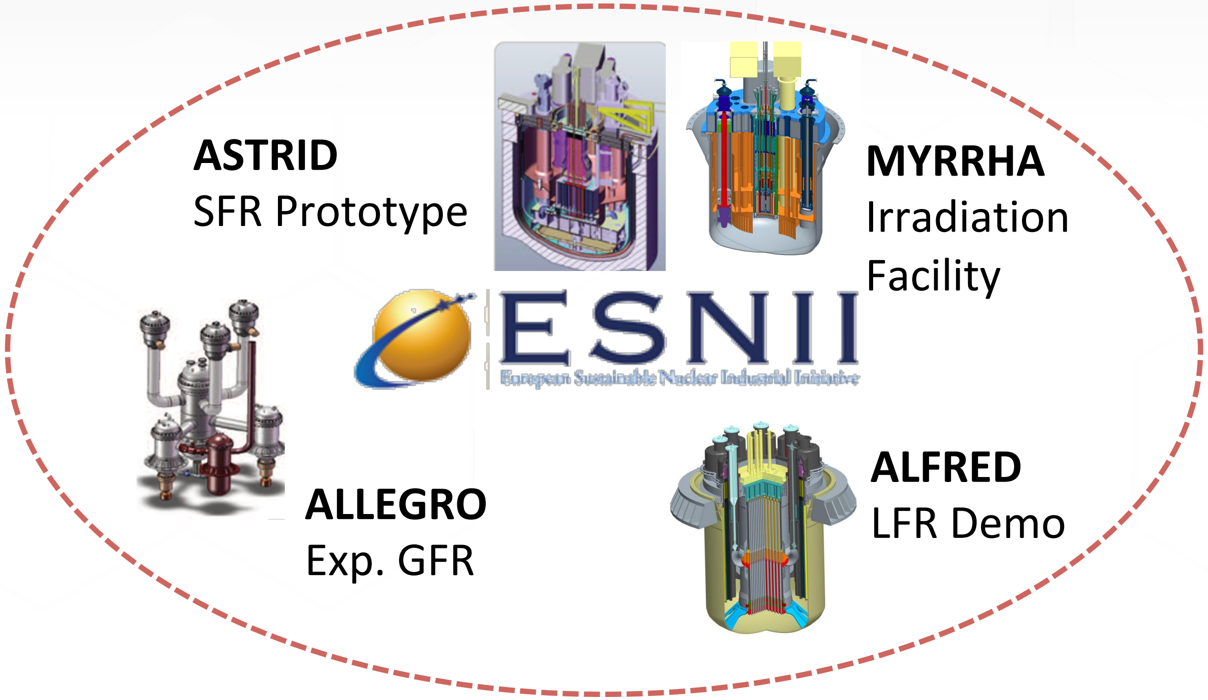
A comprehensive R&D program is necessary because of:

- **The use of a new coolant and associated technology, properties, neutronic characteristics, and compatibility with structural materials of the primary system and of the core.**

- **Innovations which require validation programs of new components and systems (the SG and its integration inside the reactor vessel, the extended stem fuel element, the dip coolers of the safety-related DHR system, pump, OCS, …)**

- **The use of advanced fuels (*at least in a further stage*).**

European Scenario



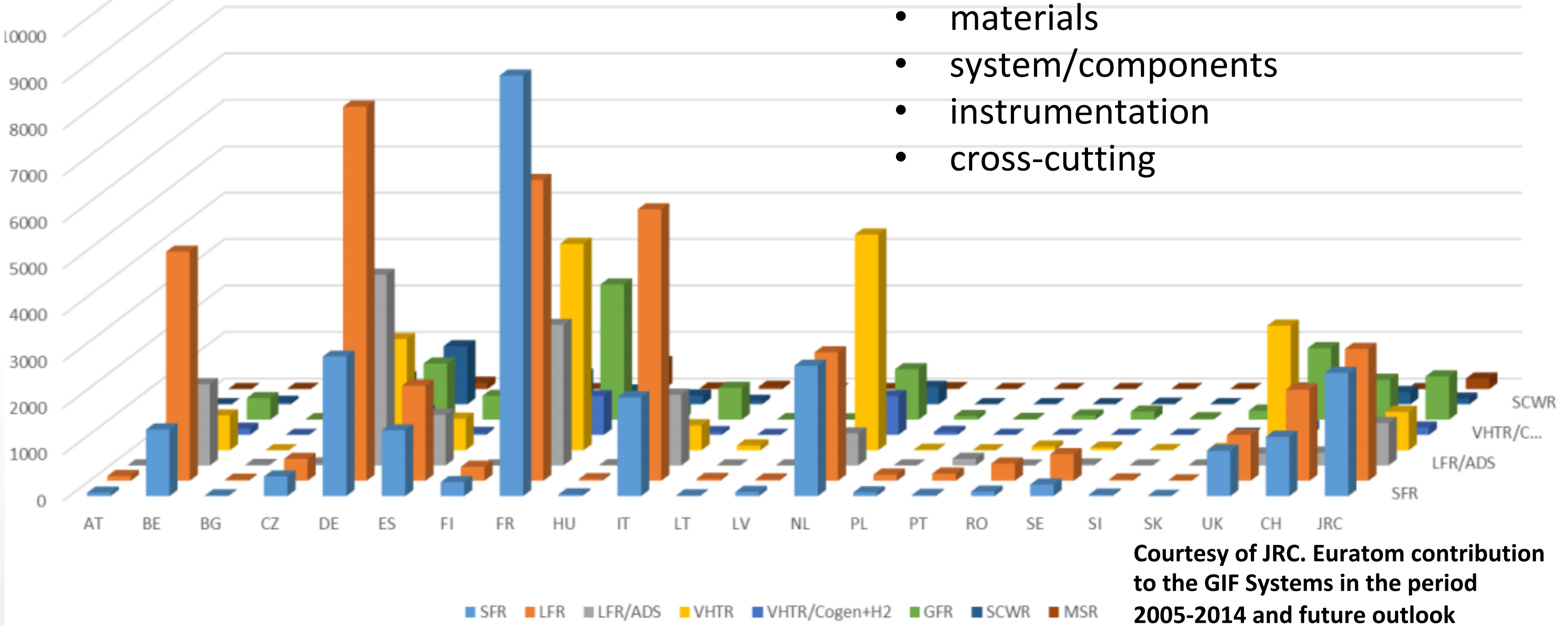
SNETP - Sustainable Nuclear Energy Technology Platform
NUGENIA - NUclear GENeration II&III Association
NC2I - Nuclear Cogeneration Industrial Initiative
ESNII - European Sustainable Nuclear Industrial Initiative

European Scenario

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

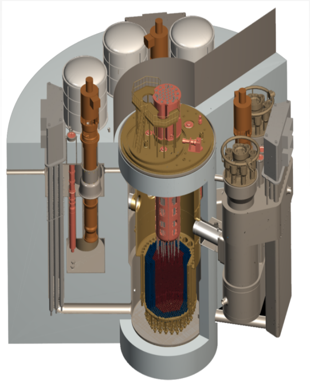
IAEA LMFNS Catalogue: ~72 facilities for HLM-based technology (56 operational):

- zero power
- accident scenarios
- thermal hydraulics
- coolant chemistry
- materials
- system/components
- instrumentation
- cross-cutting

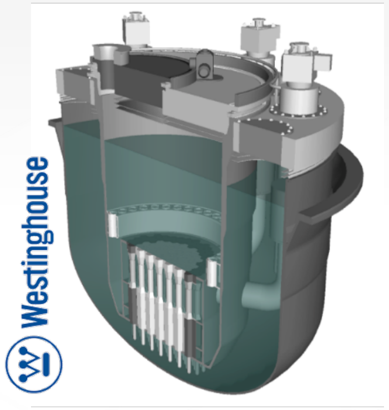


Courtesy of JRC. Euratom contribution to the GIF Systems in the period 2005-2014 and future outlook

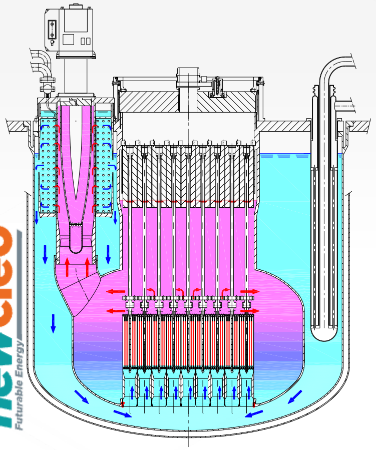
Nuclear vendors and new-comers in the LFR panorama



BREST-OD-300
300 MWe, Russia
Under construction

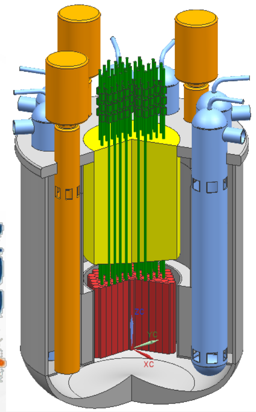


Westinghouse LFR
450 MWe, USA
Under design

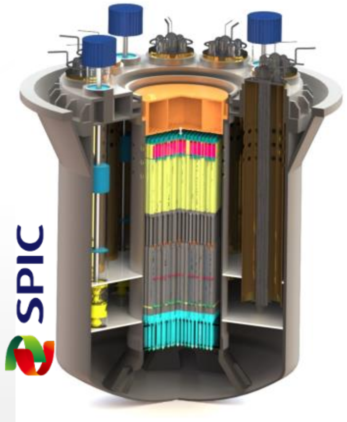


NewCleo AS-200
200 MWe, USA
Under design

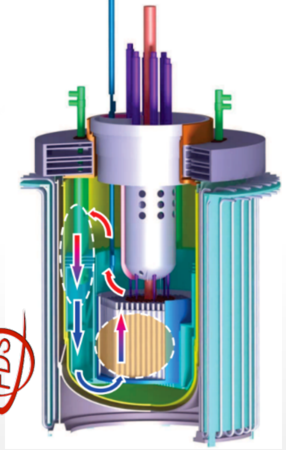
LeadCold SEALER
1-10 MWe, Sweden
Under design



CLFR-300 and CLFR-10
300/10 MWe, China
Under design



BLESS
100 MWe, China
Under design



CLEAR-1
10 MWth, China
Under design

Micro-Uranus
60 MWth, Korea
Under design

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Lastest news from around the world

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Foundation set in place for BREST reactor

24 August 2021

Share

Russia has finished pouring concrete for the foundation slab of its new BREST-OD-300 lead-cooled fast reactor at the Siberian Chemical Combine's (SCC's) Seversk site. It is part of an overall programme to close the nuclear fuel cycle.

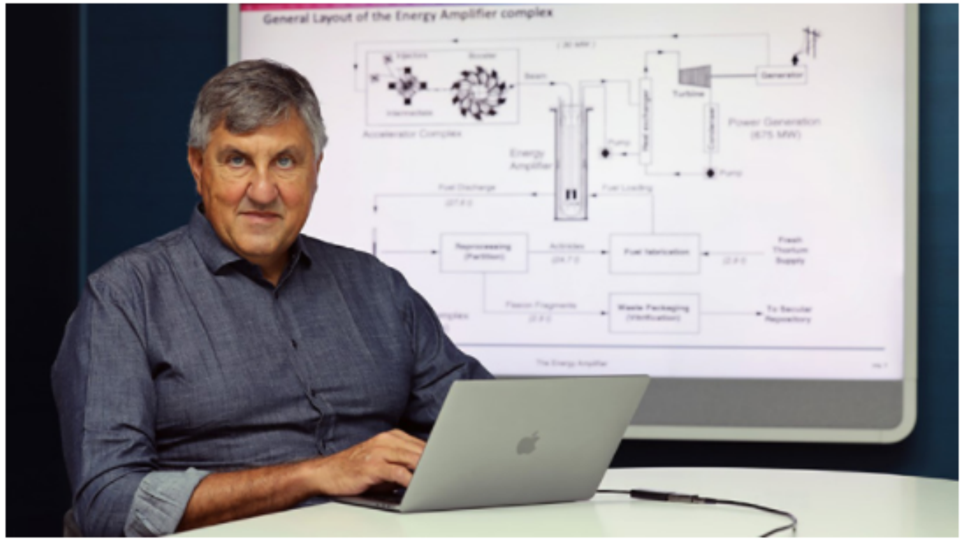
Student construction workers have had the opportunity to be involved in the project (Image: Rosatom)

The operation took 26 hours and involved around 2855 cubic metres of concrete, Rosatom said on 19 August. The work is managed by the SCC and the Titan-2 construction firm which was contracted to build the reactor building, turbine hall and related infrastructure.

newcleo powers up, closing initial capital round and acquisition of Hydromine Nuclear Energy

SOURCE: PRESS RELEASE, 31 AUGUST 2021

31 August 2021 Editor Names, News, Technology Comments Off



newcleo CEO, Stefano Buono (photo: newcleo)

newcleo, a nuclear technology company, has announced its incorporation with the closing of a USD 118 million initial capital raising and the acquisition of Hydromine Nuclear Energy S.à r.l. (HNE). newcleo's approach is based on the innovative application of well-developed technologies, including, Lead Fast Reactors (LFRs), which utilise lead as a coolant rather than water or sodium, Accelerator Driven Systems (ADSs), based on coupling a sub-critical reactor with a particle accelerator and the use of natural thorium fuel.

Some Remarks

- Nuclear will play still an important roles in the next years.
- Nuclear energy technology **is among the most reliable and safer technologies**. Nevertheless an improvement is required about:
  - **Safety**
  - **Waste**
  - **Economy**
- Gen-IV reactors have been conceived to match these goals. Among the others, **Lead cooled Fast Reactors** seems to be the most promising! (but R&D needs are not negligible…)
- In this context the **Italian contribution is significant worldwide**. ENEA and ANN led the technology development.
- International Context is positive (everyday more!!)

ALFRED Project

ALFRED: the Advanced Lead-cooled Fast Reactor European Demonstrator

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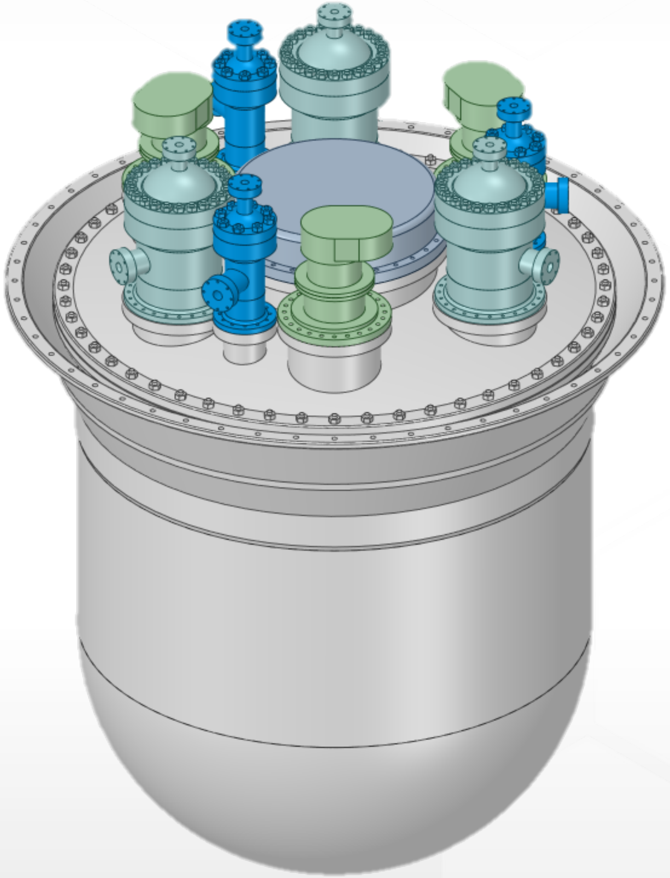
- No other advanced reactor technology can feature the same unique aspects
- One of the most promising technologies for deployment in the SMR segment
- Steadily increasing attention by industry and utilities worldwide
- Recognized by inclusion in the research agendas at international level (GIF, ESNII)

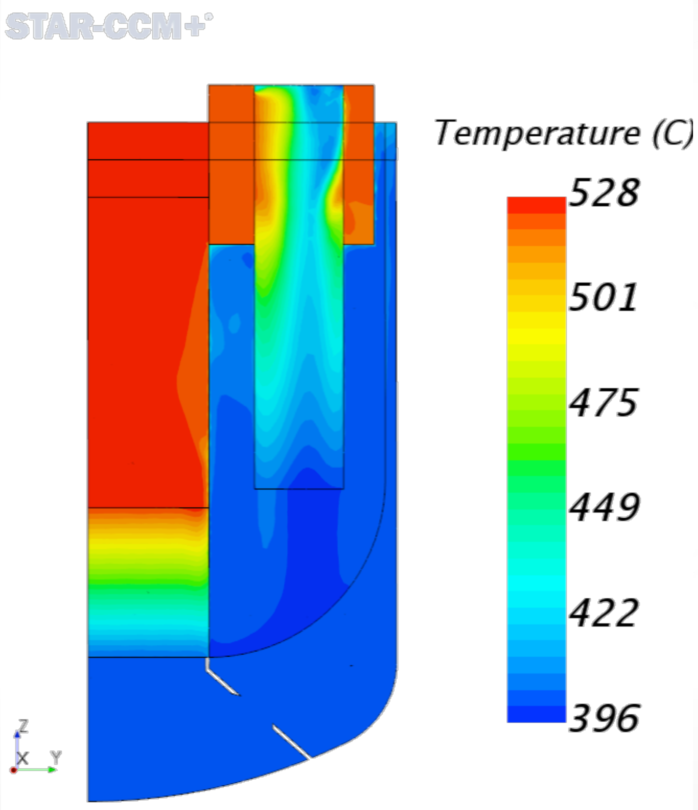


ALFRED, a **demonstration reactor**, also **prototypic of a Lead-based SMR**, to bridge the final gap between conducted research and industrial application

Primary system layout

A new configuration has been developed to address the issues of the LEADER configuration.

- Increased grace time to freezing when DHR system in operation
- Eliminated Pool Thermal Stratification
- Eliminated direct connection SGs – core
- Introduced Hot Safety Vessel
- Elimination of double wall SGs (performance)
- Safer refueling operation sequence
- Staged approach to by-pass technological limits



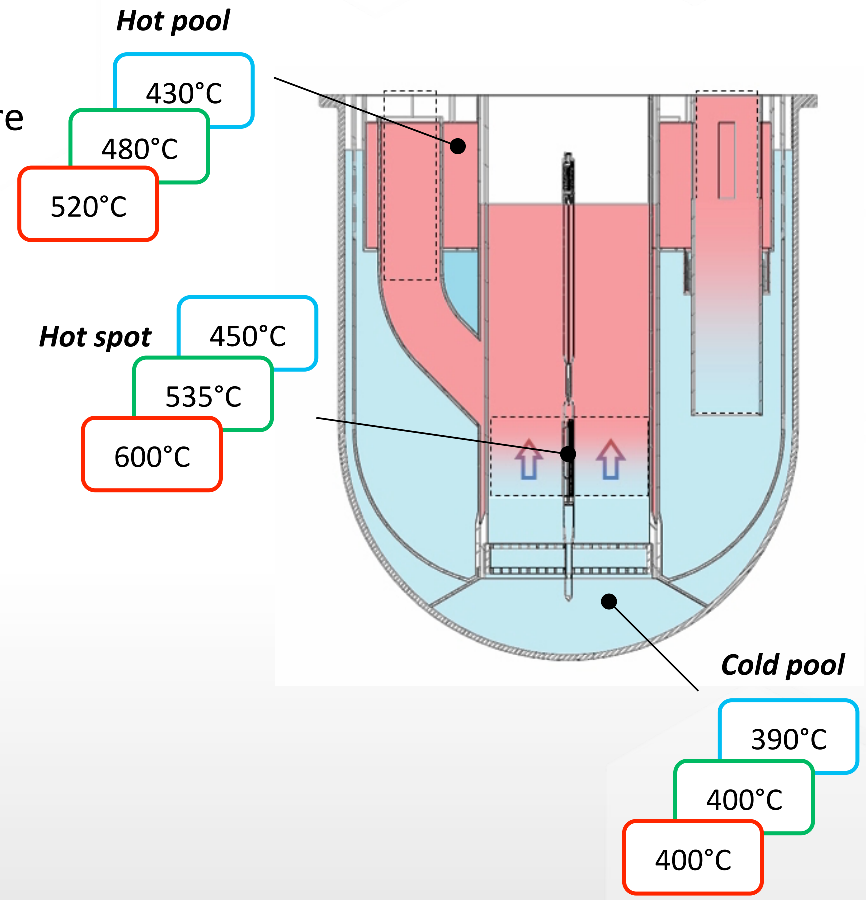
Courtesy of CRS4: SESAME, Task 3.1.2, D3.7, CFD Model of ALFRED Primary Loop

ALFRED Staged Approach

- ALFRED will facilitate licensing readiness and operational readiness for western LFR commercial reactors.

Increase in reactor coolant temperature

- **STAGE 1**
  - Proven technology, proven materials, oxygen control, low temperature
  - Aimed at in-core qualification of PLD Al_2O_3 coating for cladding
- **STAGE 2**
  - Need for FA replacement
  - Aimed at in-core qualification at higher temperature
- **STAGE 3**
  - Replacement of main components (SGs, PPs, dip coolers, ...)
  - Representative of FOAK conditions for LFR deployment



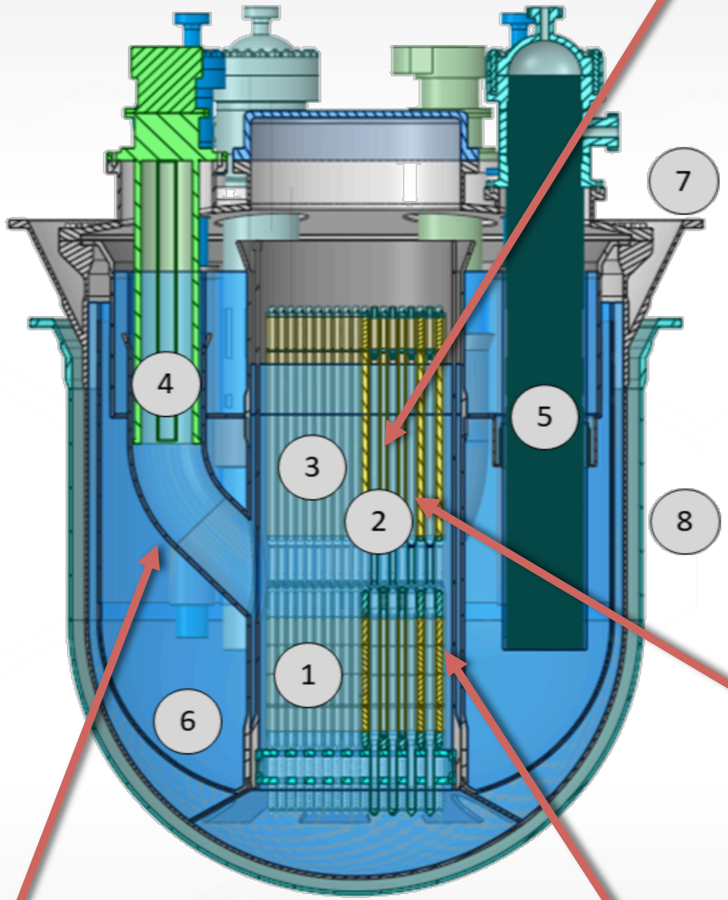
ALFRED Staged Approach

	Stage 0	Stage 1	Stage 2	Stage 3
	Commissioning	Low Temperature	Medium Temperature	SMR prototype
Core inlet temperature (°C)	390	390	400	400
Core outlet temperature (°C)	390	430	480	520
Core thermal power (MW)	**0**	**100**	**200**	**300**
Live steam pressure (bar)	/	170	175	180
Live steam temperature (°C)	/	420	435	450

- Selected temperature based on European experimental results on compatibility of proven materials with molten lead.

ALFRED Layout

Reactivity control: Two diverse and redundant systems, control and shut-down rods

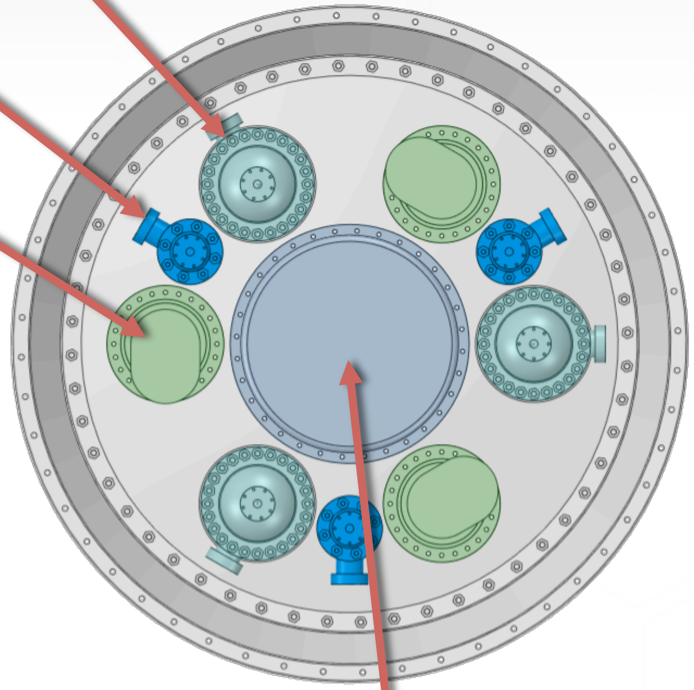


1. Core
2. Sub-Assemblies
3. Inner Vessel
4. Reactor Coolant Pump
5. Steam Generator
6. Internal Structure
7. Reactor Vessel
8. Safety Vessel

Steam Generator

Dip-cooler

Pump



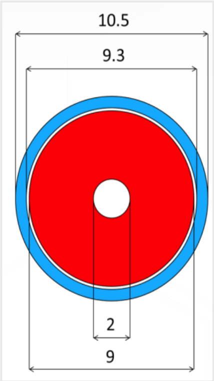
Fuel assemblies: MOX fuel, grid-spaced, hexagonal, wrapped, extended stem

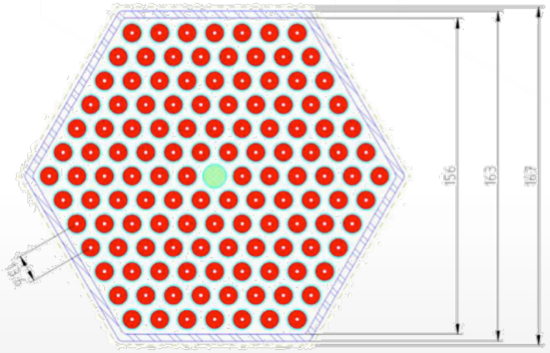
Design to ensure FA handling under lead during refueling operations

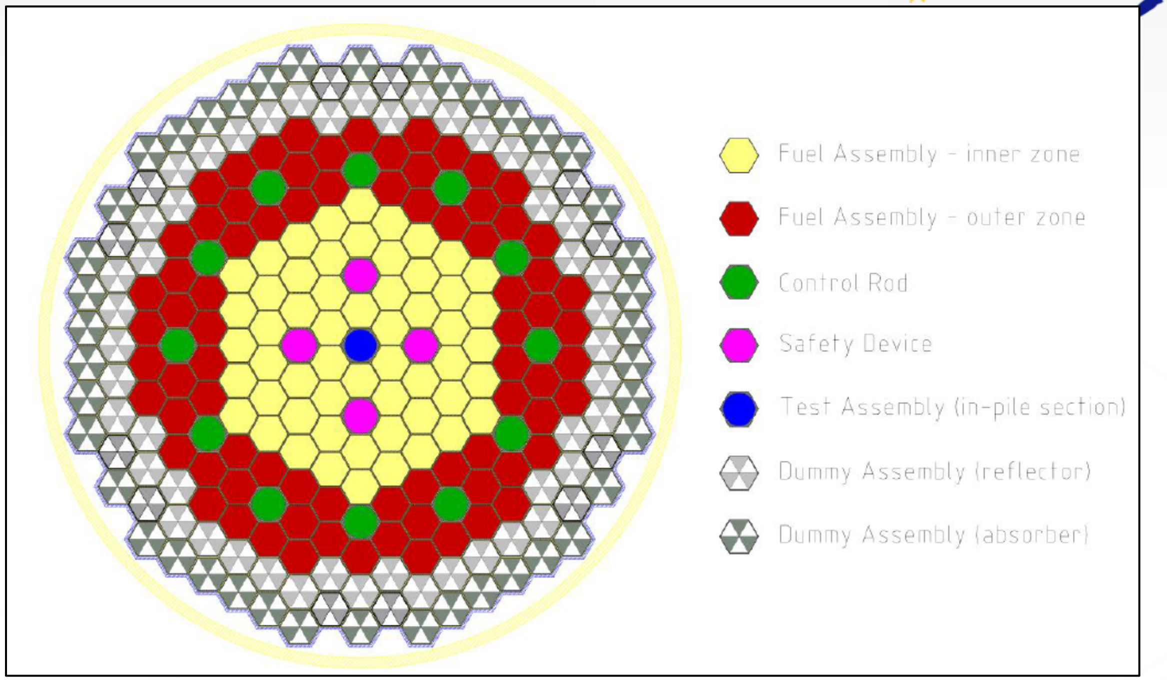
Internal Structure: no safety related, ensure pools separation and flow recirculation

Inner Vessel: safety-related, removable for out-of-vessel inspection

ALFRED Core



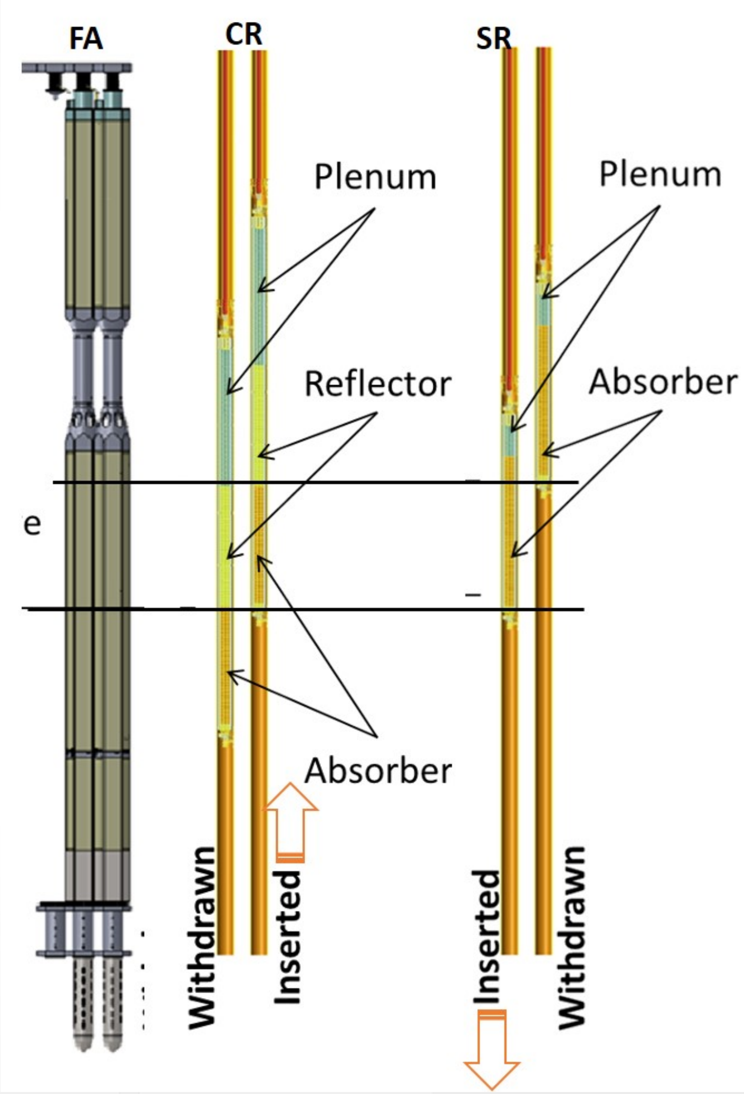




To flatten the power distribution (so as to better exploit the fuel while respecting the limits set on the peak values), a core zoning in pursued with 2 fuel enrichments:

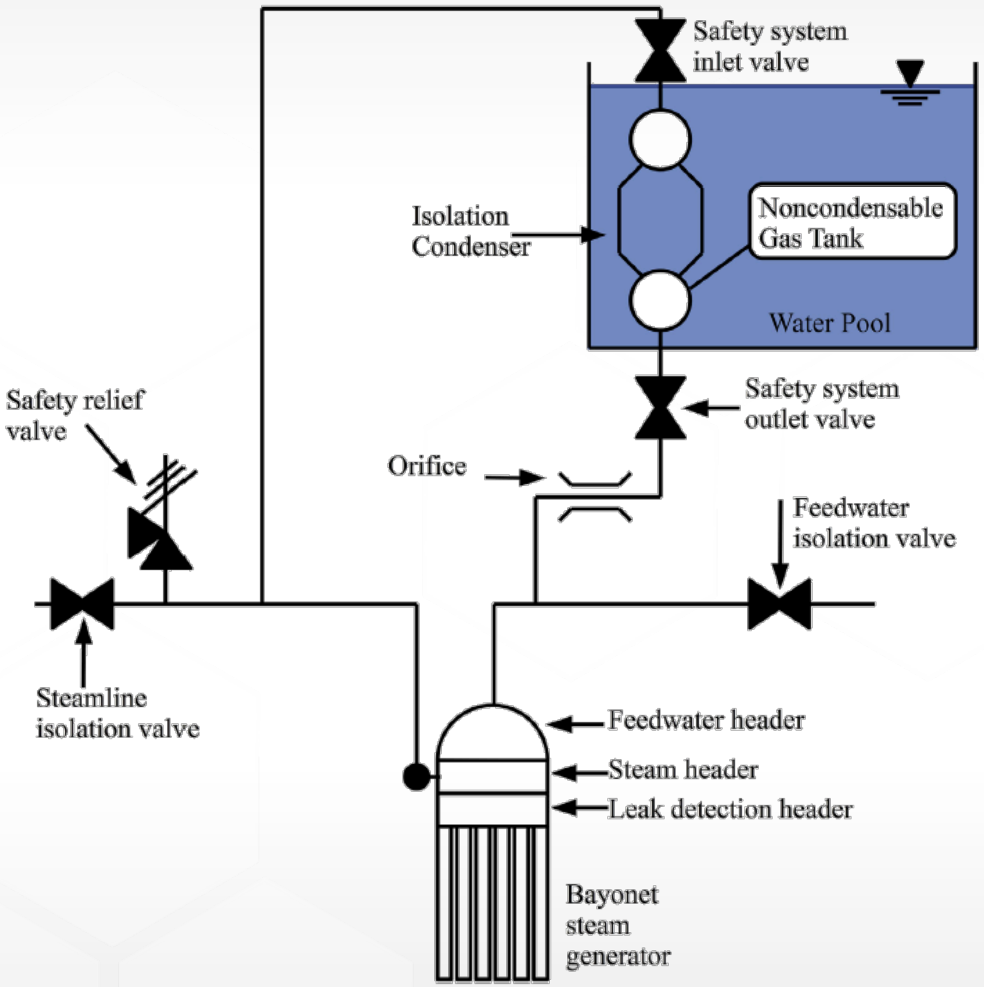
- 56 FAs in the inner zone with lower fuel enrichment (20.5 wt.% Pu)
- 78 FAs in the outer zone with higher fuel enrichment (26.2 wt.% Pu)

ALFRED Control & 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**

ALFRED DHR (Isolation Condenser)



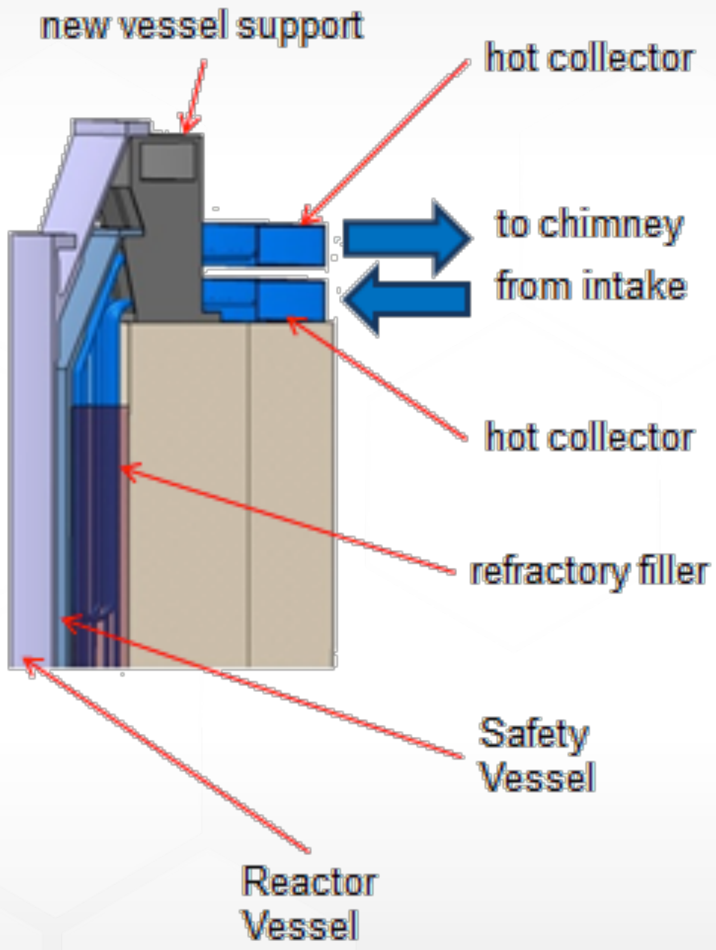
- Anti-freezing solution
  - based on the operation of the Isolation Condenser and of a tank of noncondensable gases
  - Non-condensable gases flooding the IC tubes will inhibit heat rejection to the water pool

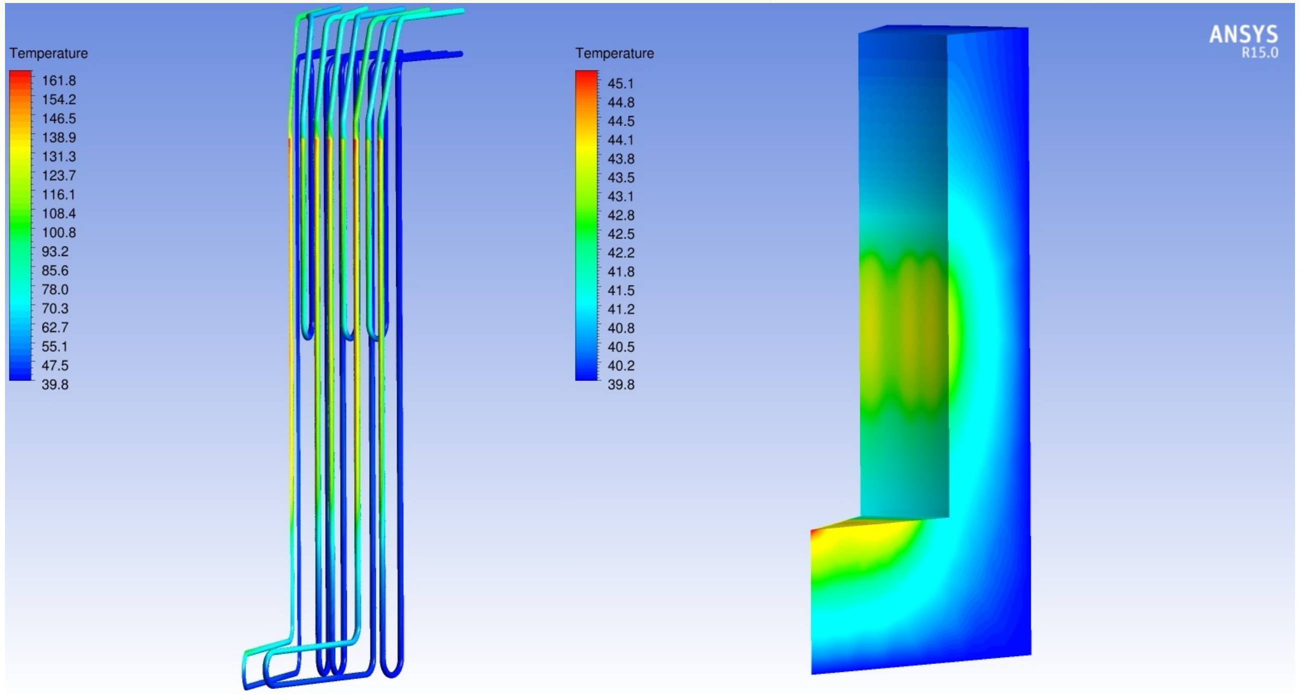
1 Loop each Steam Generator (3)

Each Isolation condenser in pool bay

Patented by Ansaldo Nucleare

ALFRED Cavity Cooling System





- Self-standing Safety Vessel
- New vessels support
- Dedicated Reactor Cavity Cooling System

FALCON: A long-lasting collaboration endeavor

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Ansaldo Energia Group

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RATEN ICN PITEŞTI

- Fuel-coolant chemistry
- Engineering support
- CFD analysis
- Balance of Plant optimization
- Analysis and E&T

POLITECNICO DI TORINO
UNIVERSITÀ DEGLI STUDI DI PALERMO
SAPIENZA UNIVERSITÀ DI ROMA
POLITECNICO MILANO 1863
UNIVERSITÀ DI PISA
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

- Coatings development
- CFD analysis
- Operator's review
- Manufacturing feasibility

CESINA Partnership
IFIN-HH
CITON

ROMATOM
FORUMUL ATOMIC ROMÂN

...on a solid basis

2011

Availability of **Romania** to **host** ALFRED

2015

ALFRED in **Smart Specialization Strategy** of South-Muntenia

2017

Romanian National Research and Innovation Plan

Jul.2020

Contract signed **ATHENA** and **ChemLab construction**

2019-2020 - **~2.5 M€** for **National R&I plan on ALFRED** (PRO-ALFRED)

2021-2023 - **22 M€** for **ATHENA** and **ChemLab** Infrastructure

2020, Jul. - Contract signed for **Athena** and **Chemlab construction**

2020, Apr. - **Integrated National Energy and Climate Change Plan** (**NECP**) for 2021-2030 Romania

2018 - **ESNII Exec Board** promoted **ALFRED** in the **Fast Track**

2017 - **National Strategy for RDI** (2015-2020)

2017 - **Roadmap** for **Research Infrastructures** in Romania for 2017-2025, Ministry of Research and Innovation

2017 - **CESINA** (academia), **ROMATOM** (nuclear industry) **partnerships and NUCLEARELECTRICA agreement**

2017 - **ALFRED** included in the **Romania National Research and Innovation Plan 2015-2020**

ALFRED

A world-class Research Infrastructure

FALCON

ATHENA – The largest pool facility in the world, for large-scale components testing in representative conditions

ChemLab – A broad-scope laboratory on the chemistry of HLMs and materials science

Meltin'Pot – A hot facility to characterize radioisotopes behavior in Lead under accident conditions

ELF – A pool facility for long-term experiments, to characterize the components and systems

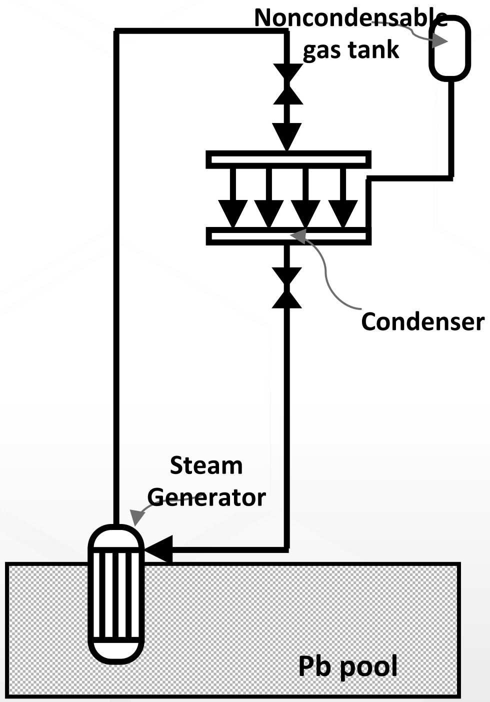
HELENA-2 – A loop facility for full-scale testing and complete thermal-hydraulic characterization of fuel and absorber assemblies

Hands-ON – A facility devoted to the testing and qualification of systems and procedures for the handling of core elements

Recent and ongoing supporting projects

PIACE

3.2 M€, 2019-2022 (G#847715)
piace.brasimone.enea.it/
In synergy with **SIRIO** facility at **SIET** funded by IT (1.4 M€)

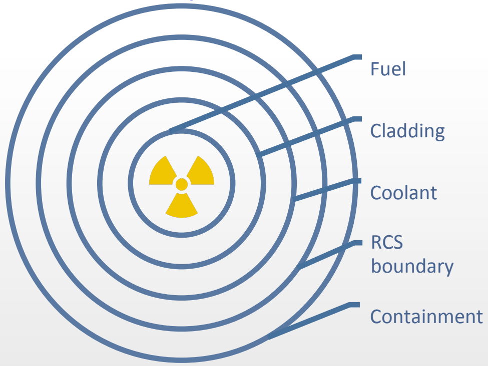


GEMMA – Generation IV Materials Maturity

6.6 M€, 2017-2021 (G#755269)
In synergy with **EERA JPNM**
eera-jpnm.eu/gemma/

PASCAL

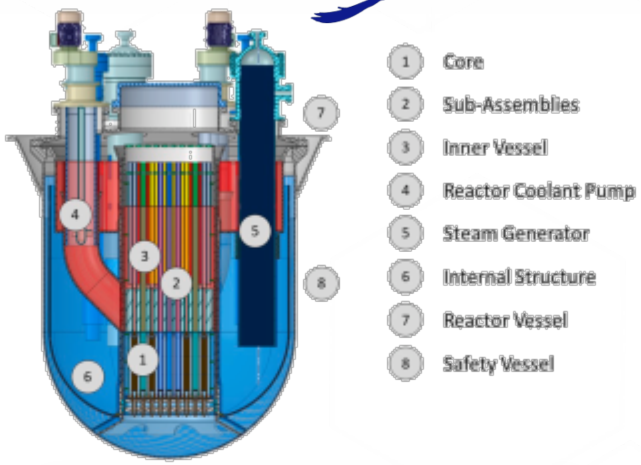
4.7 M€, 2020-2024 (G#945341)
Endorsed by **ESNII**, **EERA JPNM**, **FALCON**
pascalworkspace.eu

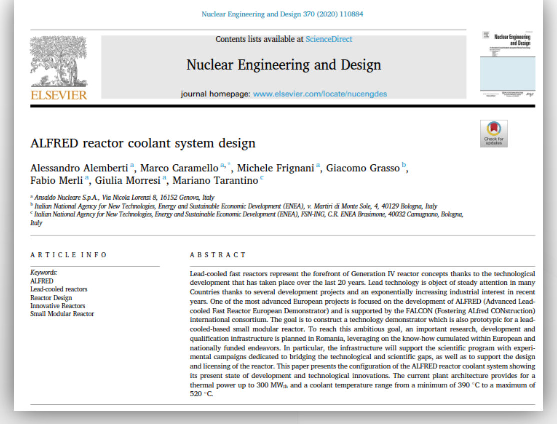


PRO ALFRED

2.5 M€, 2019-2020
Funded by RO Gvt.
proalfred.nuclear.ro/
>20 del.s in 7 WPs
Licensing Basis Document
Workshop with CNCAN

FALCON





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ALFRED reactor coolant system design

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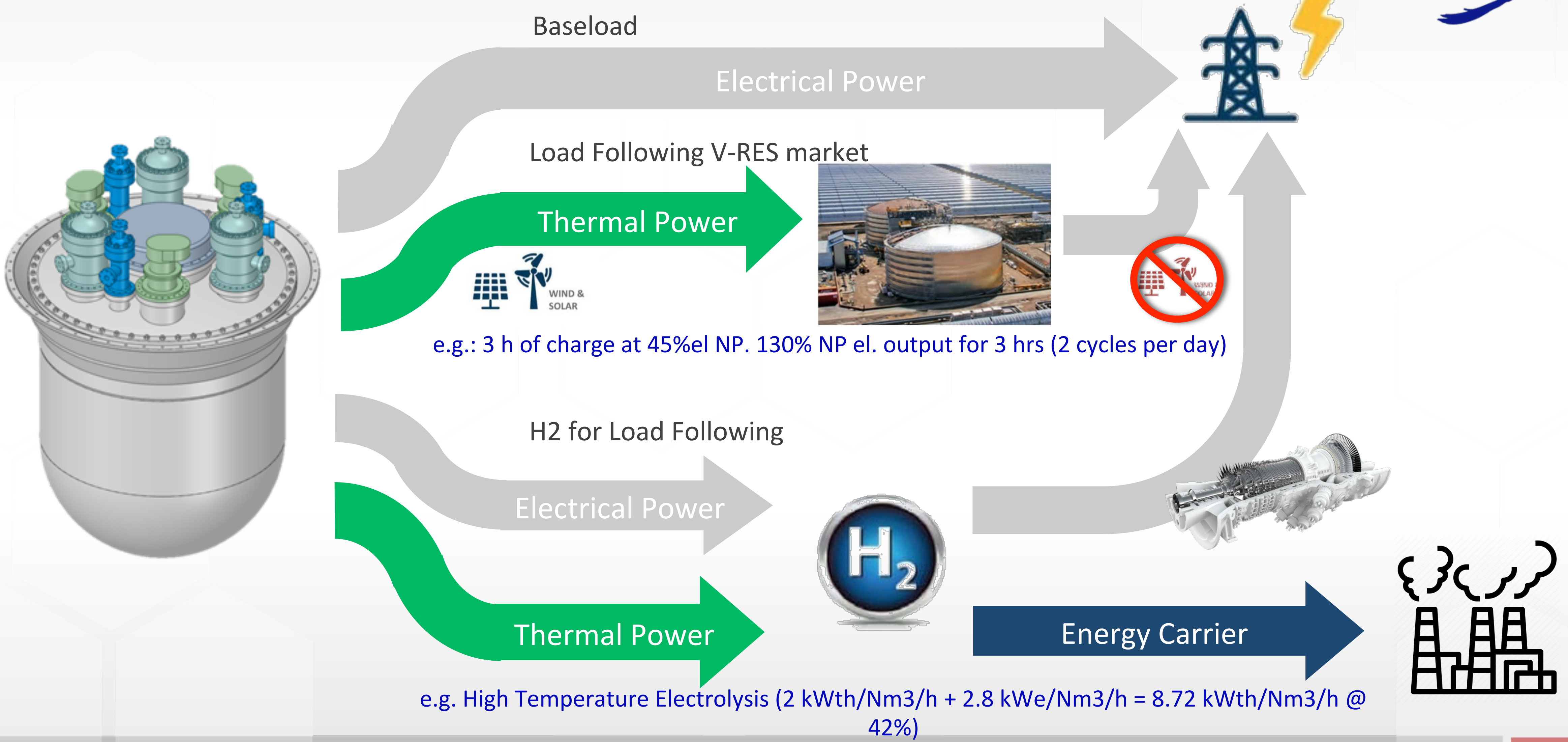
ABSTRACT

Lead-cooled fast reactors represent the forefront of Generation IV reactor concepts thanks to the technological development that has taken place over the last 20 years. Lead technology is object of steady attention in many Countries thanks to several development projects and an exponentially increasing industrial interest in recent years. One of the most advanced European projects is focused on the development of ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) and is supported by the FALCON (Fostering ALfred CONstruction) international consortium. The goal is to construct a technology demonstrator which is also prototypic for a lead-cooled-based small modular reactor. To reach this ambitious goal, an important research, development and qualification infrastructure is planned in Romania, leveraging on the know-how cumulated within European and nationally funded endeavors. In particular, the infrastructure will support the scientific program with experimental campaigns dedicated to bridging the technological and scientific gaps, as well as to support the design and licensing of the reactor. This paper presents the configuration of the ALFRED reactor coolant system showing its present state of development and technological innovations. The current plant architecture provides for a thermal power up to 300 MW_{th} and a coolant temperature range from a minimum of 390 °C to a maximum of 520 °C.

Enabling options: TES and H2 production



Take-away messages

- ALFRED will implement a staged approach to qualify the technical options for safe and competitive operation of a commercial fleet.
- Following stages conditions will be reproduced in the ALFRED core through an in-pile section to qualify protective means and innovative materials for higher temperatures.
- The demonstrator will serve as an intermediate step to address licensing challenges and lack of nuclear operational experience.
- The ALFRED staged approach is the optimum trade-off between a reasonable time-to-market and the maximum attractiveness of the LFR technology, in terms of safety, sustainability and competitiveness.
- ALFRED is, per se, a prototype for a competitive commercial SMR based on LFR technology.

ALFRED


sustainable
excellent
pan-European
ALFRED
future
open
secure
science
safe
acceptable
innovative
technology
unique