MSRE Transient Benchmark Development and Evaluation: NEUP Project Updates

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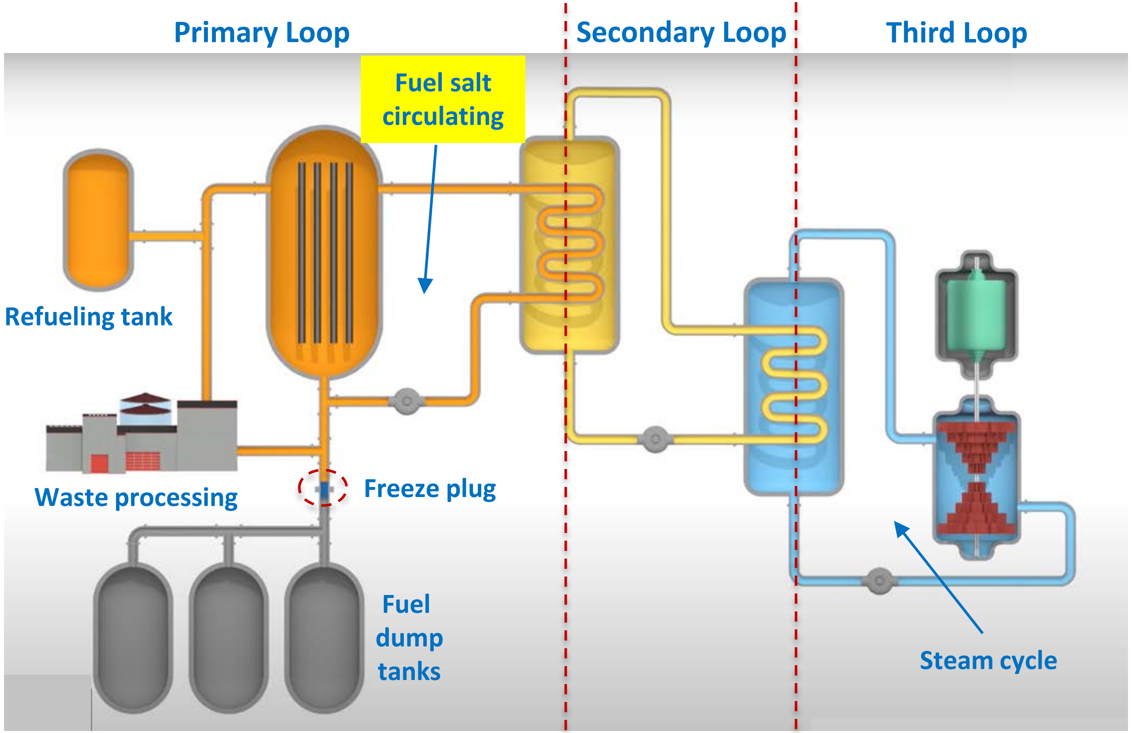
"Regenerate Undocumented Data in Historical Experiments for MSRE Transient Benchmark Development"

Award No. DE-NE0009162

Molten Salt Reactor (MSR)



A molten salt mixture is used as both fuel and coolant.

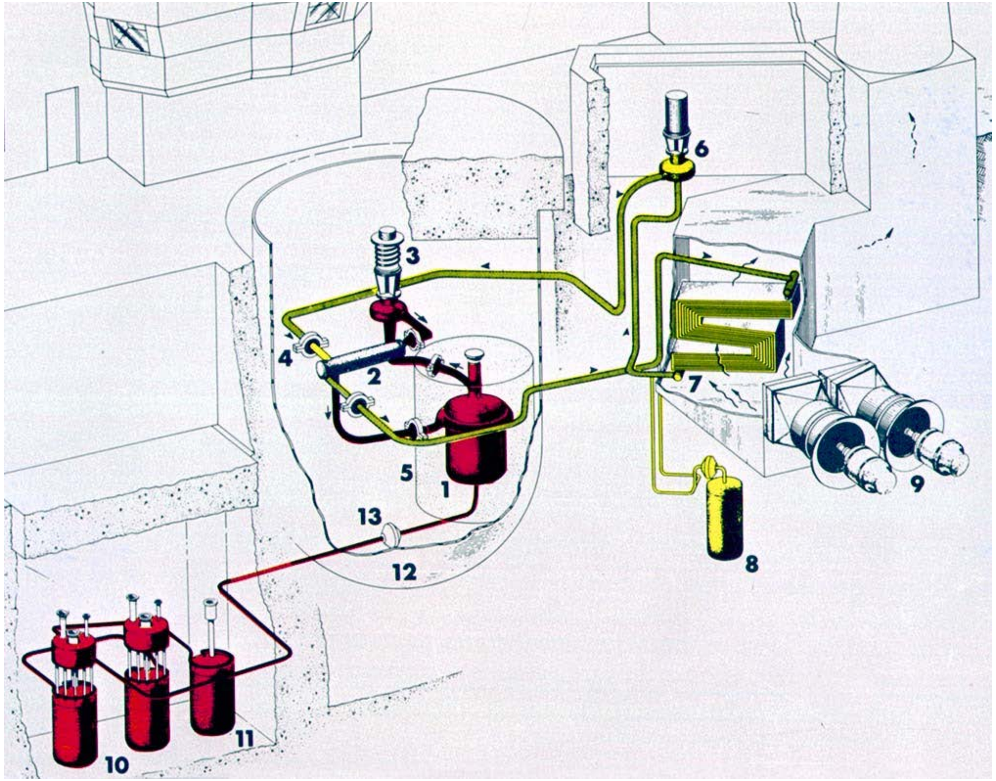
Advantages of MSR:

- High operation temperature
- Low operation pressure
- Fuel flexibility
- Versatile spectrum design
- Burn TRU and MA
- Nonproliferation
- No fuel melting concern
- Homogeneous design
- Continuous online refueling

Computational challenges:

- Fluid flow and delayed neutron precursor (DNP) drift,
- **Lack of experimental data for validation.**

Molten Salt Reactor Experiment (MSRE)



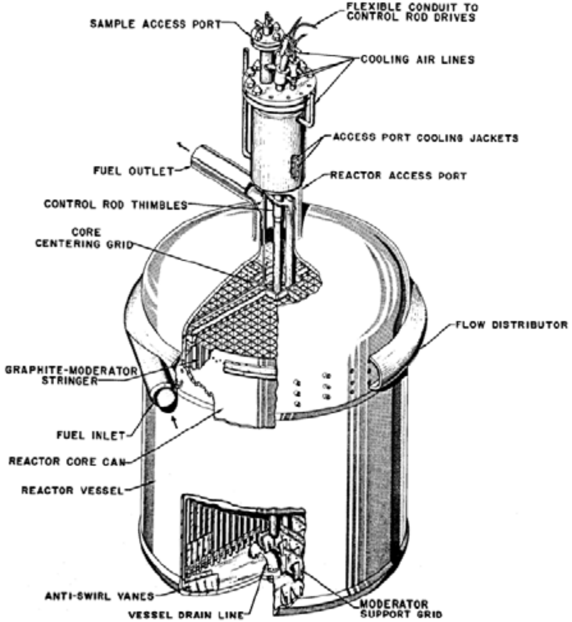
MSRE plant diagram:

(1) Reactor vessel,
(2) Heat exchanger,
(3) Fuel pump,
(4) Freeze flange,
(5) Thermal shield,
(6) Coolant pump,
(7) Radiator,
(8) Coolant drain tank,
(9) Fans,
(10) Fuel drain tanks,
(11) Flush tank,
(12) Containment vessel,
(13) Freeze valve.

Also note Control area in upper left and Chimney upper right.

MSRE Static Benchmark (UCB et al.)

- UCB and ORNL have collaborated to build statics models for the start-up zero power core of MSRE.
- The benchmark was successfully reviewed by IRPhEP committee and included in the handbook.
- A 3D high-fidelity model was developed using Serpent 2.
- The calculated k_{eff} is 2.154% larger than the experimental and benchmark model value.
- Various reactivity coefficients were calculated an showed good agreement with the experimental measurements

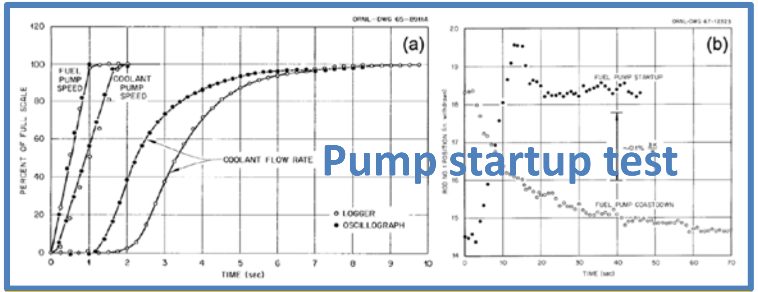


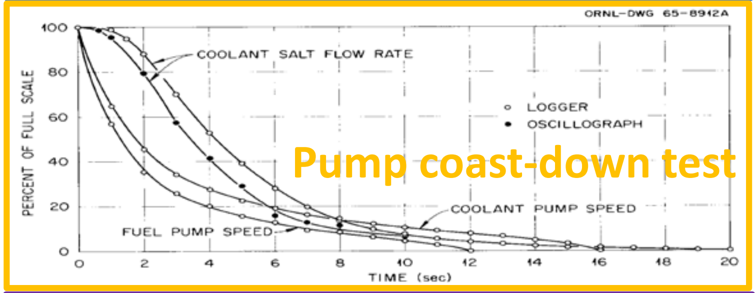
MSRE reactor vessel [1]

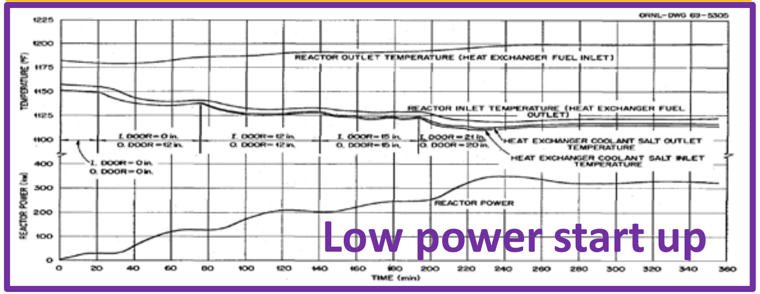
[1] R. C. Robertson, "MSRE Design and Operations Report Part I: Description of Reactor Design", ORNL-TM-0728, ORNL (1965).

MSRE Transient Experiments

- Performed at Oak Ridge National Laboratory (ORNL) during the 1960's
- The only collection of experimental data for the molten salt type of advanced reactor concepts
- **High-quality reactor statics benchmark set for the MSRE was included in the 2019 edition of IRPhEP handbook**
- Evaluations of MSRE transient experiments remain lacking







A Data Informed MSRE Transient Analysis Framework

Experimental data documented
Reactor power
Pump speed
Coolant flow rate
Coolant temperature
CR positions
Etc.

Model development

Model validation

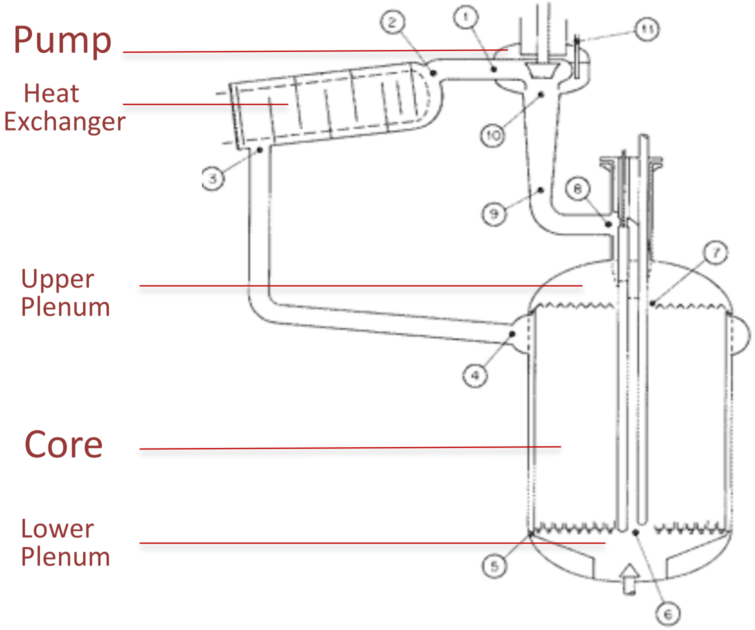
High-efficient whole-loop neutronics/thermal-hydraulics coupled MSRE model

Model completion

Lost data regeneration

Experimental data undocumented
Pump curve
Pressure loss coefficients
Etc.

MSRE Primary Loop Parameters



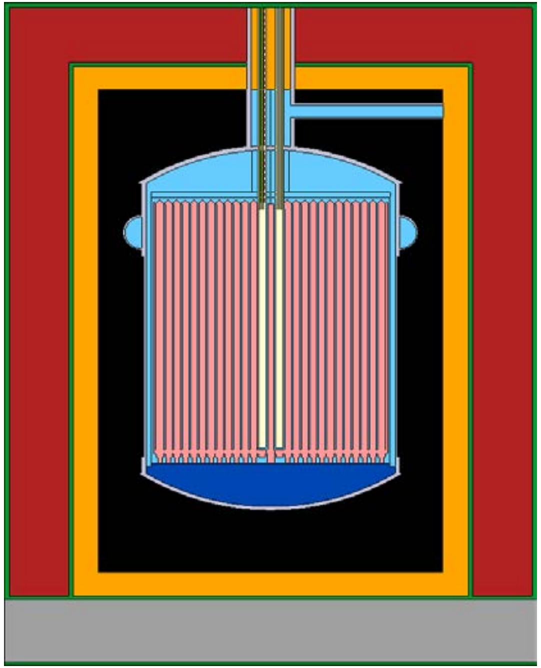
Schematic view of the fuel loop of MSRE

Geometrical Parameters of the MSRE Loop

Component	Residence Time (s)	Length(m)	Speed(m/s)
Lower Plenum	4.584	0.181	0.03948
Core	8.809	1.498	0.17004
Upper Plenum	4.266	0.174	0.040785
Pipe 8-9	0.513	0.705	1.373872
Pipe 9-10	0.273	0.376	1.375126
Pump	0.412	0.566	1.37373
Pipe 1-2	0.284	0.391	1.373538
Heat Exchanger	2.292	5.897	2.572512
Pipe 3-4	0.816	1.122	1.374086
Outer Annulus	3.64	1.579	0.433704

Start with the MSRE Static Benchmark

- Transient benchmark efforts are made on the top of the static MSRE benchmark model
- The Serpent model was used to generate homogeneous group constants and DNP fractions
- Two energy groups, Six DNP families, homogeneous regions are considered for the transient benchmark development



MSRE Transient Model

➢ **One-dimensional (1D) Two-group (2G) Diffusion Kinetics Model**

$$
\begin{cases}
\dfrac{1}{\mathrm{v}_1}\dfrac{\partial \phi_1}{\partial t} - \dfrac{\partial}{\partial x}\left[D_1 \dfrac{\partial \phi_1}{\partial x}\right] + \Sigma_{r,1}\phi_1 = (1-\beta)\left[\nu\Sigma_{f,1}\phi_1 + \nu\Sigma_{f,2}\phi_2\right] + \sum_{k=1}^{K}\lambda_k C_k, \\
\dfrac{1}{\mathrm{v}_2}\dfrac{\partial \phi_2}{\partial t} - \dfrac{\partial}{\partial x}\left[D_2 \dfrac{\partial \phi_2}{\partial x}\right] + \Sigma_{a,2}\phi_2 = \Sigma_{s,1\to 2}\phi_1, \\
\dfrac{\partial C_k}{\partial t} + u\dfrac{\partial C_k}{\partial x} = \beta_k\left[\nu\Sigma_{f1}\phi_1 + \nu\Sigma_{f2}\phi_2\right] - \lambda_k C_k, \qquad k = 1, \cdots, 6.
\end{cases}
$$

Simplified 1D Reactor Steady-State Model

- **Forward Formulation:**

$$\begin{cases} -\dfrac{d}{dx}\left[D_1\dfrac{d\phi_1}{dx}\right]+\Sigma_{r,1}\phi_1=\dfrac{1-\beta}{k_{eff}}\left[\nu\Sigma_{f,1}\phi_1+\nu\Sigma_{f,2}\phi_2\right]+\sum_{k=1}^{6}\lambda_k C_k, \\ -\dfrac{d}{dx}\left[D_2\dfrac{d\phi_2}{dx}\right]+\Sigma_{a,2}\phi_2=\Sigma_{s,1\to 2}\phi_1, \\ u\dfrac{dC_k}{dx}=\dfrac{\beta_k}{k_{eff}}\left[\nu\Sigma_{r,1}\phi_1+\nu\Sigma_{r,2}\phi_2\right]-\lambda_k C_k, \qquad k=1,\cdots,6. \end{cases}$$

- **Adjoint Formulation:**

$$\begin{cases} -\dfrac{d}{dx}\left[D_1\dfrac{d\phi_1^*}{dx}\right]+\Sigma_{r,1}\phi_1^*=\dfrac{\nu\Sigma_{f,1}}{k_{eff}}\left[(1-\beta)\phi_1^*+\sum_{k=1}^{6}\beta_k C_k^*\right]+\Sigma_{s,1\to 2}\phi_2^*, \\ -\dfrac{d}{dx}\left[D_2\dfrac{d\phi_2^*}{dx}\right]+\Sigma_{a,2}\phi_2^*=\dfrac{\nu\Sigma_{f,2}}{k_{eff}}\left[(1-\beta)\phi_1^*+\sum_{k=1}^{6}\beta_k C_k^*\right], \\ -u\dfrac{dC_k^*}{dx}=\lambda_k\phi_1^*-\lambda_k C_k^*, \qquad k=1,\cdots,6. \end{cases}$$

Homogeneous XS and DNP Parameters

Homogenized XS of the MSRE Core

Parameter	Value
D_1 [cm]	1.18219
D_2 [cm]	0.840635
$\Sigma_{r,1}$ [cm^{-1}]	0.004591
$\Sigma_{a,2}$ [cm^{-1}]	0.008244
$\Sigma_{s,1\rightarrow 2}$ [cm^{-1}]	0.003326
$\nu\Sigma_{f,1}$ [cm^{-1}]	0.000698
$\nu\Sigma_{f,2}$ [cm^{-1}]	0.010374

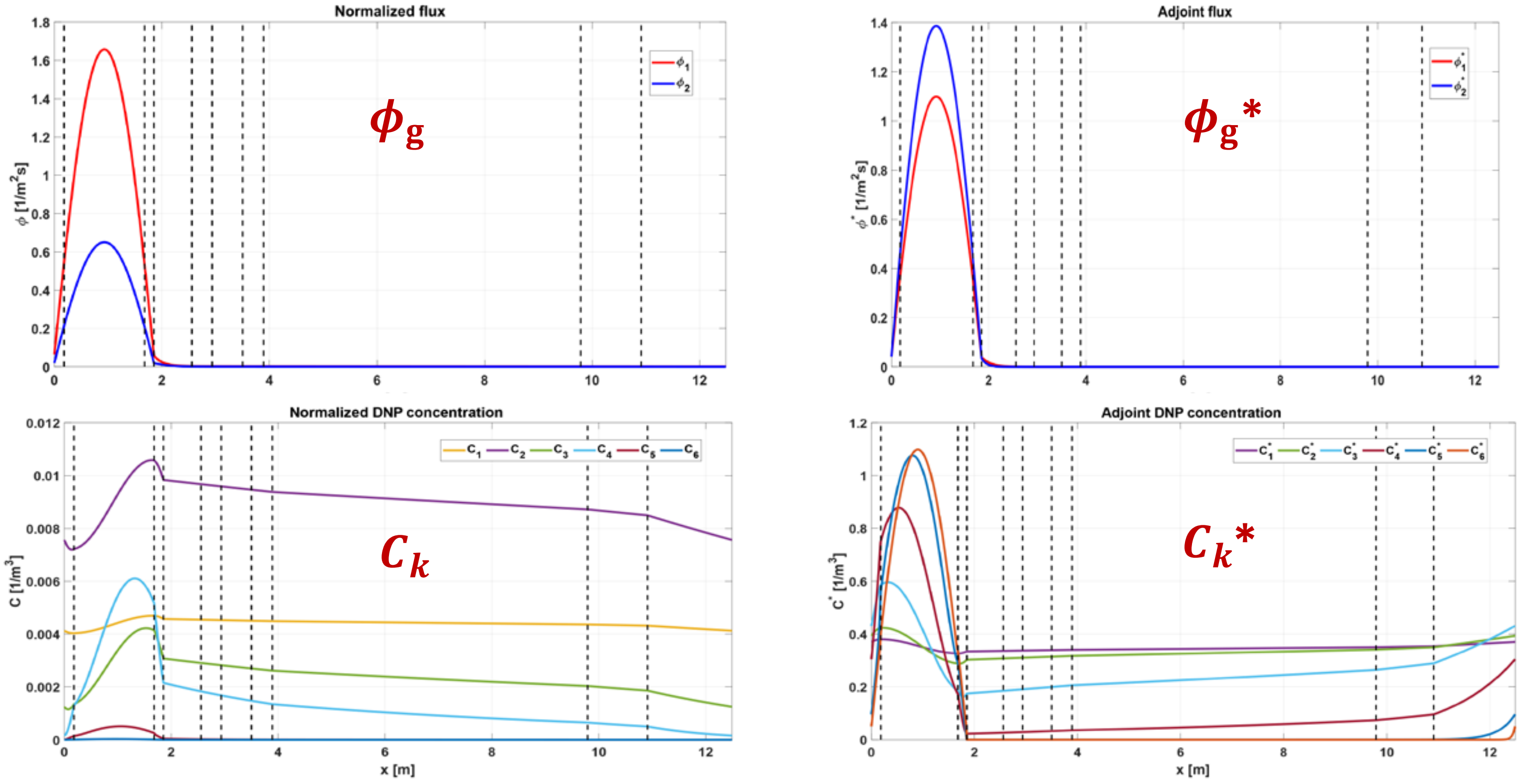
DNP Parameters Used in the Analysis

Family	1	2	3	4	5	6
$\beta / 10^{-5}$	20.7	106.9	104.1	296.2	86.2	30.8
λ [s^{-1}]	0.012	0.031	0.109	0.317	1.35	8.64

Preliminary Results

- The run time is less than one second.
- The steady-state eigenvalue is $k_{eff} = 0.96809$ for both forward and adjoint models
- The reference eigenvalue (Serpent) is $k_{eff} = 1.02133 \pm 0.00010$
- Sources of errors:
  - The hegemonized XS was were generated over the whole geometry, while in the diffusion model only the vessel length was considered.
  - The drift of the DNP
  - Radial leakage not accounted for in the 1D model.

Flux and DNP Distributions



Conclusions

- A 1D 2G neutron diffusion model coupled with six DNP groups was established with a representative MSRE 1D geometry.
- The core, lower plenum, and upper plenum were considered as one homogenized region. The zero incoming flux (zero outgoing adjoint) is considered as boundary condition for the homogenized region. Periodic boundary conditions were considered for the DNP rate.
- The homogeneous cross sections and DNP data were generated based on the MSRE static model developed by Serpent code.
- Both the forward and adjoint system of equations were solved by the COMSOL Multiphysics platform, and preliminary results were obtained.

On-going and Future Work

- Generating XS by homogenizing the regions modeled in the 1D model and albedo BCs to capture the axial leakage.
- Using correction factor (artificial cross section) for axial leakage.
- Expanding the current model to 2D/3D multi-group model.
- Developing a system-level thermal hydraulics component to provide a multiphysics coupling calculation capability.
- Selected MSRE transient experiments will be examined carefully to eventually develop a rigorous transient benchmark for the IRPhEP handbook.

Thanks & Questions?

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