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Sensitivity Study on the Natural Convection Test in the Molten Salt Reactor Experiment (MSRE) using the GAMMA+ Code

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01

Introduction

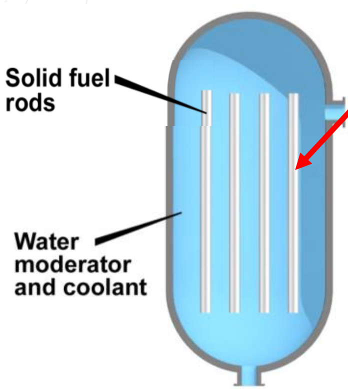
Introduction (1/6)

Molten Salt Reactor (MSR)

- **MSR, as a liquid-fueled reactor,** possesses different neutronic characteristics compared to solid-fueled reactors. This is due to **the circulation of delayed neutron precursors** from the core to the loop and back from the loop to the core.
- **Comparison of Typical Nuclear Fuel and Liquid Nuclear Fuel**

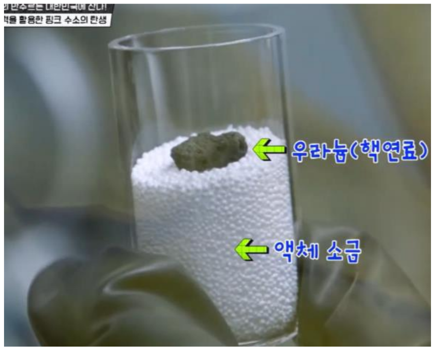
Uranium powder is fabricated into compact cylindrical fuel pellets

The pellets are inserted into rods, then grouped to form a fuel assembly

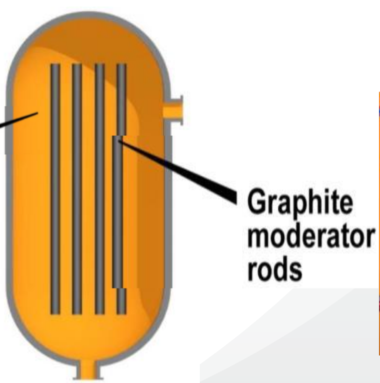


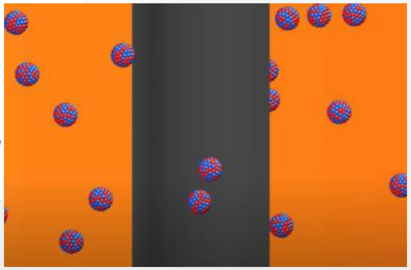
Typical Nuclear Fuel

Liquid Nuclear Fuel



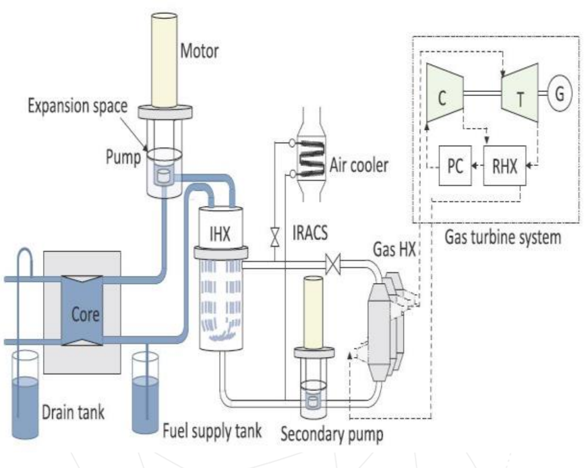
Fissile material dissolved in liquid



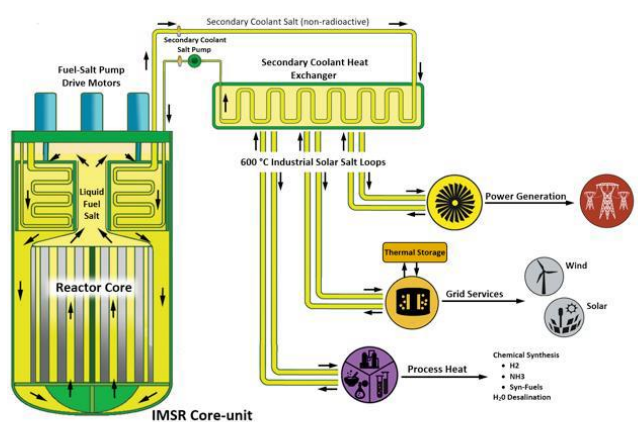


Introduction (2/6)

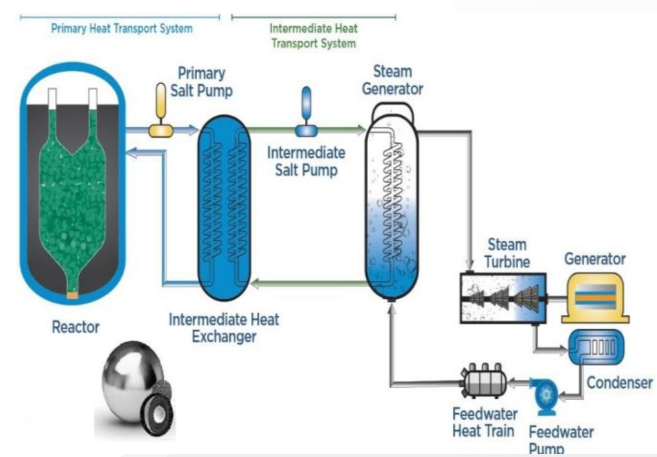
- **Definition of Molten Salt Reactor (MSR):** A Molten Salt Reactor (MSR) is a type of nuclear reactor in which molten salt plays a primary role in the reactor core, serving as fuel, coolant, and/or moderator [IAEA].
  - **Primary (or Fuel) salt system :** Absorbs heat directly from fission and transfer it
    - → **Reactor, Intermediate heat exchanger (IHX-primary), Pump**
    - → **Fuel salt:** Molten salt containing fissile materials
  - **Intermediate heat transfer system:** Separation between the nuclear and non-nuclear system (Coolant salt is used)
    - → **IHX-secondary, HX for heat transfer to Secondary system (Power conversion), Pump**
    - → **Coolant salt:** Molten salt for cooling core or Molten salt as heat transfer medium



Loop Type (MSR)



Integral Type (MSR)



Salt – only a coolant (SFR)

Introduction (3/6)

MSR Technology Development History

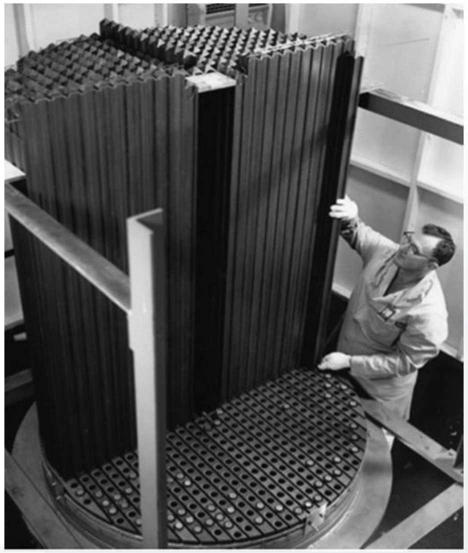
- MSR technology has a long-term development history at ORNL (Oak Ridge National Laboratory)
- Originally proposed by Ed Bettis and Ray Briant of ORNL in late 1940s
- Aircraft Nuclear Propulsion Program (1946–61)
  - Large investment ($1B)
  - Aircraft Reactor Experiment (1953–1954)*
  - Aircraft Reactor Test (1954–1957)
- Civilian Molten Salt Reactor Program (1958–1960)
- Molten Salt Reactor Experiment (1960–1969)*
- Molten Salt Demonstration Reactor
- Molten Salt Breeder Experiment (1970–1976)
- Molten Salt Breeder Reactor (1970–1976)
- Denatured Molten Salt Reactor (1978–1980)
- ORNL designed, constructed, and operated the only two MSRs - ARE and MSRE

ARE

- Long-term strategic bomber operation using nuclear power
- Originally sodium cooled, but shifted to molten salt
- Ended with advent of ICBMs in early 1960s

MSRE

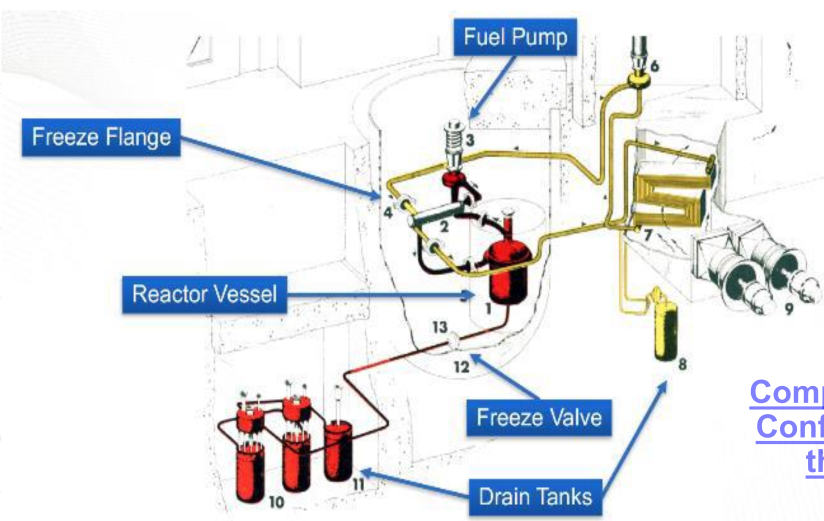
- Stop of the military use for MSR but continuous effort for power generation
- First reactor to operate solely on ^{233}U (1968)



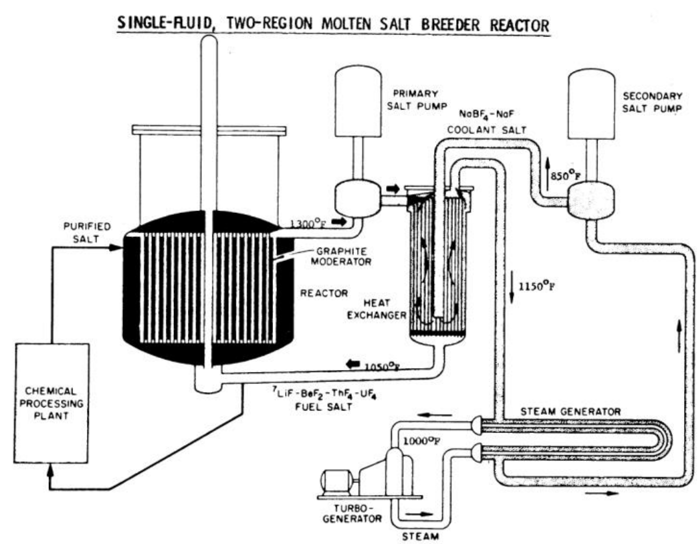
Introduction (4/6)

MSRE (Molten Salt Reactor Experiment)

- The MSRE was designed, constructed, and operated at the **ORNL in the 1960s**. It was specifically designed as an experimental reactor with a **thermal power output of 10 MW**.
- **Thermal neutron reactor** with **Graphite** (moderator) and **molten salt** (fuel/coolant, the same fluid)
- The nuclear fission reactions occur in the **active region of the reactor coolant system**, which includes the piping, fuel pumps, and heat exchangers.
- **The fuel** is composed of LiF-BeF2-ZrF4-UF4 and The liquid fuel salt in the primary loop is **circulated by fuel pumps**.



Components and Configuration of the MSRE



Introduction (5/6)

Improvement of the GAMMA+ Code for Application to Non-LWRs

- **GAMMA+: Best-estimate system transient analysis code for non-LWRs**
  - Point kinetics, thermal radiation, contact conduction, components (valve, pump, controller, etc.)
  - 1-D/Multi-D fluid dynamics & solid heat conduction
  - New features of 1-D/Multi-D stratified flow dynamics, heat conduction in fluid
- Originally developed to predict the physical phenomena expected following the anticipated & postulated accidents in a high-temperature gas-cooled reactor (HTGR)
- **Further updated with appropriate correlations and extended to Non-LWR reactors**
- **Non-Light Water Reactors (Non-LWRs):** Micro gas-cooled reactor (MMR), liquid-metal reactor (LMR) including sodium-cooled fast reactor (SFR), molten-salt reactor (MSR) and space power reactor (SPR)

Introduction (6/6)

Research Background and Objectives

- Existing research utilized **the MSRE** to conduct tests on **pump startup and shutdown, natural convection heat removal, and reactivity insertion**.
- **The GAMMA+ code** was employed to analyze these experiments.
- The GAMMA+ code uses three types of Point Kinetics (PK) models to predict the neutronic dynamic behavior of MSRs.
  - **Decay-term Point Reactor Kinetics (DT-PRK)**
  - **Delay-loop Point Reactor Kinetics (DL-PRK)**
  - **Nuclide groups Transport Kinetics (NTK)**
- In this study, the natural convection heat removal were analyzed using **the GAMMA+ code with the Nuclide groups Transport Kinetics (NTK)**. The simulation results from the GAMMA+ code were compared with the experimental data from the MSRE.
- **Two sensitivity calculations** were performed for the parameters of **different active core regions and different heat transfer correlations** in free convection conditions.

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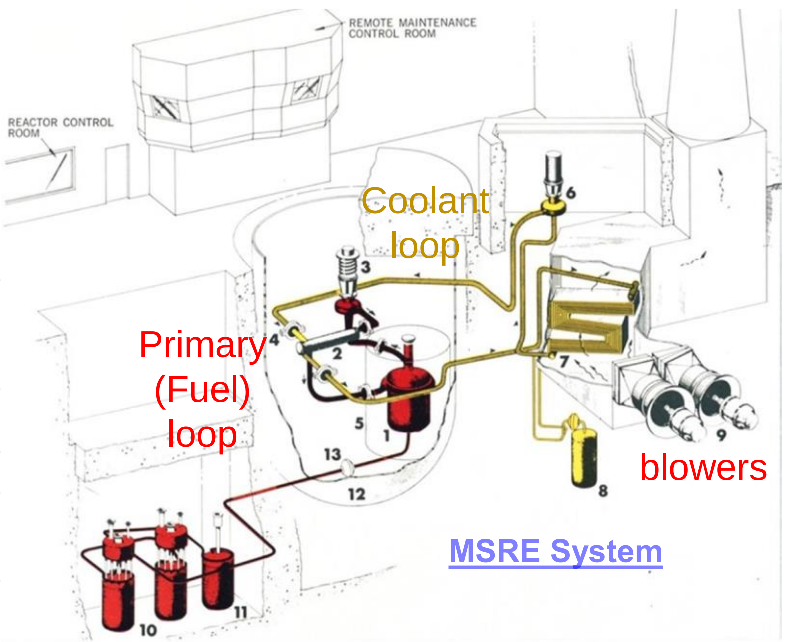
Natural Convection Test in MSRE

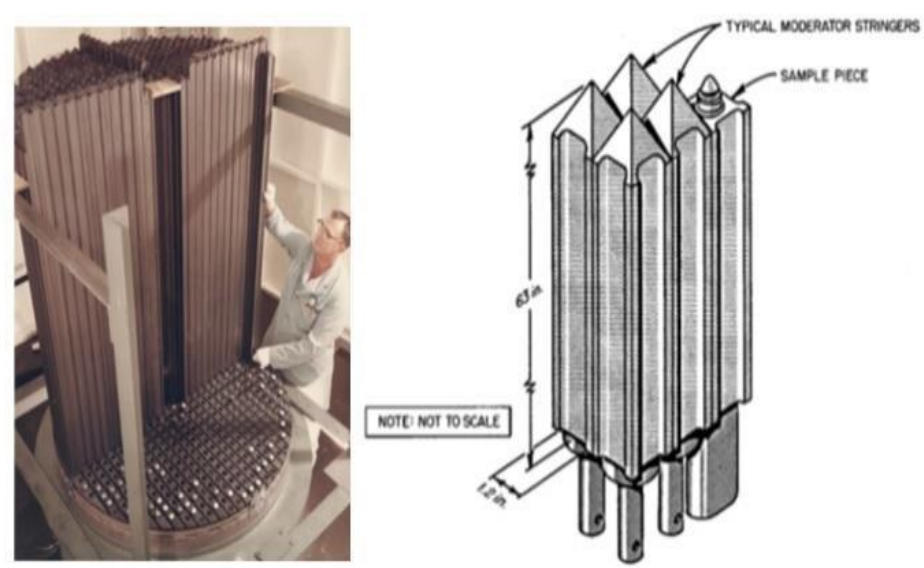
MSRE System

- **The primary loop** is cooled by a **LiF-BeF2 coolant loop** through salt-salt type heat exchangers. **The coolant loop** is further cooled by external air through an **air-cooled radiator**. **Two blowers** are used to supply air to the heat exchanger.
- **The graphite moderator** in the reactor core consists of **617 graphite structures** (stringers, 2 in × 2 in each). These graphite structures are arranged vertically and closely packed, forming approximately **1,140 equivalent fluid channels** known as vertical fuel salt channels.



MSRE System

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.

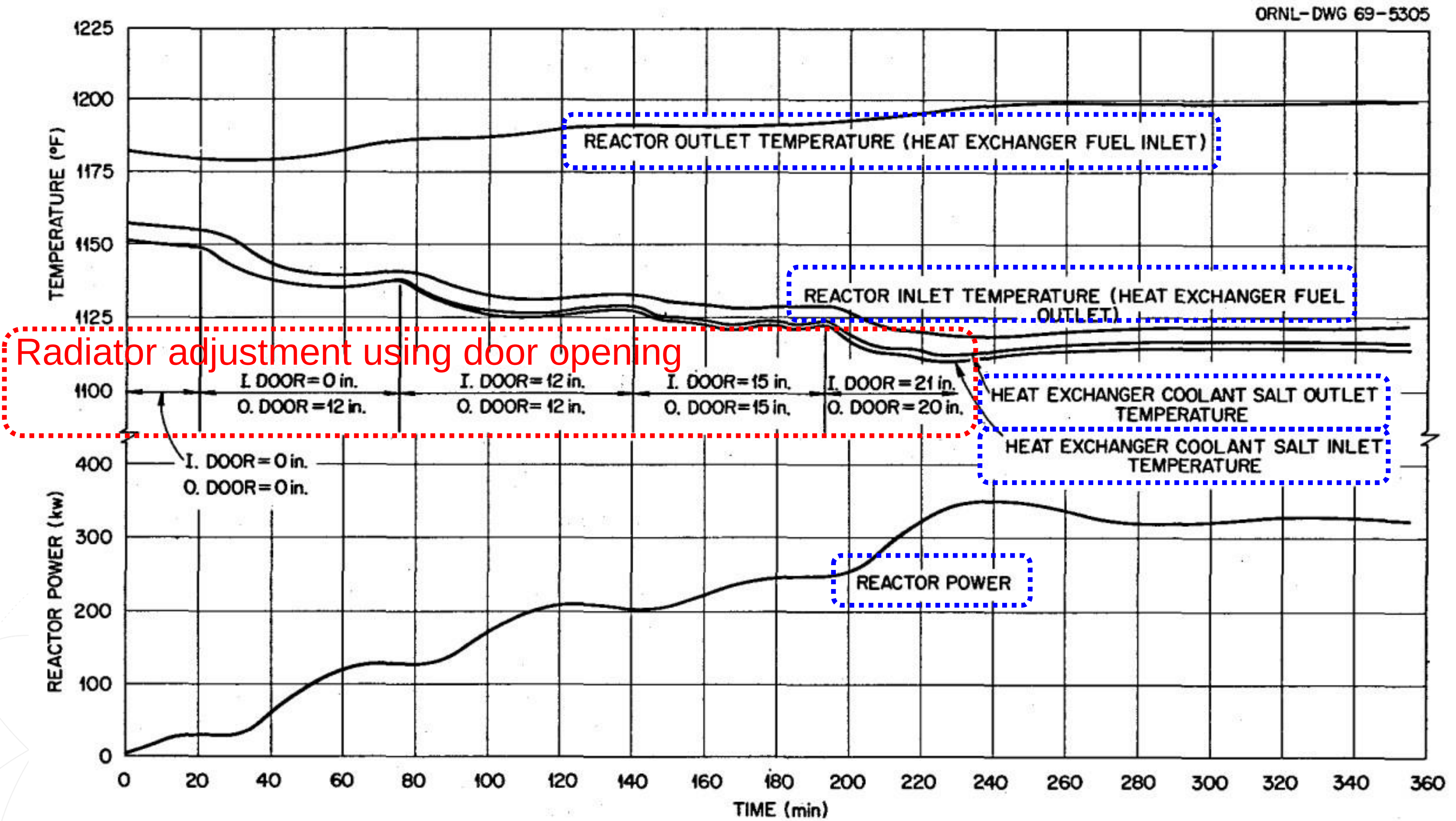


Graphite Moderator of MSRE

MSRE Natural Convection Test

- **The primary loop was cooled by the coolant salt loop** via the salt-to-salt shell and tube heat exchanger. The coolant salt was LiF-BeF2.
- **And the coolant salt loop was cooled by outside air via the air-cooled radiator**. **Two blowers** were used to supply air to the radiator.
- **A natural convection test** was performed to investigate the heat removal characteristics of the MSRE by using natural convection flow of the fuel salt.
- **Forced circulation in the coolant salt loop** was maintained during the experiment. The heat removal rate in the air radiator was **increased in steps keeping the reactor critical**. **The reactor power was solely controlled by inherent feedback of the MSRE.**
  - A natural convection test was performed **with no control rod motion such that reactor power was responding to the heat load demand from the radiator.**
  - With forced circulation in the coolant salt loop, the radiator heat removal rate was increased in steps by incrementally **opening the radiator door(s).**
  - **Each radiator adjustment** was made after the reactor power rose as a result of the previous adjustment, thereby approaching equilibrium.

MSRE Natural Convection Test



Nuclear Power and Salt Temperatures During Thermal-Convection Heat-Removal Test (ORNL-4396, Fig. 1.16.)

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03 GAMMA+ Simulation on the MSRE Natural Convection Test

GAMMA+ Input Model (1/3)

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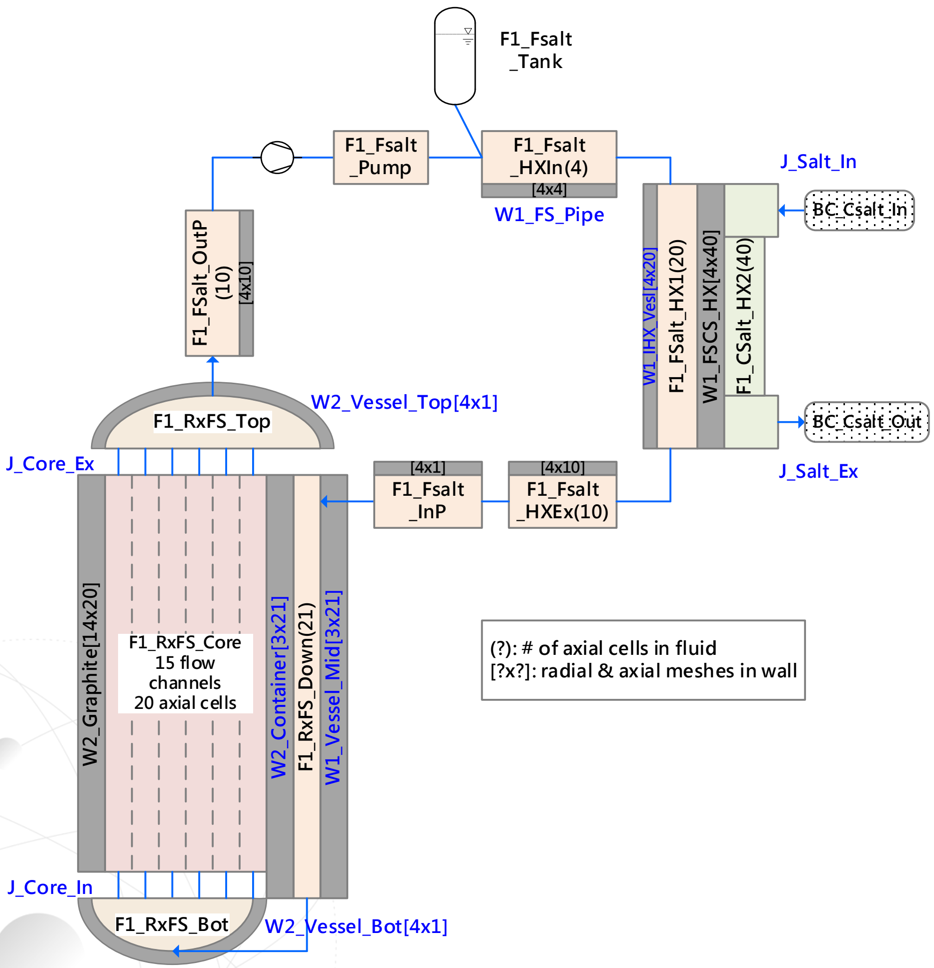
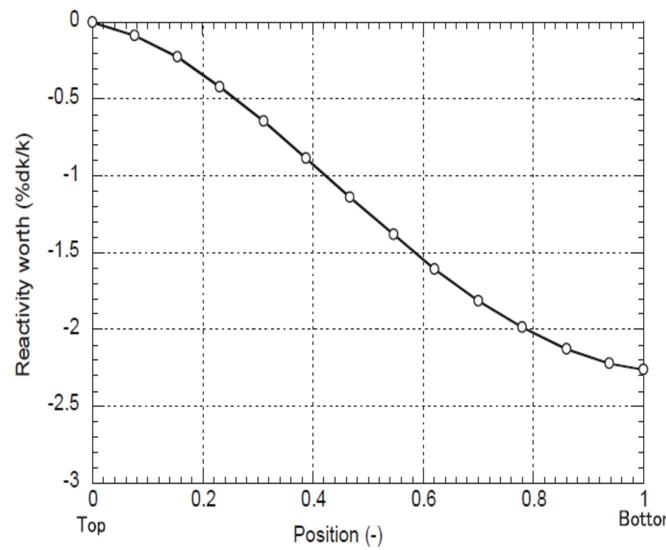
GAMMA+ Input Model for Simulating MSRE Natural Convection Test



GAMMA+ Model for MSRE Natural Convection Test



Simulation of Control Rod Movement
(Control rod worth for critical loading, ORNL-TM-4233)

GAMMA+ Input Model (2/3)

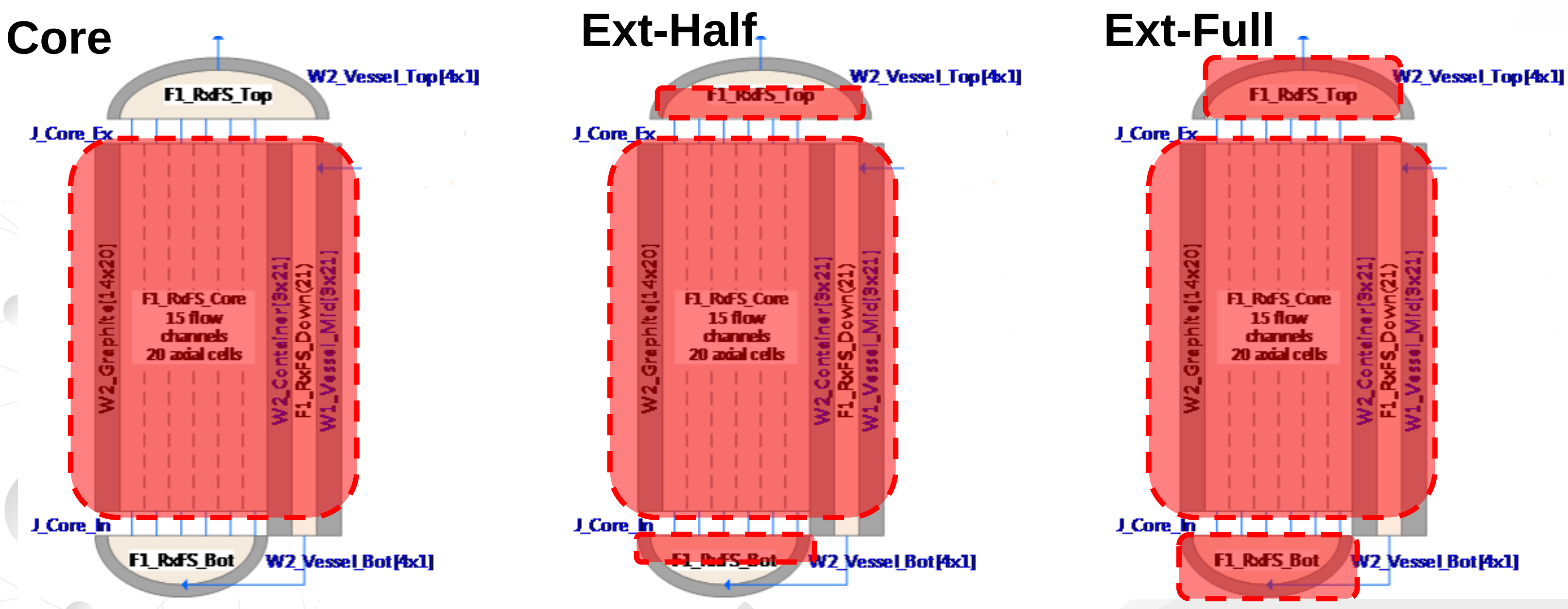
GAMMA+ Input Model for the MSRE

- **The GAMMA+ input model** consists of the fuel salt system, and the basic input model was developed by **referencing ORNL documents**.
- Although detailed cooling conditions for the air cooler were provided, **the thermal-fluid conditions (flow rate & temperature) of the coolant loop** were used as **boundary conditions.**
- Efforts were made to obtain **the concentrations of delayed neutron precursors** in the core and loop to accurately calculate the fission power.
- It can be assumed that fission power and spatial concentration have a significant impact on **the active region of the core**.
- However, in the MSRE system, fission reactions occur not only in the graphite moderator region but also in areas outside the reactor's graphite, such as the upper plenum, lower plenum, and downcomer, making it unclear to define the core region.

GAMMA+ Input Model (3/3)

GAMMA+ Input Model for the MSRE

- **The core region is not clearly defined and could be defined from the downcomer to the upper plenum or parts of the vessel.**
- In the current study, three types of active fission regions were considered:
  ① Graphite Moderator Region (**Core**)
  ② Extended Core Region Including Half of the Upper and Lower Plenums (**Ext-Half**)
  ③ Extended Core Region Including the Entire Upper and Lower Plenums (**Ext-Full**)



GAMMA+ Analysis Model (1/2)

Analysis Models on MSRE

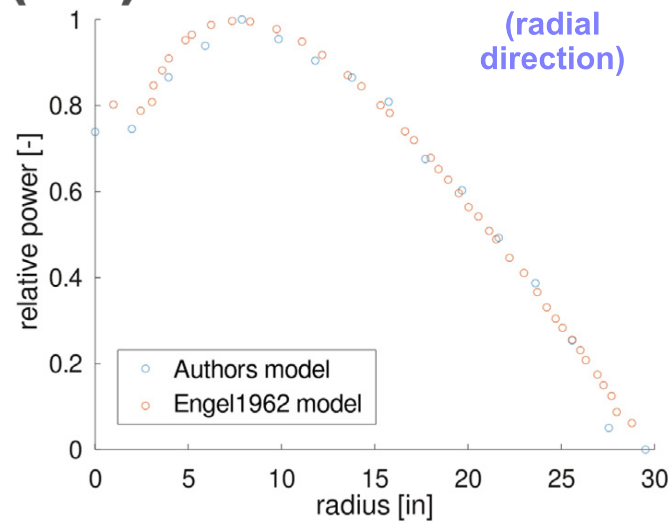
- Steady-State Calculation with the Power Output of 10 MWth

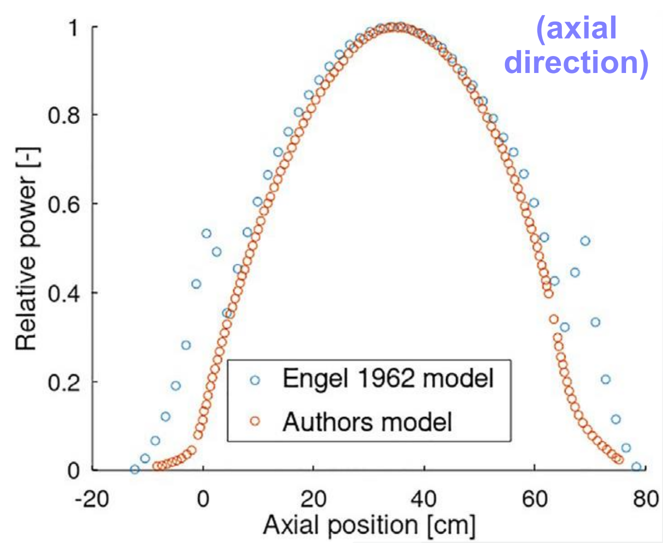
Distribution of Core Power

- SERPENT code calculation

MSRE Core Power Distribution by SERPENT Code Calculation

Total neutron energy deposition [%]	Gamma energy deposition [%]	Total energy deposition [%]	Place of deposition
76.3	2.83	79.1	Fuel core
2.84	4.69	7.53	Graphite
4.44	0.456	4.9	Upper head
4.19	0.627	4.82	Lower head
3.03	0.325	3.35	Downcomer
0.258	0.05	0.3	Fuel inlet ring





Core Power Distribution by SERPENT Code Calculation

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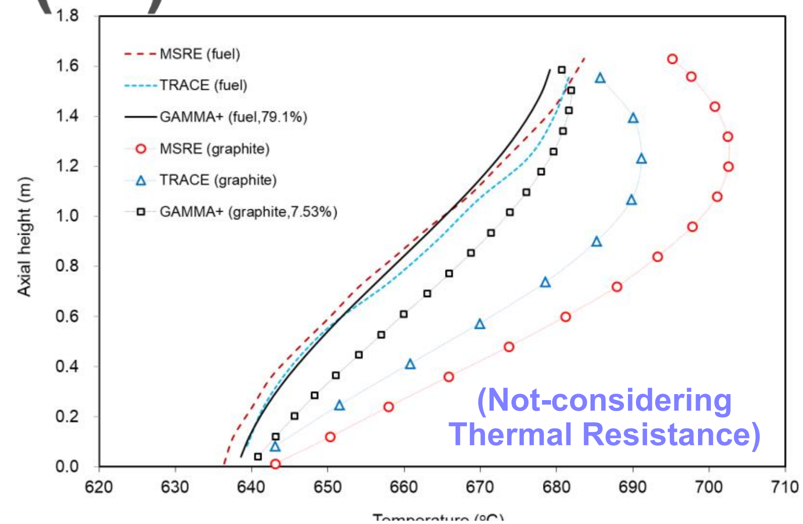
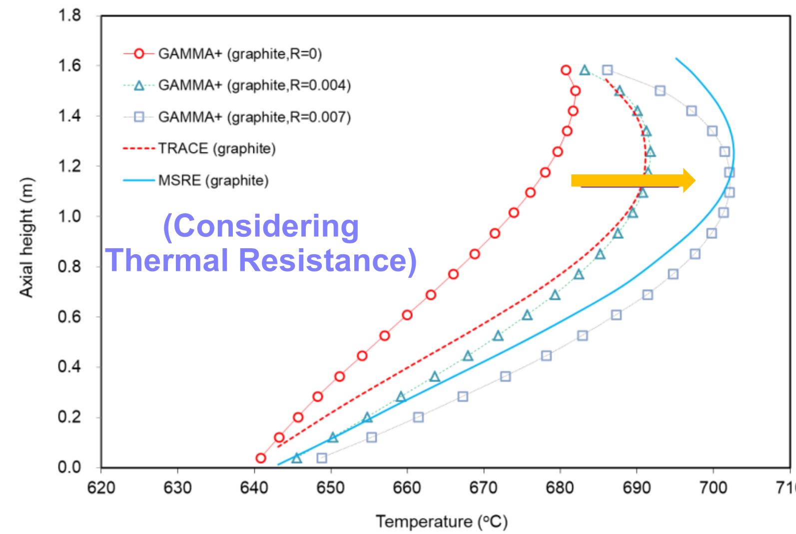
GAMMA+ Analysis Model (2/2)

GAMMA+ Steady-State Calculation

GAMMA+ Steady-State Calculation Results on MSRE Test Reactor at 100% Core Power

Major system parameters	Calculation values	Design values
Thermal power, MWth	10.0	
Fuel salt composition	$LiF-BeF_2-ZrF_2-UF_4$	
Fuel salt conditions:		
Fuel inlet/outlet temp., °C	635.1/666.4	635/662.8 (design)
Fuel salt mass flow, kg/s	162.3	162.3 (design)
Fuel salt pressure at pump suction, bar	0.486	0.48 (design)
Coolant salt composition	$LiF-BeF_2$	
Coolant salt conditions:		
Coolant hot/cold temp., °C	548.8/593.7	551.7/593.3 (design)
Coolant salt mass flow, kg/s	100.7	100.7 (design)
Coolant salt pressure at pump suction, bar	0.328	0.34 (design)
Air inlet/outlet temp., °C	37.8/149.6	37.8/149 (design)
Air mass flow, kg/s	88.0	88.2 (design)





GAMMA+ Steady-State Calculation Results on MSRE Test Reactor at 100% Core Power: Axial Temperature Profiles

Point Kinetics Models of GAMMA+ (1/3)

GAMMA+ PK models: Type 1 (DT-PRK, Decay-term point reactor kinetics)

- The concept was developed by **ORNL**, and this model modified the PK model of solid fuel reactors for MSR applications; **Equations (1) and (2) are used in PK type 1.**
- **Delayed neutron precursors may decay within the loop before returning to the core. Fuel transit time and the decay of delayed neutron precursors are considered** when the fuel salt is outside the core.

$$\frac{dP}{dt} = \frac{\rho - \beta_{eff}}{\Lambda} P + \sum_{i=1}^{6} \lambda_i C_i \quad (1)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_i - \frac{C_i}{\tau_c} + \frac{C_i(t - \tau_l)}{\tau_c} e^{-\lambda_i \tau_l} \quad (2)$$

- Here, P, ρ, βeff, Λ, C, λ, τ_{core}, τ_{loop} represent fission power, reactivity, effective delayed neutron fraction, effective prompt neutron lifetime, delayed neutron precursor concentration, delayed neutron precursor decay constant, fuel transit time within the core, and fuel transit time within the loop.
- The last two terms of Equation (2) are also applied to poisons and decay heat nuclides in the GAMMA+ code.
- A limitation of DT-PRK is that **it can only calculate heat generation within the core**.

Point Kinetics Models of GAMMA+ (2/3)

GAMMA+ PK models: Type 2 (DL-PRK, Delay-loop point reactor kinetics)

- **D. Zhang et al.** (2009) suggested additional equations to obtain the concentration of the delayed-neutron precursors in the loop as following equations of Equations (3)-(5).
- In the PK type 2(DL-PRK) of the GAMMA+ code the concentrations of the delayed-neutron precursors are separated into two parts, **inside the core and outside the core**.

$$\frac{dP}{dt} = \frac{\rho - \beta_{eff}}{\Lambda} P + \sum_{i=1}^{6} \lambda_i C_i \qquad (3)$$

$$\frac{dC_{c,i}}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_{c,i} - \frac{C_{c,i}}{\tau_c} + \frac{V_l}{V_c} \frac{1}{\tau_l} C_{l,i}(t - \tau_l) \qquad (4)$$

$$\frac{dC_{l,i}}{dt} = -\lambda_i C_{l,i} - \frac{C_{l,i}}{\tau_l} + \frac{V_c}{V_l} \frac{1}{\tau_c} C_{c,i} \qquad (5)$$

- Here V_l , V_c , $C_{c,i}$,$C_{l,i}$ are volumes of the core and the loop and concentrations of the delayed-neutron precursors in the core and the loop.
- The last two terms in the equation (4) and the equation (5) are **also implemented to poison and decay heat nuclides** in the GAMMA+ code.
- DL-PRK has capabilities to calculate the decay heat in the loop and the concentration of the delayed-neutron precursors in the loop.
- However, **the data of the entire loop is represented as the one point.**

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Point Kinetics Models of GAMMA+ (3/3)

GAMMA+ PK models: Type 3 (NTK, Nuclide groups transport kinetics)

- For PK type 3 (NTK), the following equations (6) to (7) are proposed to calculate the **concentration of delayed neutron precursors in each cell**:

$$\frac{dP}{dt} = \frac{\rho-\beta_{eff}}{\Lambda} P + \Sigma_{j=1}^{core} \sum_{i=1}^{6} \lambda_i C_{i,j} \qquad (6)$$

$$\frac{dC_{i,j}}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_{i,j} + \frac{1}{V_j}[(uAC_i)_{in} - (uAC_i)_{ex}] \qquad (7)$$

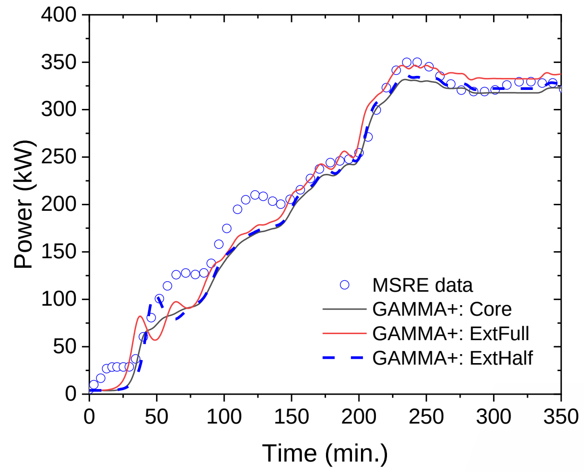
Here, j represents the cell index, V is the volume, u is the velocity, and A is the flow area.

- The PK models were further classified based on the definition of the core region:
  - **Graphite Moderator Core Region = Core**
  - **Extended Core Region Including Half of the Upper and Lower Plenums = Ext-Half**
  - **Extended Core Region Including the Entire Upper and Lower Plenums = Ext-Full**
- The fuel and graphite temperature coefficients obtained by **the Serpent calculations** (2021) for the MSRE with U-233 fuel were adopted in this work for thermal feedback.

Simulation Results (1/3)

Sensitivity on the PK models in GAMMA+

- It is very important that **the appropriate core region is properly defined** to calculate the fission of molten salt fuel accurately throughout the core and loop regions, and thus **the core region is extended from the graphite core region only to some parts of the bottom and top plena.** It is because the core region is not fixed as the molten salt coolant is circulating the primary loop.
- Through some sensitivity calculation, it is considered that the NTK model simulates the MSRE data well when **the core region is extended to include half of the bottom and top plena.**



GAMMA+ simulation results on the natural convection heat removal test of the MSRE: Sensitivity of PK models (Fig. 4)

- However, the effect of the PK model on the predicted power is not significant. The results is reasonable since the impact on **the fuel transit time is small due to low flow velocity during natural convection.** It should be noted that most of the delayed neutron precursors are decayed at the core region where they are generated.

Simulation Results (2/3)

Heat transfer models in the GAMMA+ code

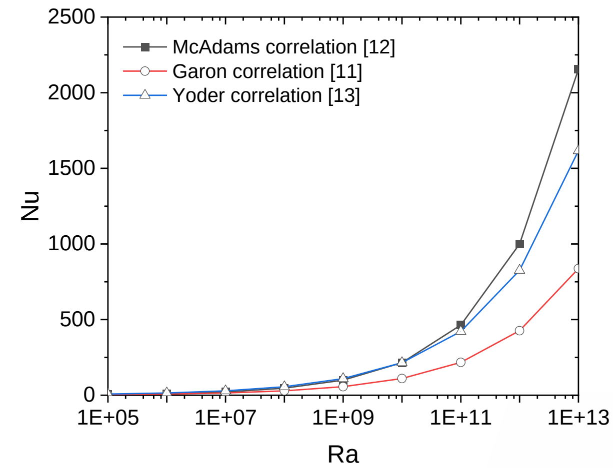
- In the GAMMA+ code **the heat transfer package** includes gas mixture heat transfer correlations, two-phase heat transfer correlations, heat transfer enhancement devices, liquid metal heat transfer correlations and molten salt heat transfer correlations.
- Among them **the molten salt heat transfer correlations** include Sohal correlation (2010) and Garon correlation (1973) for forced and free convection conditions, respectively, in GAMMA+ 2.1.

Sohal correlation: $Nu_F = 0.024 \mathrm{Re}_l^{0.807} \mathrm{Pr}_l^{0.301}$

McAdams correlation: $Nu_N = 0.10 Ra_l^{1/3}$

Garon correlati0n: $Nu_N = 0.13 Ra_l^{0.293}$

Yoder correlation: $Nu_N = 0.2601 Ra_l^{0.2918}$



The dependency of three correlations on Rayleigh number (Fig. 5)

- However, it is estimated that **the Garon correlation under-predicts** the heat transfer under the molten salt conditions. The sensitivity of three correlations on the free convection condition, which are McAdams correlation (1954), Garon correlation, and Yoder correlation (2018), is investigated.
- **The dependency of three correlations on Rayleigh number** is expressed in Fig. 5, which shows that **the values calculated from Yoder correlation is between those from McAdams and Garon correlations.**

Simulation Results (3/3)

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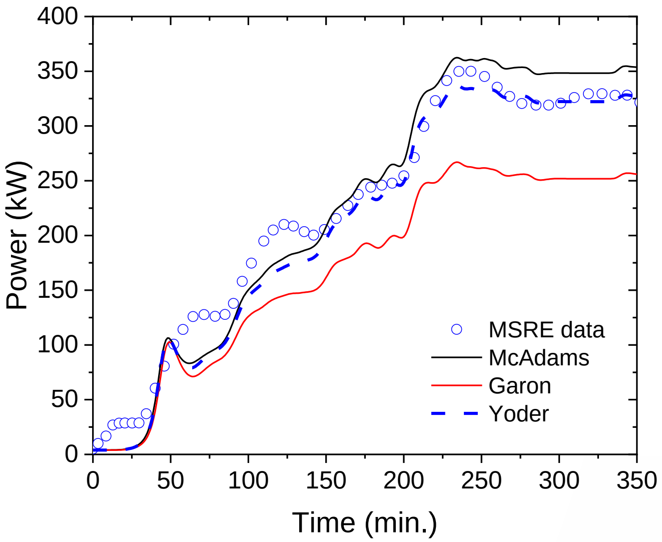
Sensitivity on the heat transfer models in GAMMA+

- In the present study the natural convection test in MSRE are simulated using the three different free convection heat transfer models in the GAMMA+ code since there seems to be high dependency on the natural convection phenomena occurred in the molten salt circulating conditions.
- As shown in Fig. 6, **the power simulated using the Yoder correlation agrees the test data better.**



GAMMA+ simulation results on the natural convection heat removal test of the MSRE: Sensitivity of heat transfer correlations (Fig. 6)

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05 Conclusions

Conclusions

- In this paper, **two sensitivity calculations** on **different active core regions and heat transfer models** were performed against the **natural convection heat removal test of the MSRE** with the **GAMMA+** code.
- First of all, the PK models of type 3 (NTK) was used and three different active core regions of **core only**, **extended half** (half of top and bottom plena included) **and extended full** (all the top and bottom plena included, or all the vessel). The impact of the selection of the active core was found to be small as it is in natural convection condition with low velocity.
- Second, **three different heat transfer correlations** were used to simulate the natural convection test using the molten salt. The GAMMA+ code best simulate the MSRE test data best using **the Yoder correlation**.
- **Further study** is necessary for the simulation of real test conditions: The exact cooling conditions for the air cooler can be given as the door opening of radiator.

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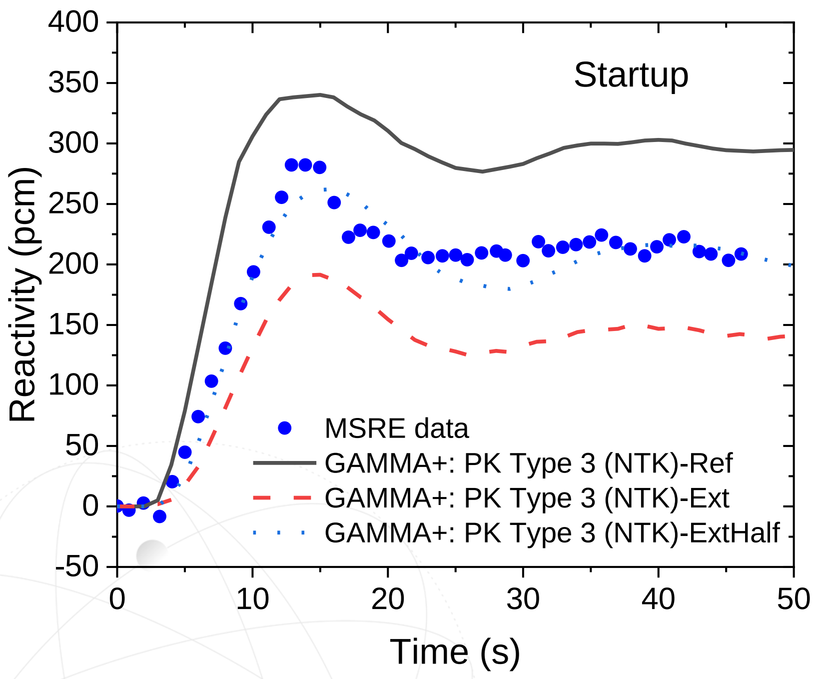
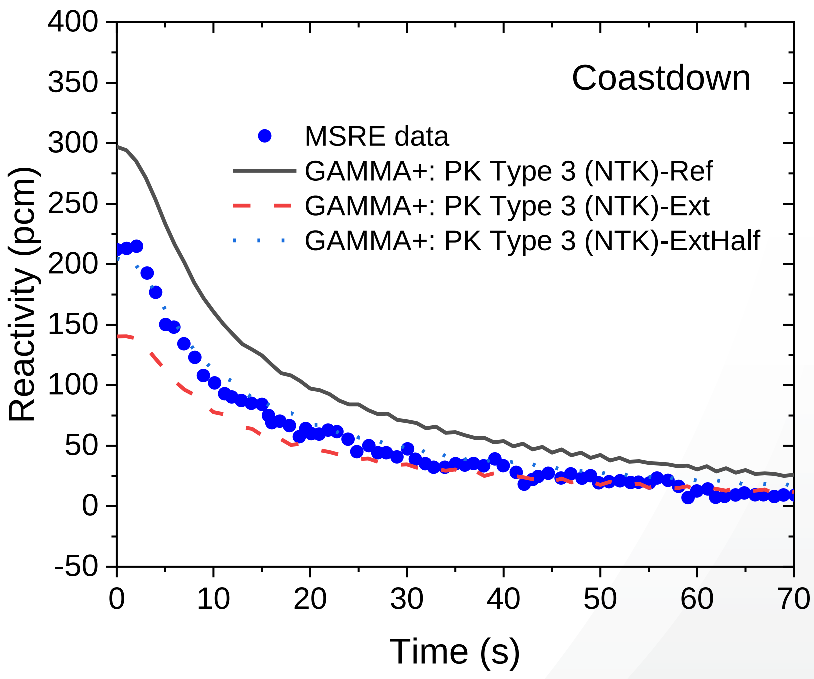
GAMMA+ Simulation Results on MSRE - Pump Startup & Coastdown -





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GAMMA+ Simulation Results on MSRE
- Reactivity Insertion Test -

Power	Period	Reactivity
1 MW	0.27 (=24.8pcm/(93pcm/s))	2.48×10^{-4}
5 MW	0.21 (=19.6pcm/(93pcm/s))	1.96×10^{-4}
8 MW	0.15 (=13.9pcm/(93pcm/s))	1.39×10^{-4}