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Fundamental Research on Molten Salt Reactors

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Outline

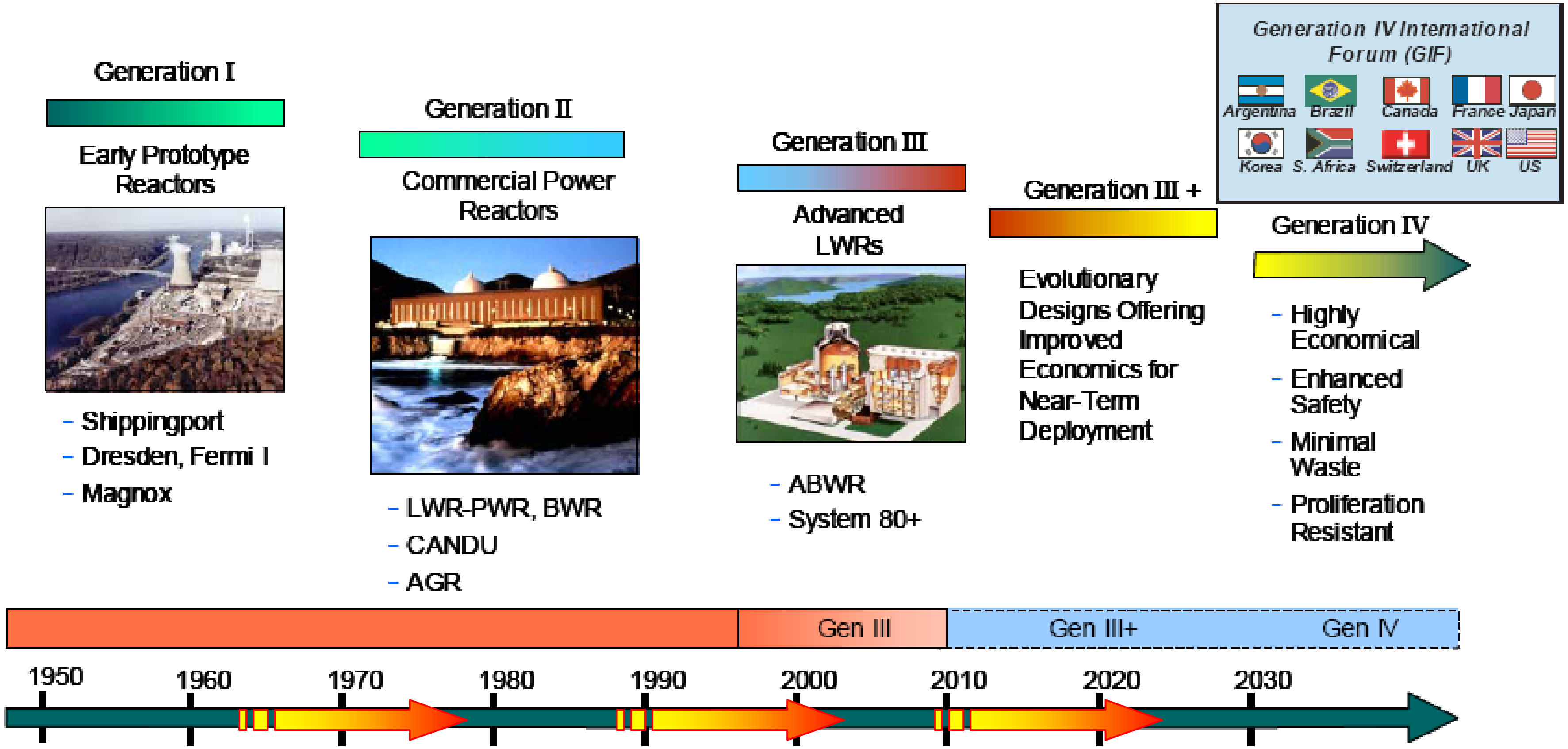
1 **Introduction**

2 **Actual work:**

- Thermophysical properties
- Neutronics
- Thermohydraulics
- Safety

3 **Concluding remarks**

Overview of the Generations of Nuclear Energy Systems



Standardization & Serialization

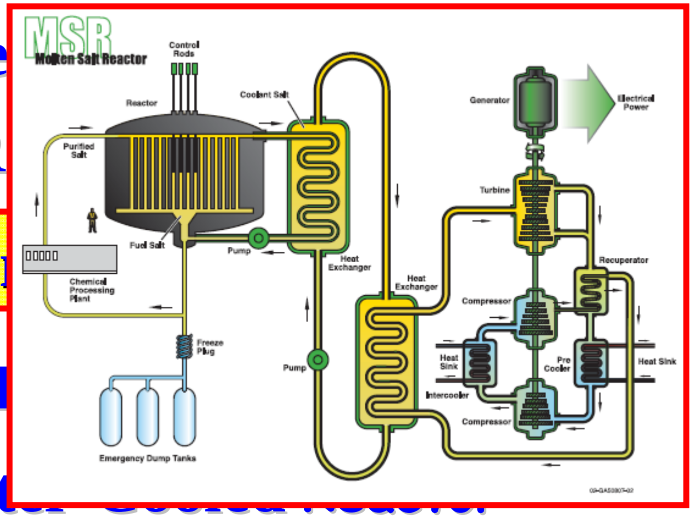
Safety

Economic & Sustainability

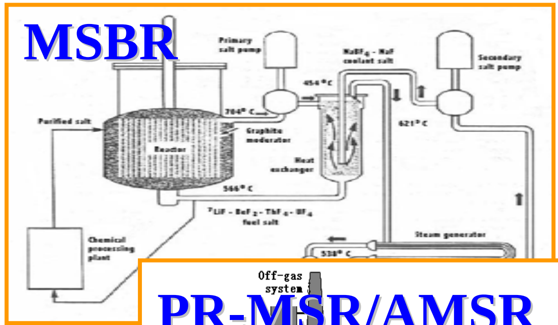
➢ Goals for Generation IV Nuclear Energy Systems and Selections

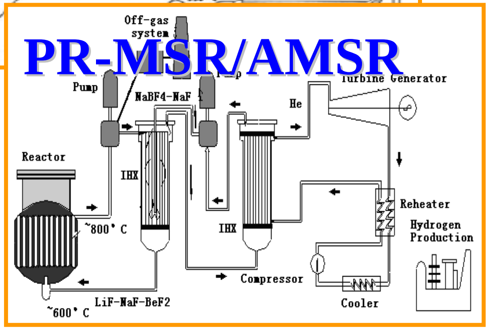
Goals
- Sustainability
- Economics
- Safety and Reliability
- Proliferation Resistance and Physical Protection

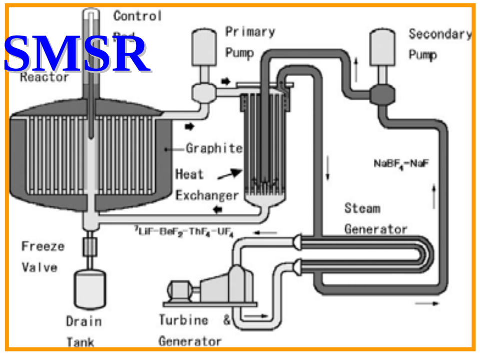
Selections
- GFR: Gas-Cooled Fast Re
- LFR: Lead-Cooled Fast R
- **MSR: Molten Salt Reactor**
- SFR: Sodium-Cooled fast
- SCWR: Supercritical-Wat
- VHTR: Very-High-Temperature Reactor

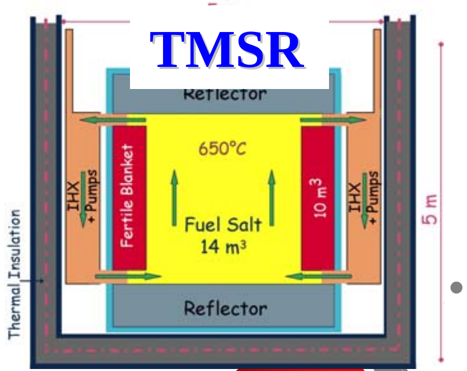


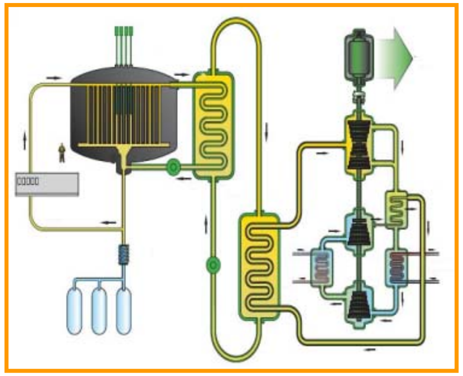
Introduction of MSR (1)

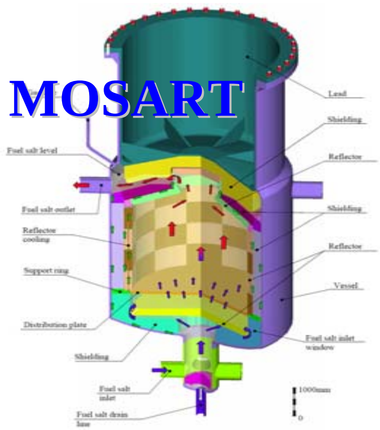












1954

ORNL: ARE, 2.5MW, for the nuclear engine of the military jet aircraft。

1960s

ORNL: MSRE, 8MW, 13000 hours。

1979

2002

GIF proposed six of generation IV r SCWR, VHTR, M LFR, GFR。

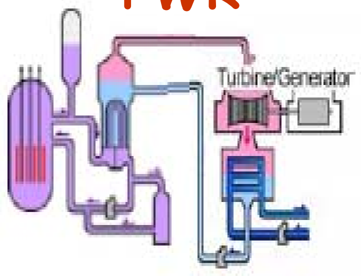
now

SMSR
MOSART
TMSR

Introduction of MSR (2)

- Liquid fuel
- Pressure < 0.5MPa
- Outflow Temperature >700^{o}C
- Brayton cycle

PWR



- Solid fuel
- Pressure: 15MPa
- Outflow T: 330^{o}C
- Rankine cycle

Advantages:

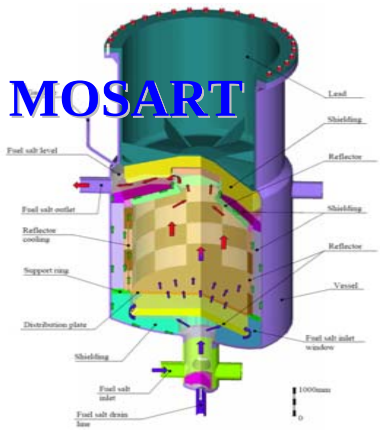
- Inherent safety feature
- Excellent neutron economy
- High thermal efficiency 45-50%
- Continuous or in-batch reprocessing
- Non-proliferation

Technology bases:

- Prototype reactors: ARE and MSRE
- Technologies for high temperature reactors:
  Brayton cycles
  Compact heat exchanges
  C-C composities

➢ Technology Gaps for MSRs

- Molten salt chemistry and control
- Solubility of minor actinides and lanthanides in the fuel
- Compatibility of irradiated molten salt fuel with structural materials
- Salt processing, separation, and reprocessing technology
- Fuel development, new cross section data
- Corrosion and embrittlement studies
- Development of tritim control technoldoy
- Graphite sealing technology and graphite stability
- Detailed conceptual design studies to develop design specifications
- ……

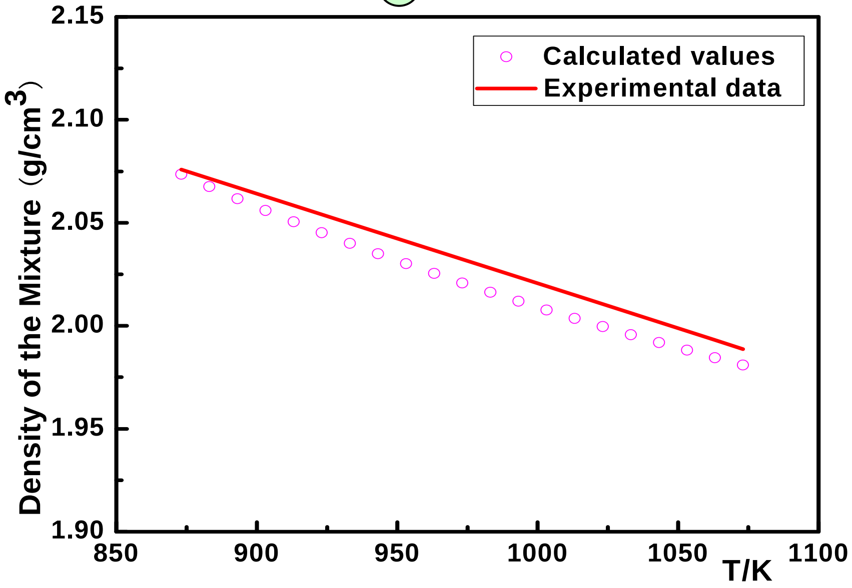


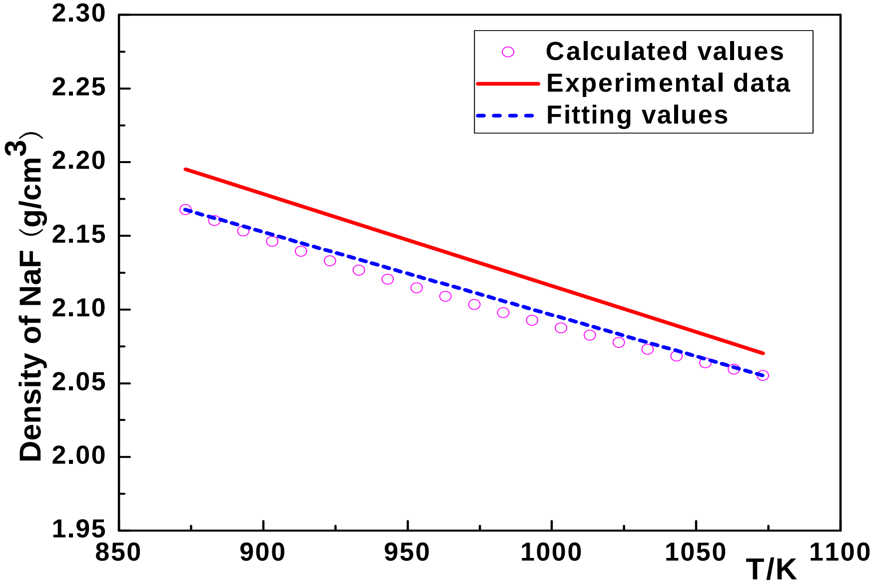
➢ Fundamental Research on MSRs

● Evaluation of static thermophysical properties

P-R Equation

$$p = \frac{RT}{v-b} - \frac{d}{v(v+b)+b(v-b)}$$





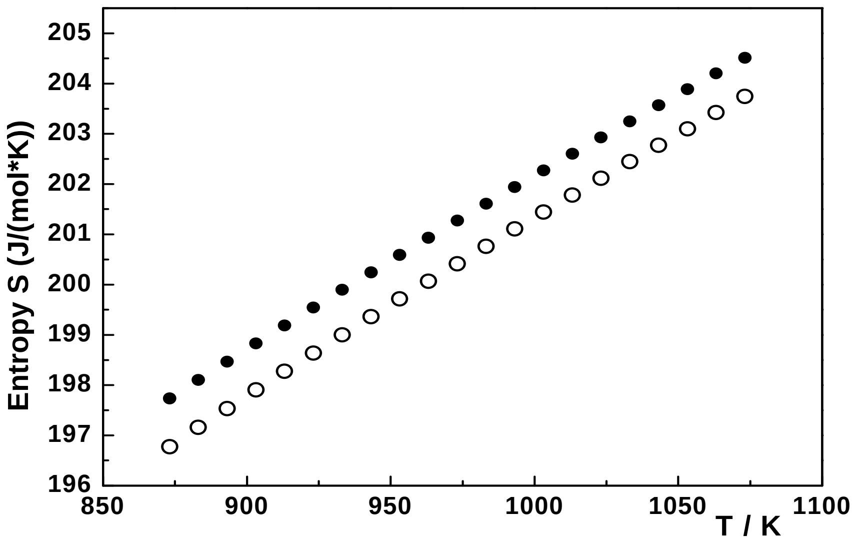
● $15LiF$-$58NaF$-$27BeF_2$ in MOSART

Fundamental Research on MSRs

- **Evaluation of static thermophysical properties**

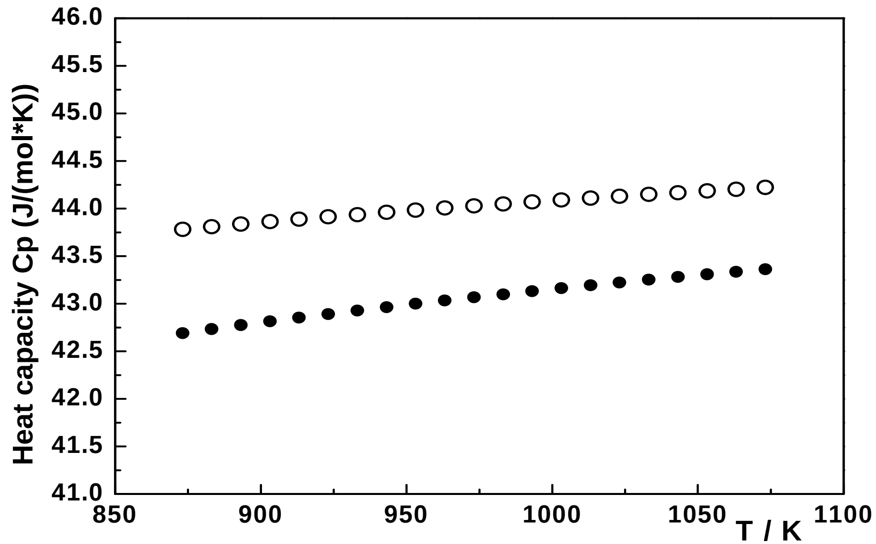
✓ **Residual function method**

$$M_r = M^*_{p,t} - M_{p,t}$$



✓ **Fugacity coefficient method**

$$d\overline{G_i} = RTd(\ln \widehat{f_i})_T$$



- **15LiF-58NaF-27BeF$_2$ in MOSART**

➢ Fundamental Research on MSRs ● Neutron physics analysis

❑ Energy-time-space dependent neutronics model

Equation for neutron flux:

$$\frac{1}{v(E)}\frac{\partial \phi(r,E,t)}{\partial t} = S(r,E,t) + \chi_p(E)\int_{E'}(1-\beta)\nu\Sigma_f(r,E')\cdot\phi(r,E',t)dE'$$

$$+\sum_{i=1}^{I}\chi_{d,i}(E)\lambda_i C_i(r,t) + \int_{E'}\Sigma_S(r,E'\rightarrow E)\phi(r,E',t)dE'$$

$$-\Sigma_t(r,E)\phi(r,E,t) + \nabla\cdot D(r,E)\nabla\phi(r,E,t) - \frac{1}{v(E)}\nabla\cdot[\mathbf{U}\phi(r,E,t)]$$

Balance equation for delayed neutron precursors:

Convective

$$\frac{\partial C_i(r,t)}{\partial t} = \beta_i\int_E \nu\Sigma_f(r,E)\cdot\phi(r,E,t)dE - \lambda_i C_i(r,t) - \nabla\cdot[\mathbf{U}C_i(r,t)]$$

Energy integration → ❑ **Multi-group diffusion model**

➢ Fundamental Research on MSRs

- **Neutron physics analysis**

$$\frac{1}{v_g}\cdot\frac{\partial\phi_g}{\partial t}+\boxed{\frac{1}{v_g}\nabla(U\phi_g)}=\nabla\cdot D_g\nabla\phi_g+\sum_{g'=1}^{g-1}\phi_{g'}\cdot\Sigma_{g'\to g}-\phi_g\cdot\Sigma_{r,g}$$

$$+\chi_{p,g}\cdot(1-\sum_{i=1}^{I}\beta_i)\cdot\sum_{g=1}^{G}(\nu\Sigma_f)_g\cdot\phi_g+\sum_{i=1}^{I}\chi_{d,g,i}\cdot\lambda_i\cdot C_i$$

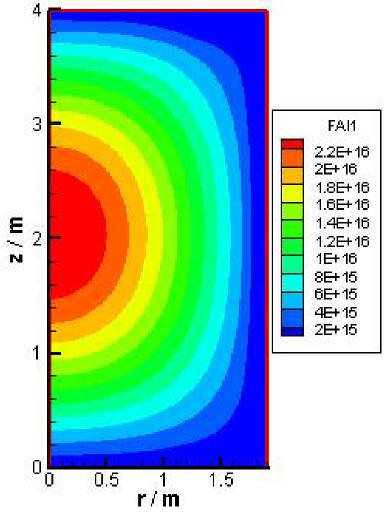
Convective

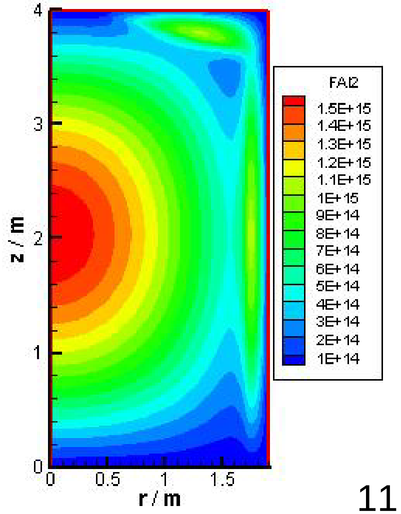
$$\frac{\partial C_i}{\partial t}+\boxed{\nabla(UC_i)}=\beta_i\cdot\sum_{g=1}^{G}\cdot(\nu\Sigma_f)_g\cdot\phi_g-\lambda_i\cdot C_i$$

- **For MOSART**

Institute	Codes	k_{eff}
BME	MCNP4C + JEFF3.1	1.00905
FZK	2D560gr. + JEFF3.0	0.99285
NRG	MCNP4C + JEFF3.1	1.00887
Polito	2D4 gr. + JEFF3.1	0.99595
RRC-KI	MCNP4B+ENDF5,6	0.99791
SCK-CEN	MCNPX250	1.00904
XJTU	NPAC-XJTU	0.99994

❑ **Neutron fluxes**

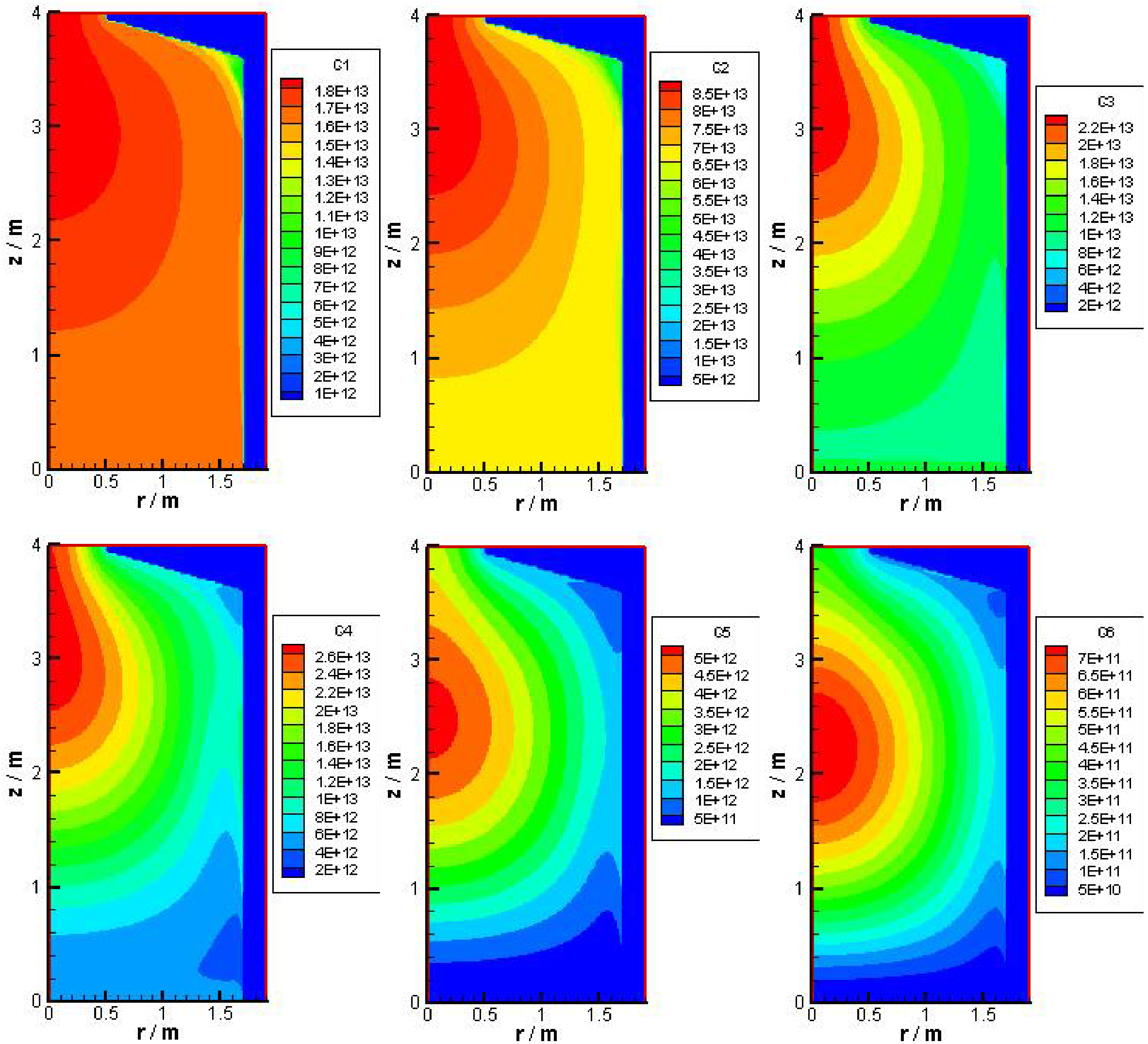




➢ Fundamental Research on MSRs

● Neutron physics analysis

❑ Delayed neutron precursors



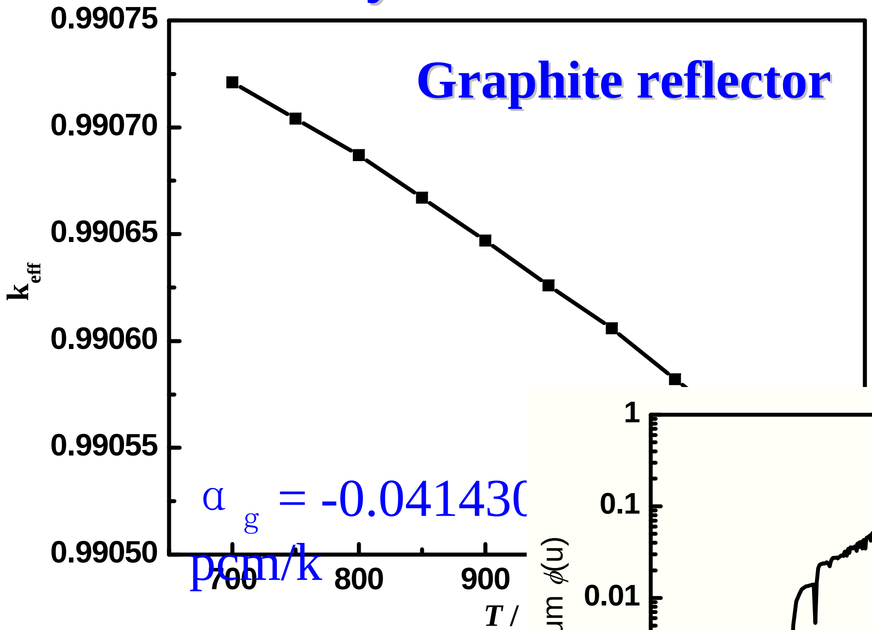
DNPs distribution show

- ✧ **Drift downsteam with the flow;**
- ✧ **The larger the decay constant, the greater the flow effects。**

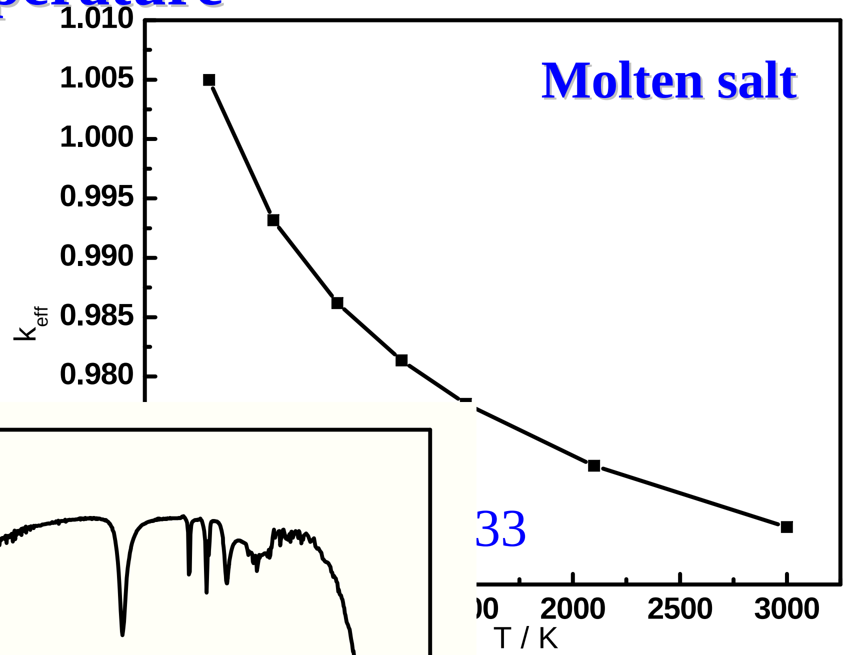
Fundamental Research on MSRs

● **Neutron physics analysis**

Reactivity coefficient of temperature



α g = -0.041430
pcm/k



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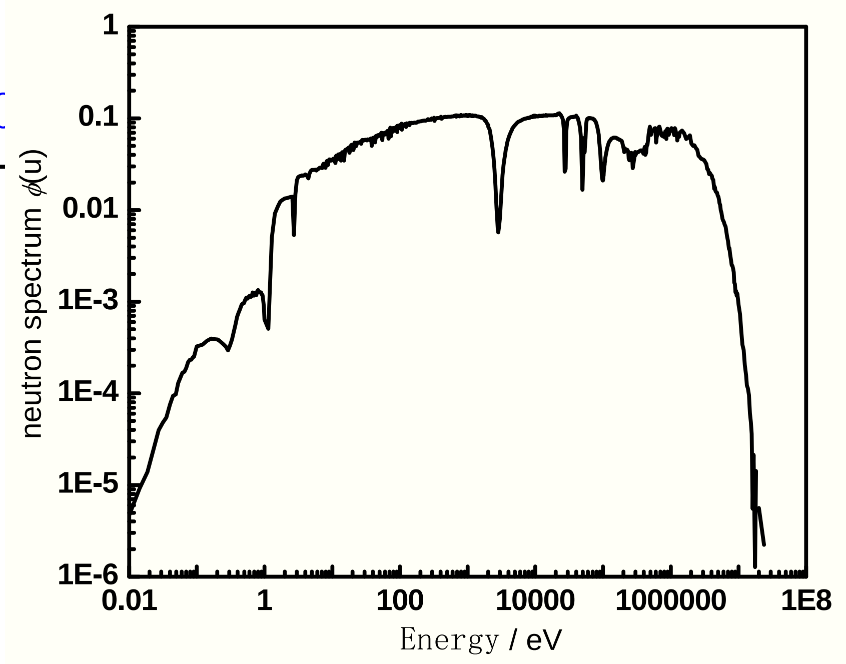
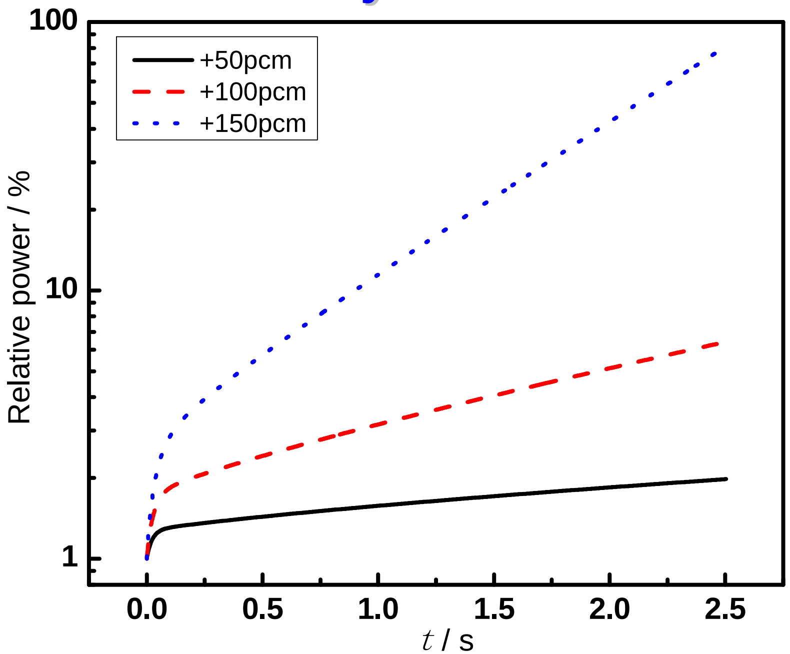


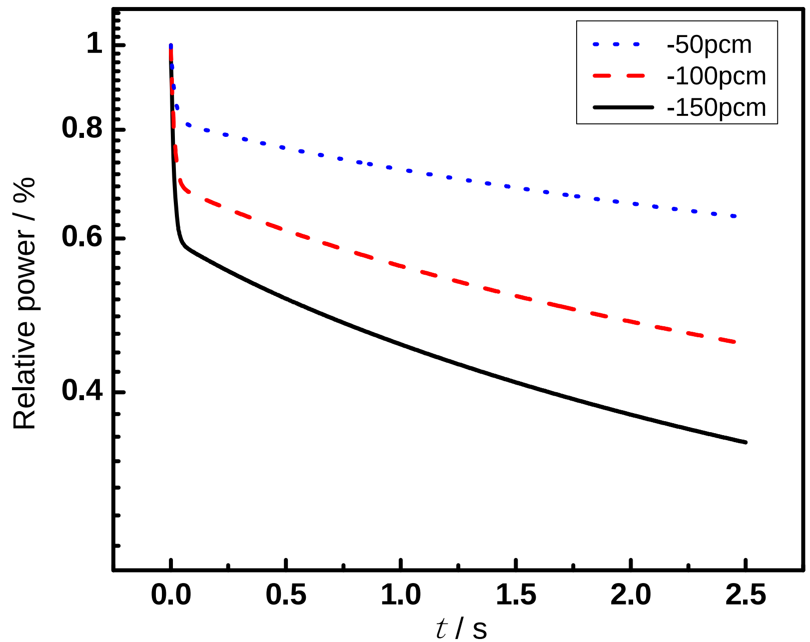
Fundamental Research on MSRs

Neutron physics analysis

Reactivity increase



Reactivity decrease



The relative power increases (decreases) greatly in short time at beginning, then changes with a certain speed.

The larger the reactivity changes, the greater the initial power generates and the faster the changing speed is.

➢ Fundamental Research on MSRs ● Thermal hydraulic analysis

✓ **ORNL: there was no decisive difference between water and molten fluorides from the flow and heat transfer viewpoint .**

❑ **Computational Fluid Dynamic (CFD) method**

$$\frac{\partial \rho u_z}{\partial z} + \frac{1}{r}\frac{\partial r \rho u_r}{\partial r} = 0$$

$$\frac{\partial(\rho u_z \cdot u_z)}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r \cdot u_z) = \frac{\partial}{\partial z}((\eta+\eta_t)\frac{\partial u_z}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}((\eta+\eta_t)r\frac{\partial u_z}{\partial r}) + S_{u_z}$$

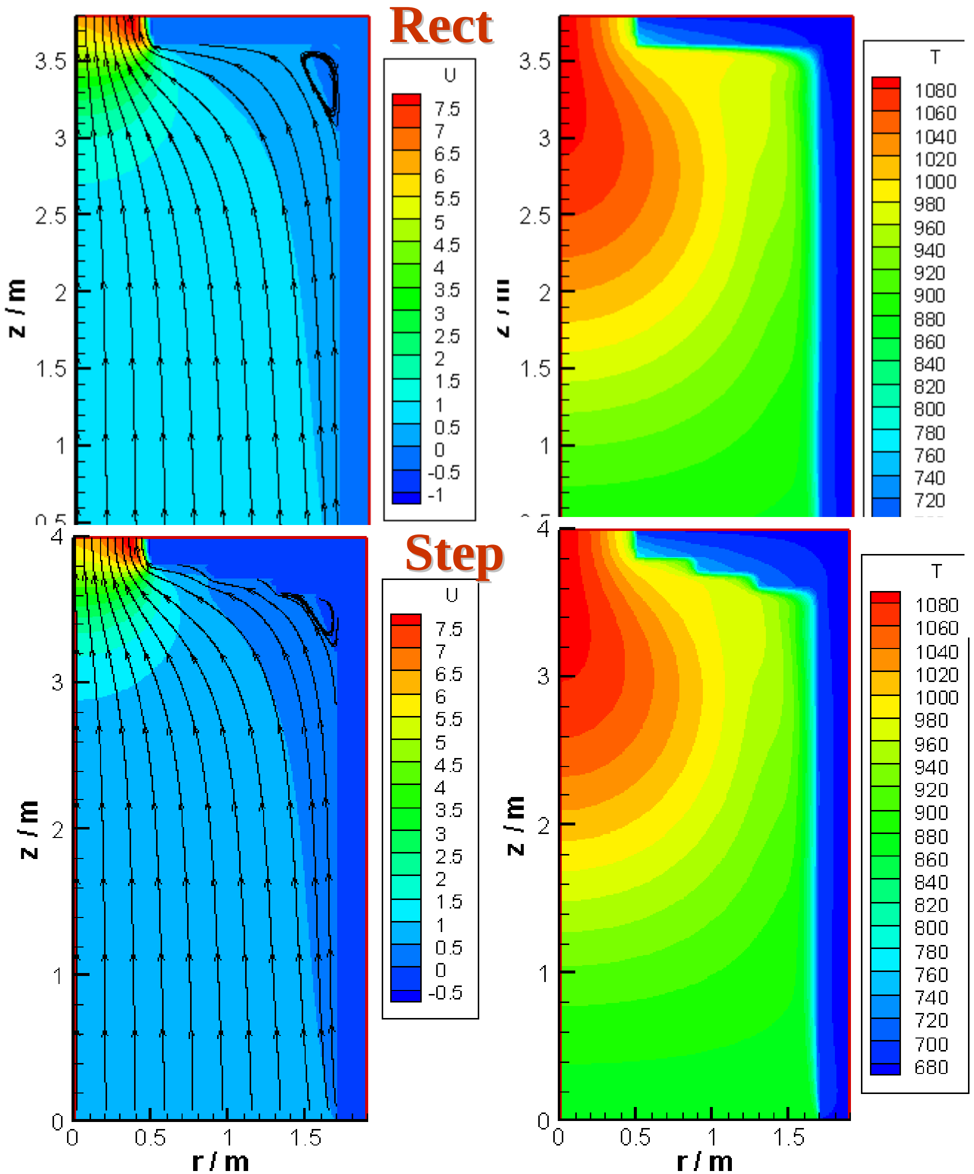
$$\frac{\partial(\rho u_z \cdot u_r)}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r \cdot u_r) = \frac{\partial}{\partial z}((\eta+\eta_t)\frac{\partial u_r}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}((\eta+\eta_t)r\frac{\partial u_r}{\partial r}) + S_{u_r}$$

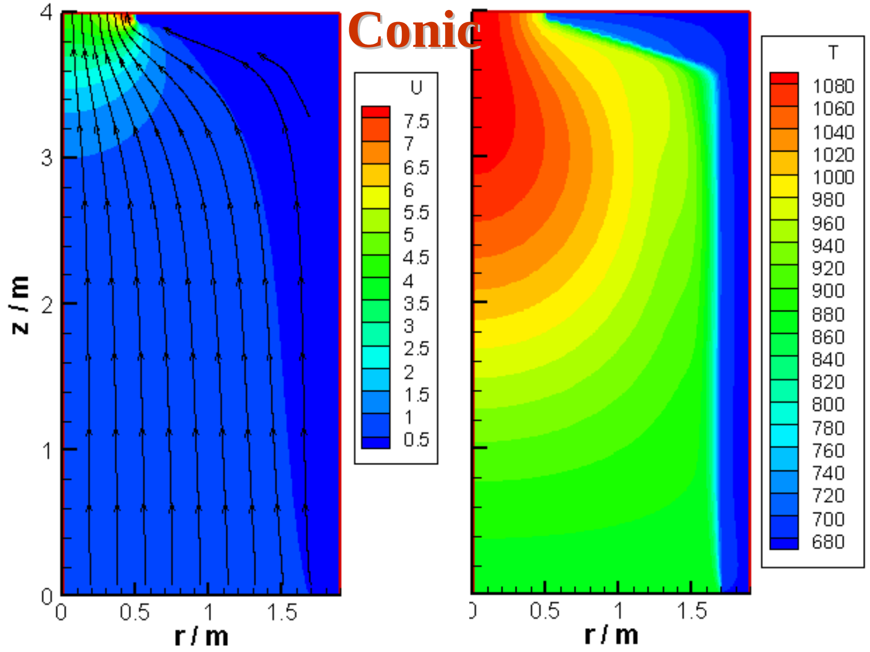
$$\frac{\partial(\rho u_z \cdot k)}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r \cdot k) = \frac{\partial}{\partial z}((\eta+\frac{\eta_t}{\sigma_k})\frac{\partial k}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}((\eta+\frac{\eta_t}{\sigma_k})r\frac{\partial k}{\partial r}) + S_k$$

$$\frac{\partial(\rho u_z \cdot \varepsilon)}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r \cdot \varepsilon) = \frac{\partial}{\partial z}((\eta+\frac{\eta_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}((\eta+\frac{\eta_t}{\sigma_\varepsilon})r\frac{\partial \varepsilon}{\partial r}) + S_\varepsilon$$

➢ Fundamental Research on MSRs

● Thermal hydraulic analysis





● **Conic design satisfy:**

-Avoid reverse or stagnant flow

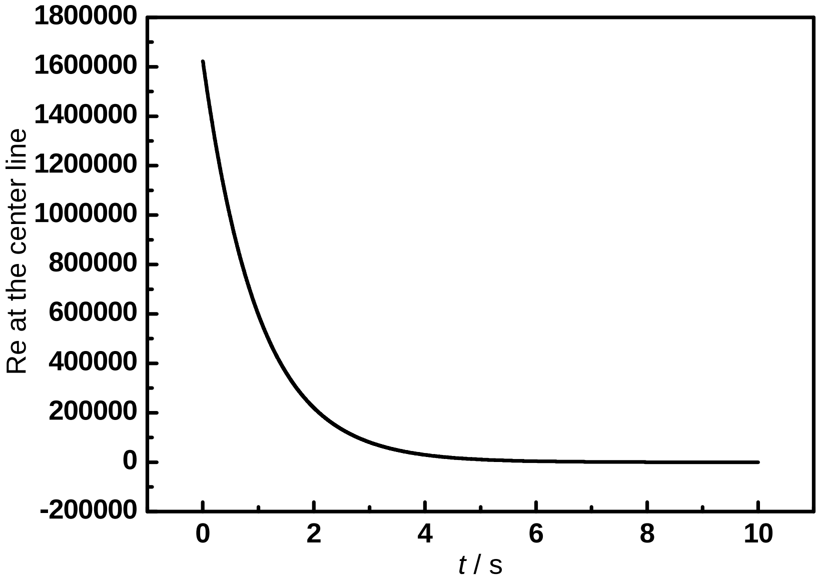
-Maximum temperature is low enough

Fundamental Research on MSRs

Thermal hydraulic analysis

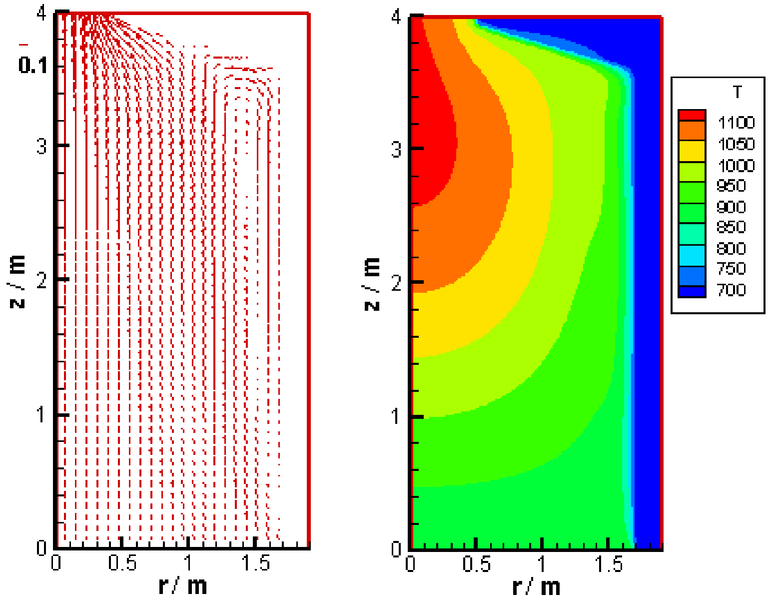
Flow decreases:

$$u_{in}(t) = u_{in}(0)e^{-\tau_{pump}\cdot t}$$

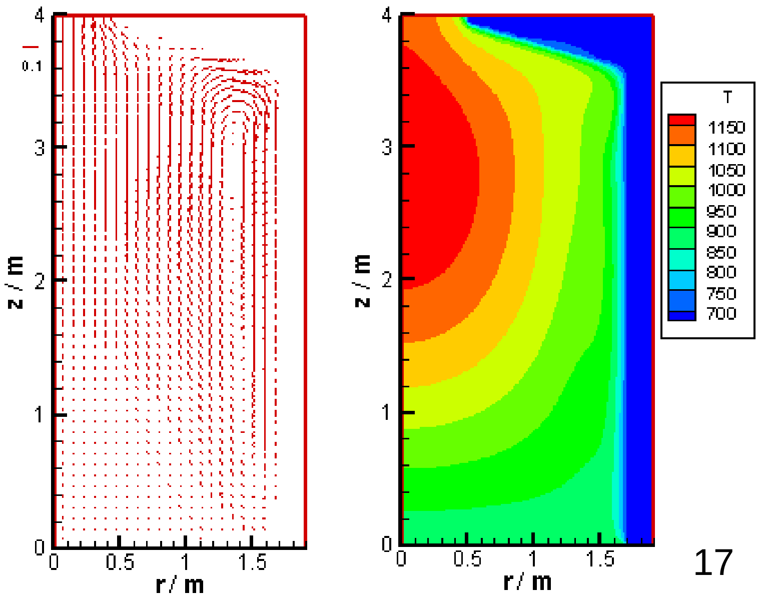


Re decreases exponentially, similar with the inlet velocity.

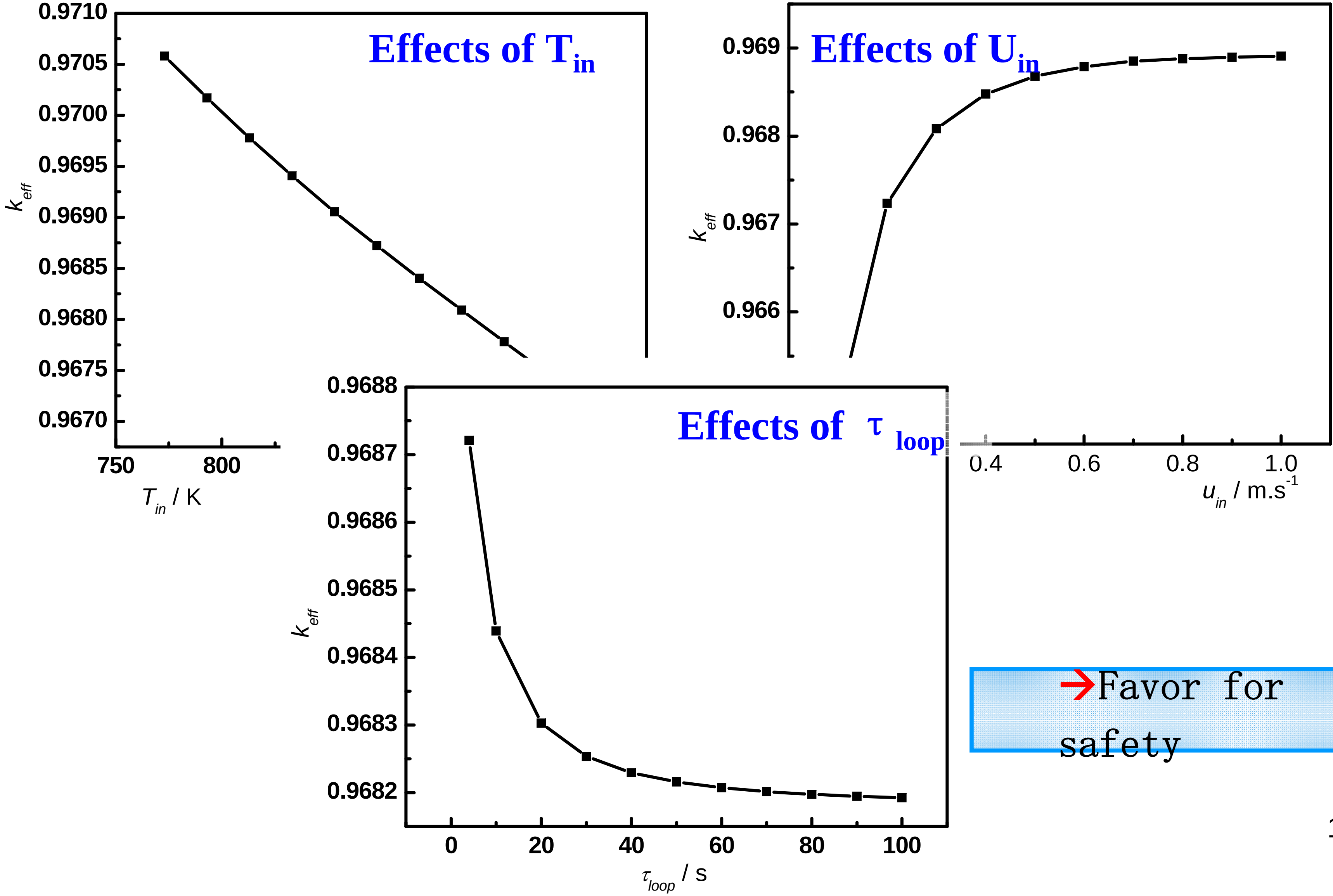
t=2s:



t=4s:



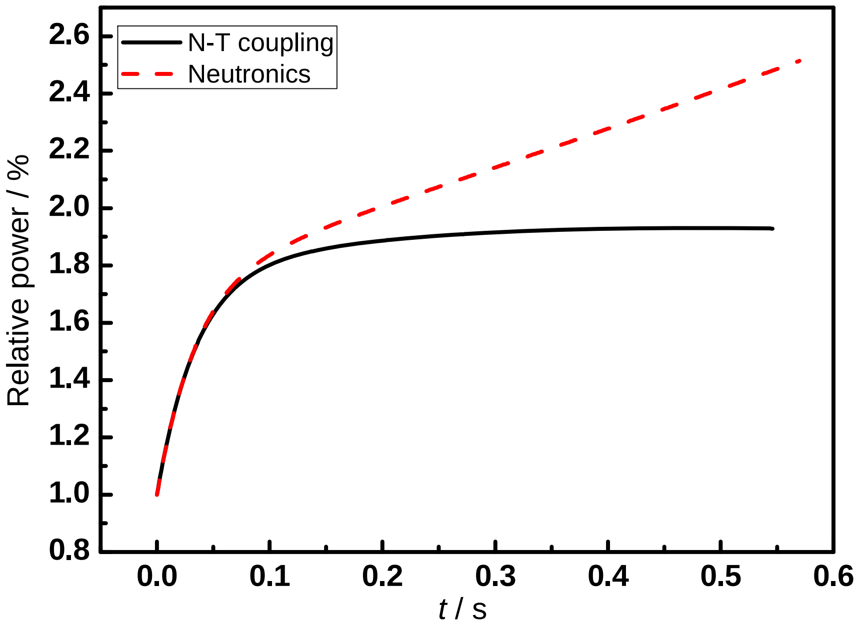
➢ Fundamental Research on MSRs ● N-T coupling: steady



→Favor for safety

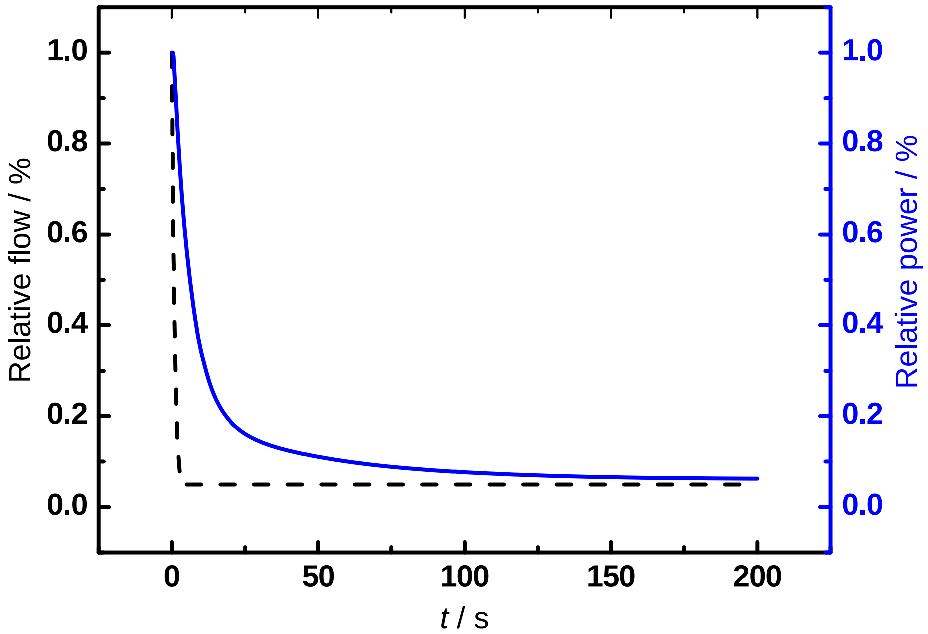
➢ Fundamental Research on MSRs ● N-T coupling: transient

□ Reactivity increases 100pcm:



Power increases suddenly, then slowly reaches a steady power.

□ Flow mass decreases:



Power decreases quickly with the flow, and slowly reaches the power matching with the flow

➢ **Fundamental Research on MSRs** ● **Safety analysis**

❑ Exact point kinetic model:

Based on the energy-time-space dependent neutronics model, using perturbation theory

$$\frac{dp_r(t)}{dt} = \frac{\rho(t) - \tilde{\beta}(t)}{\Lambda(t)} p_r(t) + \sum_{i=1} \lambda_i c_i(t)$$

$$\frac{d}{dt} c_i(t) = -\lambda_i c_i(t) + \frac{\tilde{\beta}_i}{\Lambda(t)} p_r(t) - \frac{(W, \chi_{di}(E) \nabla \cdot [\vec{U} C_i(r,t)])}{K_0}$$

$$\frac{\partial C_i(r,t)}{\partial t} + \nabla \cdot [\mathbf{U} C_i(r,t)] = -\lambda_i C_i(r,t) + \beta_i \mathbf{F} \phi(r,E,t)$$

where: $\tilde{\beta}_i = \frac{(W, \chi_{di}(E) \lambda_i C_i(r,t))}{\mathrm{Y}}$ **（Effective fraction of DNPs）**

W : **Weighted function**

➢ Fundamental Research on MSRs

- **Neutron physics analysis**

✓ **Effective fraction of delayed neutron**

- only considering the neutron importance disregarding the importance of delayed neutron

$$\nabla \cdot D_g \nabla \phi_g^* + \sum_{n=1, n\neq g}^{G} \Sigma_{g\rightarrow n}\phi_n^* - \Sigma_{r,g}\phi_g^* + (1-\beta)(\nu\Sigma_f)_g \sum_{n=1}^{G} \chi_{p,n}\phi_n^* = 0$$

$$\tilde{\beta}_i = \frac{(\phi^*, \beta_i \chi_{di}(E) F\phi)}{(\phi^*, \chi(E) F\phi)}$$

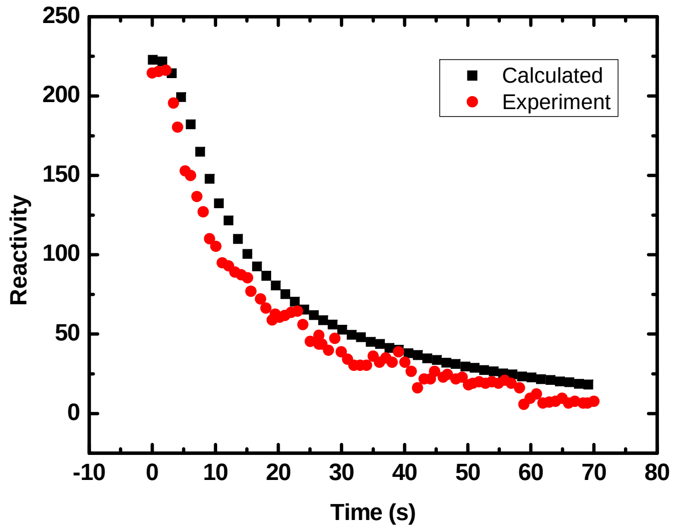
- **For MOSART**

Velocity	$\Delta\rho$ [pcm]	β_1 [pcm]	β_2 [pcm]	β_3 [pcm]	β_4 [pcm]	β_5 [pcm]	β_6 [pcm]	β_{eff} [pcm]	β_{loss} [pcm]	$\beta_{loss} / \beta_{eff,static}$
Static	0.0	7.8	77.2	54.9	118.1	61.0	20.8	339.8	0.0	0.0 %
Flate	-115.2	3.7	37.3	28.9	78.4	56.4	20.5	225.2	114.6	33.7%
Parabolic	-131.8	3.6	36.4	27.1	69.3	53.0	20.1	209.5	130.3	38.4%
RRC-KI	-143.4	2.8	29.4	24.1	68.5	53.1	19.9	197.8	142.0	41.8%
XJTU	-127.0	3.6	36.3	27.5	70.5	53.5	20.1	211.5	128.3	37.8%

Fundamental Research on MSRs

✓ Modified point model ($W = 1$)

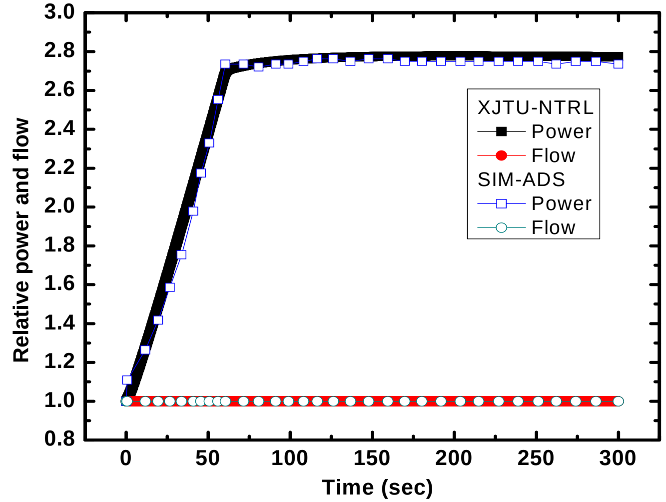
$$\begin{cases} \frac{dn(t)}{dt} = \frac{(\rho(t) - \tilde{\beta}_{eff})}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i c_{c,i} \\ \frac{dc_{c,i}}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i c_{c,i} + c_{l,i} \frac{1}{\tau_l} (\frac{V_l}{V_c}) - c_{c,i} \frac{1}{\tau_c} \\ \frac{dc_{l,i}}{dt} = -\lambda_i c_{l,i} + c_{c,i} \frac{1}{\tau_c} (\frac{V_c}{V_l}) - c_{l,i} \frac{1}{\tau_l} \end{cases}$$

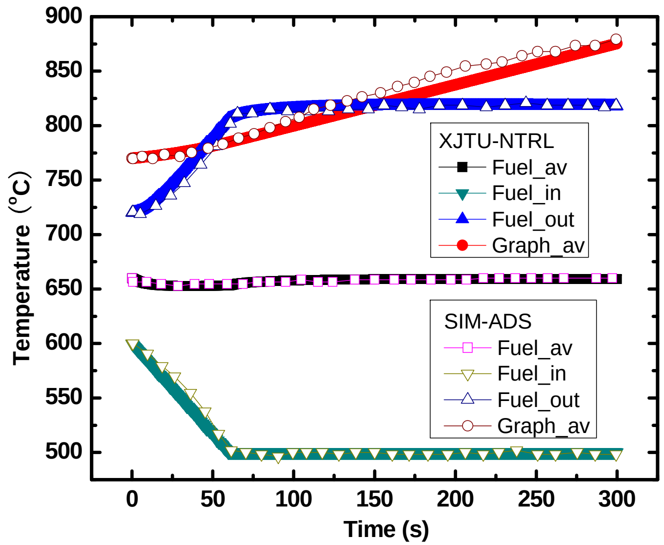


MSRE:coastdown

MOSART: UOC

● Safety analysis





Fundamental Research on MSRs

● Safety analysis

✓ Comparison of modeling options for delayed neutron precursor movement in molten salt reactors

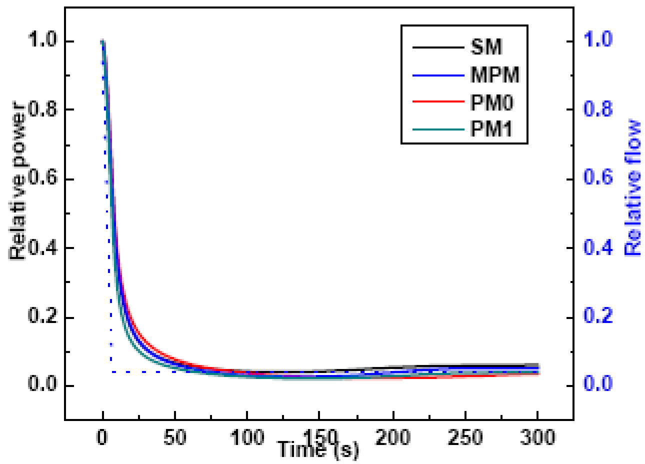
●

SM

$$\frac{dc_i(t)}{dt} = -\lambda_i c_i(t) + \frac{\beta_i}{\Lambda(t)} n(t)$$

$$\frac{\partial C_i(r,t)}{\partial t} + \nabla \cdot [\vec{U} C_i(r,t)] = -\lambda_i C_i(r,t) - \frac{(W, \chi_{di}(E)\nabla \cdot [\vec{U} C_i(r,t)])}{K_0} + \beta_i F \phi n(t)$$

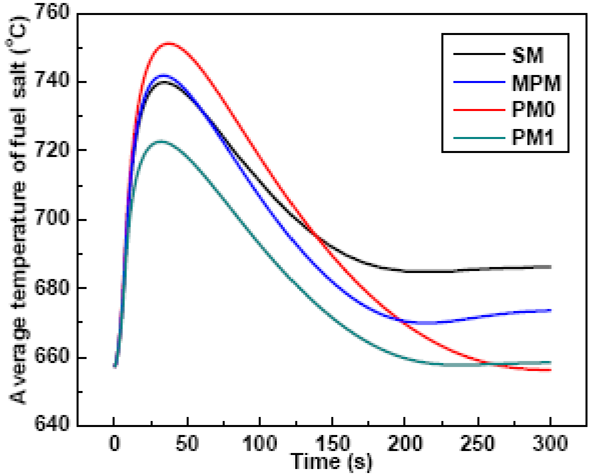
MOSART: ULOF

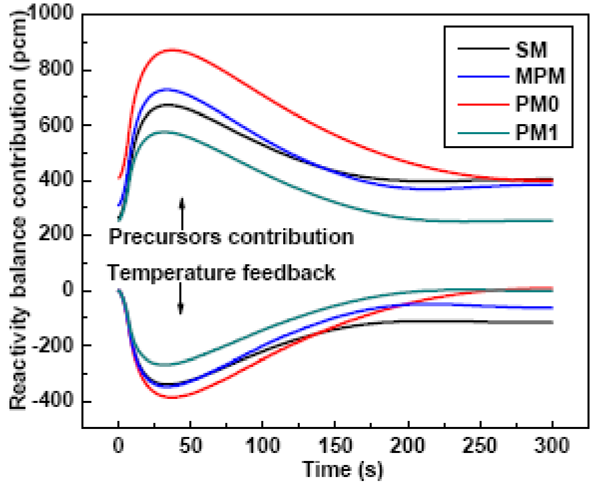


SM: spatial model

MPM: modified point model

PM: point model





➢ Conclusion Remarks

- **We studied the static thermophysical properties, neutron physics, thermal hydraulics, N-T coupling and safety characteristics by founding theoretical models and designing micro-computer codes.**

- **The established models are applied to MOSART, the results of which demonstrate the validation of the models.**

- **MOSART is a promising reactor with inherent safety (negative temperature coefficient, flow effects…).**