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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>950 MWt (~450 MWe Net)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>~47%</td>
</tr>
<tr>
<td>Primary coolant</td>
<td>Liquid lead</td>
</tr>
<tr>
<td>Secondary coolant</td>
<td>Supercritical water</td>
</tr>
<tr>
<td>Neutron spectrum</td>
<td>Fast</td>
</tr>
<tr>
<td>Configuration</td>
<td>Independent unit for single or two-unit site</td>
</tr>
<tr>
<td>Fuel</td>
<td>Oxide (Phase 1); Advanced fuel (Phase 2)</td>
</tr>
<tr>
<td>Operating pressure, MPa</td>
<td>0.1 (primary) / ~34 (secondary)</td>
</tr>
</tbody>
</table>
| Lead coolant min/max temperature, ºC | 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
**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
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

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Westinghouse LFR: A Global Program

Westinghouse Sweden

Westinghouse US

Westinghouse Mangiarotti (Italy)

Westinghouse UK

Global collaborations

[Logos of various organizations associated with Westinghouse LFR]
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

<table>
<thead>
<tr>
<th>System Level Tools</th>
<th>Component Level Tools</th>
<th>High Resolution Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAS4A/SASSYS-1</td>
<td>PyARC</td>
<td>FEA (ANSYS Mechanical)</td>
</tr>
<tr>
<td>GOTHIC</td>
<td>ANTEO+</td>
<td>CFD (ANSYS CFX &amp; STAR-CCM+)</td>
</tr>
<tr>
<td>FATE</td>
<td>TRANSURANUS</td>
<td></td>
</tr>
<tr>
<td>RELAP5 MOD3.3</td>
<td>SAS4A</td>
<td></td>
</tr>
<tr>
<td>SAM</td>
<td>SERPENT</td>
<td></td>
</tr>
</tbody>
</table>
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.
  • Expanded 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”
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
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 LFR Safety PIRT carried out in collaboration with ENEA, Ansaldo, Fauske & Associates and Argonne
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.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Category</th>
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<tbody>
<tr>
<td>1.10</td>
<td>Base LFR Fuel Channel</td>
<td>Simple Steady State Cases</td>
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<tr>
<td>3.8</td>
<td>LFR Temperature-Dependent Coolant Density</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>LFR Temperature-Dependent Coolant Heat Capacity</td>
<td>Material Property Cases</td>
</tr>
<tr>
<td>3.10</td>
<td>LFR Temperature-Dependent Coolant Thermal Conductivity</td>
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</tr>
<tr>
<td>3.11</td>
<td>Temperature-Dependent Built-In Lead Properties</td>
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<tr>
<td>5.28</td>
<td>LFR Equilibrium Temperature Distribution</td>
<td>Heat Removal System Cases</td>
</tr>
<tr>
<td>5.29</td>
<td>LFR Equilibrium Pressure Distribution</td>
<td></td>
</tr>
</tbody>
</table>
Validation Cases of SAS for Sodium Fast Reactors

➢ 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
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

### Table: Validation Cases of SAS for UO2/MOX Fuel

<table>
<thead>
<tr>
<th>Test name</th>
<th>Reactor</th>
<th>Fuel pellet</th>
<th>Accident</th>
<th>Clad Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI3</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>Rapid TOP</td>
<td>Yes</td>
</tr>
<tr>
<td>BI3</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>LOF+Rapid TOP</td>
<td>Yes</td>
</tr>
<tr>
<td>E12</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>Slow TOP</td>
<td>Yes</td>
</tr>
<tr>
<td>BCF1</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>Slow TOP</td>
<td>Yes</td>
</tr>
<tr>
<td>PF1</td>
<td>SUPER PHENIX</td>
<td>Annular MOX</td>
<td>Slow TOP</td>
<td>No</td>
</tr>
<tr>
<td>MF2</td>
<td>SUPER PHENIX</td>
<td>Annular MOX</td>
<td>Slow TOP</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test name</th>
<th>Reactor</th>
<th>Fuel pellet</th>
<th>Clad</th>
<th>Peak Burnup(at%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIG 1</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>SS316</td>
<td>1</td>
</tr>
<tr>
<td>RIG 2</td>
<td>PFR</td>
<td>Solid MOX</td>
<td>SS316</td>
<td>2.9</td>
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<tr>
<td>SCARABIX</td>
<td>SUPER PHENIX</td>
<td>Annular MOX</td>
<td>15-15Ti</td>
<td>6.4</td>
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<tr>
<td>VIGGEN-4</td>
<td>PHENIX</td>
<td>Solid MOX</td>
<td>15-15Ti</td>
<td>11.8</td>
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<tr>
<td>MK-2</td>
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<td>Solid MOX</td>
<td>SS316</td>
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<td>LVD</td>
<td>PFR</td>
<td>Annular MOX</td>
<td>PE16</td>
<td>23.1</td>
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</table>
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.
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
Primary Loop
Lead coolant – 10 bar(g) / 400-650 °C
3” SS piping
Secondary Loop
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

- 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.