# Coupled Neutronics-Thermal Hydraulics Assessment of Graphite Moderated Molten Salt Reactors

Ashkhen Nalbandyan[1], Esben Bryndt Klinkby[1], Bent Lauritzen[1],
Jacob Groth-Jensen[2], Rowan Steyn[2]

[1]Nutech, Technical University of Denmark (DTU)

[2]Seaborg Technologies, Copenhagen, Denmark

# Outline

- Small Modular and Molten Salt Reactors
- Coupled Neutronics-Thermal Hydraulics Analysis of the MSRE
  - Scope of Work
  - Model Description
  - Serpent2.1.30-OpenFOAMv1806 Coupling Scheme
- Steady State Results
  - Temperature and velocity distribution
- Transient Results
  - Step Reactivity Insertion

# Small Modular Reactors - Main Advantages

## How small is small?

Small Modular Reactor (SMR) = Advanced reactor producing up to 300 MWe per module.

## SMR advantages

- Load following capability
- Low capital costs
- Passive and inherent safety features

## SMRs under development - Almost 50 design concepts, e.g.

- NuScale (60 MWe, Integral PWR, USA)
- Terrestrial Energy (192 MWe Integral MSR, Canada)
- Seaborg Technologies (250 MWe CMSR, Denmark)

$\Longrightarrow$ of those 10 design concepts are Molten Salt Reactors

# Molten Salt Reactors - Advantages

Molten Salt Reactors use mainly fluoride or alternatively chloride salts as primary coolant with either solid or liquid fuel.

## Why liquid molten salt fuel?

- Low pressure operation - Less safety concerns, lightweight construction
- Passive and inherent safety features - Fuel draining, strong negative feedback coefficients
- Potentially low fuel fabrication costs.
- High temperature heat production for industrial applications
- Good load following capabilities

# Molten Salt Reactors - Modelling Challenges

Code development and validation for licensing purposes is a challenge:
Tight coupling of neutron kinetics and thermal hydraulics

- Delayed neutron precursor drift modelling: no regulatory compliant software designed for this
- Turbulence modelling to predict stagnation and recirculation zones
- Safety assessment and risk analysis: Definition of severe accidents for a liquid fuel

This work presents an example of coupled neutronics-thermal hydraulics approach for modelling of liquid fuel reactors.

# Scope of work

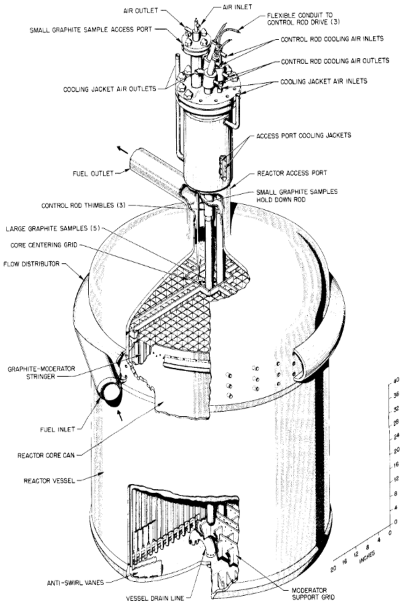
**Approaches to the modelling of liquid fuel relevant phenomena :**

- Development of in-house codes coupling neutronics (deterministic approach) and thermal-hydraulics.
- Utilization of exisiting CFD codes (OpenFOAM, COMSOL) to solve for determinsitic neutron transport.
- Utilization of exisiting Monte Carlo neutronics software (mainly Serpent) to couple externally to CFD codes - An example is this work.

## Reference case: Molten Salt Reactor Experiment (MSRE)

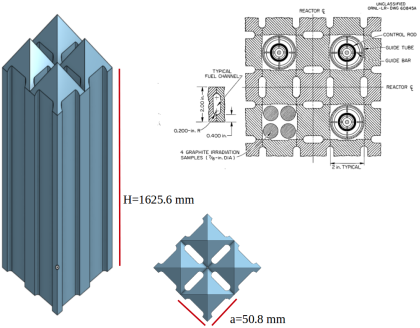
- Implementing the coupling mechanism for neutronics and thermal hydraulics (Serpent2.1.30/OpenFOAM1806):
  - Standard multiphysics coupling setup for OF and Serpent
  - Drift of delayed neutron precursors (an approach developed in this work)
- Steady state analysis
- Transient analysis: step reactivity insertion

# The MSRE




- Single - fluid, unclad, graphite - moderated molten salt reactor.
- Design power of 10 MWth.
- Fuel: Design - $LiF$ - $BeF_2$ - $ZrF_4$ - $ThF_4$ - $UF_4$.
- Operation: June 1965 - December 1969

# MSRE typical graphite stringer

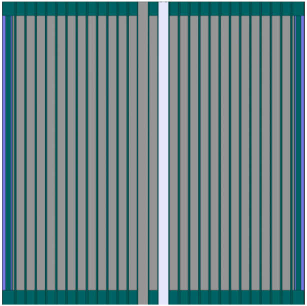



| | |
|---|---|
| Total fuel flow | 75.7 l/s |
| Average power density | 14 kW/l |
| Fuel inlet T (flow distributor) | 908.5 K |
| Fuel outlet T (core outlet) | 933.2 K |
| Fuel inlet p | 1.38 bar |
| Fuel outlet p | 0.48 bar |

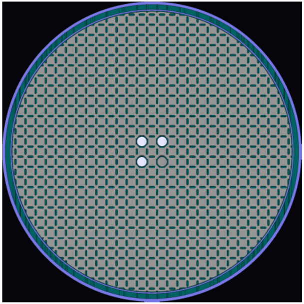
Table: Main core parameters for 10 MW nominal power

# Entire core Serpent model

Core side view



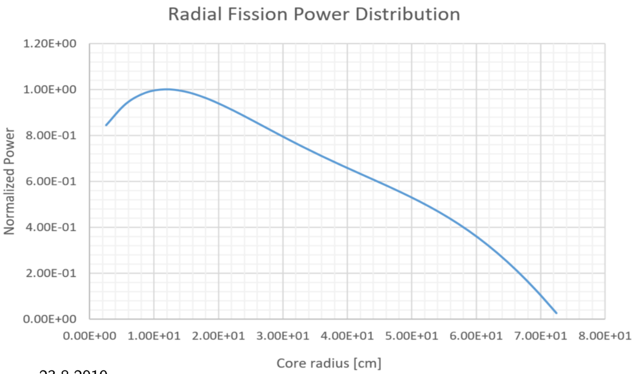
Core top view: three control rod thimbles and an experimental graphite assembly are in the center



- Uniform temperature - 922 K
- Fresh fuel is considered
- Control rods are Gd oxide - Al oxide cylinders and experimental sample rod is a pure graphite cylinder.

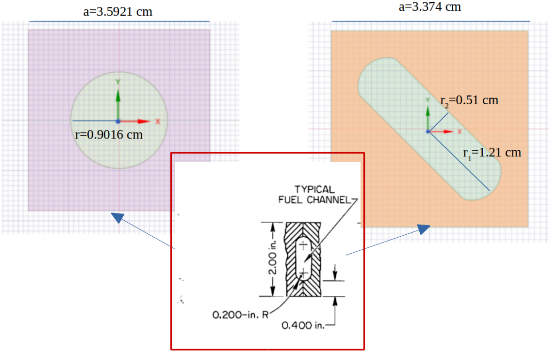
# Entire core Serpent model - Power distribution

Fuel composition vector for $k_{eff}$=1:
LiF(70 mol %)
$BeF_2$ (24.85 mol%)
$ZrF_4$(5 mol%)
$UF_4$(0.15 mol%)
Fissile isotope enrichment: 93% $^{235}$U



# Single Channel CFD model

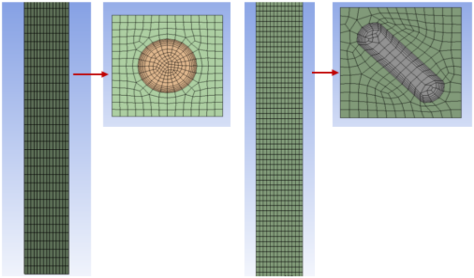
Cylindrical fuel channel: comparison to the ORNL analytical model (left) and realistic stadium-shaped channel (right).

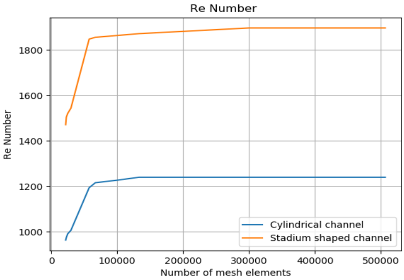


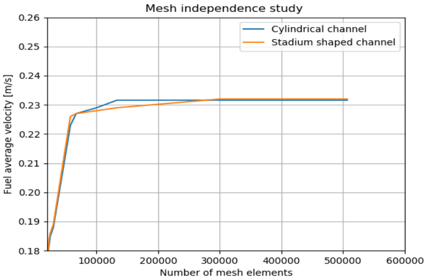

Constant fuel volume fraction:

$$\gamma = \frac{V_{fuel}}{V_{moderator} + V_{fuel}} = 0.224$$

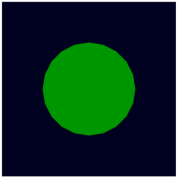
# Single Channel CFD Mesh





# Single Channel Neutronics Model



(a) Cylindrical fuel channel

(b) Stadium-shaped fuel channel

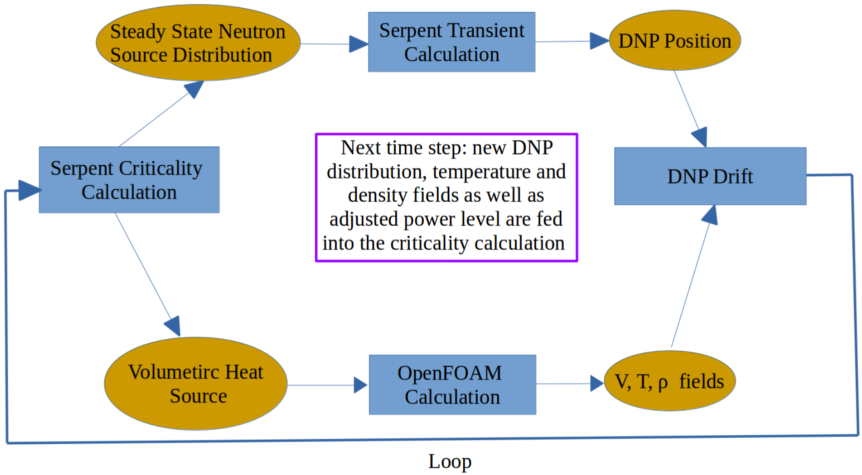
## Neutronics boundary and initial conditions

| | |
|---|---|
| Fuel temperature | 923.5 K |
| Graphite axial boundaries | Vacuum |
| Graphite radial boundary | Reflective |

## CFD boundary conditions

| | |
|---|---|
| Fuel inlet velocity | 0.183 m/s |
| Fuel inlet temperature | 923.5 K |
| Fuel/Graphite Interface T | Coupled |
| Graphite top and bottom | Zero Gradient |
| Graphite perimeter | Symmetry |

# General Coupling Scheme



# Treatment of Delayed Neutron Precursors (DNP) - ORNL model

The DNP drift included in point-kinetics equation:

$$L\Phi + (1-\beta_T) f_p P\Phi + \sum_{n=1}^{6} \lambda_i f_{di} c_i = \frac{1}{v}\frac{\partial \Phi}{\partial t} \tag{1}$$

$$\frac{\partial c_i}{\partial t} = \beta_i P\Phi - \lambda_i c_i - \frac{\partial}{\partial z}(v c_i) \tag{2}$$

$$c_i(z) = \alpha_k c_i^o(z) \tag{3}$$

## Procedure

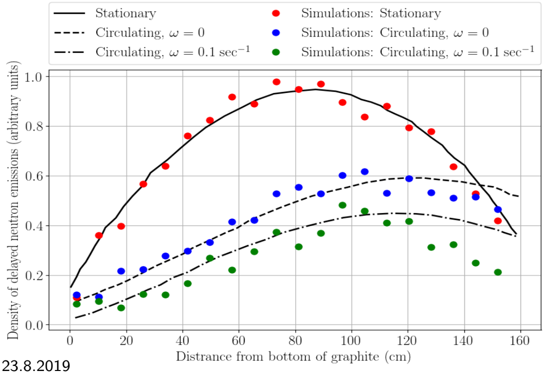
- Calculate static and adjoint axial fluxes
- calculate the DNP concentration $c_i^o(z)$ for a given inverse period
- Calculate $c_i(z)$ according to (3)

See ORNL- TM- 1626 report for detailed explanations.

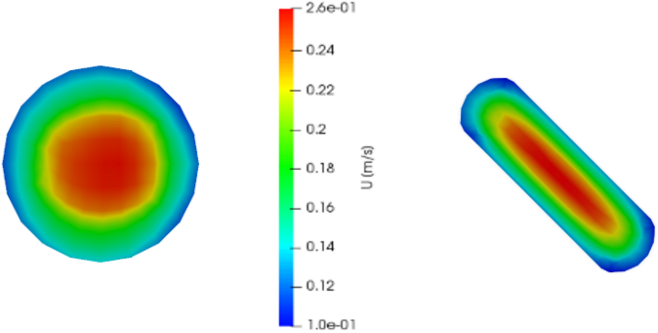
# Treatment of DNP - Our Approach and Comparison

## Procedure

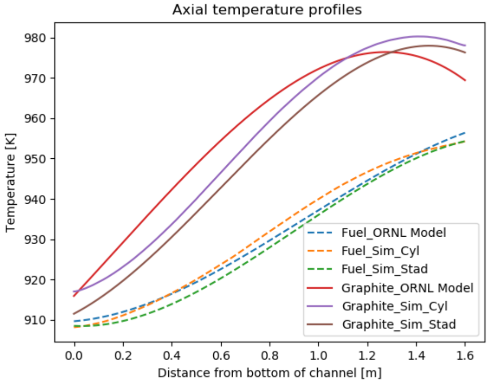
- Read the DNP position file from Serpent source generation and the OpenFOAM velocity distribution file
- Extract velocity corresponding to each DNP position
- Calculate average velocity for each axial region (10 in this case)
- Shift the DNPs in each region by corresponding average velocity and write new DNP position file



# Steady State Results - Velocities



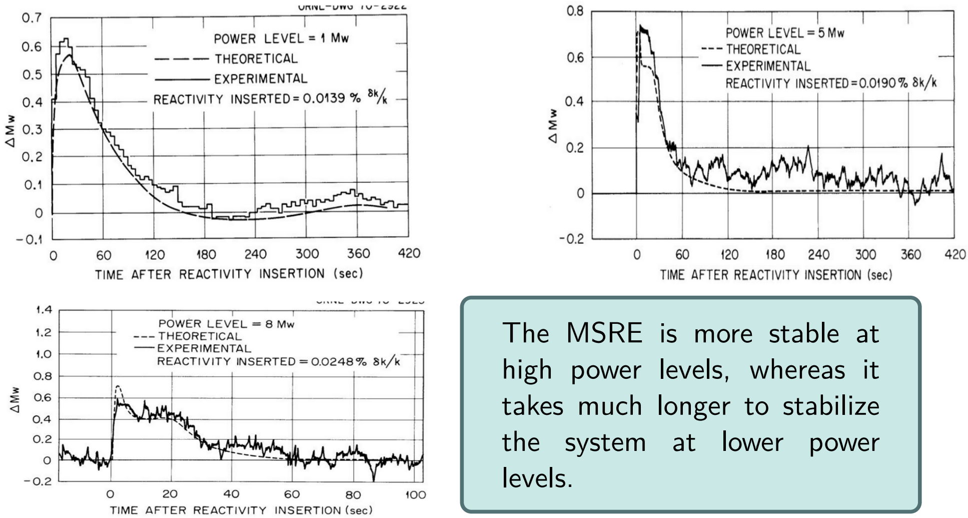
# Steady State Results - Axial Temperature Profile




| Model | Fuel[K] | Graphite T [K] | Δ T [K] |
|---|---|---|---|
| ORNL | 930.7 | 957 | 26.3 |
| Cylindrical channel | 931.5 | 955 | 23.5 |
| Stadium shaped | 929 | 950 | 21 |

$$T_g = T_f + \Delta T \tag{4}$$

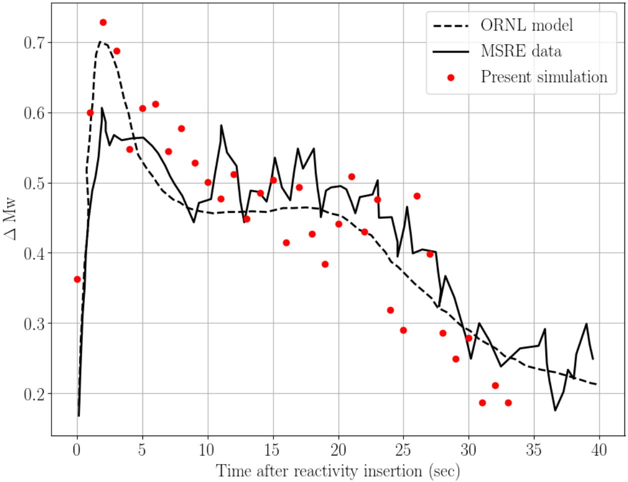
# Reactivity Insertion Analysis




The MSRE is more stable at high power levels, whereas it takes much longer to stabilize the system at lower power levels.

# Results of Transient

## Step reactivity insertion at nominal power of 8 MW (0.0248 $\%\delta$ k/k)



# Conclusion & Outlook

Serpent and OpenFoam are coupled in this work and a methodology for DNP treatment was developed.

- The steady state temperature distributions in fuel and graphite are in good agreement with the ORNL calculations.
- DNP axial distribution agrees with ORNL model calculations.
- The reactor power response to step reactivity insertion is in good agreement with the ORNL experimental results.

## Future work

- Elaborate the coupling method and DNP treatment
- Scale up the method to a feasible tool for MSR simulation

# THANK YOU FOR YOUR ATTENTION!