Fast Reactor R&D in PIONEER

Fuels, Materials, Design and Safety Support Analyses

IAEA TM Advances and Innovations in Fast Reactor Design and Technology

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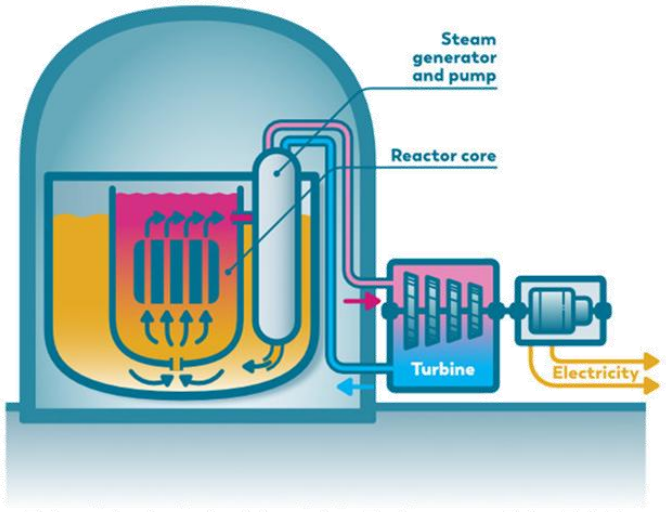
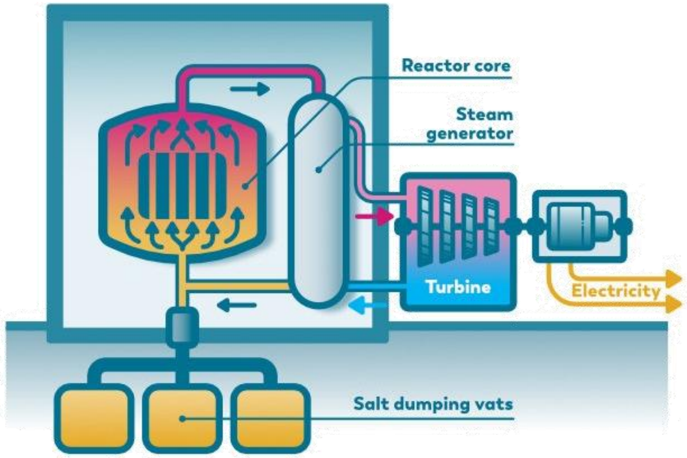
Contents

Introduction

- Nuclear energy provides carbon free electricity and heat.
- Uranium reserves can serve the world for 1 or 2 centuries with a once-through cycle in LWRs.
- Liquid metal fast reactors (LMFR) increase sustainability of the fuel cycle providing energy for the coming millenia.
- Thorium can be efficiently used in a molten salt fueled reactor (MSR).
- LMFR and MSR both operate at high temperature opening possibilities for cogeneration.

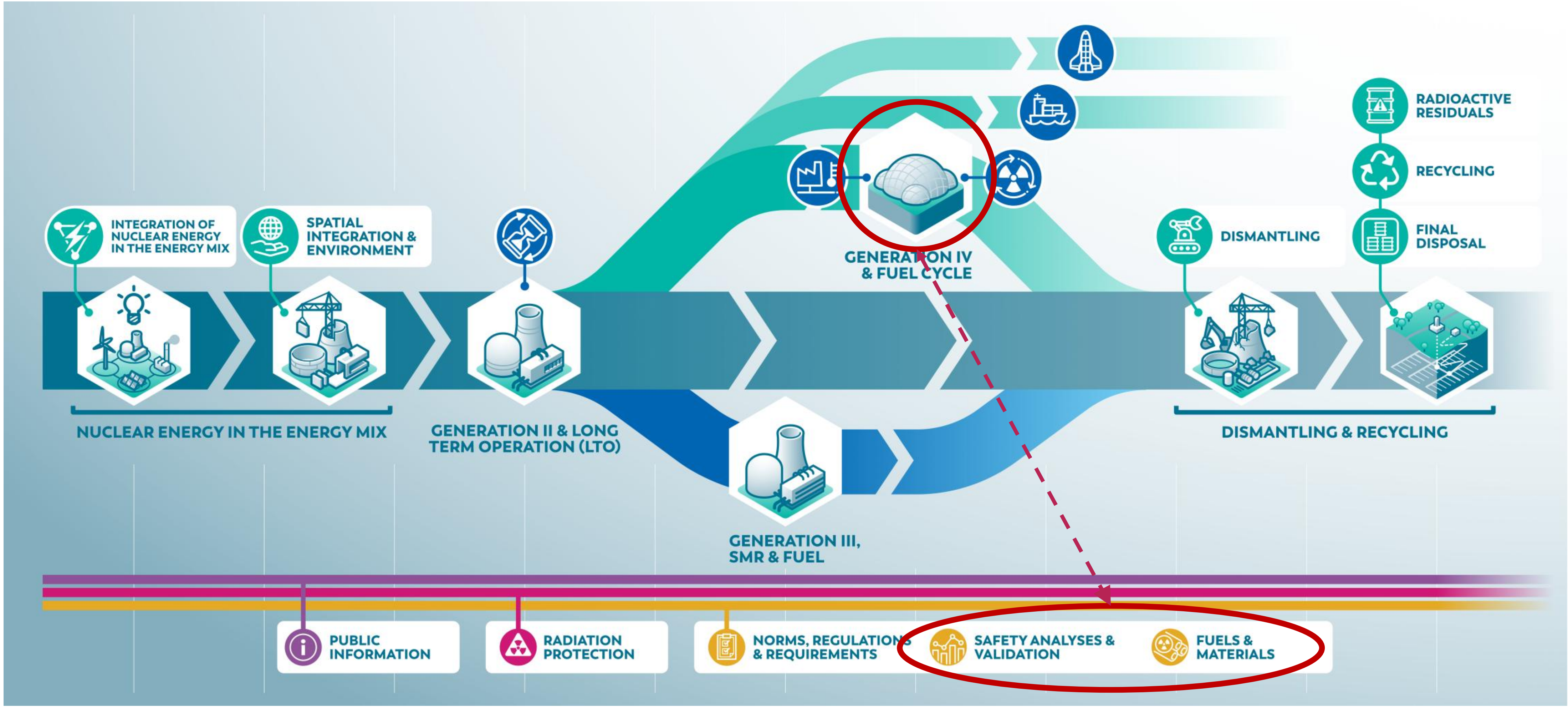




Introduction: PIONEER

- Dutch multi-annual Program for Innovation and cOmpetence development for NuclEar infrastructurE and Research (PIONEER)
- Budget: ~10 Meuro/yr
- International cooperation encouraged
  - Collaborative EU projects
  - IAEA
  - OECD
  - Bilateral

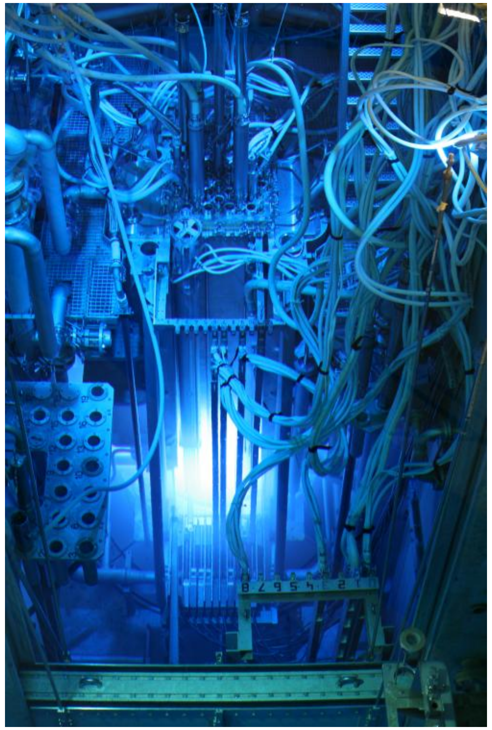
Introduction: PIONEER '25-'28 Research Topics



Fuel Irradiation Tests

Fuel Irradiation Tests

- Historic tests
  - Transmutation
  - MOX fuels
  - Nitride fuels
  - Thorium

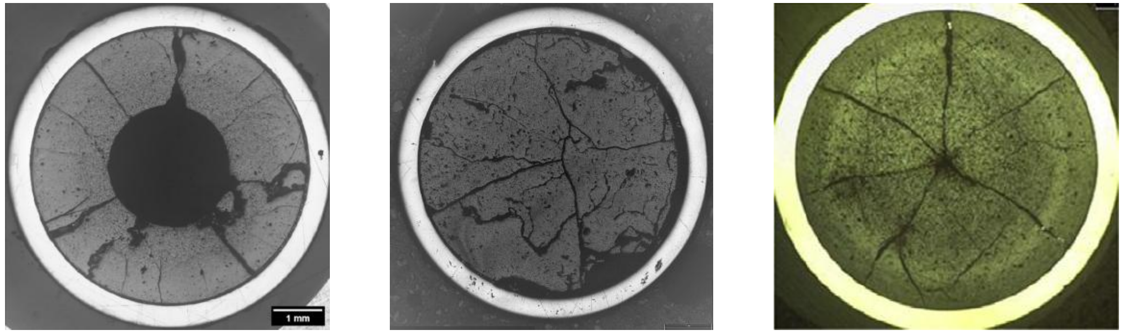


Fuel Tests	
Name	**Description**
OTTO	Once Through Pu Transmutation
THORIUM CYCLE	Thorium Fuel
EFFTRA	Transmutation
HELIOS	Minor actinide fuels & targets
CONFIRM	Nitride fuels
FUJI	Breeder reactor fuels
MARIOS	Minor actinide fuels
SMART	Nitride fuels

Fuel Irradiation Tests

- Recent tests
  - Irradiation in the HFR
  - PIE in hot cells
  - Transmutation of minor actinides
  - Oxide solid fuels
  - Fuel rodlets or pellets
  - Molten salt fuel tests

Irradiation	Fuel Type	Reactor Type	Reference
TRABANT	MOX 40% Pu	LMFR	Van Til et al. (2024)
MARINE	UO_2 15% Am	LMFR	Van Til et al. (2023)
SPHERE	MOX 3% Am	LMFR	Lainet et al. (2024) Gallais-During et al. (2018)
SALIENT	78% LiF 22% ThF_4	MSR	Hania et al. (2021)



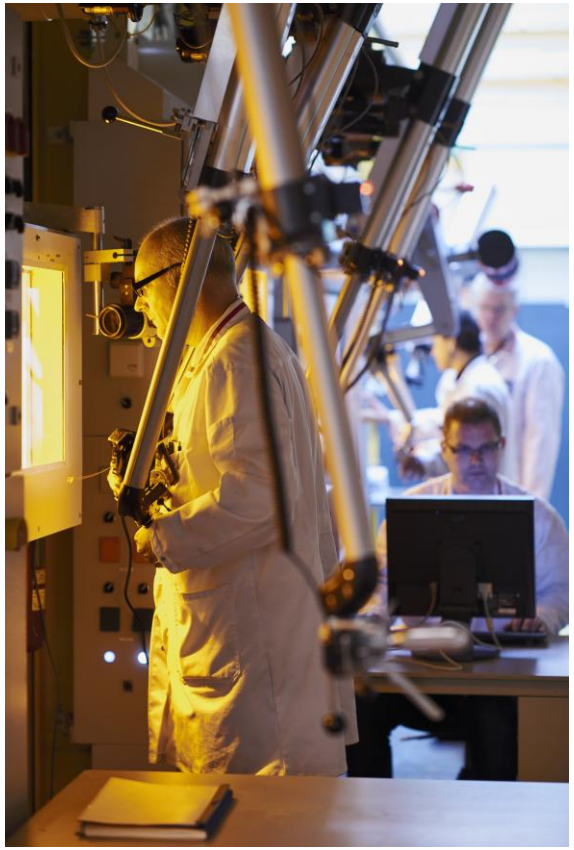
TRABANT, MARINE, SPHERE pellet fuel micrographs after irradiation

Filling of a SALIENT capsule

Material Irradiation Tests

Material Tests

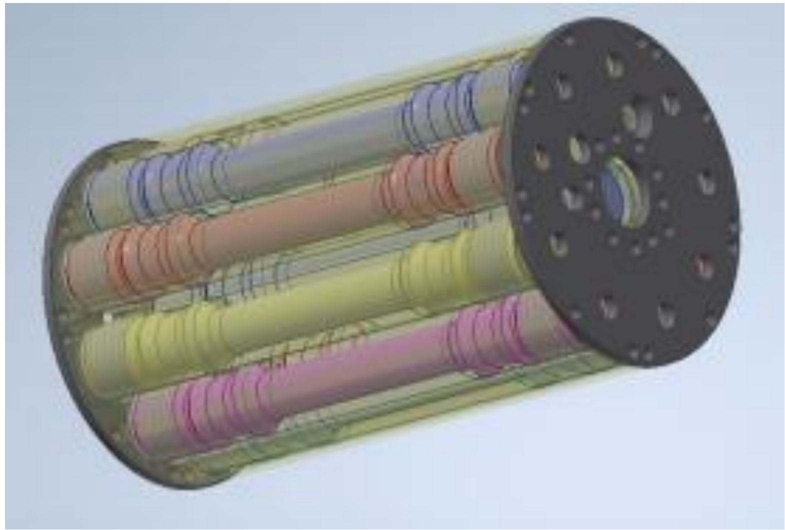
- Historic tests
  - High temperature materials
  - Target materials
  - Interaction with coolants



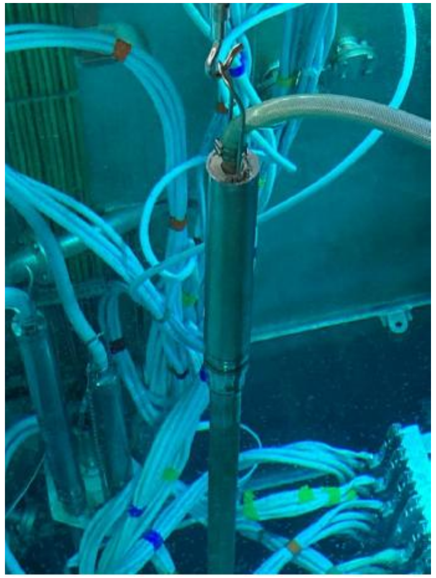
Material Tests	
Name	Description
SUMO	9Cr steel & joints
SOSIA	9Cr creep and creep fatigue
IBIS	Material in lead-bismuth
EXTREMAT	High temperature advanced materials
BODEX	Transmutation targets
EXOTIC	Solid tritium breeder materials
CORONIS	Cu Cr Zr materials

Material Tests

- Recent test: ENICKMA
  - tensile/low cycle fatigue
  - stress relaxation samples
  - inert atmosphere
  - representative temperatures (650-750°C)



- Materials
  - Hastelloy N (Haynes)
  - Hastelloy 242 (Haynes)
  - MONICR (CV Rez)
  - GH3535 (SINAP)
  - HN80MTY (COMTES FHT)
  - 316L(N) (CEA)

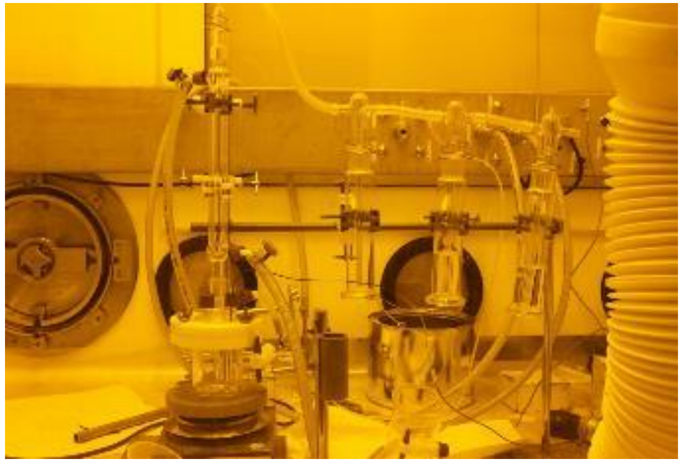


ENICKMA specimens

Processing

Processing

- MOX dissolution (PUREX)
  - Understand mechanism and improve dissolution process for MOX with high Pu content
  - Limited information in literature
  - Solubility of MOX drops significantly with increasing Pu
  - Solubility of irradiated fuel several orders of magnitude higher compared to unirradiated fuel
- TRABANT fuel pins (>40% Pu)
  - Several dissolution methods being studied
  - Dissolution in nitric acid alone does not lead to complete dissolution
  - Two step dissolution is promising option and is being studied



Dissolution of fuel pin segments

Determination of U, Pu vector

Processing

- Molten Salt Fuels
  - Several options reviewed
  - Options needed for fluoride and chloride salts
  - Dehalogenation and vitrification works well
  - Various glass types being investigated
  - Discussions with Dutch waste organization COVRA on Waste Acceptance Criteria (WAC)

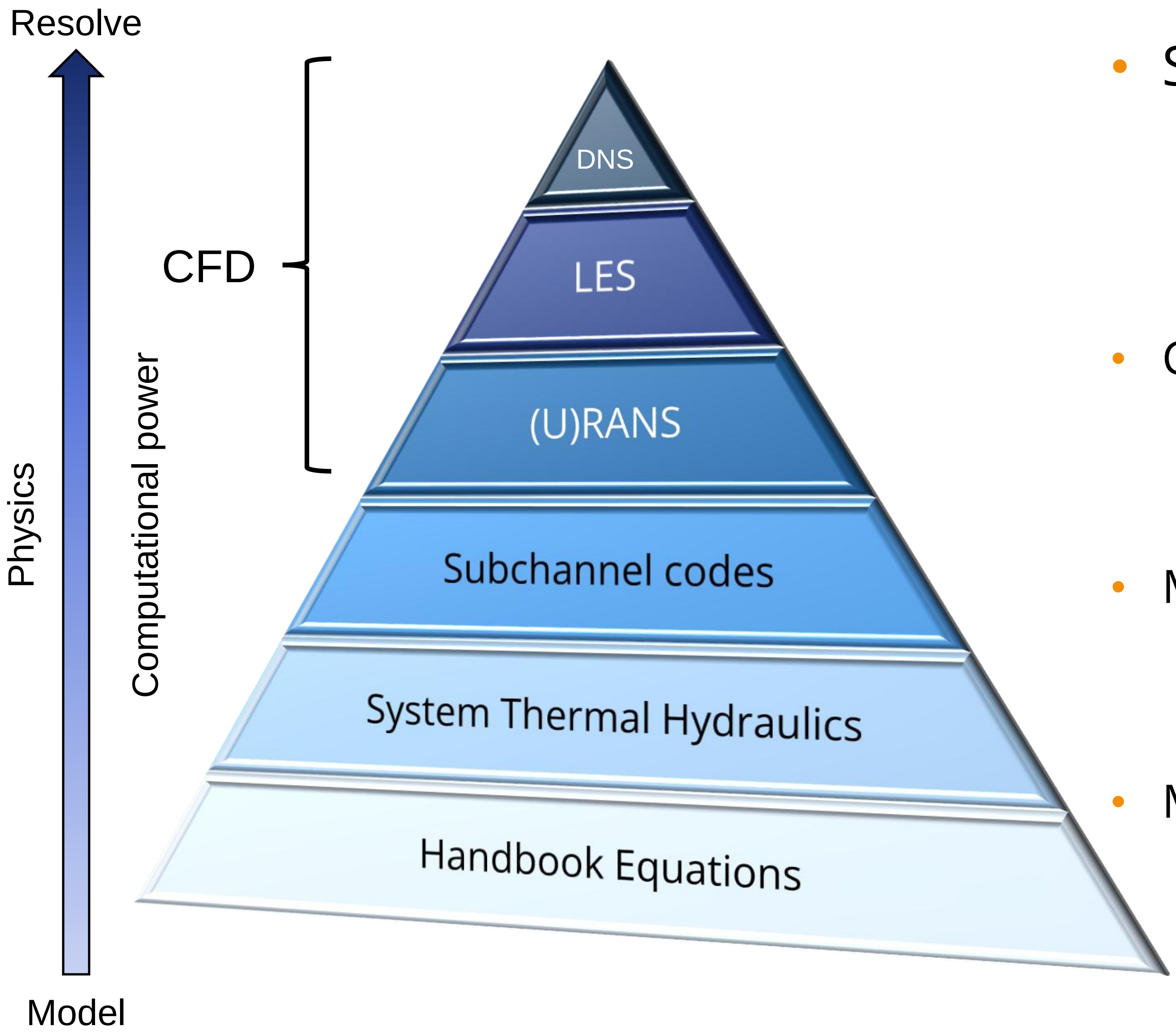
Surrogate vitrified molten salt waste

Vitrification oven

COVRA intermediate radioactive waste storage

Design & Safety Analyses

Modelling Approaches and Tools



- System Thermal Hydraulics
  - Backbone of licensing analyses
  - Limited number of calculational nodes
  - Fast simulations on system level
- Computational Fluid Dynamics
  - Large computational grid
  - Turbulence modelling (different levels)
- Multi-scale
  - Coupling of two computational approaches with different levels of resolution (STH-CFD)
- Multiphysics
  - Coupling of two computational approaches with different physics (neutronics-thermal hydraulics)

Design and Safety Analyses: Pool and System

Application	Steady -state	Loss-of -Flow	Loss-of-Heat Sink	Transient Overpower	Start-up & Shutdown	Asymmetric Flow	Other Topics	Simulation
ALFRED	X							STH, CFD
ASTRID		X						STH
Molten Salt Cavity							SET	Multiphysics
CIRCE-ICE	X	X	X					CFD
CIRCE-HERO	X	X	X					STH, CFD, Multi-scale
EBR II		X						STH, Multi-scale
ELSY					X		Sloshing	STH, CFD
ESCAPE	X	X	X			X		STH, CFD, Multi-scale
ESFR		X		X		X	Sloshing	STH, CFD
FFTF		X						STH
MSFR	X							Multiphysics
MSRE	X				X		RIA	STH, CFD, Multiphysics
Phénix		X				X		STH, Multi-scale
SEALER-Arctic	X			X				STH, CFD
SEALER-UK	X	X				X		CFD
TALL-3D	X	X						STH, CFD, Multi-scale

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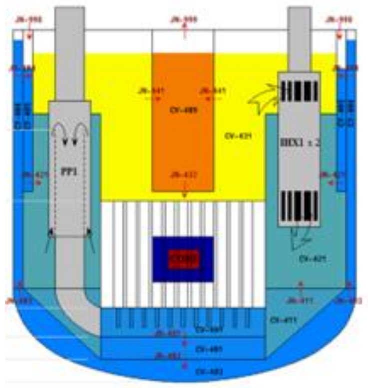
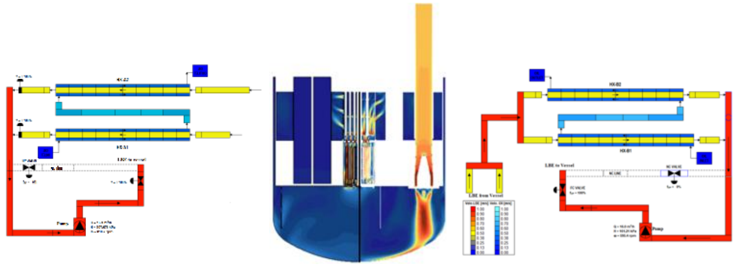
Design and Safety Analyses: Pool and System

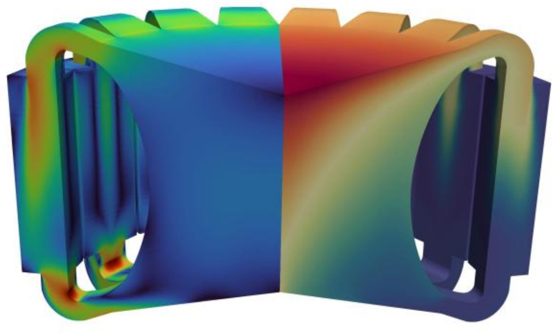
- Phénix: STH and multi-scale simulation
  - Validation of STH; Proof-of-principle multi-scale simulation at NRG PALLAS
- ESCAPE: STH, CFD, and multi-scale
  - Validation of numerics; comparison of accuracy and effort of different simulation methods
- MSFR: multiphysics
  - Proof-of-principe multiphysics with MUSCLE-Foam
- MSRE: STH, CFD, and multiphysics
  - Validation of STH and multiphysics (in progress: see next slide)



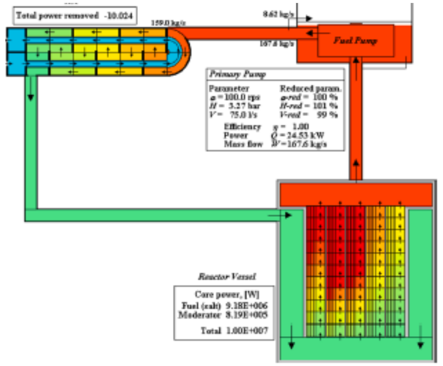
Phénix



ESCAPE



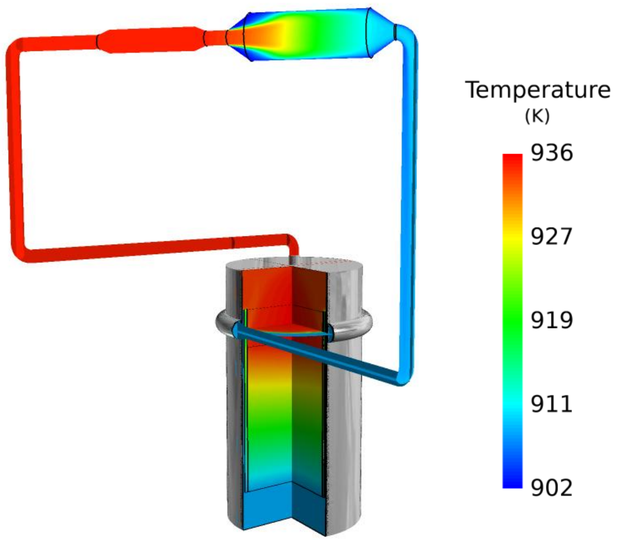
MSFR

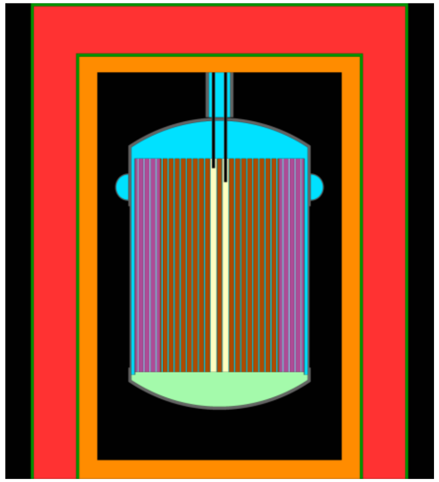


MSRE

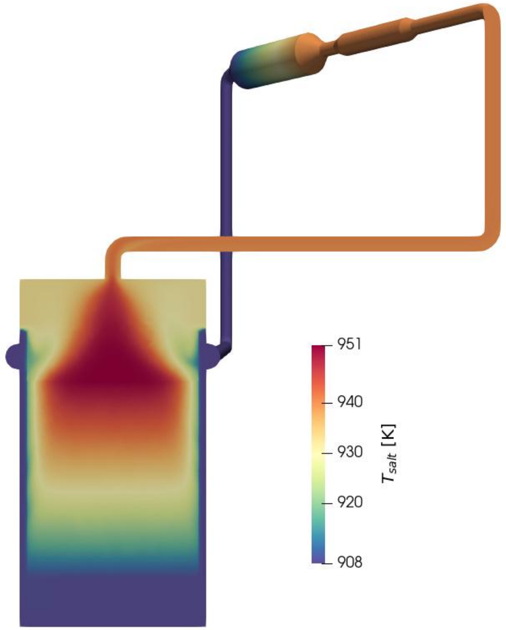
Design and Safety Analyses: Pool and System

- Thermal hydraulics only
  - Fixed design power (10 MWth)
  - Tuning of porous media and HEX
  - Comparison to experiments and SPECTRA
- Multi-physics (preliminary)
  - Diffusion solver
  - Cross-sections from literature (calculation with SERPENT 2 in progress)



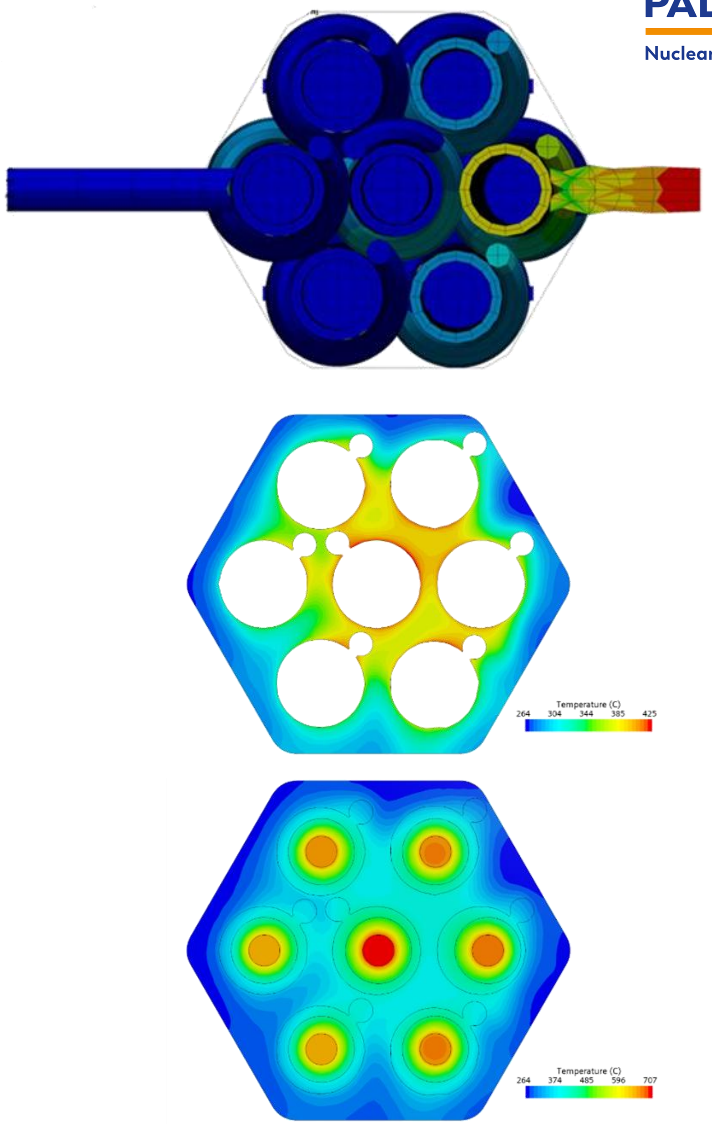


MUSCLE-Foam



Design and Safety Analyses: Core

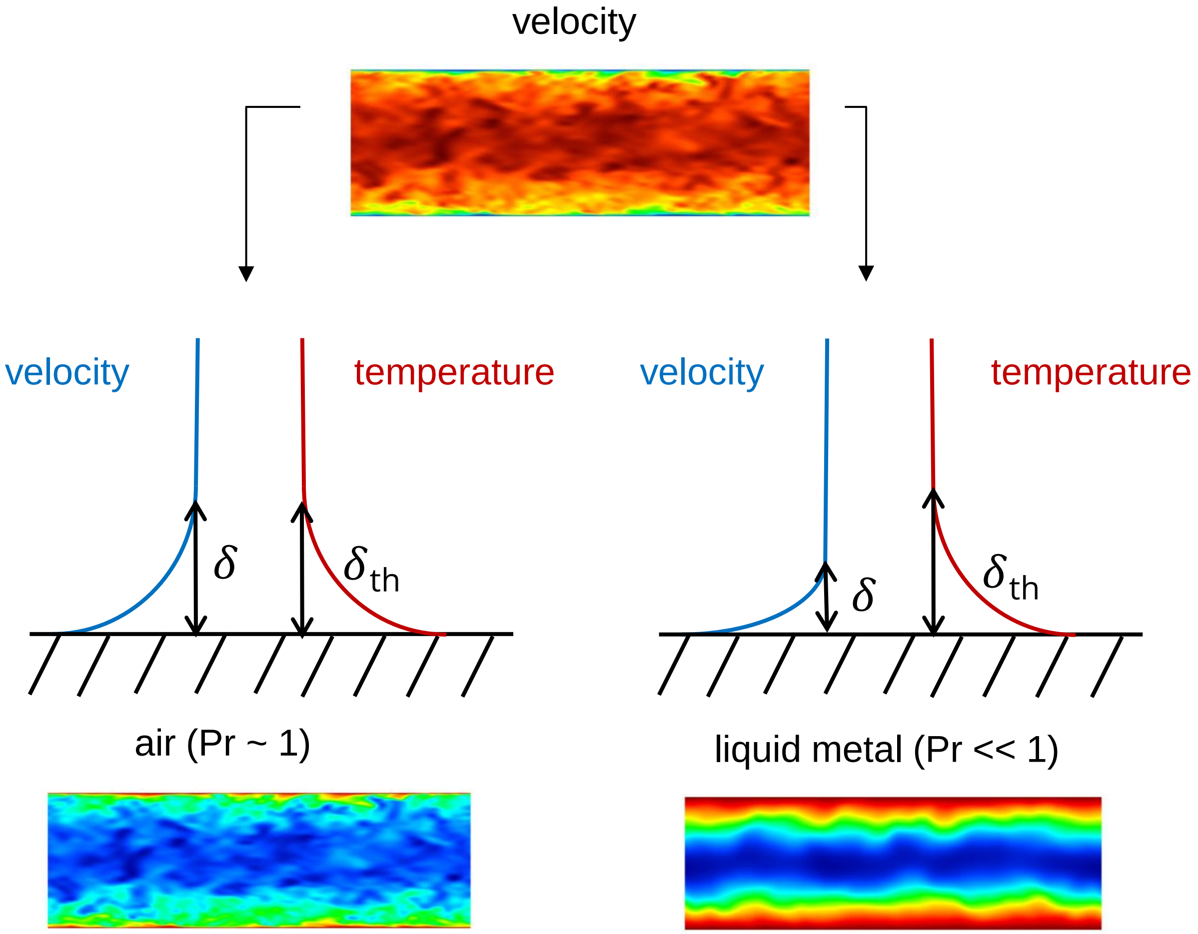
- Wire wrapped
  - Nominal geometries and nominal conditions are considered validated (Roelofs et al., 2019).
  - Validation for non-nominal geometries:
    - Eccentrically placed bundle (Sosnovsky et al., 2015 NURETH)
    - Inlet or internal blockages (Roelofs et al., 2025 NT).
    - Deformed pins or assemblies (Roelofs et al., 2025 NURETH)
- Grid-spaced
  - nominal geometries and nominal conditions can be considered validated (Roelofs et al., 2023 NE&D).
  - Validation for non-nominal geometries:
    - Inlet or internal blockages (Mathur et al., 2020 NE&D).
    - Deformed pins or assemblies (Roelofs et al., 2025 NURETH)



Pre-test simulation of Influence of deformed pin

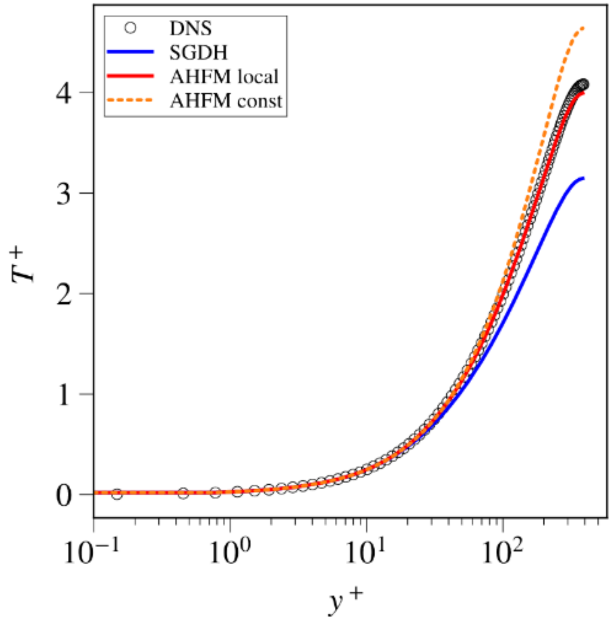
Design and Safety Analyses: Heat Transport

- Academic Models
  - Too complex, instable
  - Not for industrial simulation
  - Not available in most codes
- Pragmatic Models
  - Reynolds analogy couples momentum and thermal field
  - Not applicable to liquid metals
  - Use increased turbulent Prandtl number as work-around
  - Advanced pragmatic models under development (Mathur et al., 2023 NE&D / Habiyaremye et al., 2024 NSE)



Advanced model based on local flow conditions for low Prandtl number fluids:

- *Forced convection:* √
- *Natural convection:* ✗ *(no data)*



Summary

Summary

- Fast Reactor R&D in PIONEER
  - Reactor types
    - LMFR and MSR
  - Topics
    - Fuels and materials
      - Irradiation in HFR and PIE in hot cells
      - Processing
    - Design and Safety Analyses
      - Various modelling approaches
        - STH / CFD / Multi-scale / Multiphysics
      - Pool and System
        - Validation and assessment of different approaches
      - Core
        - Focus on non-nominal geometries and conditions (blockages and deformations)
      - Heat Transfer
        - Advanced turbulent heat flux model development and assessment

High Flux Reactor (HFR)

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Acknowledgements

European Commission

- Dutch PIONEER R&D program funded by Ministry of Economic Affairs and Climate
- Various Euratom projects sponsored by the European Commission

Thank You

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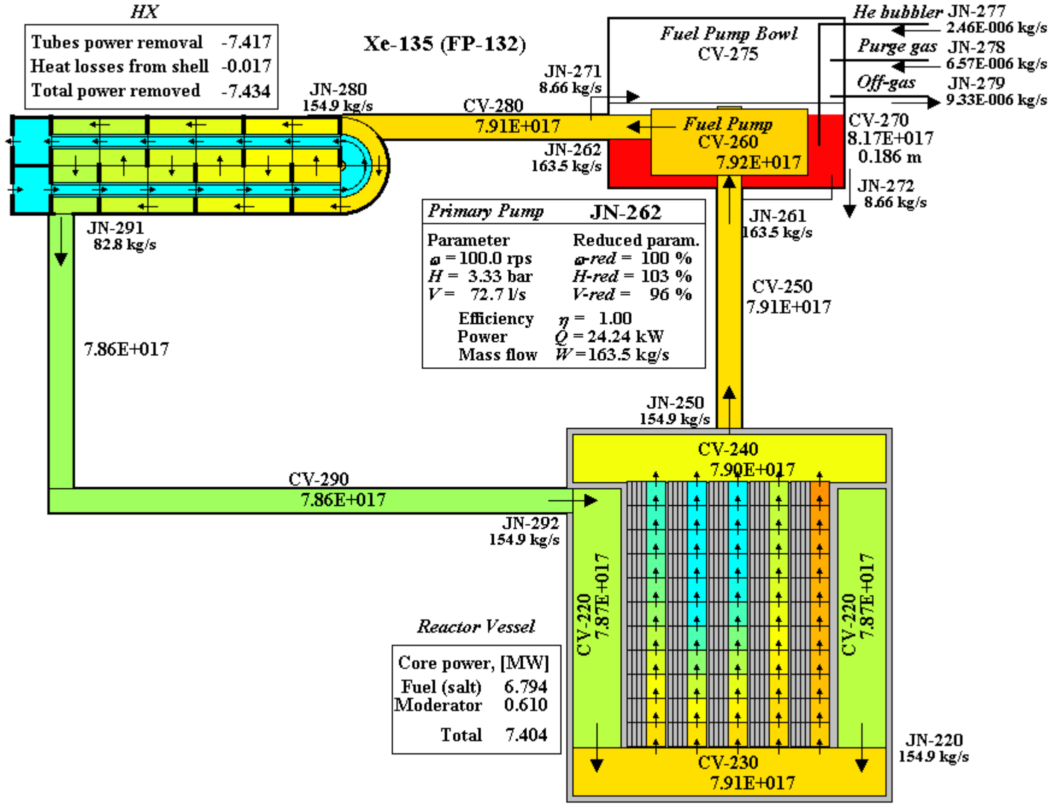
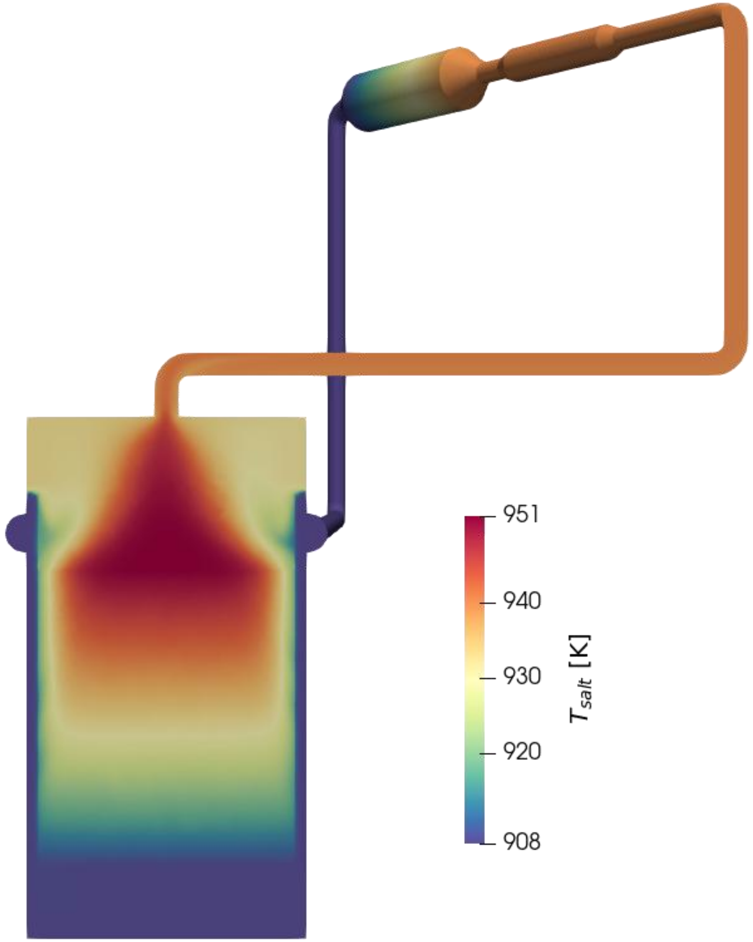
TH Safety Assessment
MSR Pool & System

- MSRE is unique source for validation of multi-physics thermal hydraulics with neutronics analysis.
- SPECTRA multi-physics module tracking DNPs
- Preliminary MUSCLE-Foam model of MSRE



MUSCLE-Foam



SPECTRA and MUSCLE-Foam models of MSRE