Evaluation of Delayed Neutron Fraction in TRU-loaded Molten Salt Reactor

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Introduction (1/2)

Molten-salt reactor (MSR)

- Reactor that uses molten salt as fuel and coolant
- No severe accident / Strong negative feedback
- One of the most promising reactors of Gen IV

Oak Ridge National Laboratory (ORNL) MSR

- Thermal neutron
- It needs to online fuel reprocessing → Hard to commercialize due to proliferation issue
- Graphite moderator → Large amount of radioactive waste

→ Molten Salt Fast Reactor can overcome aforementioned adversities

Molten-salt fast reactor

- Exclusion of graphite moderator → Less radioactive waste / more simple structure
- High conversion ratio → High fuel economy from high burnup

Introduction (2/2)

Change of reactor parameters by fuel circulation

– Delayed neutron fraction (β)

- $$\beta_g = \frac{\iiint\limits_{\text{In core}} \nu_{d,g}\Sigma_f(\vec{r},E)\phi(\vec{r},E,\vec{\Omega})dVdEd\vec{\Omega}}{\iiint\limits_{\text{In core}} \nu\Sigma_f(\vec{r},E)\phi(\vec{r},E,\vec{\Omega})dVdEd\vec{\Omega}}$$
- Providing longer reactor period / offering criterion for desirable reactor control

– Delayed neutron fraction (β) loss due to fuel circulation

- Delayed neutrons emitted in inactive core region are deserted without being used for fission
- Demanding more precise reactivity control → may incur safety concerns

– Reactivity loss due to fuel circulation

- Analogous to the case of delayed neutron fraction

Objectives

– Analyzing MSR using Monte Carlo based core analysis code

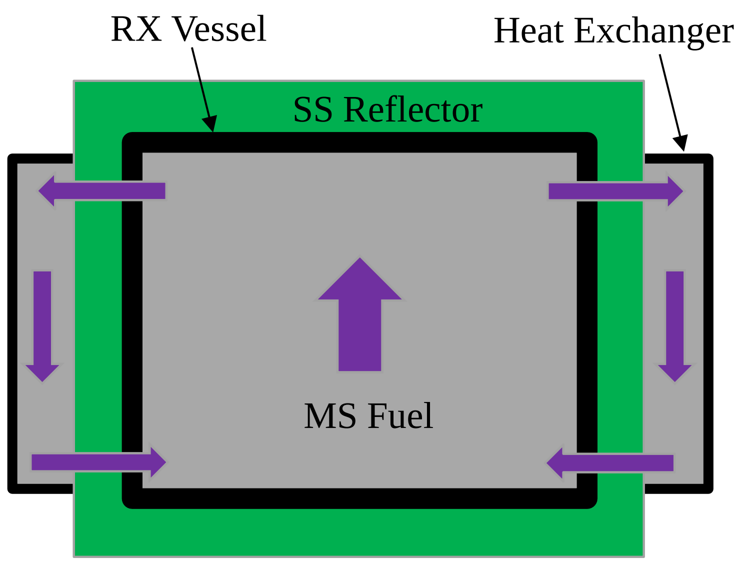
– Observing change of reactor parameters due to fuel circulation

– Sensitivity analyses of reactor parameters with respect to salt composition & circulation

Description of the Simplified MSR Core (1/4)

Reactor model

- For simplification, cylindrical core is modelled
- Reflector for neutron economy
- Inactive core (heat exchanger) at outside of reflector
  - Connected to active core → fuel circulation



Dimension and composition of materials

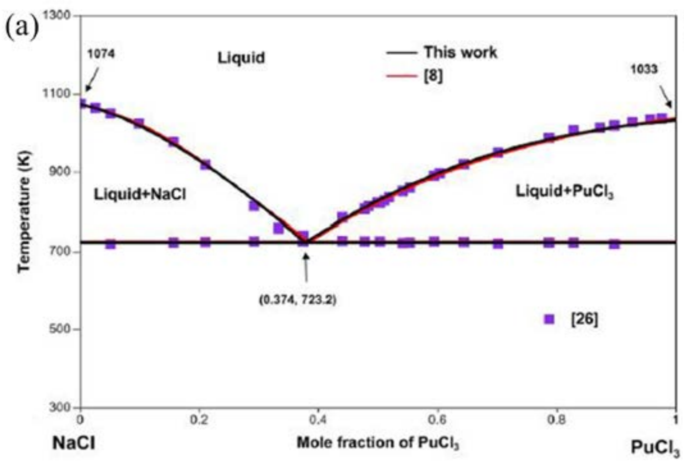
- Reactor vessel
  - Material: Hastelloy-N (Nickel based alloy)
  - Thickness: 10 cm
- Reflector
  - Material: Stainless steel
  - Thickness: 40 cm
- Fuel salt in core
  - Three candidates: $NaCl$-$TRUCl_3$, KCl-$TRUCl_3$, $NaCl$-$MgCl_2$-$TRUCl_3$

Description of the Simplified MSR Core (2/4)

Compositions of fuel salts

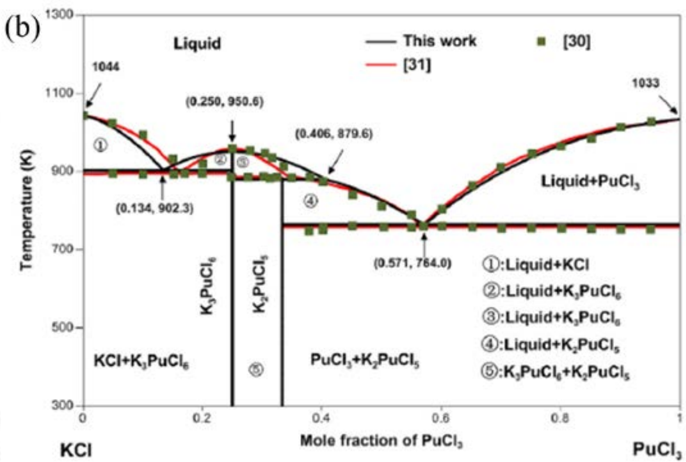
- Eutectic points of these three salts for liquid state
- Phase diagram of $PuCl_3$ have been used for $TRUCl_3$ (Differentiation have been made for TRU)
  - Melting points of all three salts lie below 500℃

NaCl-$PuCl_3$



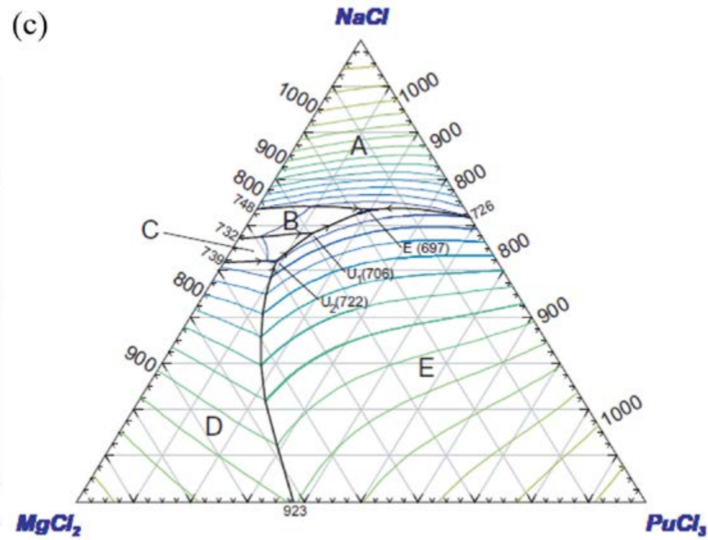
NaCl-$TRUCl_3$:
(62%, 38% in a/o)

KCl-$PuCl_3$



KCl-$TRUCl_3$:
(43%, 57% in a/o)

NaCl-$MgCl_2$-$TRUCl_3$



NaCl-$MgCl_2$-$TRUCl_3$:
(62%, 18%, 20% in a/o)

TRU composition vector

– Actual TRU

Element	Mass ratio
U	20.18
TRU	70.95
RE	8.87

Element	Mass ratio	Element	Mass ratio	Element	Mass ratio
U	20.177	Bk	3.04E-11	Nd	4.562
Ac	7.27E-10	Cf	1.36E-07	Pm	0.010
Th	5.25E-05	Yb	7.00E-07	Gd	0.184
Pa	4.20E-06	Lu	2.29E-20	Tb	0.003
Np	4.350	Y	0.011	Dy	0.002
Pu	60.583	La	0.588	Ho	1.06E-04
Am	5.513	Ce	2.309	Er	4.08E-05
Cm	0.508	Pr	1.200	Tm	3.32E-07

Conventional TRU composition from spent nuclear fuel

– Pure TRU

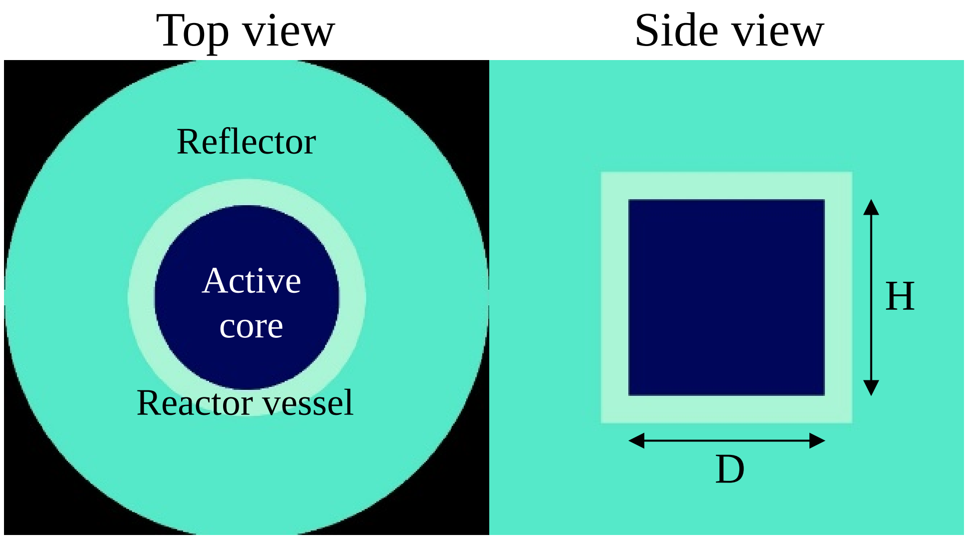
Element	Mass ratio
TRU	100.00

Element	Mass ratio	Element	Mass ratio	Element	Mass ratio
Ac	1.02E-09	Np	6.131	Cm	0.716
Th	7.40E-05	Pu	85.383	Bk	4.28E-11
Pa	5.92E-06	Am	7.770	Cf	1.92E-07

Actual TRU and pure TRU both will be used for core analysis

Simplified cylindrical MSR core

- Square cylinder model (H / D = 1.0)
  - Moderately minimizes the reactor volume
- Excluded inactive core for simple analysis



Numerical calculation for core dimension

Fuel	Actual TRU		Pure TRU	
	D [cm]	k_{eff} (± SD [pcm])	D [cm]	k_{eff} (± SD [pcm])
62NaCl-38TRUCl_3	70	1.07804 (± 20)	50	1.07006 (± 21)
43KCl-57TRUCl_3	62	1.09866 (± 23)	42	1.04250 (± 23)
62NaCl-18MgCl_2 -20TRUCl_3	110	1.04445 (± 21)	80	1.06828 (± 20)

High composition of TRU results in small size of reactor

KAIST iMC

– Monte Carlo based neutron transport and reactor analysis code
– It can analyze change of reactor properties during flowing fuel
– Sample number
  - History number: 50,000
  - Inactive cycle number: 50
  - Active cycle number: 200

Recirculation time according to fuel speed

– Fuel flows from bottom to top with constant speed (V_{fuel})
– Fuel departing from the core comes back after some time elapsed (T_c: recirculation time)

V_{fuel} [cm/s]	0	5	7.5	10	15
T_c [s]	-	30	20	15	10

No differentiation of travel length through inactive core

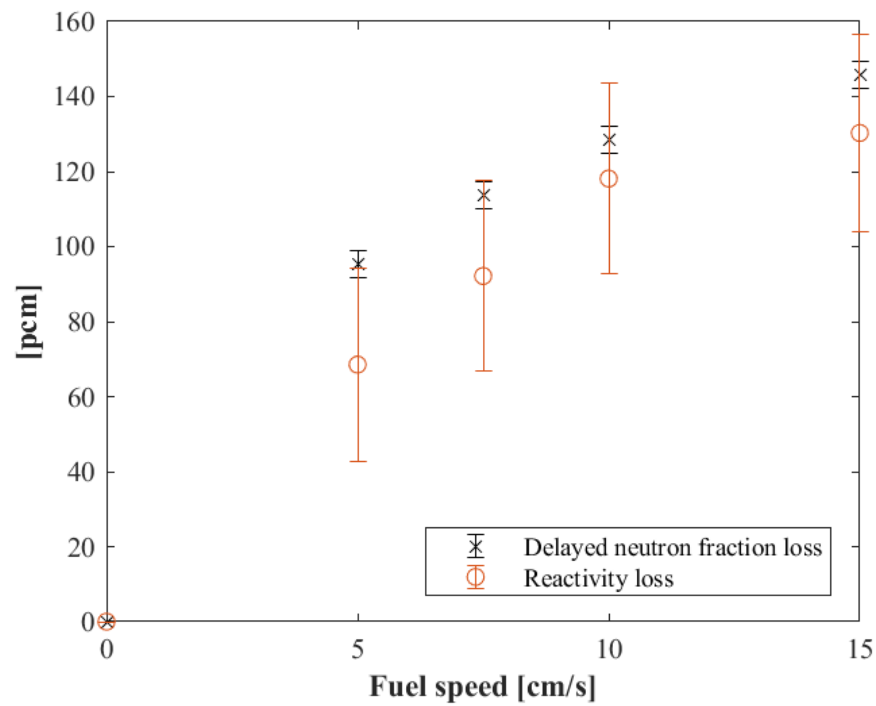
Numerical Results (2/8)

Delayed neutron fraction loss and reactivity loss using actual TRU

– $62NaCl\text{-}38TRUCl_3$ (Actual TRU)

- Diameter: 70 cm
- Multiplication factor: 1.07804 (±20 pcm)
- Delayed neutron fraction with stationary fuel: 296 (±3 pcm)

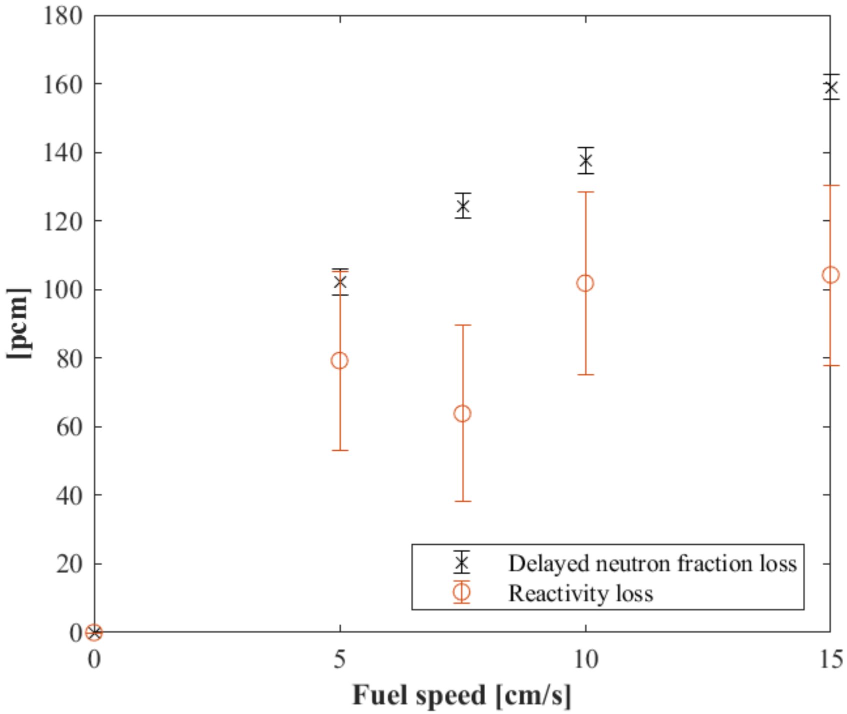
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	95 (±4)	69 (±26)
7.5	114 (±4)	92 (±25)
10	128 (±4)	118 (±25)
15	146 (±4)	130 (±26)



Delayed neutron fraction loss and reactivity loss using actual TRU

– 43KCl-57TRUCl_3 (Actual TRU)
  - Diameter: 62 cm
  - Multiplication factor: 1.09866 (±23 pcm)
  - Delayed neutron fraction with stationary fuel: 298 (±3 pcm)

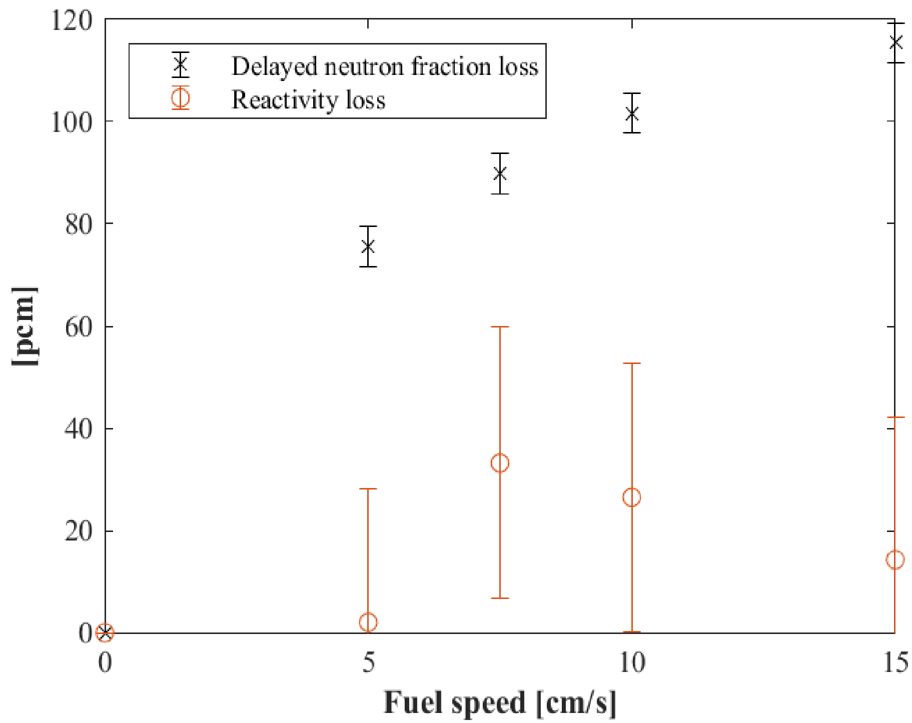
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	102 (±3)	79 (±25)
7.5	124 (±3)	64 (±26)
10	138 (±4)	102 (±27)
15	159 (±3)	104 (±26)



Delayed neutron fraction loss and reactivity loss using actual TRU

– 62NaCl-18$MgCl_2$-20$TRUCl_3$ (Actual TRU)
  - Diameter: 110 cm
  - Multiplication factor: 1.04445 (±21 pcm)
  - Delayed neutron fraction with stationary fuel: 300 (±3 pcm)

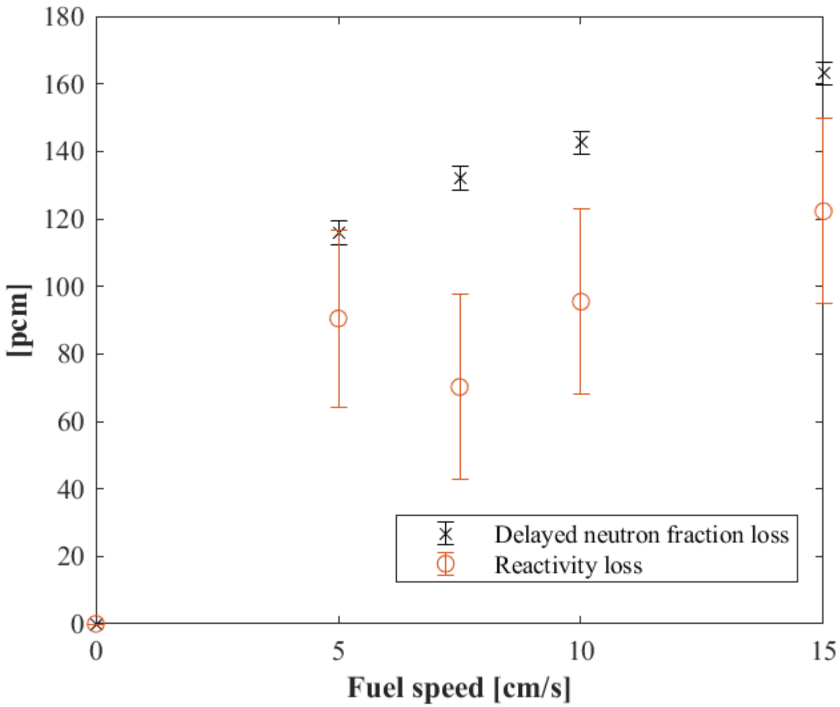
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	76 (±4)	2 (±26)
7.5	90 (±4)	33 (±27)
10	102 (±4)	26 (±26)
15	115 (±4)	14 (±28)



Delayed neutron fraction loss and reactivity loss using pure TRU

– 62NaCl-38TRUCl_3 (Pure TRU)
  - Diameter: 50 cm
  - Multiplication factor: 1.07006 (±21 pcm)
  - Delayed neutron fraction with stationary fuel: 274 (±3 pcm)

V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	116 (±4)	90 (±26)
7.5	132 (±4)	70 (±27)
10	143 (±3)	95 (±27)
15	163 (±3)	122 (±27)

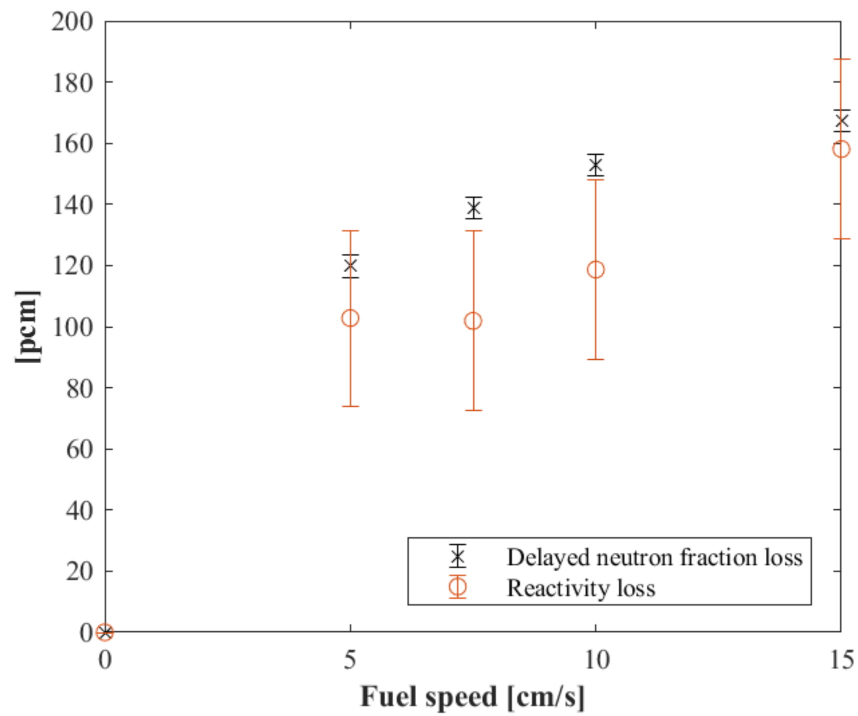


Numerical Results (6/8)

Delayed neutron fraction loss and reactivity loss using pure TRU

– $43KCl\text{-}57TRUCl_3$ (Pure TRU)
  - Diameter: 42 cm
  - Multiplication factor: 1.04250 (±23 pcm)
  - Delayed neutron fraction with stationary fuel: 270 (±3 pcm)

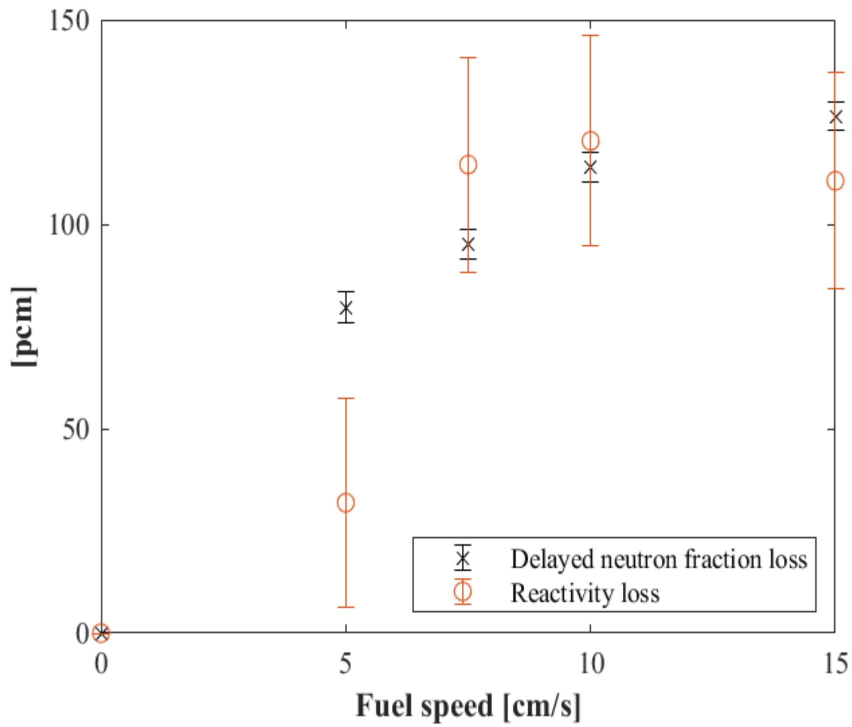
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	120 (±4)	103 (±29)
7.5	139 (±4)	102 (±29)
10	153 (±3)	119 (±29)
15	167 (±3)	158 (±29)



Delayed neutron fraction loss and reactivity loss using pure TRU

– 62NaCl-18$MgCl_2$-20$TRUCl_3$ (Pure TRU)
  - Diameter: 80 cm
  - Multiplication factor: 1.06828 (±20 pcm)
  - Delayed neutron fraction with stationary fuel: 272 (±3 pcm)

V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]
0	-	-
5	80 (±4)	32 (±25)
7.5	95 (±4)	115 (±26)
10	114 (±4)	120 (±26)
15	126 (±3)	111 (±27)



Delayed neutron fraction loss and reactivity loss

– Actual TRU

	$62NaCl\text{-}38TRUCl_3$		$43KCl\text{-}57TRUCl_3$		$62NaCl\text{-}18MgCl_2\text{-}20TRUCl_3$	
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]	β loss [pcm]	ρ loss [pcm]	β loss [pcm]	ρ loss [pcm]
0	-	-	-	-	-	-
5	95 (±4)	69 (±26)	102 (±3)	79 (±25)	76 (±4)	2 (±26)
7.5	114 (±4)	92 (±25)	124 (±3)	64 (±26)	90 (±4)	33 (±27)
10	128 (±4)	118 (±25)	138 (±4)	102 (±27)	102 (±4)	26 (±26)
15	146 (±4)	130 (±26)	159 (±3)	104 (±26)	115 (±4)	14 (±28)

– Pure TRU

	$62NaCl\text{-}38TRUCl_3$		$43KCl\text{-}57TRUCl_3$		$62NaCl\text{-}18MgCl_2\text{-}20TRUCl_3$	
V_{fuel} [cm/s]	β loss [pcm]	ρ loss [pcm]	β loss [pcm]	ρ loss [pcm]	β loss [pcm]	ρ loss [pcm]
0	-	-	-	-	-	-
5	116 (±4)	90 (±26)	120 (±4)	103 (±29)	80 (±4)	32 (±25)
7.5	132 (±4)	70 (±27)	139 (±4)	102 (±29)	95 (±4)	115 (±26)
10	143 (±3)	95 (±27)	153 (±3)	119 (±29)	114 (±4)	120 (±26)
15	163 (±3)	122 (±27)	167 (±3)	158 (±29)	126 (±3)	111 (±27)

Summary and Conclusions

1. Fuel flow results in delayed neutron fraction loss and reactivity loss

2. Factors affecting attributes of the reactor

- Fuel circulation speed:
  - Faster the fuel circulation goes → more loss of delayed neutron fraction and reactivity
- Composition of fuel salt:
  - Higher Pu concentration → the smaller reactor size → longer residence time in inactive core → more loss of delayed neutron fraction and reactivity

3. Meticulous measures must be taken for selecting fuel salt and its circulation speed

Thank you for your attention.

Any question?