A Study on Breakeven Feasibility in Molten Salt Fast Reactors

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Introduction (1/3)

Molten Salt Reactor (MSR)

- Reactor which consists of molten salt where the fuel acts as both fuel and coolant
- The dissolved (liquid) fuel circulates between the active core ↔ heat exchanger
- Superior inherent safety features:
  - No severe accident, No hydrogen explosion, Operation under atmospheric pressure
  - Strong negative feedback originating from thermal expansion of fuel salt

Critical drawbacks of MSRE like technologies

- Thermal spectrum MSR, which demands usage of moderator (additional waste)
- The MSRE utilized graphite moderator (material integrity deteriorated due to radiation)
- Usage of Li-F fuel salt results in production of H-3 & Proliferation issue due to online fuel reprocessing

Advanced MSR design often exploits fast spectrum (MSFR: Molten Salt Fast Reactor)

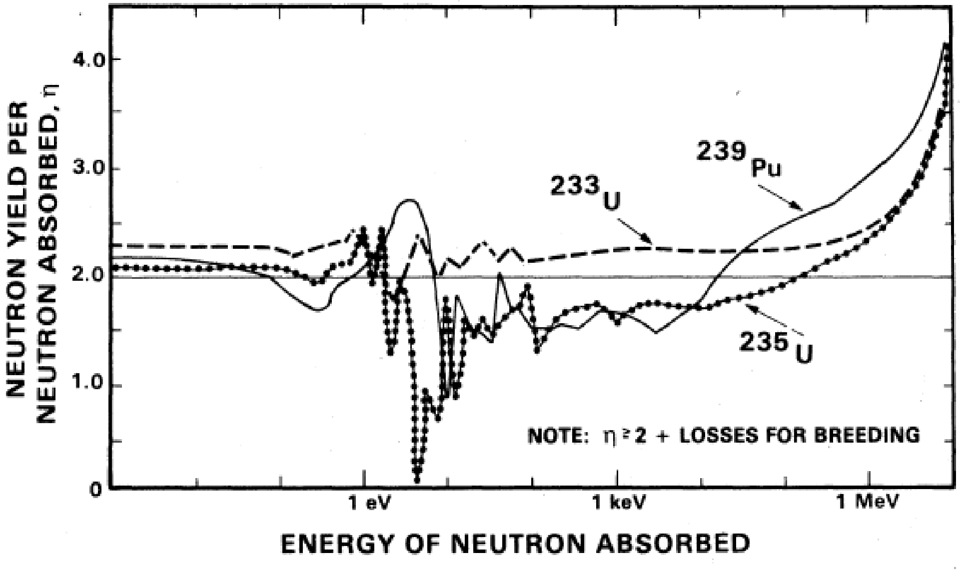
- MCRE (INL; US), MCFR (TerraPower; US), SSR (Moltex; UK), PMFR (KOR), …

Molten Salt Fast Reactor is being desired guideline for development of MSR to improve economy and safety.

Introduction (2/3)

Breakeven concept

- Equilibrium between the loss and gain of fissile material (Conversion ratio ≥ 1.0)
- Usage of LEU-based molten salt fuel cannot guarantee sufficient conversion ratio for breakeven



Potential of plutonium

- Pu-239 has relatively high eta value
- Instead of U-235, Pu-239 is included to achieve initial criticality & higher conversion ratio
- Pu can be replaced by extracted TRU from spent fuel
  - Currently, there is 19,500 tons of spent fuel in Korea
  - Amount that can be utilized about 300 years solely powering electricity in Korea via nuclear

구분	TRU (U+Pu+MA) (kg / 다발)	총 다발 수	총 TRU 질량 (kg)
경수로	456.8	21,829	9,971,393
중수로	19.08	497,068	9,483,214
합계	-	-	19,454,526

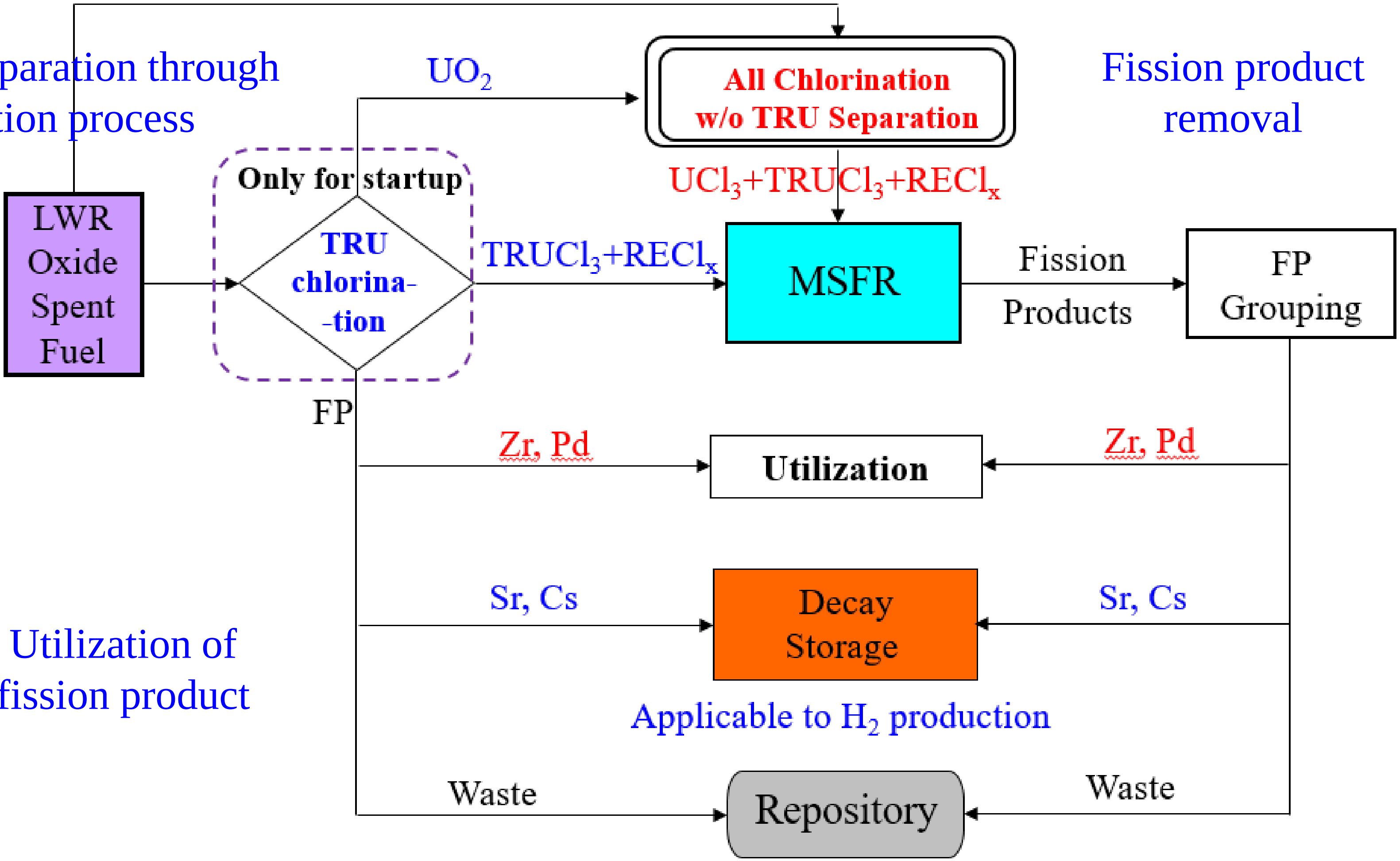
To achieve breakeven, TRU-U-based molten salt can be utilized.

Introduction (3/3)

Objectives

TRU + RE separation through chlorination process

Fission product removal



All Chlorination w/o TRU Separation

UO_2

UCl_3+$TRUCl_3$+$RECl_x$

LWR Oxide Spent Fuel

Only for startup

TRU chlorina--tion

$TRUCl_3$+$RECl_x$

MSFR

Fission Products

FP Grouping

FP

Zr, Pd

Utilization

Zr, Pd

Sr, Cs

Decay Storage

Sr, Cs

Applicable to H_2 production

Waste

Repository

Waste

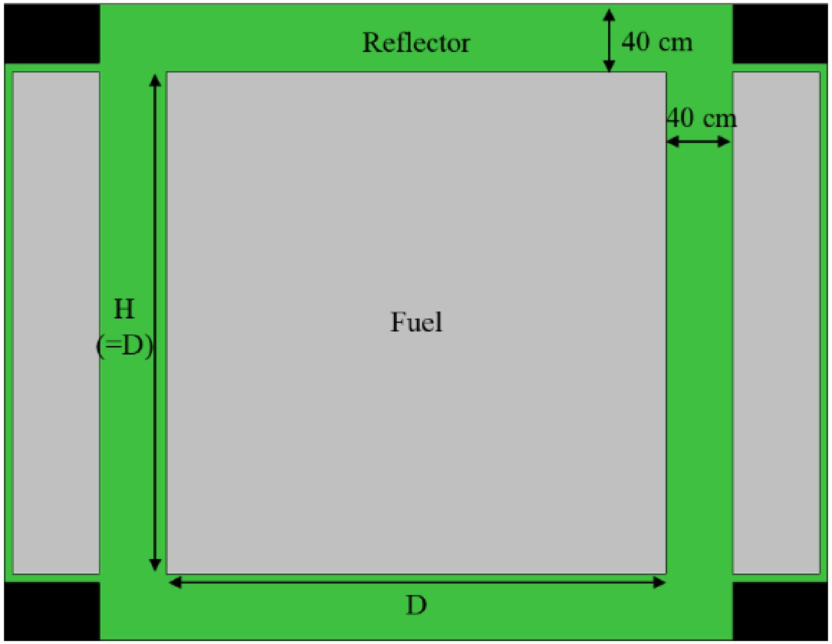
Utilization of fission product

In this study, the feasibility of breakeven using MSFR will be examined.

Description of Core and Fuels (1/4)

Reactor Layout

- Cylindrical geometry
- Reflector: stainless steel, 40cm
- Diameter = Height
  - 200cm, 300cm, 400cm
- Inner surface of reflector:
  - 0.1 cm Hastelloy-N is coated
- Volume of active core = volume of inactive core
- Operating temperature: 650°C



Candidates of Fuels

- $KCl\text{-}TRUCl_3\text{-}UCl_3$
- $NaCl\text{-}KCl\text{-}TRUCl_3\text{-}UCl_3$
- $NaF\text{-}KF\text{-}TRUF_4\text{-}UF_4$

Eutectic properties of LEU-based molten salt fuel

	Molar composition	Melting temperature	Uranium Density*
$KCl\text{-}UCl_3$	46-54	558°C	2.179 g/cm^3
$NaCl\text{-}KCl\text{-}UCl_3$	42.9-20.3-36.8	470°C	1.740 g/cm^3
$NaF\text{-}KF\text{-}UF_4$	45.0-22.2-32.8	535°C	2.600 g/cm^3

* Corresponding temperature is the same as operating temperature. (650°C)

Description of Core and Fuels (2/4)

TRU composition

- Pure TRU (Plutonium + Minor Actinides)

Element	Weight fraction	Element	Weight fraction	Element	Weight fraction
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	7.77	Cf	1.92E-07

- Actual TRU (Plutonium + Minor Actinides + Rare Earths)

Element	Weight fraction	Element	Weight fraction	Element	Weight fraction
Ac	9.11E-10	Cf	1.7E-07	Pm	0.013
Th	6.58E-05	Yb	8.77E-07	Gd	0.231
Pa	5.26E-06	Lu	2.87E-20	Tb	0.004
Np	5.450	Y	0.014	Dy	0.003
Pu	75.896	La	0.737	Ho	1.33E-04
Am	6.907	Ce	2.893	Er	5.11E-05
Cm	0.636	Pr	1.503	Tm	4.16E-07
Bk	3.81E-11	Nd	5.715		

Description of Core and Fuels (3/4)

Properties about pure TRU-based fuel

		KCl-$TRUCl_3$-UCl_3	NaCl-KCl-$TRUCl_3$-UCl_3	NaF-KF-$TRUF_4$-UF_4
H = D = 200 cm	Molar composition	46.0-9.8-44.2	42.9-20.3-8.2-28.6	45.0-22.2-8.0-24.8
	U mass	22446 kg	17008 kg	24701 kg
	Pu + MA mass	5013 kg	4912 kg	8025 kg
	Initial k	1.00087 ± 0.00013	1.00681 ± 0.00013	1.00685 ± 0.00009
H = D = 300 cm	Molar composition	46.0-7.6-46.4	42.9-20.3-6.3-30.5	45.0-22.2-7.3-25.5
	U mass	79598 kg	61270 kg	85811 kg
	Pu + MA mass	13132 kg	12747 kg	24741 kg
	Initial k	1.00209 ± 0.00012	1.00314 ± 0.00012	1.00588 ± 0.00007
H = D = 400 cm	Molar composition	46.0-6.6-47.4	42.9-20.3-5.5-31.3	45.0-22.2-7.0-25.8
	U mass	192680 kg	148995 kg	205675 kg
	Pu + MA mass	27023 kg	26369 kg	56203 kg
	Initial k	1.00544 ± 0.00012	1.00112 ± 0.00011	1.00351 ± 0.00007

Fuel composition is based on the eutectic composition of uranium-based molten salts.
Sum of TRU and U is fixed and the fractions of them are adjusted to achieve criticality.

Description of Core and Fuels (4/4)

Properties about RE-included TRU-based fuel

		$KCl-TRUCl_3-UCl_3$	$NaCl-KCl-TRUCl_3-UCl_3$	$NaF-KF-TRUF_4-UF_4$
H = D = 200 cm	Molar composition	46.0-12.0-42.0	42.9-20.3-9.9-26.9	45.0-22.2-9.6-23.2
	U mass	21327 kg	15999 kg	23106 kg
	Pu + MA mass	5073 kg	4903 kg	7961 kg
	Initial k	1.00794 ± 0.00013	1.00599 ± 0.00013	1.00328 ± 0.00009
H = D = 300 cm	Molar composition	46.0-9.2-44.8	42.9-20.3-7.6-29.2	45.0-22.2-8.8-24.0
	U mass	76848 kg	58657 kg	80751 kg
	Pu + MA mass	13140 kg	12712 kg	24652 kg
	Initial k	1.00357 ± 0.00012	1.00323 ± 0.00012	1.00398 ± 0.00007
H = D = 400 cm	Molar composition	46.0-8.1-45.9	42.9-20.3-6.7-30.1	45.0-22.2-8.5-24.3
	U mass	186565 kg	143280 kg	193745 kg
	Pu + MA mass	27413 kg	26555 kg	56427 kg
	Initial k	1.00665 ± 0.00011	1.00658 ± 0.00011	1.00524 ± 0.00007

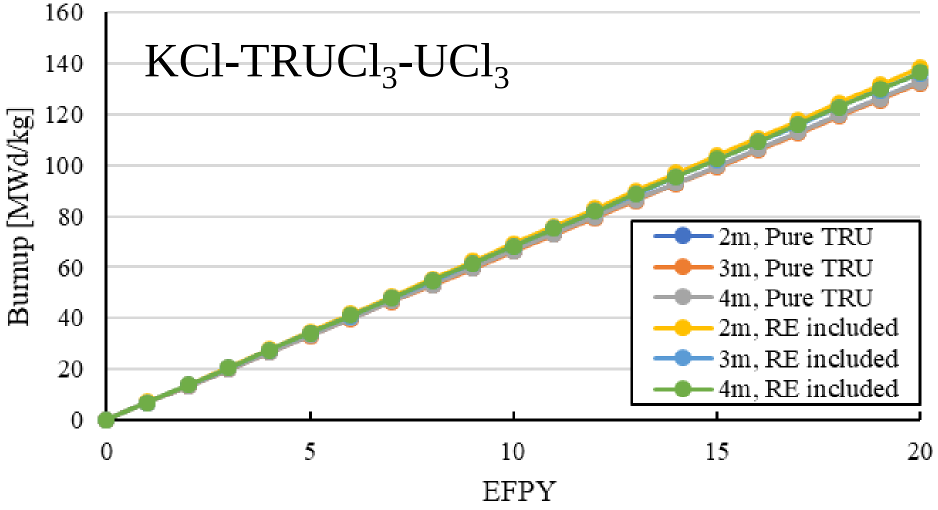
Fuel composition is based on the eutectic composition of uranium-based molten salts.
Sum of TRU and U is fixed and the fractions of them are adjusted to achieve criticality.

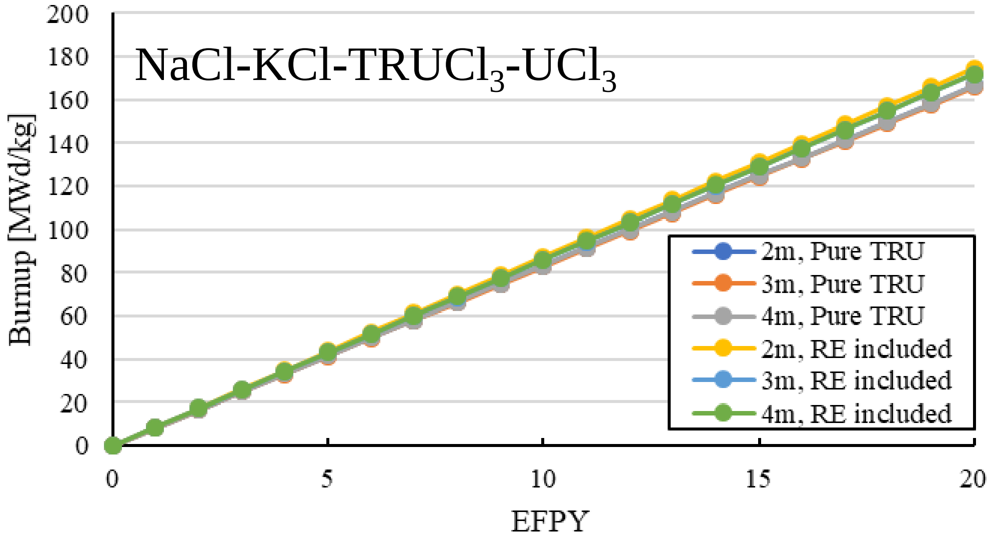
Numerical Results (1/6)

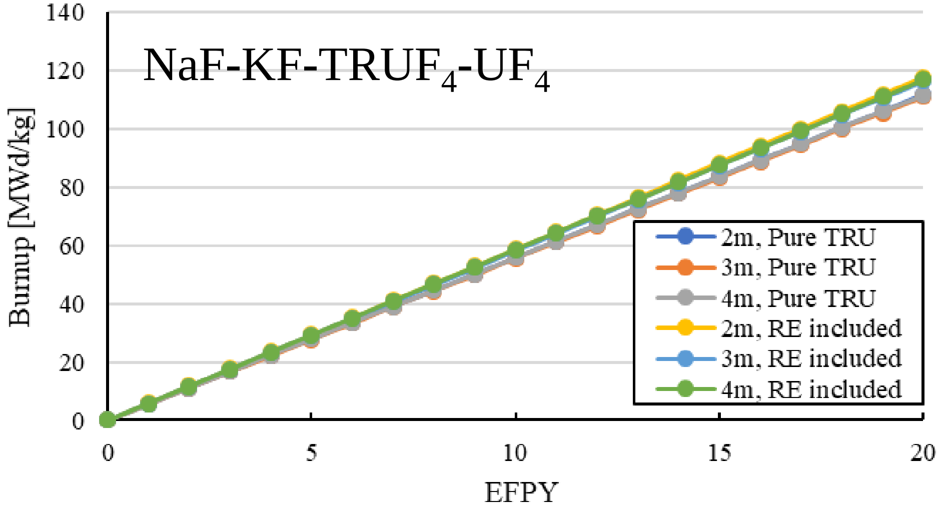
Burnups .vs. Full-power operation time

- Program: Serpent 2.2.0, library: ENDF/B-VII.1
- History: 100,000, inactive cycle: 100, active cycle: 300

Diameter	Power
200 cm	500 MWth
300 cm	1680 MWth
400 cm	4000 MWth





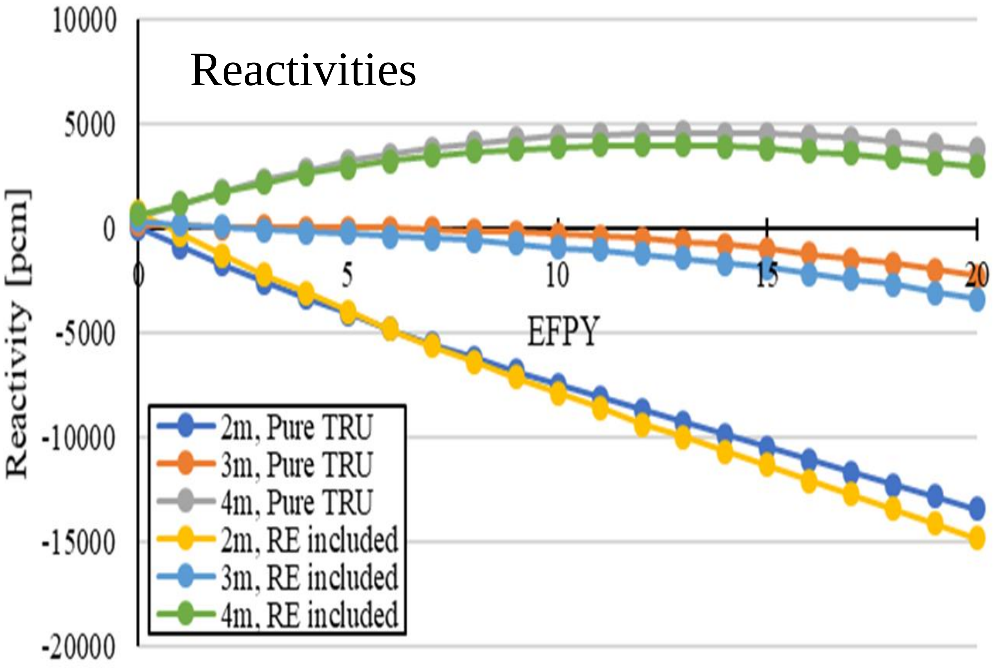


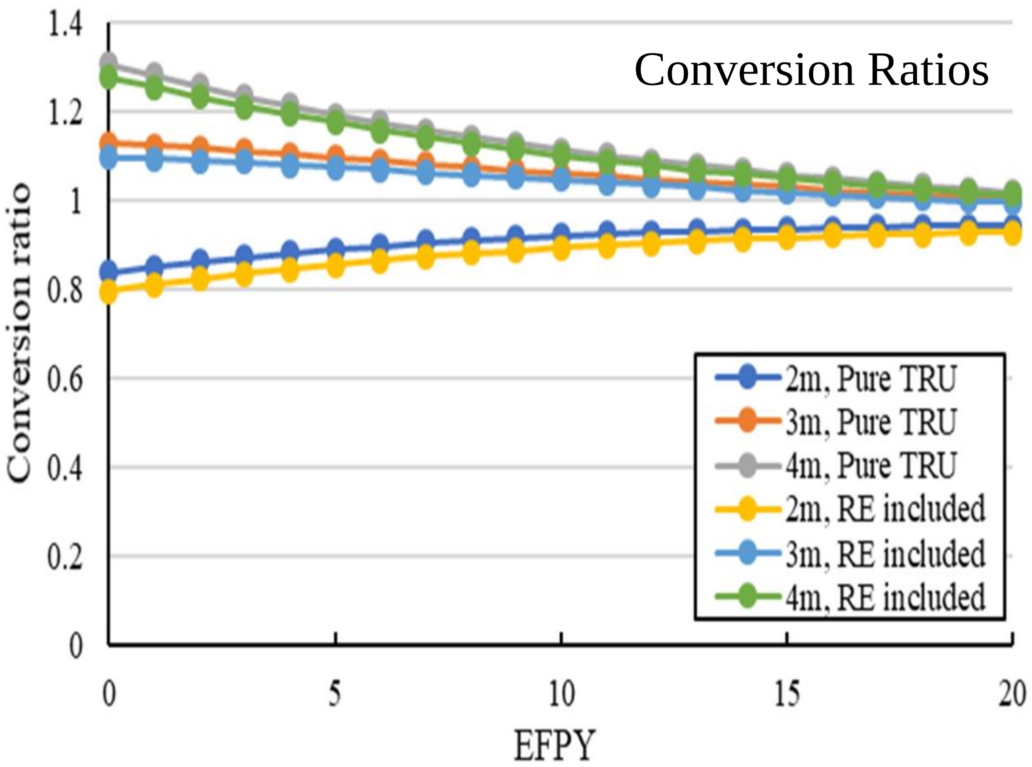
Numerical Results (2/6)

Reactivities and conversion ratios .vs. Full-power operation time

- Fuel: KCl-$TRUCl_3$-UCl_3
- Program: Serpent 2.2.0, library: ENDF/B-VII.1
- History: 100,000, inactive cycle: 100, active cycle: 300

Diameter	Power
200 cm	500 MWth
300 cm	1680 MWth
400 cm	4000 MWth


Reactivities

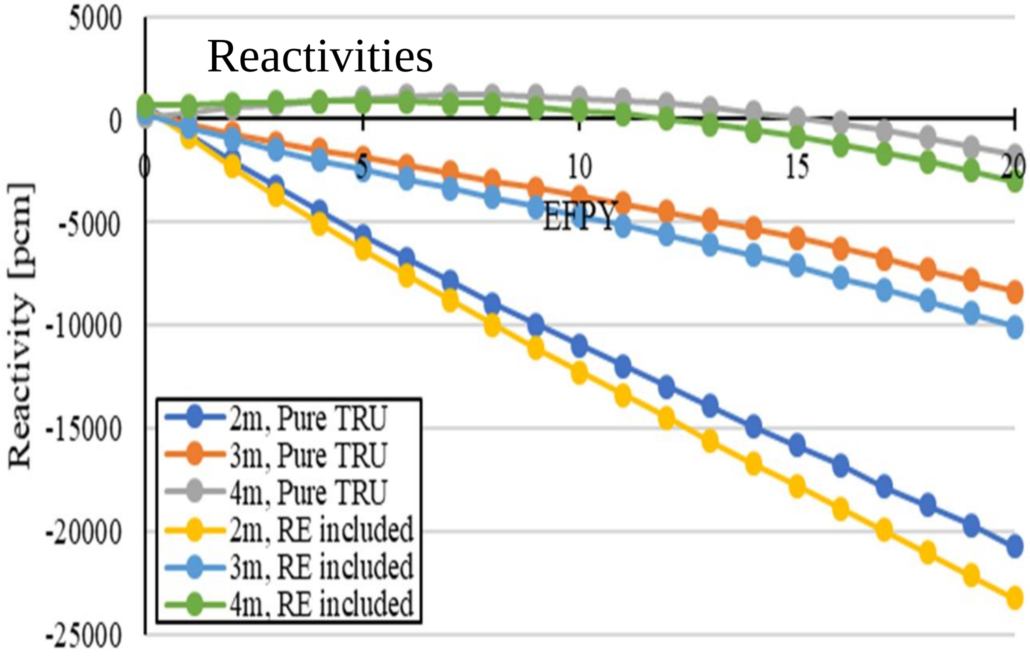

Conversion Ratios

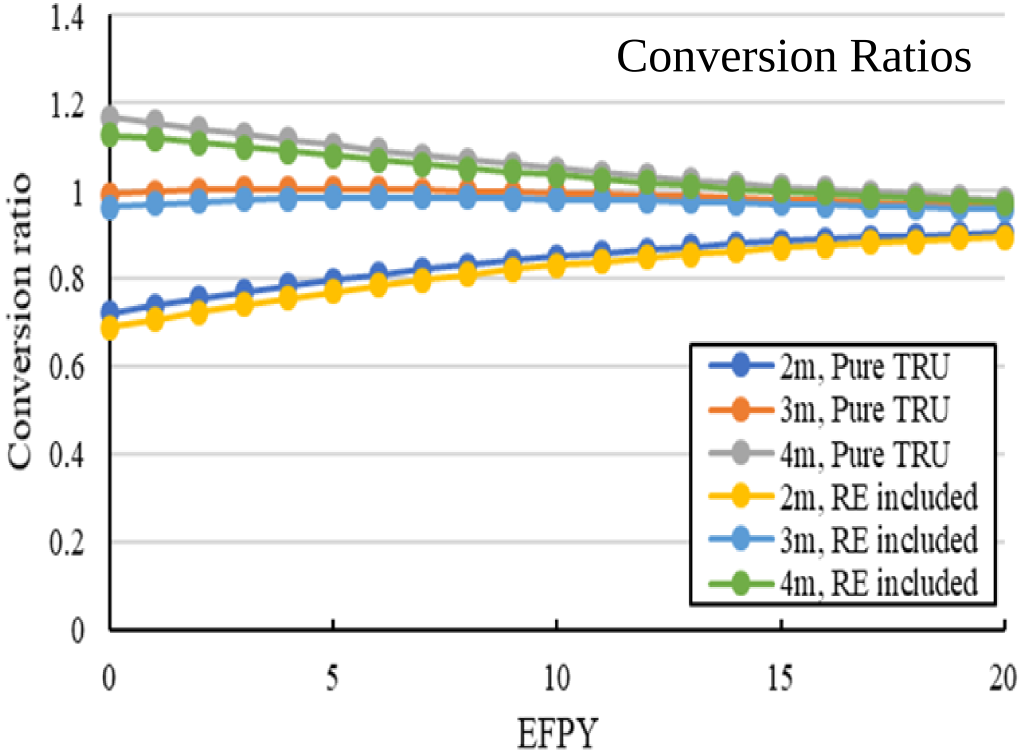
Numerical Results (3/6)

Reactivities and conversion ratios .vs. Full-power operation time

- Fuel: NaCl-KCl-$TRUCl_3$-UCl_3
- Program: Serpent 2.2.0, library: ENDF/B-VII.1
- History: 100,000, inactive cycle: 100, active cycle: 300

Diameter	Power
200 cm	500 MWth
300 cm	1680 MWth
400 cm	4000 MWth


Reactivities

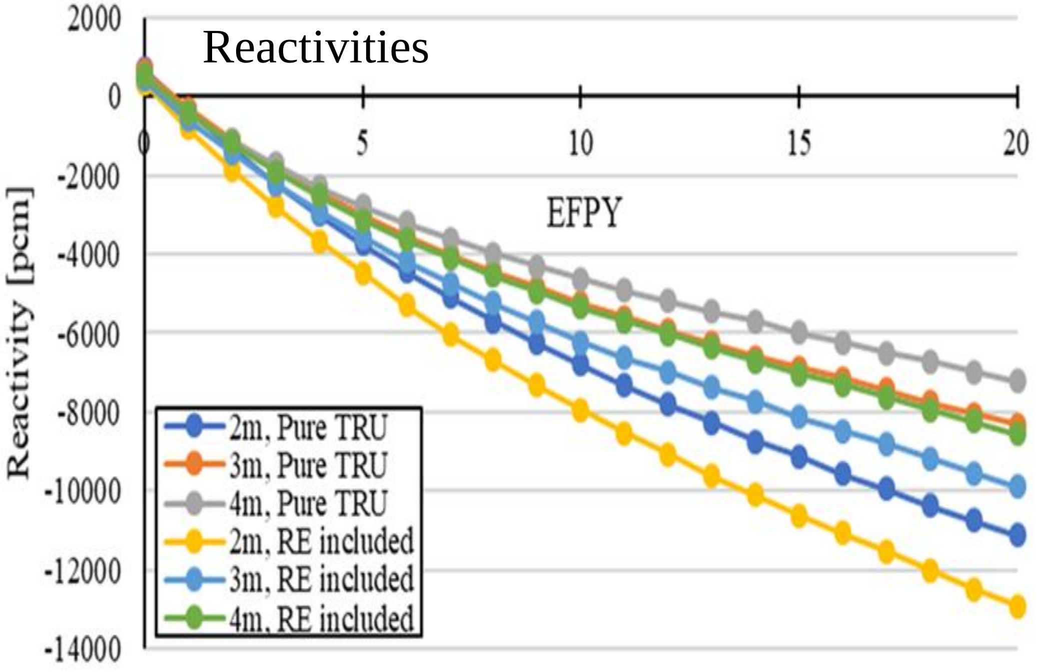

Conversion Ratios

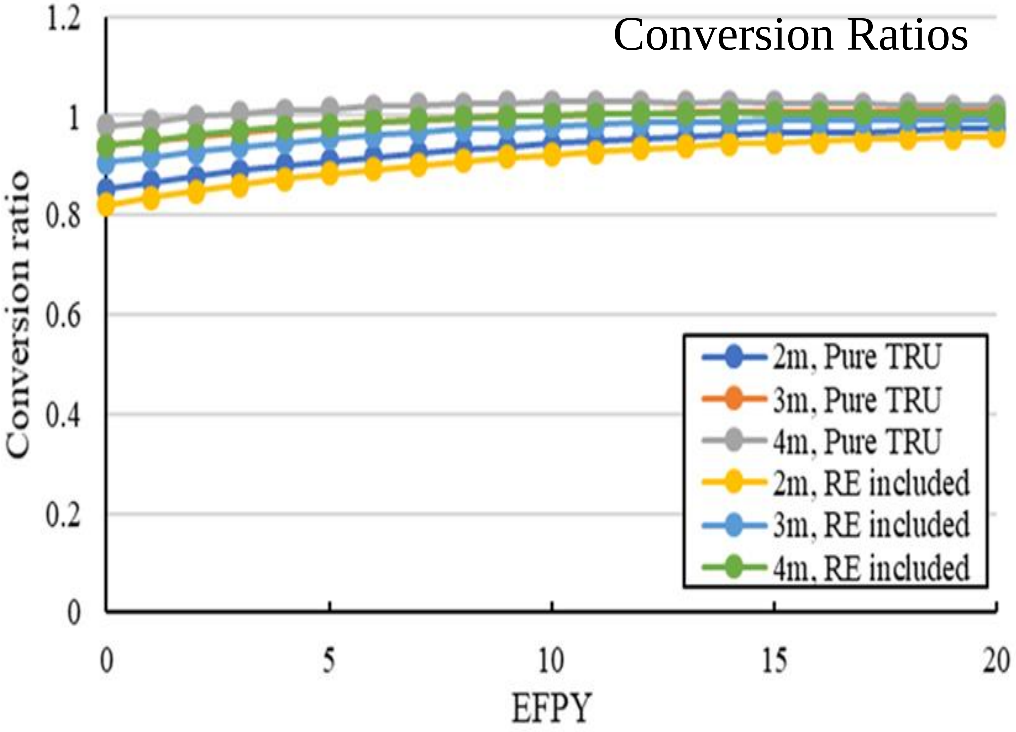
Numerical Results (4/6)

Reactivities and conversion ratios .vs. Full-power operation time

- Fuel: NaF-KF-TRUF$_4$-UF$_4$
- Program: Serpent 2.2.0, library: ENDF/B-VII.1
- History: 100,000, inactive cycle: 100, active cycle: 300

Diameter	Power
200 cm	500 MWth
300 cm	1680 MWth
400 cm	4000 MWth





Numerical Results (5/6)

Summary (pure TRU)

Fuel	D (= H)	Reactor power	Maximum reactivity	Reactor lifetime	Conversion ratio	Discharge burnup
$KCl\text{-}TRUCl_3\text{-}UCl_3$	**200 cm**	500 MWth	60 pcm	< 1 year	0.84	< 7 MWd/kg
	300 cm	1680 MWth	170 pcm	6 years	1.10-1.13	40 MWd/kg
	400 cm	4000 MWth	4610 pcm	> 20 years	1.02-1.31	> 133 MWd/kg
$NaCl\text{-}KCl\text{-}TRUCl_3\text{-}UCl_3$	**200 cm**	500 MWth	680 pcm	< 1 year	0.72	< 8 MWd/kg
	300 cm	1680 MWth	300 pcm	< 1 year	0.99	< 8 MWd/kg
	400 cm	4000 MWth	1180 pcm	15 years	1.01-1.17	125 MWd/kg
$NaF\text{-}KF\text{-}TRUF_4\text{-}UF_4$	**200 cm**	500 MWth	680 pcm	< 1 year	0.85	< 6 MWd/kg
	300 cm	1680 MWth	620 pcm	< 1 year	0.94	< 6 MWd/kg
	400 cm	4000 MWth	350 pcm	< 1 year	0.98	< 6 MWd/kg

- Proper reactor size for appropriate reactor lifetime is 300 cm and 400 cm for $KCl\text{-}TRUCl_3\text{-}UCl_3$ and $NaCl\text{-}KCl\text{-}TRUCl_3\text{-}UCl_3$ fuel, respectively.
- It can be found that fluoride fuel is not suitable for the breakeven.

Numerical Results (6/6)

Summary (RE-included TRU)

Fuel	D (= H)	Reactor power	Maximum reactivity	Reactor lifetime	Conversion ratio	Discharge burnup
KCl-TRUCl$_3$-UCl$_3$	**200 cm**	500 MWth	770 pcm	< 1 year	0.80	< 7 MWd/kg
	300 cm	1680 MWth	370 pcm	2 years	1.09-1.10	14 MWd/kg
	400 cm	4000 MWth	4000 pcm	> 20 years	1.01-1.28	> 137 MWd/kg
NaCl-KCl-TRUCl$_3$-UCl$_3$	**200 cm**	500 MWth	600 pcm	< 1 year	0.69	< 9 MWd/kg
	300 cm	1680 MWth	310 pcm	< 1 year	0.96	< 9 MWd/kg
	400 cm	4000 MWth	890 pcm	12 years	1.02-1.13	103 MWd/kg
NaF-KF-TRUF$_4$-UF$_4$	**200 cm**	500 MWth	330 pcm	< 1 year	0.82	< 6 MWd/kg
	300 cm	1680 MWth	410 pcm	< 1 year	0.91	< 6 MWd/kg
	400 cm	4000 MWth	520 pcm	< 1 year	0.94	< 6 MWd/kg

- Overall behavior of results are similar to those of pure TRU-based fuels.
- Proper reactor size for appropriate reactor lifetime 400 cm for NaCl-KCl-TRUCl$_3$-UCl$_3$ fuel.
- For KCl-TRUCl$_3$-UCl$_3$ fuel, it is expected that the reactor size should be larger than 300 cm.
- It can be found that fluoride fuel is not suitable for the breakeven.

Summary and Conclusions

The feasibility of achieving breakeven was examined for 18 different reactors

- KCl-TRUCl$_3$-UCl$_3$, NaCl-KCl-TRUCl$_3$-UCl$_3$, NaF-KF-TRUF$_4$-UF$_4$ (Pure TRU, RE-included TRU)
- Diameters of reactors were postulated as 200 cm, 300 cm, and 400 cm.
- Analysis has been performed through fuel depletion calculations.

The results gives high potential to achieve long lifetime and high fuel utilization

- It can be found that fluoride fuel is not suitable for the breakeven.
- For KCl-TRUCl$_3$-UCl$_3$, appropriate reactor size is estimated to over 300 cm.
- For NaCl-KCl-TRUCl$_3$-UCl$_3$, appropriate reactor size is estimated to about 400 cm.
- High burnup up to 100 MWd/kgU can be achieved without reprocessing.
- TRU from spent fuel of PWR or CANDU can be utilized.
- If some reprocessing is introduced, semi-permanent operation may be realized.

Thank You

Any Questions?