Westinghouse

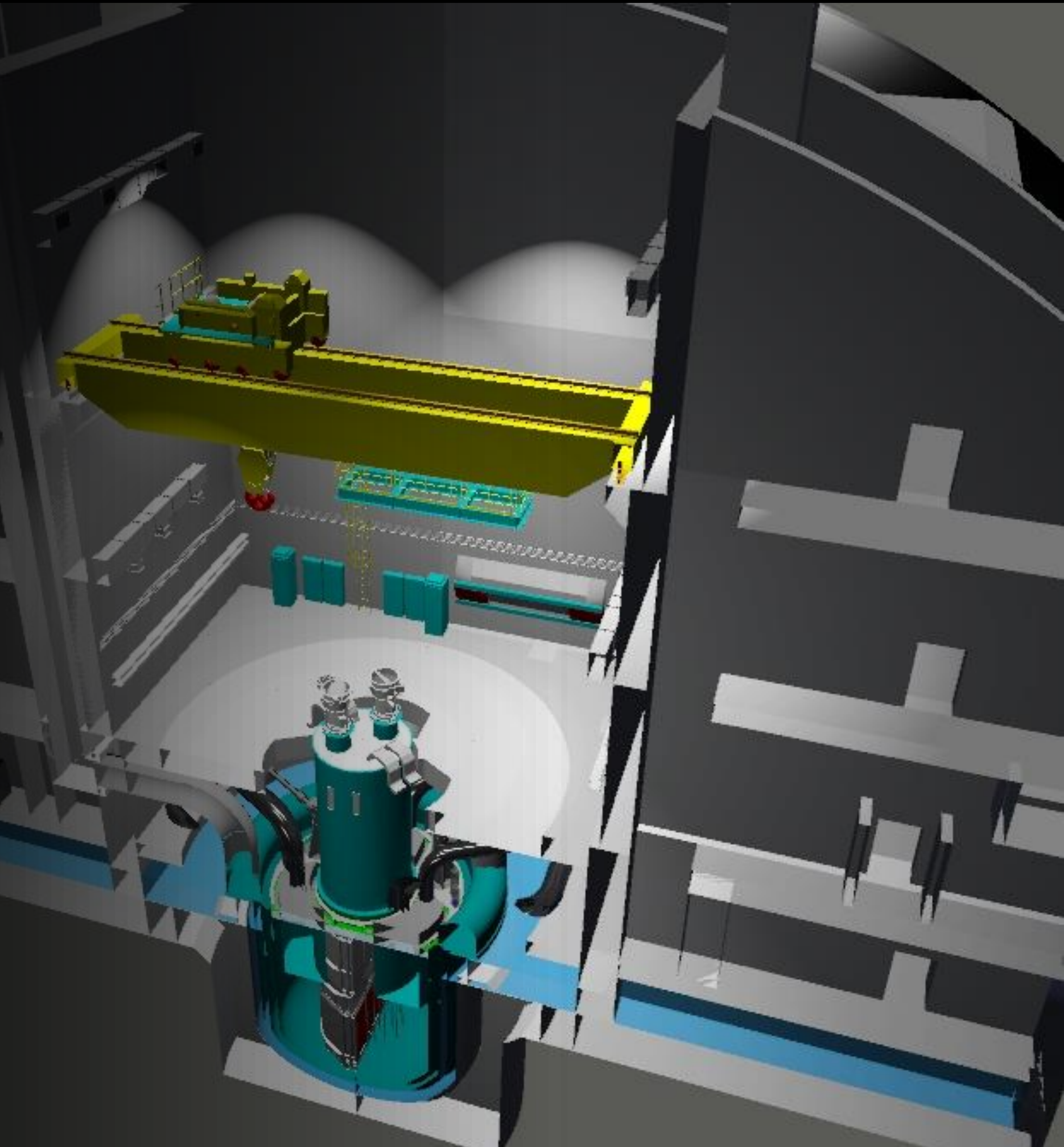
Applicability Enhancement of SAS4A/SASSYS-1 Computer Code to Lead Fast Reactor Systems

Technical Meeting on State-of-the-art Thermal Hydraulics of Fast Reactors

Camugnano, Italy, 26 Sept. –30 Sept. 2022

Jun Liao, Dan L. Wise, Megan Durse, Paolo Ferroni (Westinghouse Electric Company, USA)

Sung Jin Lee (Fauske & Associates, USA)



Outline

- Introduction to the Westinghouse Lead-cooled Fast Reactor (LFR)
- LFR Safety Analysis Codes: SAS4A/SASSYS-1 and GOTHIC
- Progress of Verification and Validation of SAS4A/SASSYS-1 and GOTHIC
- Planned Verification and Validation for SAS4A/SASSYS-1 and GOTHIC
- Conclusions

Introduction to the Westinghouse Lead-cooled Fast Reactor

Mission and Development Status

The Westinghouse LFR is a forward-thinking concept designed to:

- Achieve a step-change in economic competitiveness
- Achieve versatility in applications, beyond electricity
- Accommodate transition to closed fuel cycle, if/when needed

Developed leveraging Westinghouse's demonstrated experience in commercializing nuclear power plants globally

Strengthened by international collaborations selected to best complement capabilities

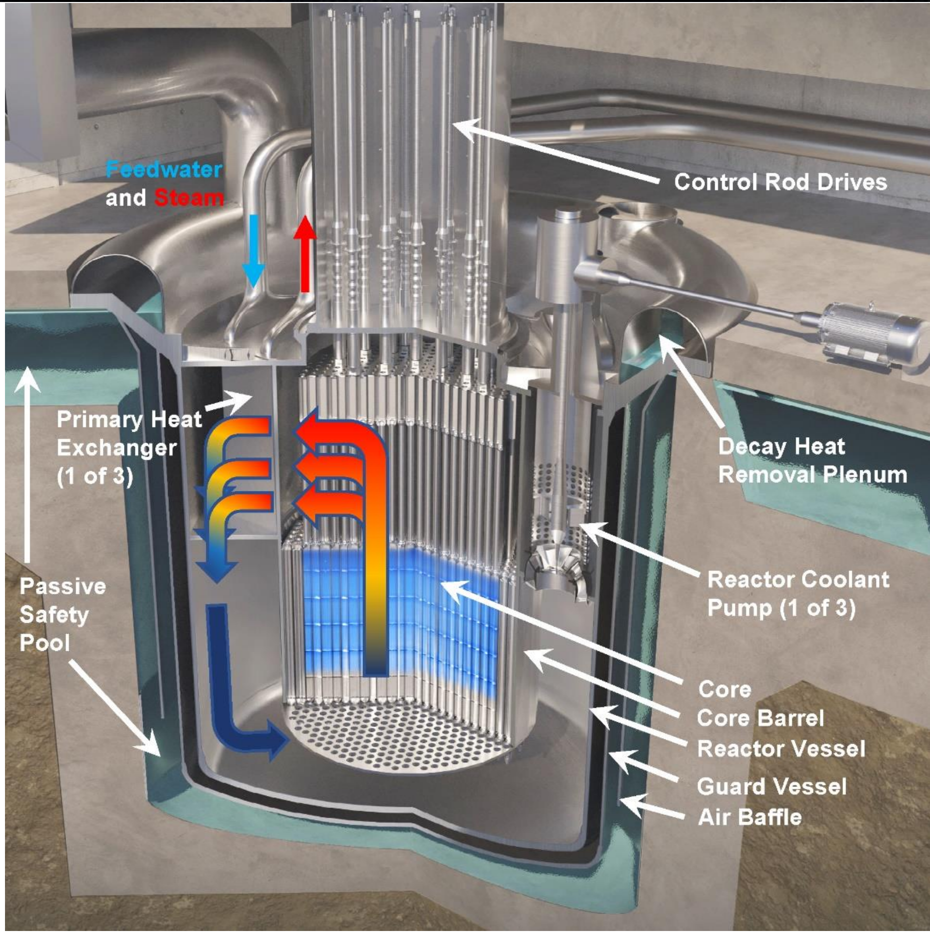
Development status:

- Near completion of conceptual design
- Demonstration of key systems, components and materials starting in 2022
- Pre-licensing engagement ongoing with UK Regulators

Westinghouse LFR's Key Characteristics

- Pool-type, passively safe, modular construction lead-cooled fast reactor

Reactor power	950 MWt (~450 MWe Net)
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 – shutdown, decay heat removal
- Fuel cycle flexibility typical of fast reactors
- Innovations to improve economics and enhance market versatility:
  - High-performance materials for heavy-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

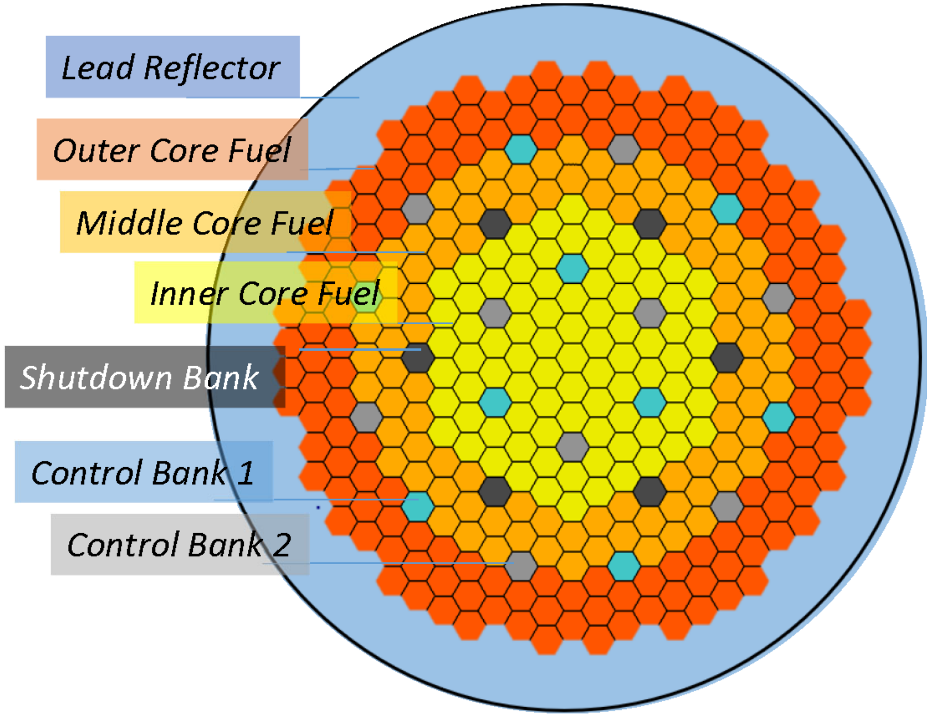
LFR Fuel and Fuel Cycle

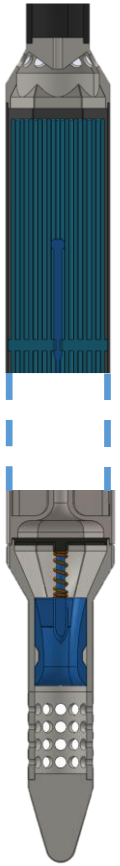
Fuel materials

- UO_2 with 15-15Ti-type austenitic steel cladding for LFR start-up core
- UN with advanced cladding (steel or SiC) 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
- Synergy with Westinghouse ATF and High Burnup/High Energy fuel development program

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:
  - ~8 years (UO_2); ~15 years (MOX/UN)
  - Single-batch core designs
- Refueling scheme: direct-to-cask with no assembly shuffling. No spent fuel pool

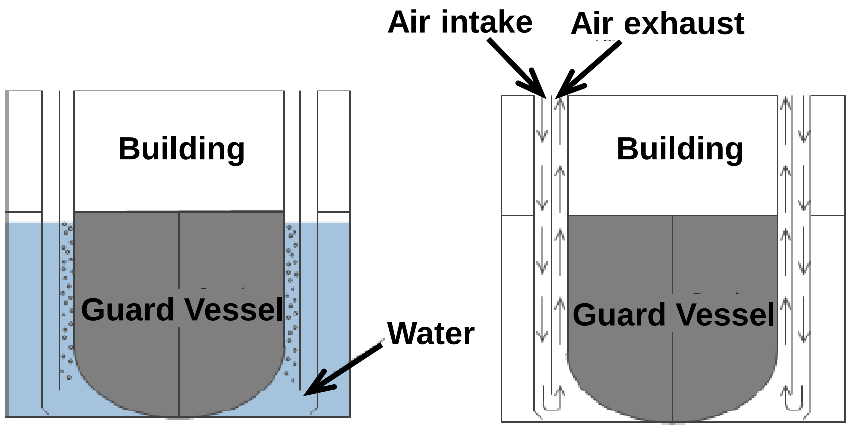




Emergency Passive Heat Removal System (PHRS)

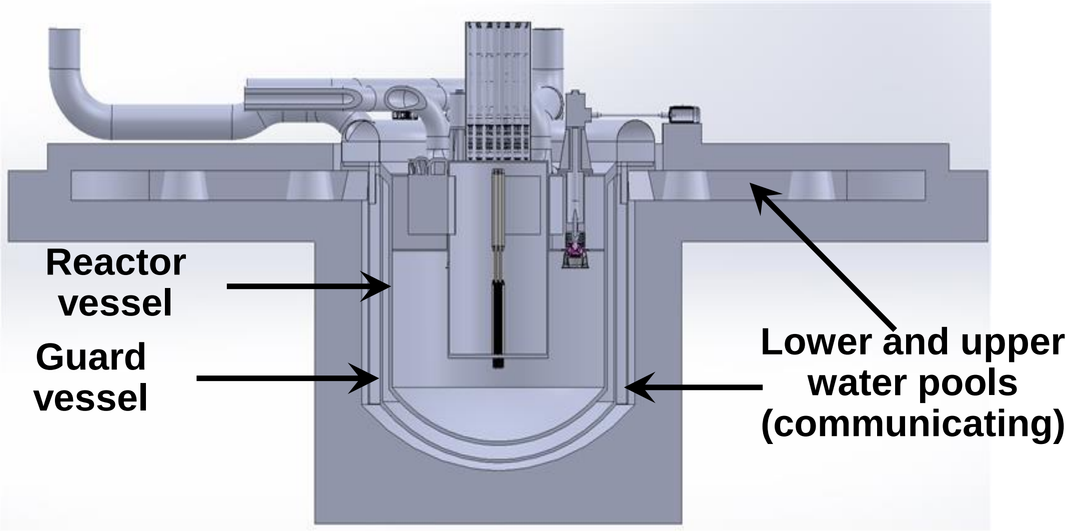
- LFR PHRS design requirements:
  - IAEA passive safety category B: No moving parts
  - Capable to remove decay heat of 950MWt LFR core
  - Capable of extended long term heat removal
- Leverage knowledge of AP1000® passive containment cooling system and SFR reactor vessel auxiliary cooling system

- The LFR PHRS design features
  - Pool of water surrounds Guard Vessel
  - Water-cooling during DBA (7 days)
  - Transition to (indefinite) air-cooling in extended long-term cooling
  - Fully passive, no I&C support, no need for actuation
  - System always on
  - Performance primarily driven by radiation heat transfer between RV and GV, which is very low during normal operation but kicks in during transients



Water-cooling mode (notional)

Air-cooling mode (notional)



Westinghouse LFR: A Global Program

Westinghouse Sweden

Westinghouse US

Westinghouse Mangiarotti (Italy)

Westinghouse UK

Global collaborations

Argonne National Laboratory

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

Fauske & Associates, LLC

Ansaldo Nucleare – Ansaldo Energia Group

Department for Business, Energy & Industrial Strategy

Los Alamos National Laboratory Est. 1943

Westinghouse

Oak Ridge National Laboratory

National Nuclear Laboratory

Prifysgol Bangor University

PennState

BYU

VPE Vacuum Process Engineering

INL Idaho National Laboratory

Nuclear AMRC

Jacobs

Frazer-Nash Consultancy

Echogen power systems

University of Pittsburgh

Wisconsin University of Wisconsin-Madison

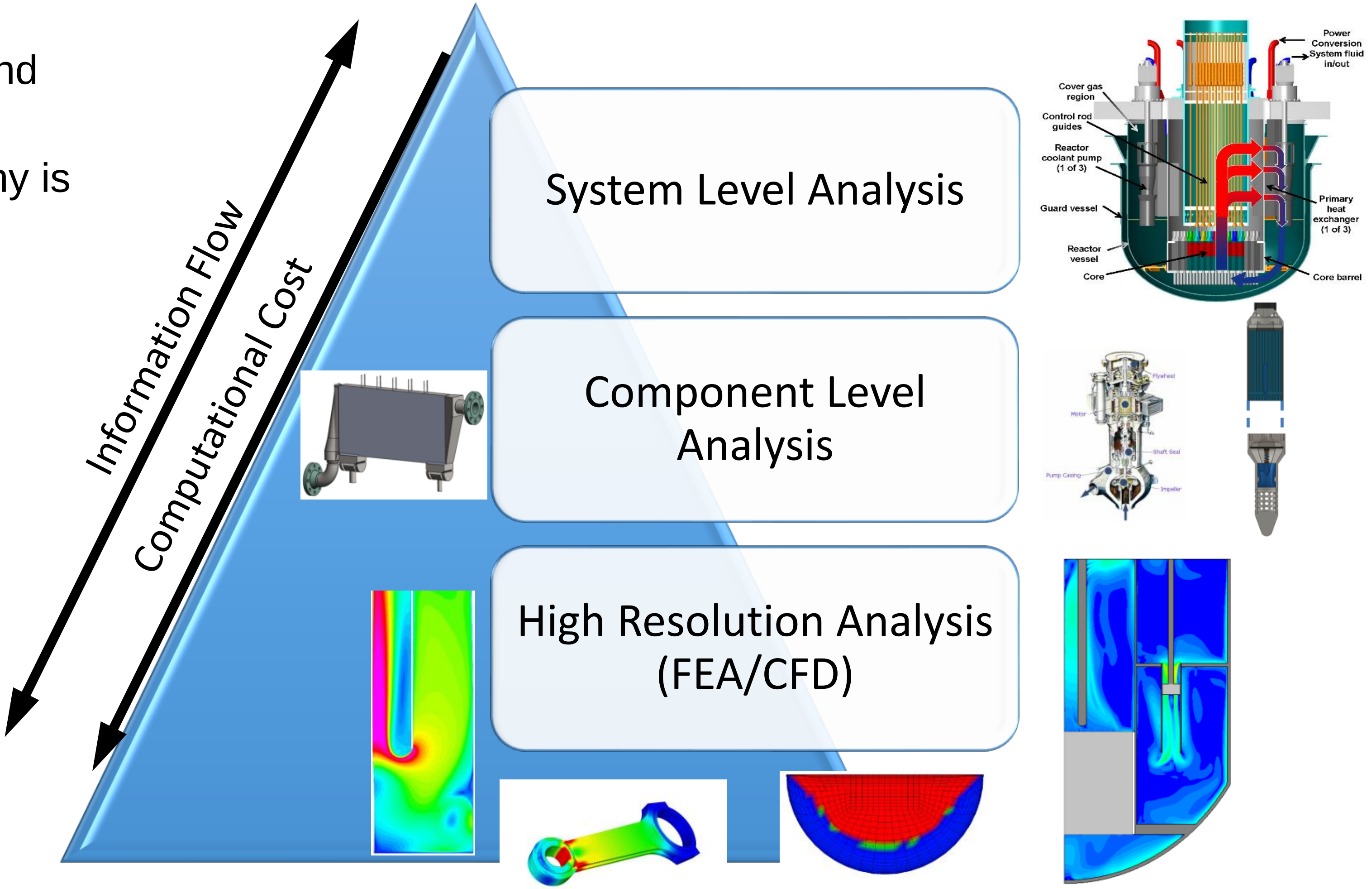
Manchester 1824

LFR Safety Analysis Codes: SAS4A/SASSYS-1 and GOTHIC

Overview of LFR Modeling and Analysis

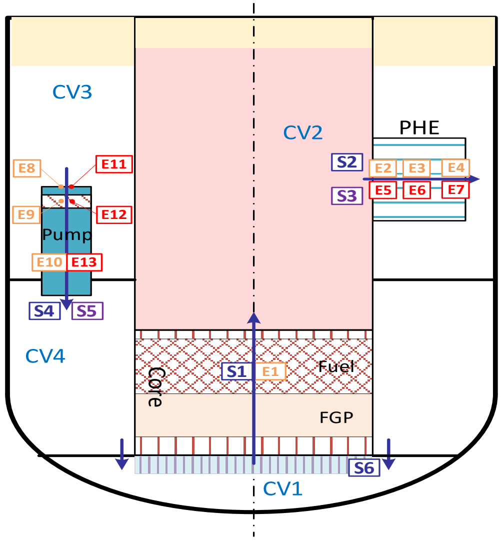
- Multiphysics: thermal-hydraulics, reactor physics, structural mechanics, dose analysis, etc.
- Phenomena involve a wide range of length and time scales.
- Multiscale/multi-resolution simulation hierarchy is needed.
- LFR M&S tools attributes:
  - Industry proven
  - Low maintenance cost
  - Versatile applications
  - High resolution (when required)
  - Coupled simulations
- Advanced M&S is under expansion for LFR

System Level Tools	Component Level Tools	High Resolution Analysis
SAS4A/SASSYS-1 GOTHIC FATE RELAP5 MOD3.3 SAM	PyARC ANTEO+ TRANSURANUS SAS4A SERPENT	FEA (ANSYS Mechanical) CFD (ANSYS CFX & STAR-CCM+)



SAS4A/SASSYS-1 Overview

- SAS4A/SASSYS-1 (SAS) is a safety analysis code for liquid metal fast reactors
  - Developed by Argonne National Laboratory in the 1970s', primarily for sodium fast reactors
  - Has been used as the safety analysis tool for sodium fast reactors extensively.
  - Expansed to lead based reactor since lead properties subsequently added in 1990s.
- Westinghouse has been using SAS4A/SASSYS-1 for LFR since 2017
- SAS4A/SASSYS-1 plays an important role in the development of LFR.
  - Analysis/scoping tool for the design of W-LFR system
  - Support the development of testing plan and PIRT.
  - Safety analysis code (AOO, DBA, BDBA) for the licensing of LFR.



SAS4A/SASSYS-1 Development for LFR Systems

- Enhance application to the LFR system
  - Computer code capability to address LFR design features.
  - Computer code verification and validation (V&V) status.

- Key developments are supported by four US Department of Energy-funded projects, jointly with Argonne National Laboratory
  - Gateway for Accelerated Innovation in Nuclear (GAIN) project: "*Development of an Integrated Mechanistic Source Term Assessment Capability for Lead and Sodium-Cooled Fast Reactors*"
  - Technology Commercialization Fund (TCF) project: "*Joint Development of SAS4A Code in Application to Oxide-fueled LFR Severe Accident Analysis*"
  - TCF project: "*Qualification of System-Level Advanced Reactor Safety Analysis Software for Lead Systems*"
  - TCF project: "*Capability Enhancement for System-level Thermal Hydraulic Modeling of Lead Fast Reactors*"

Key SAS4A/SASSYS-1 Development (1)

- Improvement of Lead/LBE properties
  - Lead and LBE property libraries in SAS were improved to be consistent with OECD lead and LBE database.
- Development of mechanistic source term analysis capability
  - FATE is a general source term analysis tool for various advanced reactors.
  - Coupling SAS4A/SASSYS-1 with FATE to provide capability of mechanistic source term analysis for LFR
  - Radionuclide Release Module (RRM) was developed.
  - RRM was validated against multiple experiments
  - Demonstrational results were presented.
- Enhancement of oxide fuel model
  - Develop UO2 and MOX fuel model for design basis accident and severe accident analyses.
  - Improved Oxide fuel performance module
  - Improved cladding module
  - Stochastic cladding failure propagation model for LFR

Key SAS4A/SASSYS-1 Development (2)

➢ Development of primary heat exchanger model

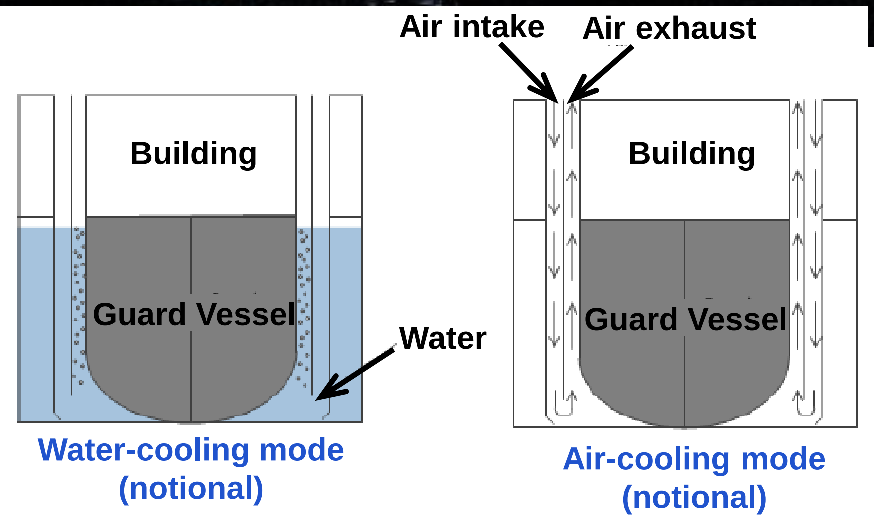
- LFR design adopts primary heat exchangers inside the reactor vessel.
- Primary heat exchanger was modeled for intermediate loop.
- SAS has been improved to address the design feature.

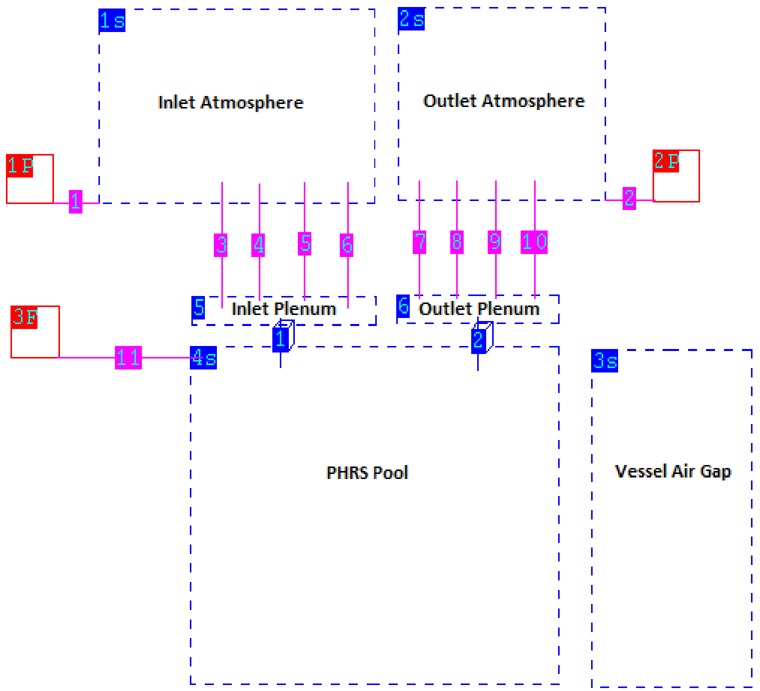
➢ Development of PHRS modeling

- The SAS is capable to model passive air cooling with RVACS model, but unable to address water cooling.
- PHRS modeling is addressed by the GOTHIC computer code.
- Coupling SAS with GOTHIC provides analysis capability of LFR system.
- *GOTHIC code is discussed on the next page*

GOTHIC Overview

- GOTHIC is a high-pedigree system/containment analysis computer code.
- GOTHIC is a general-purpose thermal-hydraulics software package for design, licensing, safety and operating analysis of nuclear power plant containments, confinement buildings and system components.
- Capable to model two-phase flow and heat transfer.
- Westinghouse has extensive usage of GOTHIC for light water reactors.
- The GOTHIC code is selected to model LFR PHRS and it is coupled with the SAS4A/SASSYS-1 code to perform safety analysis of the LFR.



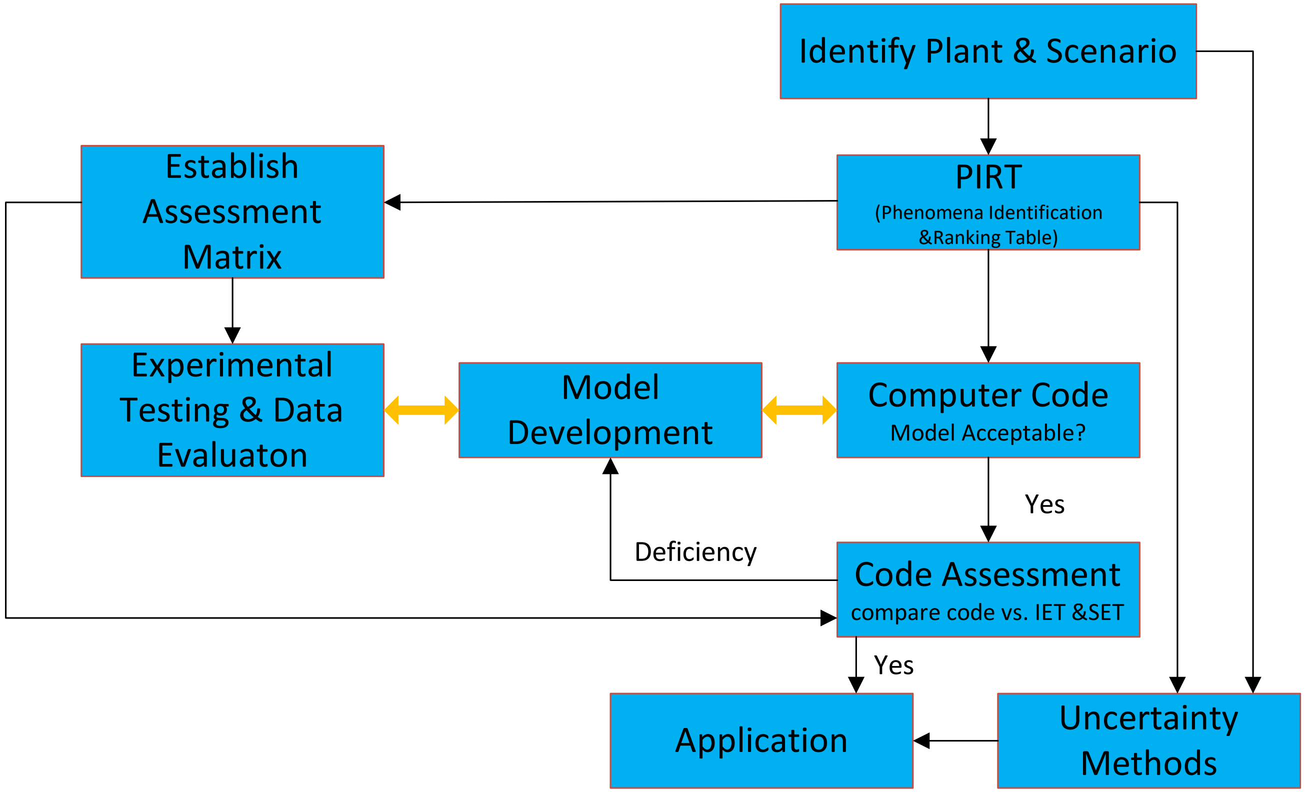


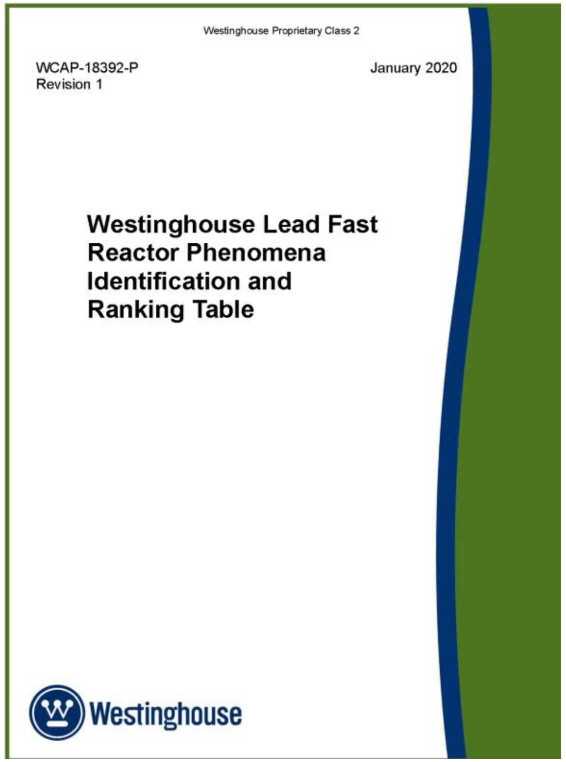
Progress in Verification and Validation of SAS4A/SASSYS-1 and GOTHIC

Safety Analysis Development

US NRC developed EMDAP and PIRT to guide safety analysis development

- Evaluation Model Development and Assessment Process (EMDAP)
- Phenomena Identification and Ranking Table (PIRT) defines requirements for modeling and analysis tool and necessity of experimental data.




Westinghouse Proprietary Class 2

WCAP-18392-P
Revision 1

January 2020

Westinghouse Lead Fast Reactor Phenomena Identification and Ranking Table

Westinghouse

Westinghouse LFR Safety PIRT carried out in collaboration with ENEA, Ansaldo, Fauske&Associates and Argonne

Westinghouse LFR Safety PIRT guides code qualification

Verification of SAS for Liquid Metal Reactors (SFR and LFR)

- The SAS4A/SASSYS-1 V&V Test Suite currently contains over 300 test cases. These tests incorporate verification, validation and training input models for various components and system configuration.
- It was developed for SFR. Most of test cases are equally applicable to both the SFR and the LFR.
- These additional verification test cases for LFR generated acceptable results and enhanced applicability of SAS4A/SASSYS-1 to LFR.

Case	Description	Category
1.10	Base LFR Fuel Channel	Simple Steady State Cases
3.8	LFR Temperature-Dependent Coolant Density	Material Property Cases
3.9	LFR Temperature-Dependent Coolant Heat Capacity	
3.10	LFR Temperature-Dependent Coolant Thermal Conductivity	
3.11	Temperature-Dependent Built-In Lead Properties	
5.28	LFR Equilibrium Temperature Distribution	Heat Removal System Cases
5.29	LFR Equilibrium Pressure Distribution	

Validation Cases of SAS for Sodium Fast Reactors

Westinghouse

- TREAT fuel failure benchmarking
- The Reactor Vessel Auxiliary Cooling System (RVACS) benchmarking against Natural Convection Shutdown Heat Removal Test Facility (NSTF) experimental data
- International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP)
  - The EBR-II SHRT benchmark with SHRT-17 and SHRT-45R tests, protected and unprotected (respectively) full power loss of flow transients
  - The Phénix NC Benchmark Test, a protected loss of heat sink transient from 35% power and 70% flow conditions
  - FFTF loss of flow without scram (LOFWOS) test

Validation Cases of SAS for UO2/MOX Fuel

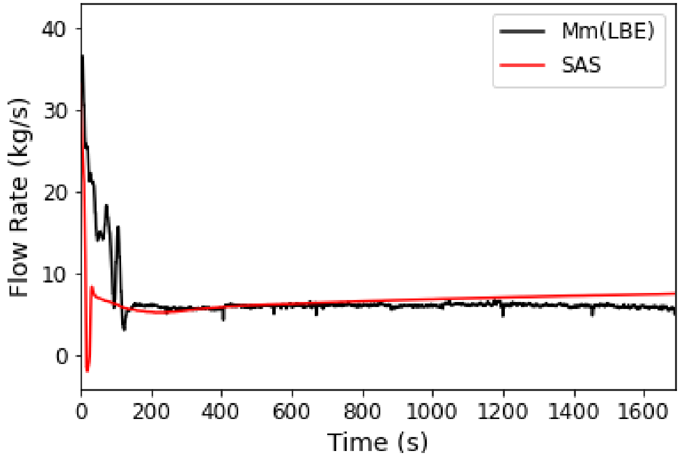
- Extensive validations against the measured data from fuel irradiation experiments were performed to justify the models
  - Normal Operation Fission Gas Release:
  - Fast Transient Fission Gas Release:
  - Transient Fuel Failure

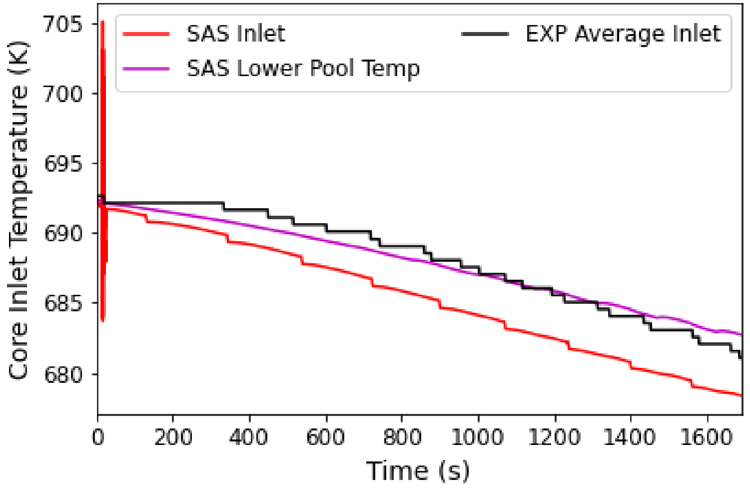
Test name	Reactor	Fuel pellet	Accident	Clad Failure
AI3	PHENIX	Solid MOX	Rapid TOP	Yes
BI3	PHENIX	Solid MOX	LOF+Rapid TOP	Yes
E12	PHENIX	Solid MOX	Slow TOP	Yes
BCF1	PHENIX	Solid MOX	Slow TOP	Yes
PF1	SUPER PHENIX	Annular MOX	Slow TOP	No
MF2	SUPER PHENIX	Annular MOX	Slow TOP	No

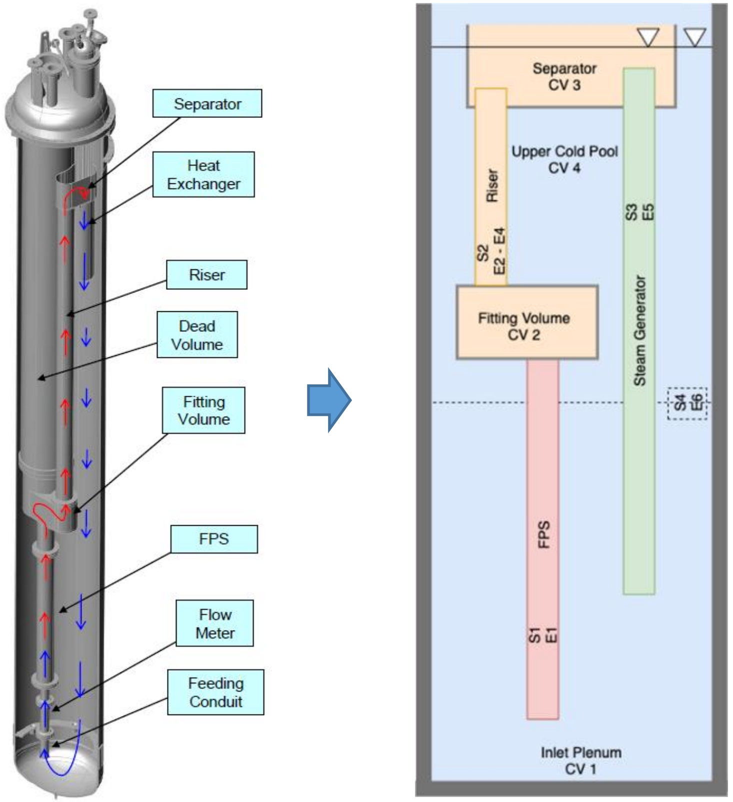
Test name	Reactor	Fuel pellet	Clad	Peak Burnup(at%)
RIG 1	PHENIX	Solid MOX	SS316	1
RIG 2	PFR	Solid MOX	SS316	2.9
SCARABIX	SUPER PHENIX	Annular MOX	15-15Ti	6.4
VIGGEN-4	PHENIX	Solid MOX	15-15Ti	11.8
MK-2	JOYO	Solid MOX	SS316	14.4
LVD	PFR	Annular MOX	PE16	23.1

SAS Validation - CIRCE Integral Effects Test

- To enhance V&V status, the SAS verification test suite form sodium system is extended to lead system.
- The CIRCE facility operated by ENEA (Italy) was selected to perform benchmarking.
- Model development and benchmarked against loss of flow test.







GOTHIC Validation

- Some of the applicable phenomena to PHRS analysis are listed as follows:
  - Pressure Drop (Single Phase, Bubbly Flow, Film-Drop Flow)
    - FLECHT SEASET Natural Circulation Tests
  - Thermal Convection (Natural, Forced, and Mixed)
  - Thermal Conduction in Solids
  - Thermal Diffusion (Vapor and Liquid)
  - Thermal Radiation
    - Conductor Surface-to-Surface Radiation, analytic solution
  - Condensation on Walls
  - Liquid Hold Up in Vertical Flow
  - Boiling Heat Transfer
  - Pool Boiling
  - Pool Heat Transfer
  - Pool Surface Evaporation
  - Natural Circulation
- Additional Validation against PHRS testing is ongoing.

Planned Verification and Validation for SAS4A/SASSYS-1 and GOTHIC

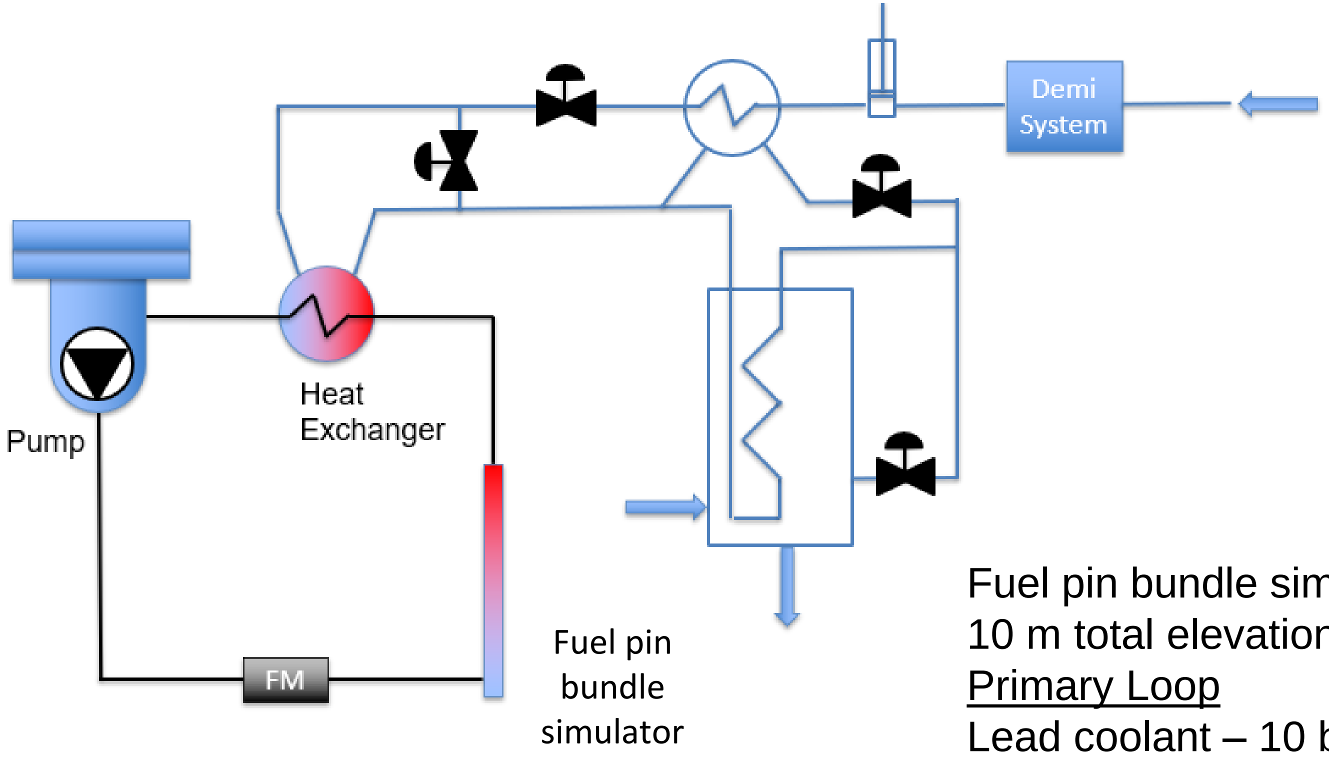
Additional Verification and Validation Plan

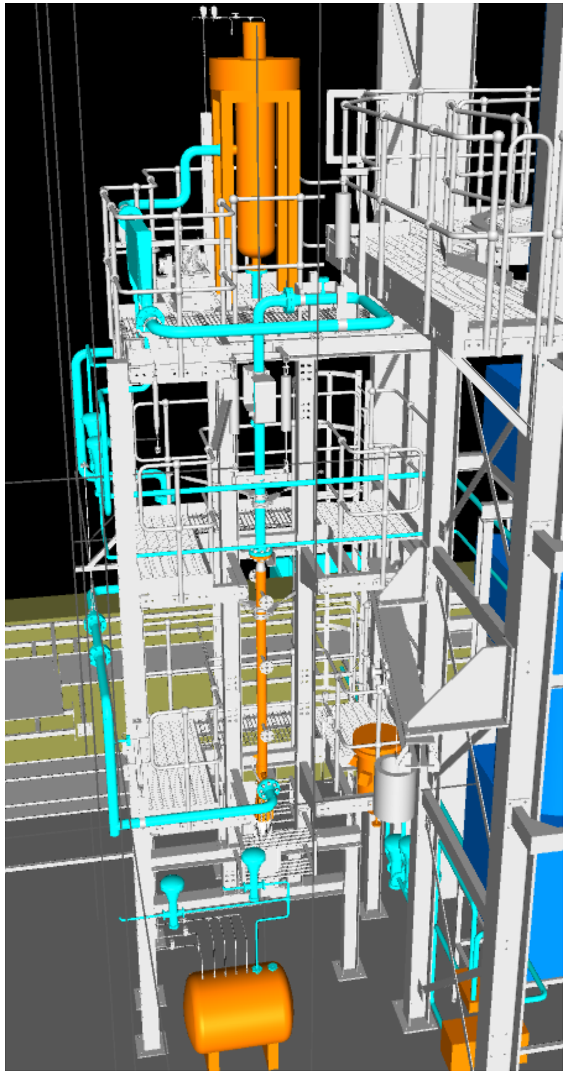
- The Westinghouse LFR testing program provides experimental data for verification & validation of modeling and analysis computer codes
  - Testing plan is primarily driven by LFR PIRT, which identified important but low state-of-knowledge items.
- NACIE-UP benchmarking (2022-2025)
  - ENEA operates the NACIE-UP facility
  - Validation for the SAS code as a part of IAEA CRP
- Versatile Lead Facility (VLF) benchmarking (2021-2023)
  - The facility is supported by UK BEIS AMR program
  - Validation for the SAS code
- Passive Heat Removal Facility (PHRF) (2021-2023)
  - The facility is supported by UK BEIS AMR program
  - Validation for the GOTHIC code
- Integral Effects Test for LFR
  - Facility is under planning
  - Validation for the coupled SAS-GOTHIC code

VLF and PHRF are presented in next slides.

Versatile Loop Facility (VLF)

Under construction at Ansaldo Nuclear – Wolverhampton (UK)



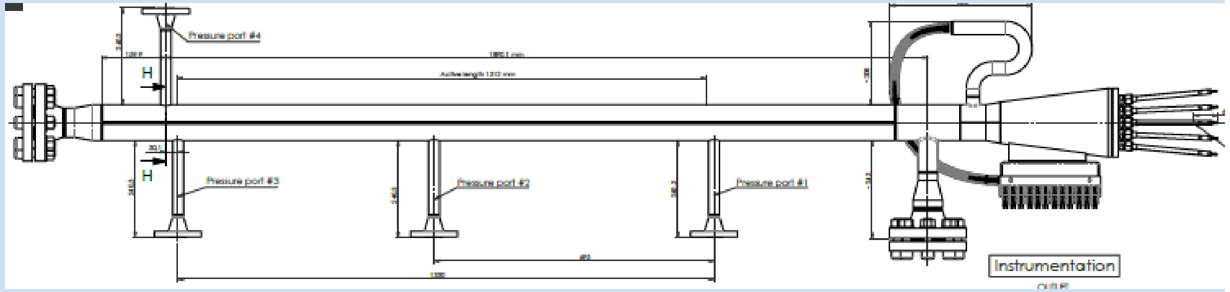


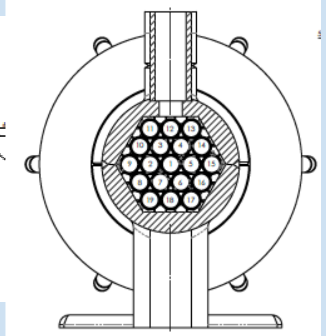
Fuel pin bundle simulator power: 500 kW
10 m total elevation
<u>Primary Loop</u>
Lead coolant – 10 bar(g) / 400-650 °C
3'' SS piping
<u>Secondary Loop</u>
Supercritical water – 300 bar(g) / 20-620 °C
1'' SS piping
DACS I/O > 300 signals

- Validation for CFD and SAS code

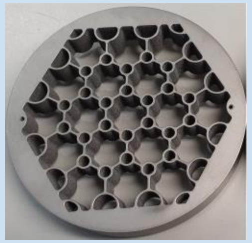
Versatile Loop Facility – Status of Key Components

- Fuel Pin Bundle Simulator
  - Design: completed
  - Aluminization trials: completed
  - Under manufacturing

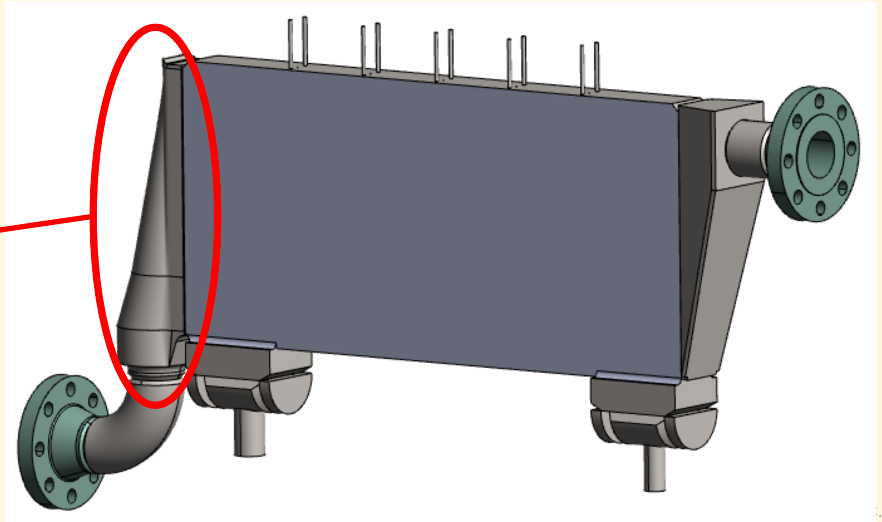




THERMOCOAX



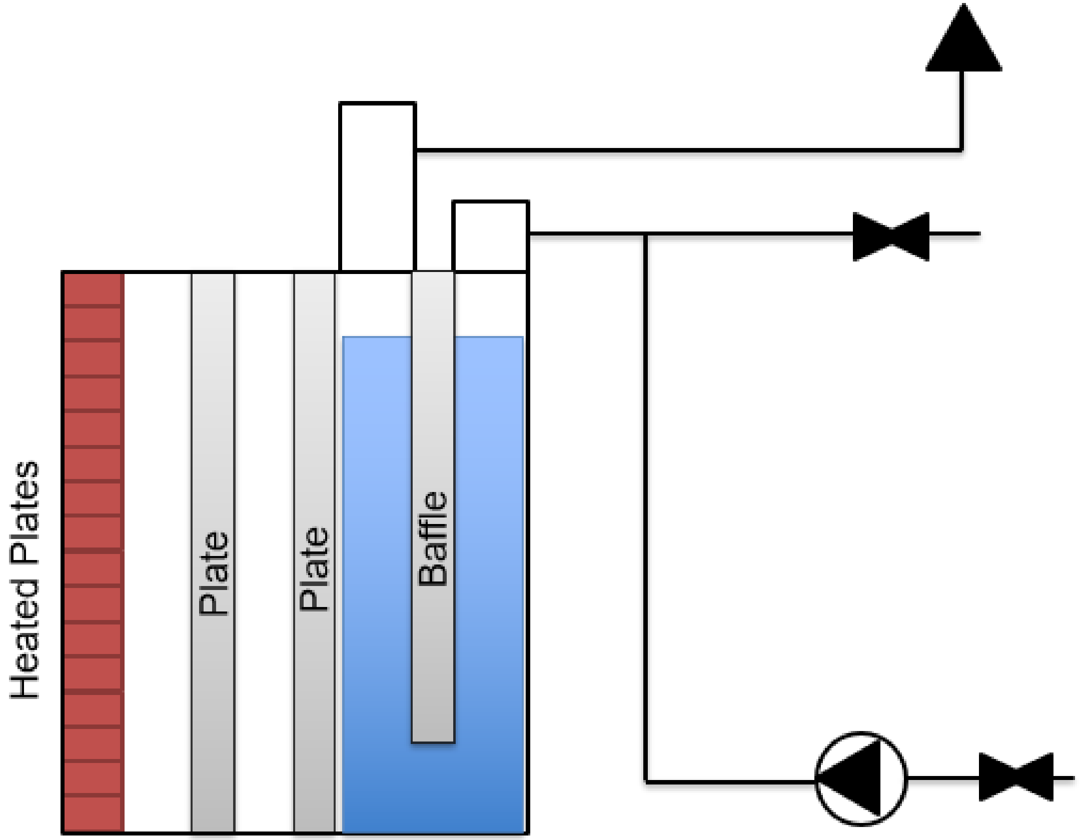
- Microchannel-type primary heat exchanger
  - Design: completed
  - Under manufacturing



VLF operation: fall 2022

Passive Heat Removal Facility (PHRF)

Under construction at Ansaldo Nuclear – Wolverhampton (UK)



PHRF reproduces Westinghouse LFR's Passive Heat Removal System

Total thermal power: 500 kW
> 20 m total elevation
> 8 m heated section (2 m width)

DACS I/O > 300 signals

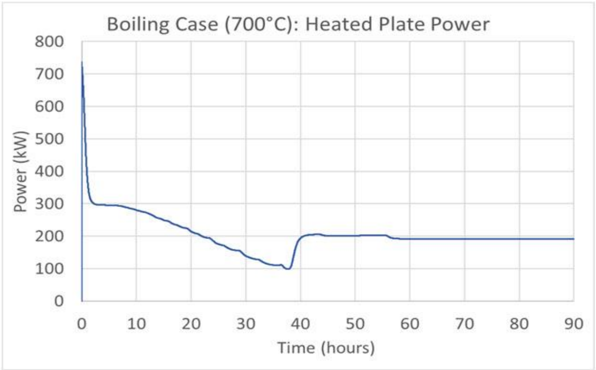
Test heat transfer on large surfaces immersed in water

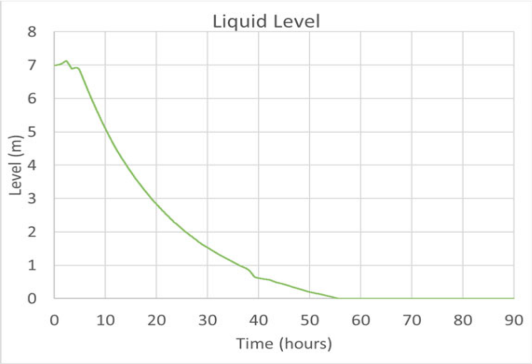
Single-phase, subcooled and saturated boiling can be achieved

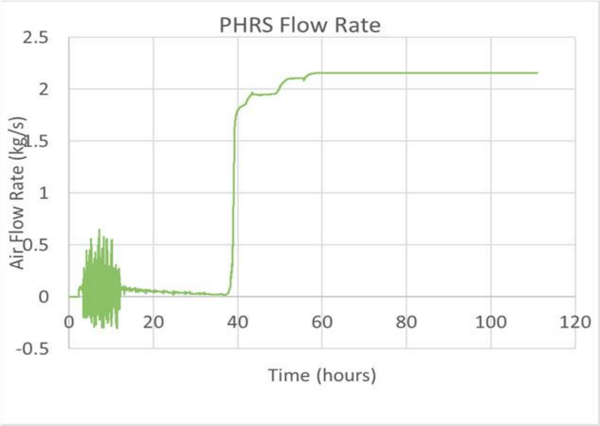
Test transition from water to air heat transfer (boil-off) and air natural circulation.

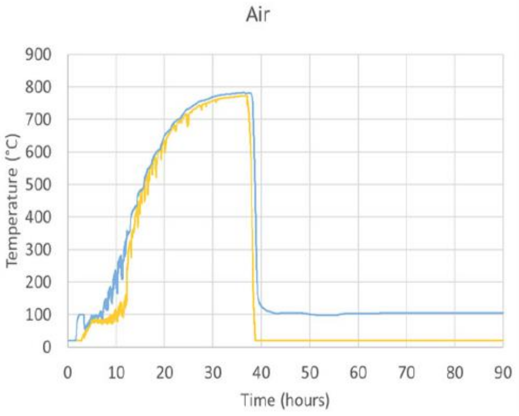
Passive Heat Removal Facility - Status

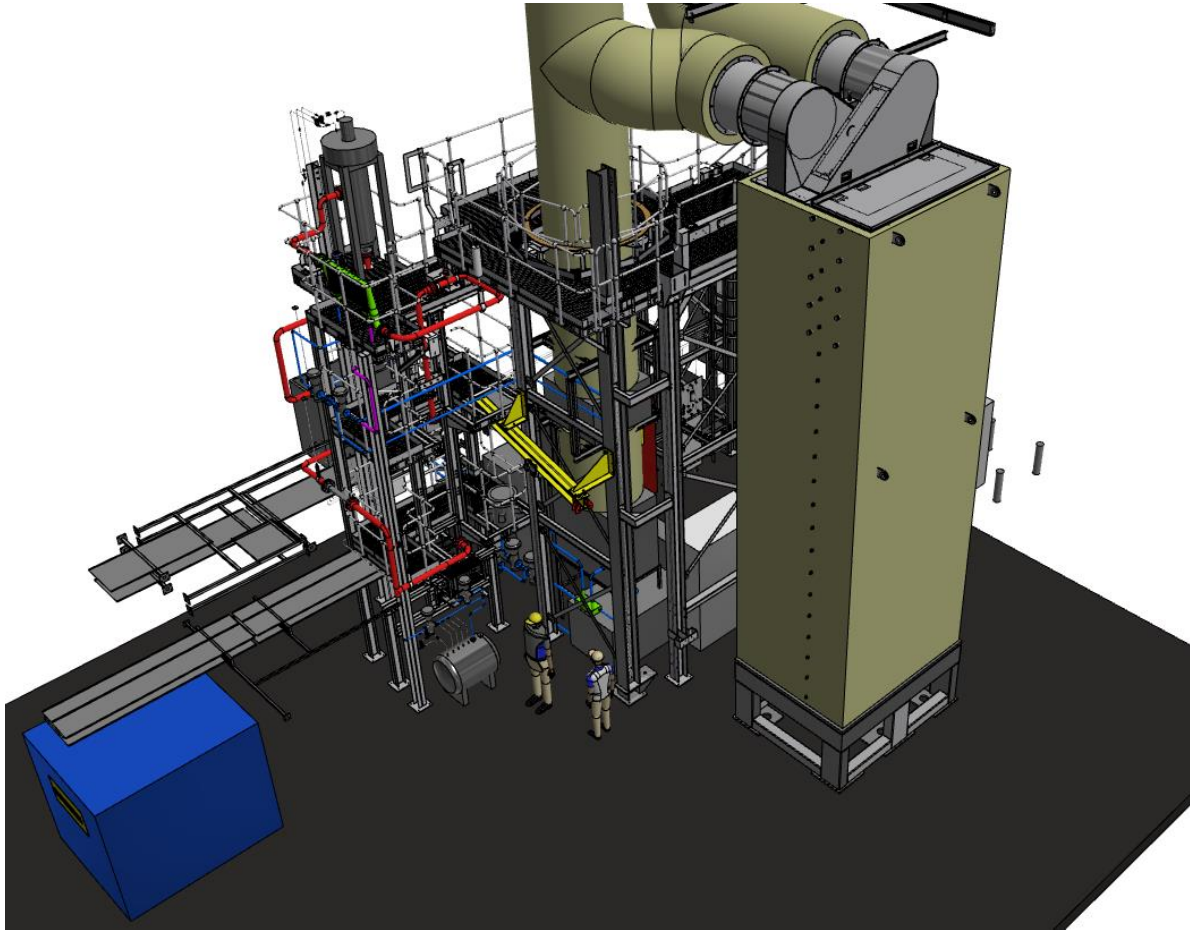
- Design for manufacturing completed
- Heating plates and power controllers procured
- Under manufacturing. Start of operation in fall 2022
- Validation for CFD and GOTHIC code











Conclusions

- Westinghouse is continuing development of LFR as its next generation of high-capacity nuclear power plants
- The safety analysis tool : SAS4A/SASSYS-1 and GOTHIC; the capability is enhanced for the LFR system
- Applicability to LFR is enhanced by the verification and validation database for the LFR system.
- Additional V&V is supported by the LFR testing program and leveraging UK AMR program and IAEA CRP.
- The applicability is enhanced and code readiness is increased.