Westinghouse Lead Fast Reactor

Paolo Ferroni, PhD, Consulting Engineer
Fausto Franceschini, PhD, Consulting Engineer
Alex Levinsky, PhD, Lead Engineer

National Academy of Sciences Meeting on Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors

December 3, 2021

WAAP-12140, Rev.1

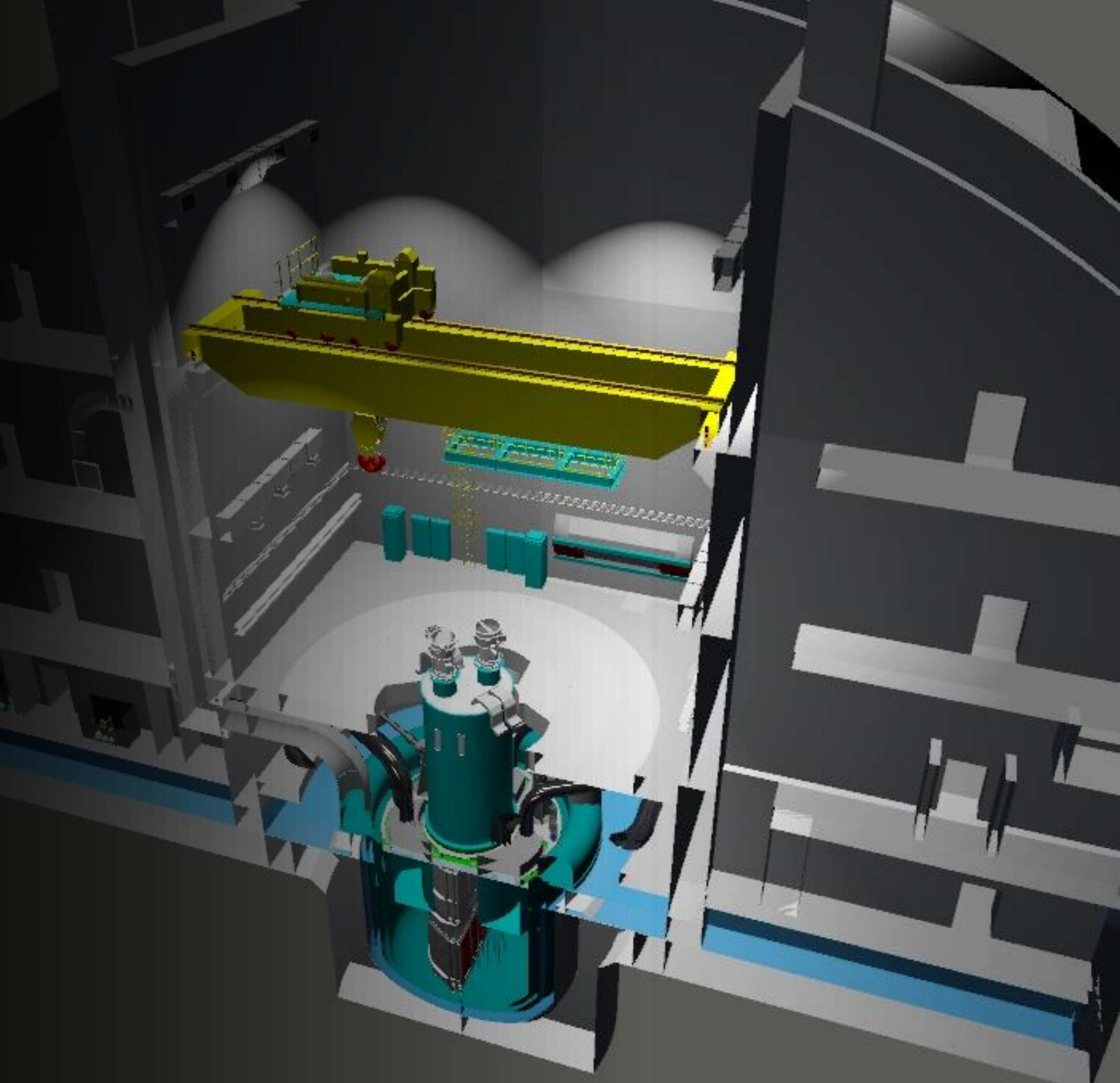


Table of Contents

- Westinghouse’s reactor portfolio and where LFR fits
- LFR overview
  - Plant general characteristics
  - Notable safety attributes
  - Core, fuel and fuel cycle
  - Main waste streams
  - Development status and path to deployment
- Recent developments
  - A network of test facilities being built to accelerate LFR development
- Conclusions

Westinghouse – Reactor Portfolio

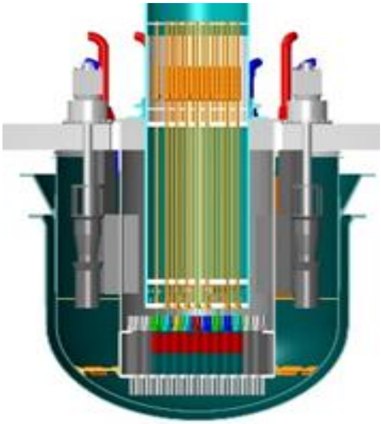
Westinghouse

STRATEGIC VISION

Provide innovative advanced reactor technology solutions that enable our customers to meet near- and long-term clean energy source and decarbonization objectives

MARKET SEGMENTS

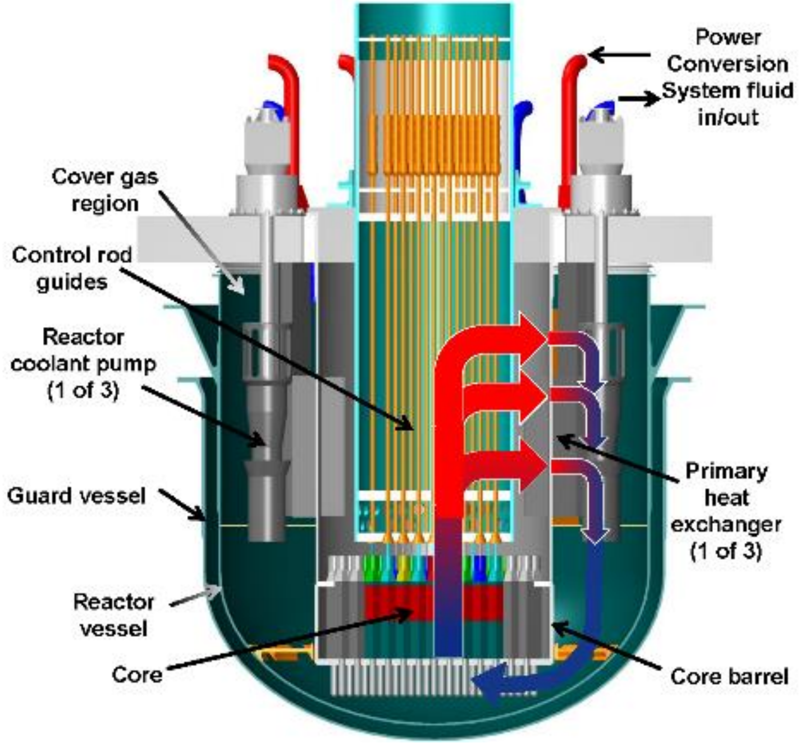
AP1000® (1100 MWe)	**eVinci Microreactor™** (5 MWe)	**Lead Fast Reactor** **(~450 MWe)**
Fulfills the need for large nuclear baseload power through safe, proven, LWR technology	Replace diesel generation where economics, logistics, environmental needs and/or reliability demand an alternate clean generation source	Innovative reactor technology with the goal to offer lower cost than today's technology and fulfill missions beyond electricity



Westinghouse LFR's key characteristics

- Development program started in 2016. Primary missions: best economics and market versatility
- Pool-type, passively safe, modular construction lead-cooled fast reactor

Reactor power	950 MWt (~450 MWe)
Efficiency	~47%
Primary coolant	Liquid lead
Secondary coolant	Supercritical water
Neutron spectrum	Fast
Configuration	Independent unit for single or two-unit site
Fuel	Oxide (Phase 1); Advanced fuel (Phase 2)
Operating pressure, MPa	0.1 (primary) / ~34 (secondary)
Lead coolant min/max temperature, ˚C	390 / 530 (Phase 1) 390 / 650 (Phase 2)



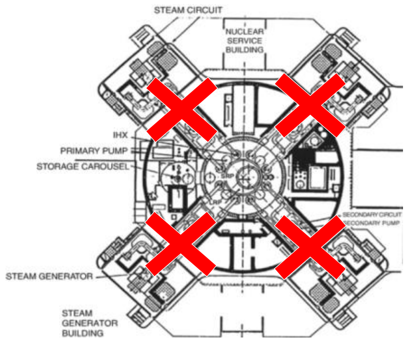
- Enhanced passive safety
- Fuel cycle flexibility typical of fast reactors
- Innovations to improve economics and enhance market versatility:
  - High-performance materials for high-duty components → improved economics through higher efficiency
  - Hybrid micro-channel-type heat exchangers → compact vessel and simplified safety
  - Atmosphere as the ultimate heat sink → enhanced siting opportunities with no need for vicinity of water bodies
  - Thermal energy storage → flexible electricity without changing core power

Notable safety attributes promote economic competitiveness

- **Relatively low power density core and reduced stored energy in the primary system allow eliminating conventional high-pressure resistant containment**

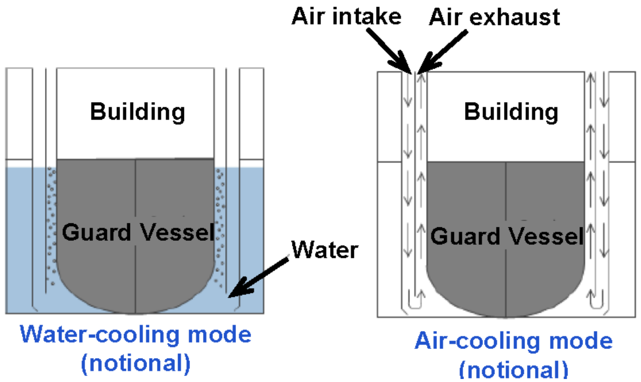
Maximum primary system potential energy (thermal + compression + H_2) (GJ/m3)*		
PWR (p=16 MPa; T=300°C)	SFR (p=0.1 MPa; T=500°C)	LFR (p=0.1 MPa; T=500°C)
~22	~10	~1

- **Extremely high boiling point of lead coolant (1700°C) combined with integral configuration of primary system make coolant boiling and loss of core cooling unrealistic**



- **Lack of exothermic reactions between lead coolant and balance of plant fluid enhances safety and allows elimination of intermediate loops typical of other advanced reactors**

- **Emergency decay heat removal system is always ON and does not require any I&C signal or operators' intervention for actuation**
  - Fully passive: Relies on heat transfer to a pool of water surrounding the Guard Vessel, which transitions to natural circulation of air once water is depleted
  - Performance is triggered by radiative heat transfer between RV-GV → kicks in only when really needed, with minimum heat losses during normal operation

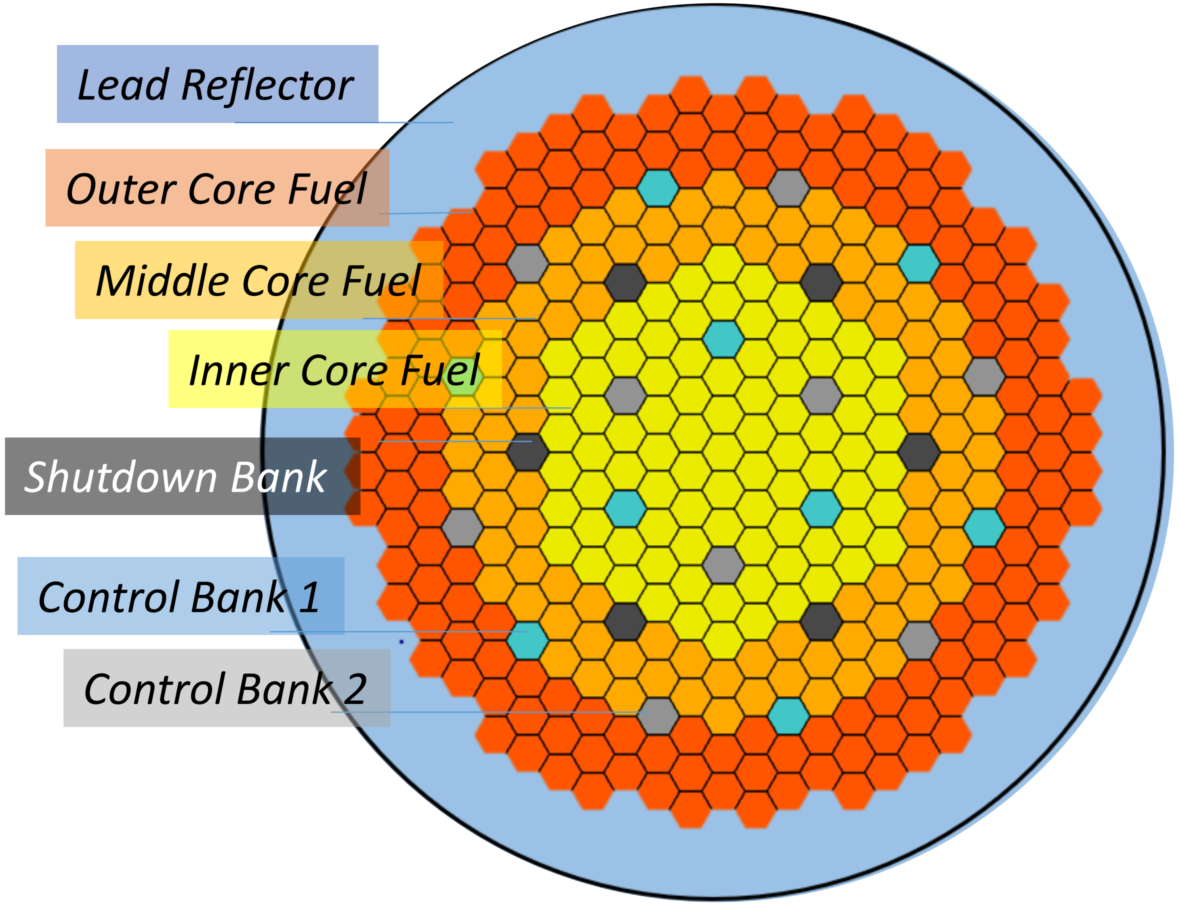


*From ICAPP 2011, Paper 11465 , "Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters". G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

Core Design and Reactivity Control

➢ Core and Fuel bundle configuration

- 325 fuel bundles with 3 enrichment zones
- Longer active length and lower core power density than typical FRs
- Grid spacer-supported hexagonal array
- Fuel pellets in cylindrical cladding
  - Oxide fuel with steel cladding (near-term)
  - Nitride fuel with advanced cladding (longer-term)



➢ Reactivity control

- Two primary reactivity control banks, each with shutdown capability
- One bank of shutdown assemblies
- Passive shutdown

Fuel and Fuel Cycle

Fuel materials

- UO_2 with steel cladding for LFR start-up core
- UN with advanced (steel or SiC) cladding for future performance enhancements
- MOX for Pu recycle if/when pursued
- Advanced fuel options are backfittable, no change to internals or control system will be required for incorporation
- Cladding material options being tested and downselected through corrosion testing campaign

Synergy with Westinghouse ATF and High Burnup/High Enrichment fuel development programs

Fuel cycle and refueling

- Reference fuel cycle: open
  - Flexibility to transition to semi-open or closed cycle if pursued by national policies
- Long cycle length:
  - 10 years (UO_2); 15-20 years (MOX/UN)
  - Single-batch core designs
- Refueling scheme: direct-to-cask with no assembly shuffling. No spent fuel pool

UO_2 Core – Key Performance Parameters

	Units	Value
Fuel pellet material	-	UO_2
Cladding material	-	15-15 Ti
Number of fuel bundles	#	325
Fuel bundle flat-to-flat	cm	15.2
Active fuel height	m	>1
Fuel pins per bundle	#	91
Rel. volume Fuel/Lead/Steel	%	39/36/22
Core average U-235	w/o	13.8
Cycle length	years	10
Reactivity swing	pcm	2500
Peak burnup	GWd/tiHM*	80
Peak fast fluence	n/cm^2	1.7E+23
Peak cladding DPA (estimate)	DPA	80
Fuel utilization	GWhr-e/kgU-235	4.7

* tiHM = initial tonnes of Heavy Metal

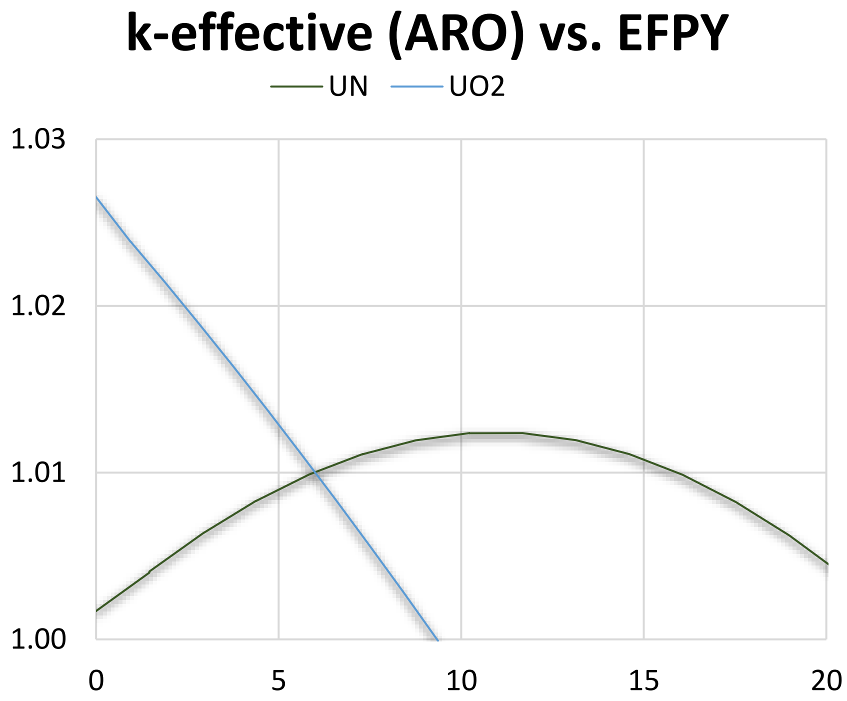
Best trade-off in short-term viability and performance with full flexibility to accommodate advanced fuel solutions

Performance Enhancements with UN Fuel

	Units	UO_2	UN*
Number of Fuel Bundles	#	325	Same
Fuel bundle flat-to-flat	cm	15.2	Same
Active fuel height	m	>1	Same
Cladding material	-	15-15 Ti	DS4**
Fuel pins per bundle	#	91	61
Fuel volume fraction	%	39	40
Core HM Content	tHM	Ref	1.4 x Ref
Core average U-235	w/o	13.8	11.9
Cycle Length	years	10	20
Reactivity swing	pcm	2500	1200
Peak burnup	GWd/tiHM	80	130
Peak fast fluence	n/cm^2	1.7E+23	4.1E+23
Est. Peak DPA on cladding	DPA	80	210
Fuel utilization	GWhr-e/kgU-235	4.7	10.6

* UN with natural Nitrogen. Further performance enhancements possible by adopting N-15 enriched UN

** Double-stabilized stainless steel. Further performance enhancements possible by adopting SiC cladding



Significant performance enhancements by switching to UN fuel for subsequent LFR reloads

Fuel Cycle Flexibility with MOX Fuel

	Units	UO_2	MOX	MOX
Fuel Cycle	-	**Open**	**Semi-open**	**Closed**
Main Fissile material	-	U-235	Pu	Pu
Fissile Source	-	Ore	LWR Pu	LFR Pu
Fertile Source	-	Ore	U tails	U tails
Fissile Enrichment	w/o	13.6	15.5	15.1
Cycle Length	years	10	15	15
Reactivity swing	pcm	2500	1300	1350
Peak burnup	GWd/tiHM*	80	140	135
Peak fast fluence	n/cm^2	1.7E+23	3.5E+23	3.4E+23
U requirements – from ore	MT/GWe-yr	417	NA**	NA
U requirements – from tail	MT/GWe-yr	NA***	7	1

* tiHM = initial tonnes of Heavy Metal

** Not accounting for the ore requirements that went into LWR Pu fuel

*** Depleted U tails will be produced in the UO_2 open cycle

Full fuel cycle flexibility to meet various national policies objectives on actinide recycle and used fuel disposal

Waste streams overview

	LFR component	Waste Category [1]	Quantity, Content, Activity
Waste from Operation	Used nuclear fuel	HLW	60 to 80 metric tons (= 1 core load) every 10 (UO_2 option) to 20 (MOX, UN options) years. Quantity, content and activity depend on the fuel used (UO_2, MOX or UN), adopted cycle and cooling time before disposal.
	Solid, liquid and gaseous waste from operation (not wetted by lead)	LLW (subclass to be defined)	To be determined. Quantity, content and activity depend on the adopted processes and technologies.
	Any lead wetted component replaced during operation	LLW (subclass to be defined)	To be determined. Quantity, content and activity depend on the components' replacement frequency and adopted technologies for treatment before disposal/recycle
	Minor amounts of lead from the purification of the primary system	LLW (subclass to be defined)	To be determined. Quantity, content and activity depend on the adopted technologies for lead purification and treatment.
Waste from Decommissioning	Lead	LLW (subclass to be defined)	~2000 metric tons. Content and activity depend on purity level of "fresh" lead, on the approach to lead purification and on waiting time before disposal
	Non-fuel components within the reactor coolant system (lead wetted)	LLW (subclass to be defined)	Frequency of replacement (during operation) and treatment before disposal to be determined. They will have an impact on activity
	Components outside of the reactor vessel	LLW-A	Quantity, content and activity to be determined.

[1] Nuclear Regulatory Commission (NRC) Classification

Waste streams: Used Nuclear Fuel (1)

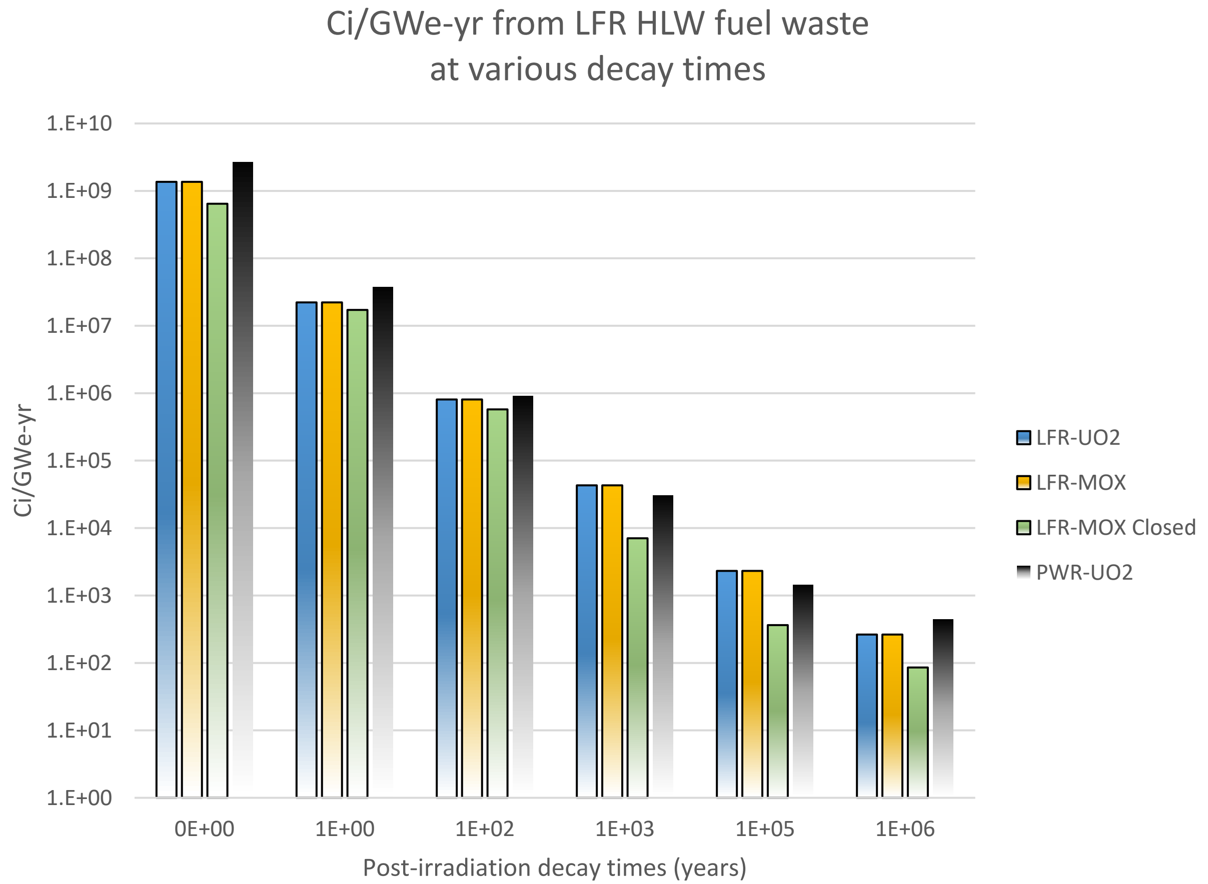
LFR fuel and waste mass flows for various fuel cycle options in Slide 10
(Current PWR included for comparison)

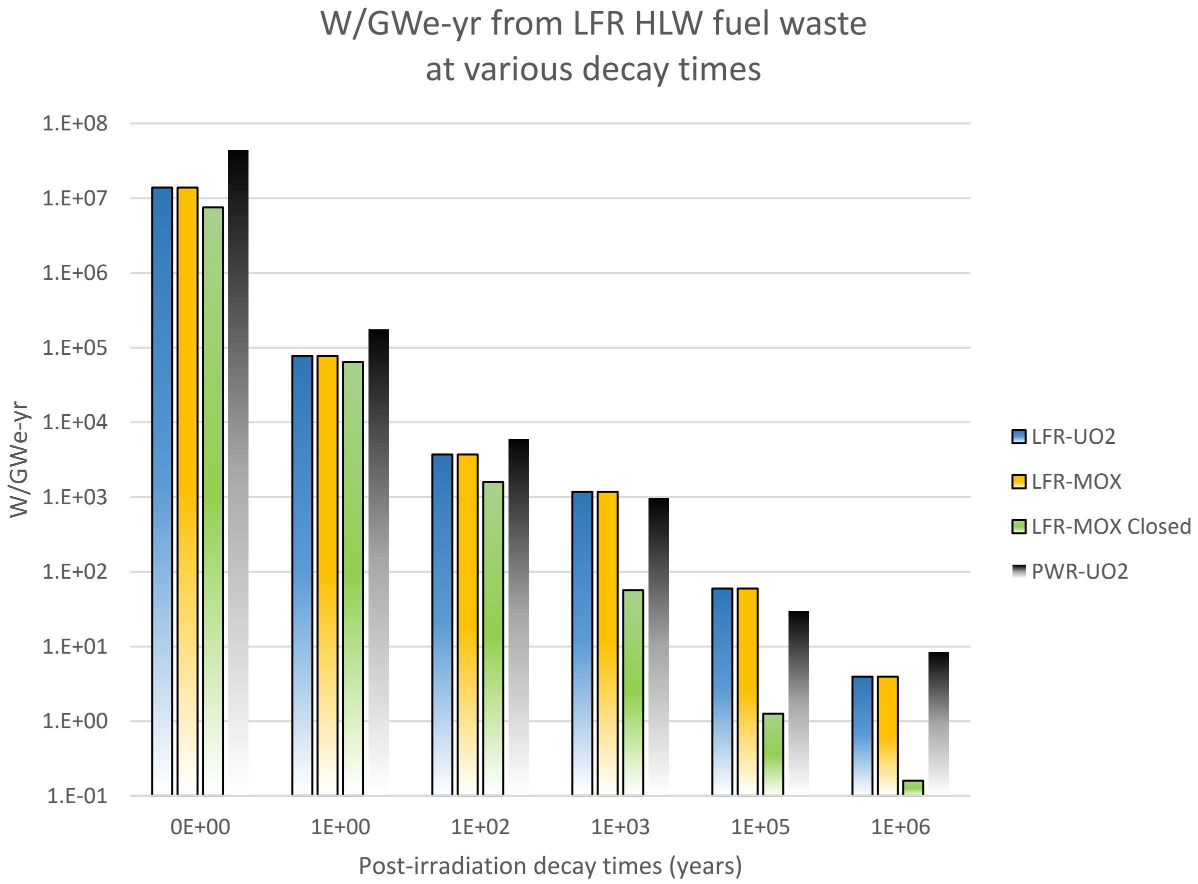
		PWR	LFR	LFR	LFR
Power	GWe	1.112	0.465	0.465	0.465
Fuel Cycle	Open/Closed	Open	Open	Open	Closed
Fuel	-	UO_2	UO_2	MOX	MOX
Thermal Efficiency	%	0.31	0.48	0.48	0.48
Cycle Length	Years	1.5	10	15	15
Discharge Burnup	GWd/tiHM	55	55	93	93
Core HM	MT	80	61	57	57
Fissile (U-235 or TRU)	% of HM	4.8	13.6	15.5	15.1
Fissile requirements	MT iFissile/GWe-yr	1.0	1.9	1.3	1.2
Fuel requirements	MT HM/GWe-yr	21.3	13.7	8.2	8.2
U mine requirements	MTU3O8/GWe-yr	257	403	0	0
(1)Depleted U: Waste(+) or Reuse(-)	MT Dep U/GWe-yr	182	326	-7	-1
Fuel HLW(2)	MT/GWe-yr	22.8	15.6	9.3	0.9

Note (1): Depleted U waste (+) from U-235 enrichment (UO2), or depleted U consumption (-) such as for MOX
Note (2): Fuel HLW consists of Spent Nuclear Fuel except for the LFR MOX closed cycle where it consists of reprocessing wastes (actinide losses and fission products)

Waste streams: Used Nuclear Fuel (2)

Fuel HLW Radioactivity (Ci/GWe-yr) and Decay Heat (Watts/GWe-yr)
at various post-irradiation cooling times





Note: Fuel HLW consists of Spent Nuclear Fuel except for the LFR MOX closed cycle where it consists of reprocessing wastes, e.g. 1% of the reprocessed inventory for U/Pu, 100% for Np/Am/Cm and 100% for the Fission Products

Waste streams: Used Nuclear Fuel (3)

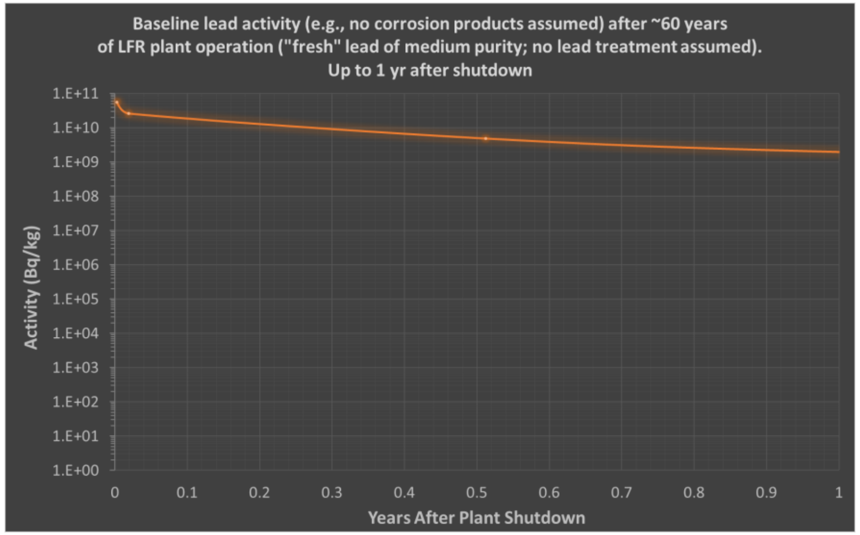
LFR Fuel HLW Composition
(Current PWR included for comparison)

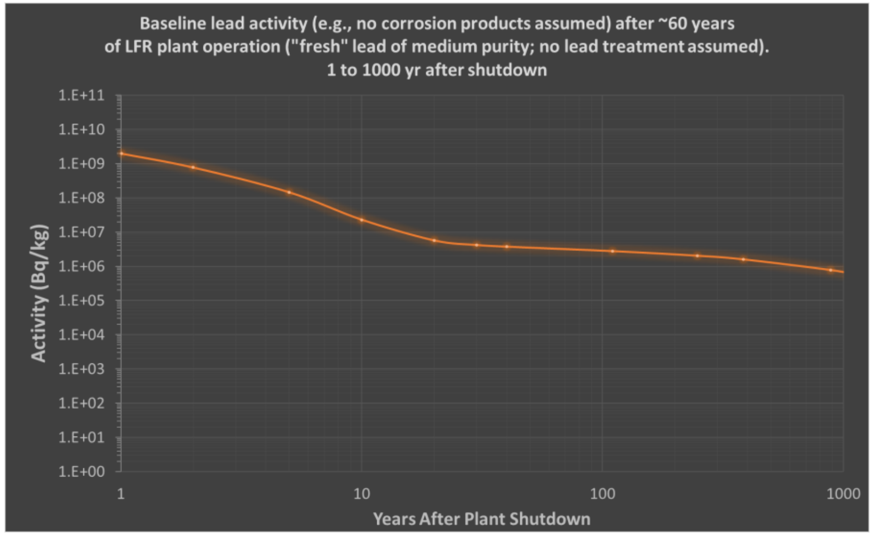
		PWR	LFR	LFR	LFR
Power	GWe	1.112	0.465	0.465	0.465
Fuel Cycle	Open/Closed	Open	Open	Open	Closed
Fuel	-	UO_2	UO_2	MOX	MOX
(1) Fuel HLW	MT/GWe-yr	22.8	15.6	9.3	0.9
HM	MT/GWe-yr	20.1	12.9	7.4	0.1
(2) U	% of HM	99.1%	95.7%	82.2%	42.5%
(2) Np	% of HM	0.0%	0.1%	0.0%	7.2%
(2) Pu	% of HM	0.9%	4.2%	17.0%	8.5%
(2) Am	% of HM	0.07%	0.01%	0.2%	41.6%
(2) Cm	% of HM	0.02%	0.00%	0.00%	0.17%
Fission Products	MT/GWe-yr	1.2	0.8	0.7	0.8
Fuel assembly structure (Zr or SS)	MT/GWe-yr	6.5	4.2	2.7	2.7

Note (1): Fuel HLW consists of Spent Nuclear Fuel except for the LFR MOX closed cycle where it consists of reprocessing wastes, e.g. 1% of the reprocessed inventory for U/Pu, 100% for Np/Am/Cm and 100% for the Fission Products Note (2): Fuel HLW elemental ratio calculated at 100 years of SNF (or reprocessing waste) post-irradiation cooldown

Waste streams: lead activity profile during/after decommissioning

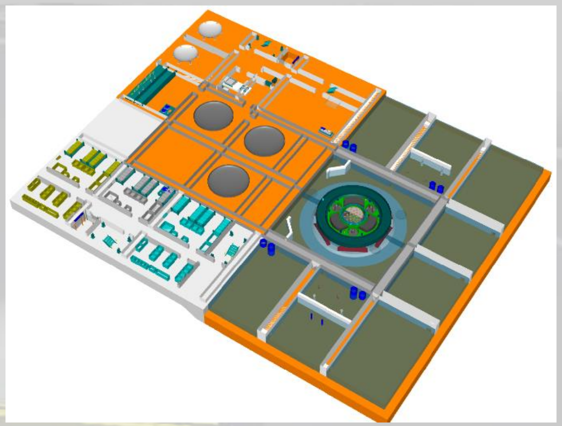
- Lead activity is the result of the activation of:
  - Lead itself (including impurities already present in fresh lead), referred to as “baseline lead activity”
  - Impurities resulting from operation, e.g. corrosion products released from structural components
- In the LFR, a Lead Processing System (LPS) monitors and controls lead chemistry, including impurity content. The specifications and performance of this system are still under development
- The plots below show the time profile of the baseline lead activity, and refer to a “fresh” lead of medium purity
  - It has been estimated that, without LPS, operation impurities can increase lead activity by up to 1-2 orders of magnitude relative to baseline
  - The LPS will limit such an increase
  - Further reduction in activity is possible by increasing purity level of “fresh” lead

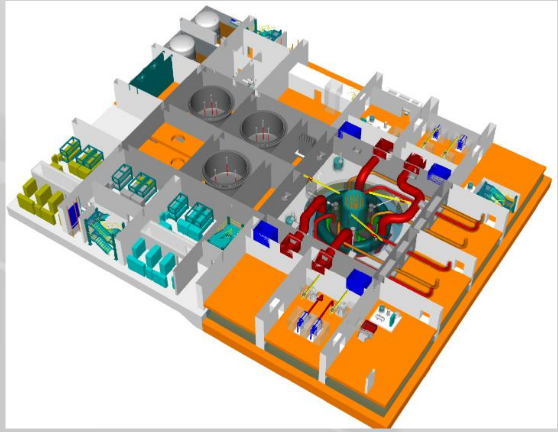


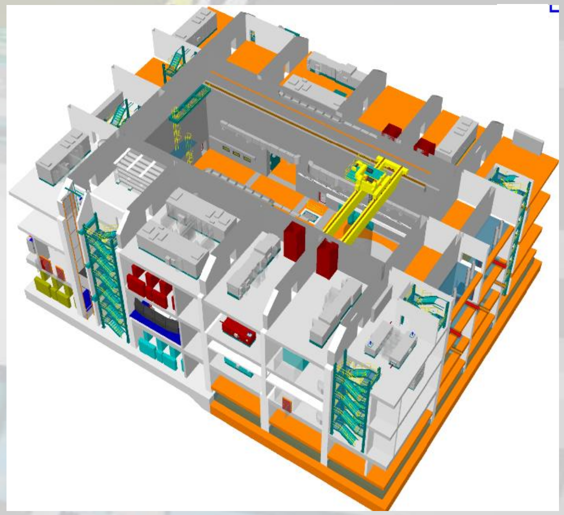


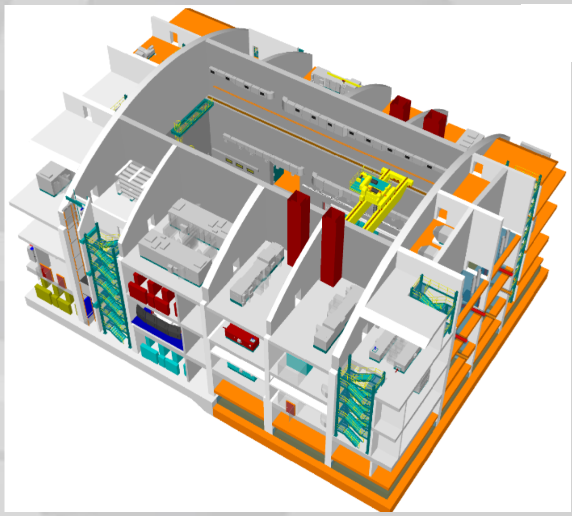
LFR development status

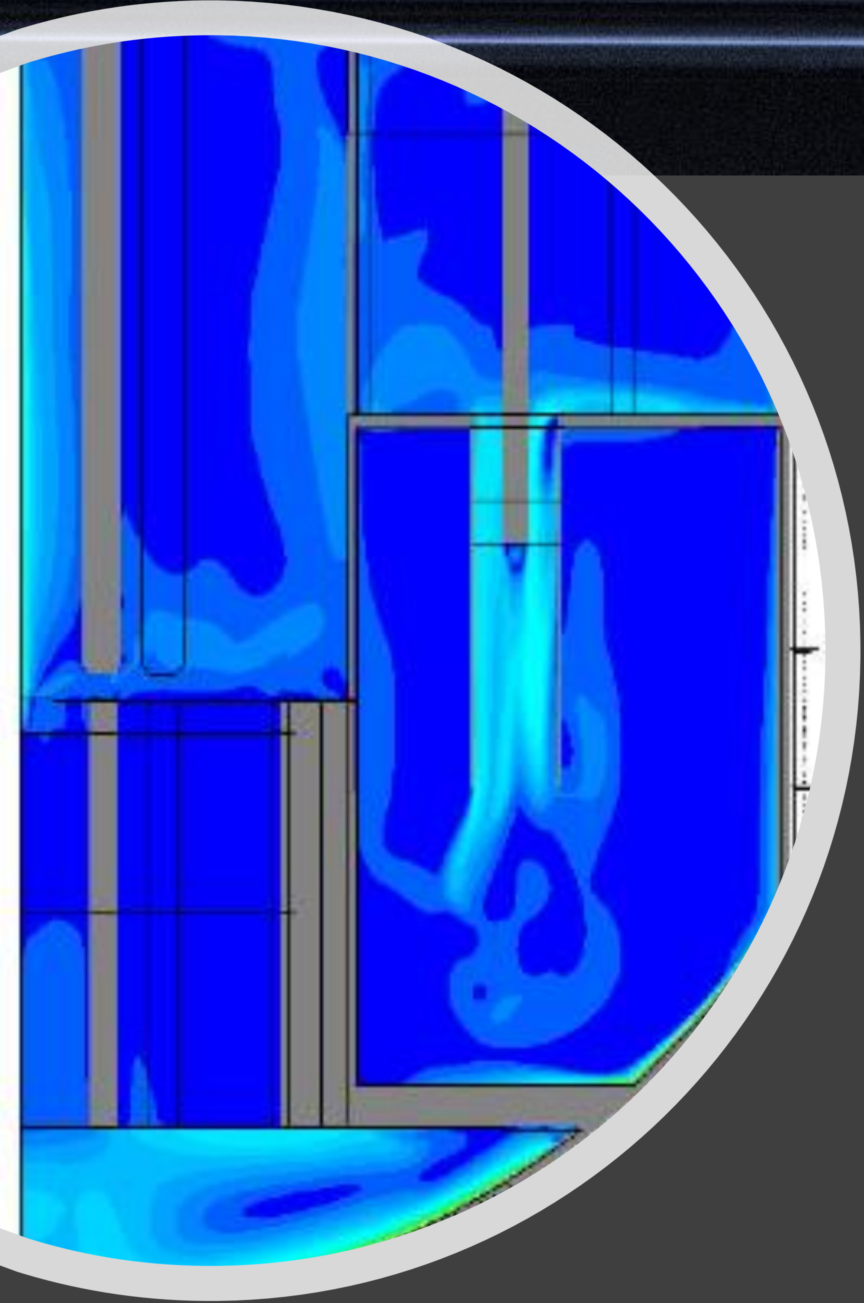
- **Design**: conceptual design near completion
- **Testing**: Three test rigs currently being utilized in the US (2) and Italy (1). Nine test rigs under design/construction in the UK (8) and US (1).
  - Corrosion/erosion (5 rigs)
  - Fuel manufacture (2 rigs)
  - Plant safety and reliability (3 rigs)
  - Lead's effect on materials' mechanical properties (2 rigs)
  - Component testing, e.g. fuel bundle and HX mockups (1)
  - Instrumentation testing, e.g. Under-Lead Viewing (2 rigs)
- **Licensing**: pre-licensing engagement meetings ongoing with UK Regulators
- **Reactor demonstration**: ongoing talks
  - Electric demo followed by nuclear demo
  - Commercialization in the 2030s'

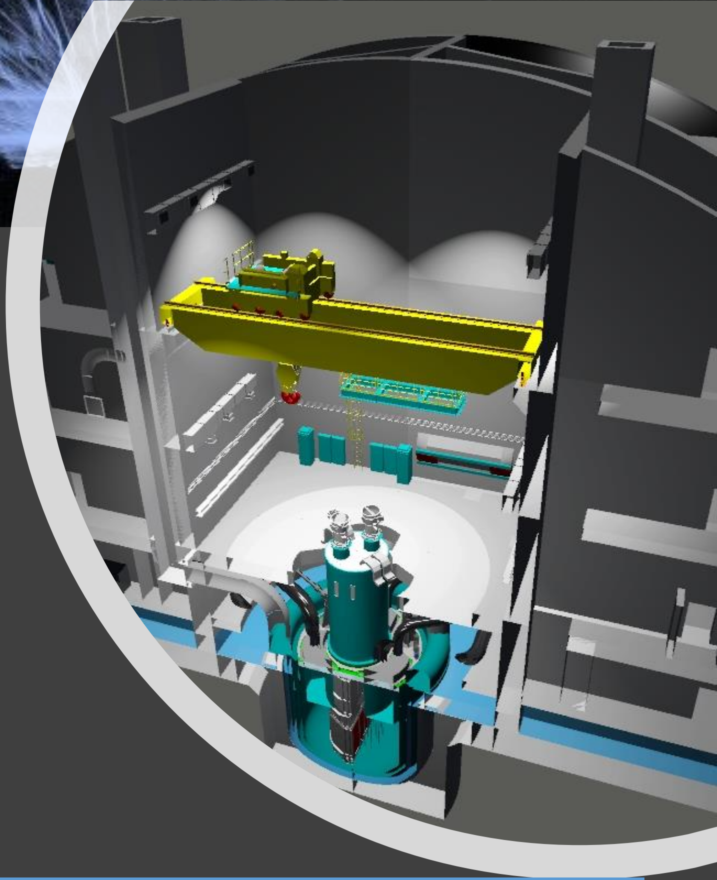












Global efforts toward LFR development

- Westinghouse US
- Westinghouse UK
- Westinghouse Mangiarotti (Italy)
- Westinghouse Sweden
- Global partnerships

Westinghouse LFR global collaborations

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

Argonne NATIONAL LABORATORY

ANSALDO NUCLEARE
Ansaldo Energia Group

Department of Energy · United States of America

Department for Business, Energy & Industrial Strategy

ECHOGEN power systems

MANCHESTER 1824

OAK RIDGE National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

NATIONAL NUCLEAR LABORATORY

Westinghouse

UNM

PRIFYSGOL BANGOR UNIVERSITY

University of Pittsburgh 1787

Brigham Young University, Founded 1875, BYU, Provo, Utah

INL Idaho National Laboratory

FRAZER-NASH CONSULTANCY

FAUSKE & ASSOCIATES, LLC

NUCLEAR AMRC

Jacobs

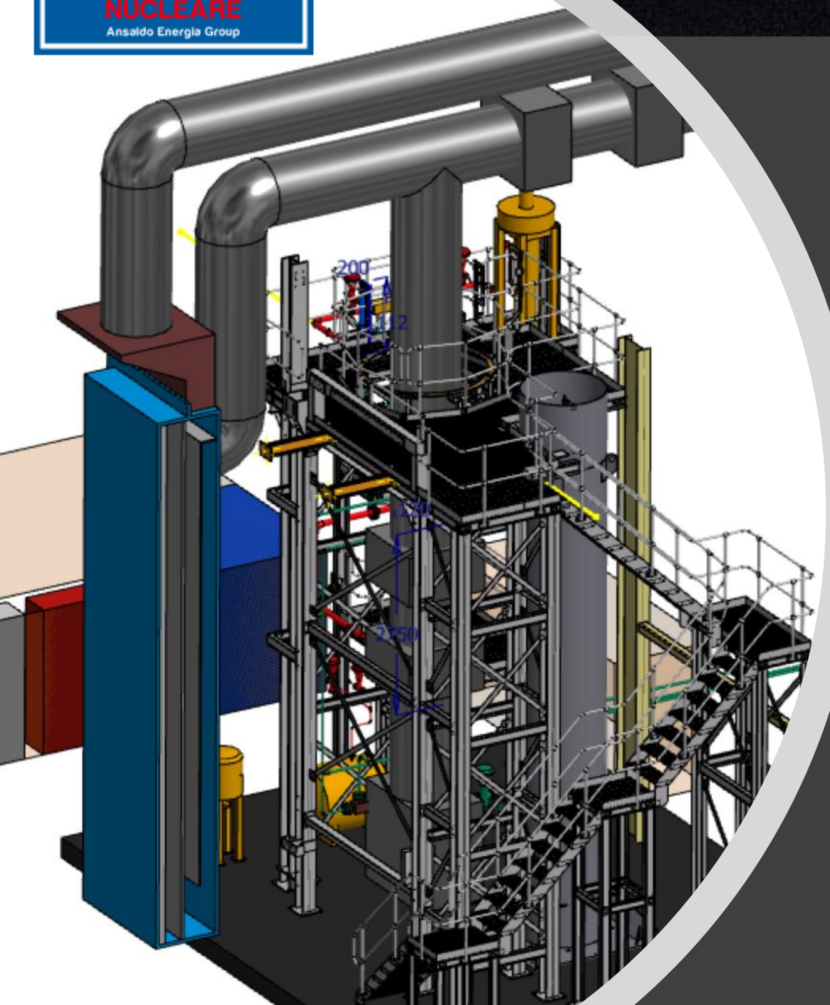
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

VPE VACUUM PROCESS ENGINEERING

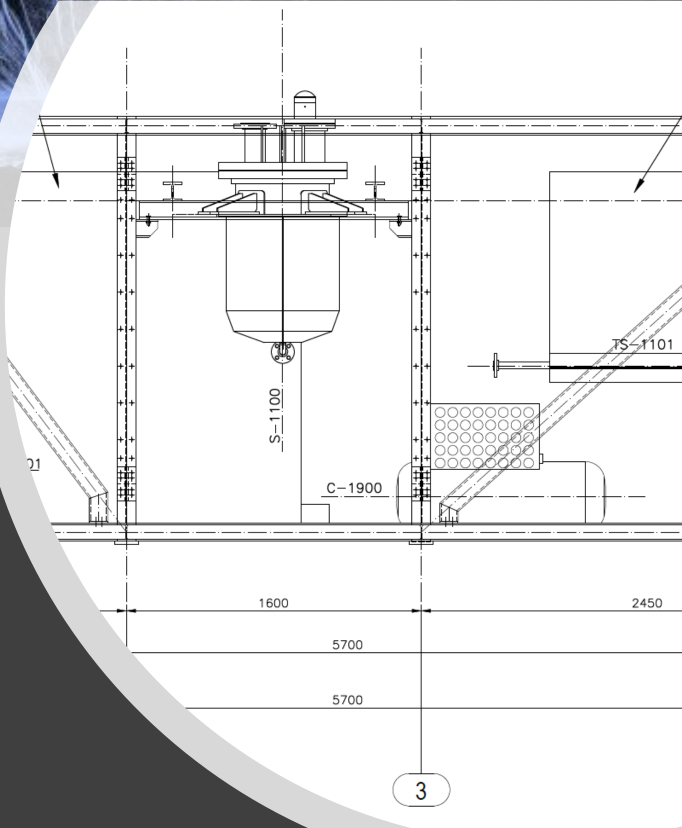
Westinghouse

CLEAN ENERGY
TECHNOLOGY PARK
Springfields

ANSALDO NUCLEARE
Ansaldo Energia Group



Passive Heat Removal Facility



A network of eight state-of-the-art test facilities is being built in the UK to accelerate development of the Westinghouse LFR

- Lead freezing test facility
- Heat exchanger failure test facility (Lead-to-H_2O interaction)
- High-temperature stagnant lead corrosion test facility
- High-temperature flowing lead corrosion test facility
- High-velocity lead corrosion/erosion test facility
- Mechanical property characterization test facility
- Component test facility (fuel bundle, heat exchanger, etc.)
- Passive Heat Removal test facility

Start of operation in 2022

Department for Business, Energy & Industrial Strategy

Conclusions

- LFR is Westinghouse's next generation of high-capacity nuclear power plants. Economic competitiveness and market versatility are its main missions
- LFR design is progressing, and conceptual design is near completion
- A network of test facilities is being set up in the UK to demonstrate key LFR's materials, systems and components, in collaboration with domestic and international partners
- A staged approach to development is adopted, with a nearer-term demonstration at reduced-duty conditions followed by performance enhancement enabled by, primarily, progress in materials development
- LFR fuel development program synergistic with Westinghouse fuel strategy at large
- An open fuel cycle is used as reference. However, LFR's fuel cycle flexibility is valued as a way to meet potentially varying national policies objectives, globally, on actinide recycle and used fuel disposal

Westinghouse

Thank you for your attention!

Westinghouse Electric Company

@WECNuclear

Westinghouse Electric Company

wecchinanuclear

westinghousenuclear.com