Assessment of Fission Product Migration in Molten Salt and Metal Reactor (MSMR)

Transactions of the Korean Nuclear Society Spring Meeting

Jeju, Korea, May 18-19, 2023

May 18, 2023

Eunhyug Lee[1], Tae-suk Oh[1], Jaehyun Ryu[1] and Yonghee Kim[1]

[1]Korea Advanced Institute of Science and Technology (KAIST)

Contents

Introduction (1/2)

Needs for mobile power source

- Deployment of large nuclear reactors becomes inadequate for:
  - Military base
  - Mining industry
  - Small village in remote area
  - In space (Moon & Mars) and spacecraft…
- Often, fossil fuel (mostly diesel) based generators are utilized
  - Adverse effect(s) stemming from CO_2 emission
- As one of the remedies, miniaturized reactor concept is pursued

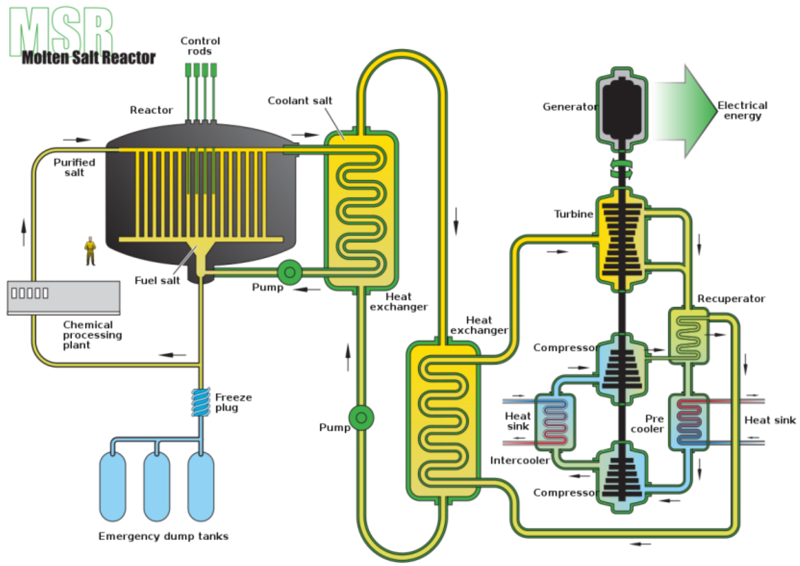
Ultra-micro reactor

- A miniaturized reactor small enough to be loaded in a container and could be easily transported by a vehicle
  - Container size: 234.8 cm width, 239.0 cm or 269.5 cm height
- Realization via Molten Salt Reactor (MSR) concept?

Introduction (2/2)

Molten salt reactor (MSR)

– Reactor which consists of molten salt (dissolved fuel), where the salt acts as both fuel and coolant
  - circulates between the active core and heat exchanger
– Superior inherent safety attributes:
  - No meltdown, no hydrogen explosion
  - Strong negative feedback originating from thermal expansion of fuel salt



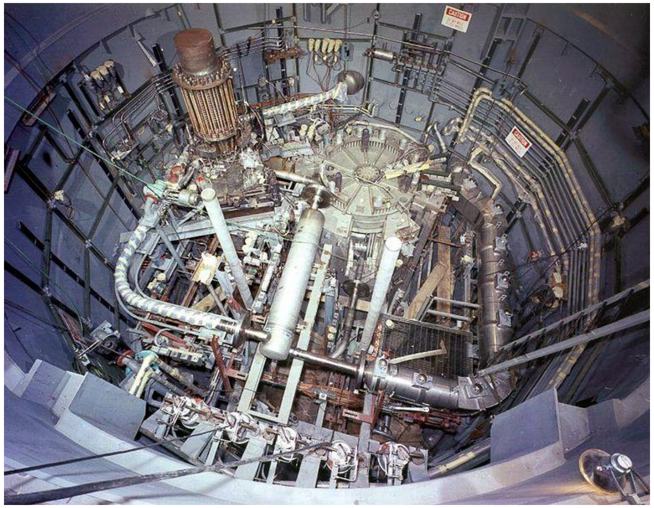
Schematic diagram for MSR

Limitation of Thermal spectrum MSR

– Proliferation concern by online fuel reprocessing
– Production of radioactive waste from the usage of graphite moderator & Generation of tritium

Limitation of HALEU-loaded MSFR for ultramicro reactor

– HALEU: High Assay Low Enriched Uranium (<19.75 w/o)
– Calculated cylindrical MSFR size for criticality (NaCl-UCl_3 fuel / eutectic composition)
  - Reactor diameter should be at least 215 cm & Fuel inventory about 20-30 tons.
  - Too large to be loaded in a container ---
  - **To overcome, MSMR concept is proposed.**



ORNL MSRE

Concept and Modelling of MSMR (1/4)

Liquid metal as fuel

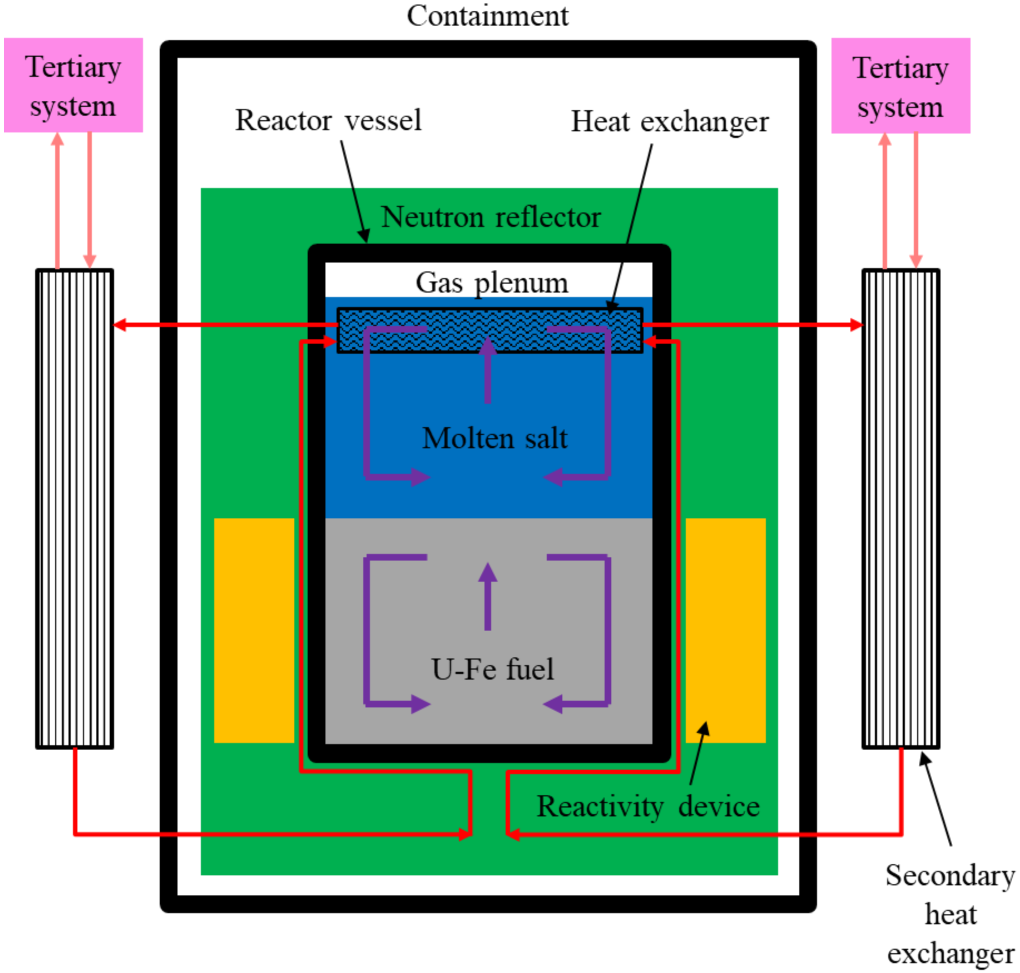
- Generates the heat
- Compact fuel
  - High conversion ratio
  - Small core size
  - Low fuel mass

Molten salt as coolant

- Natural circulation or pump operation
- Trap of non-gaseous fission products
  - Noble metal in the liquid fuel
  - Non-noble metal (Cs, I, Sr etc) in the salt

Secondary system

- Removing heat from primary system
  - Flowing through the heat exchanger
  - Cooling outer surface of reactor vessel



Liquid metallic fuel (U-Fe alloy)

– Eutectic composition:
  - 66-34 (number), 89-11 (mass)
  - Melting temperature: 723℃

– Density for U and Fe

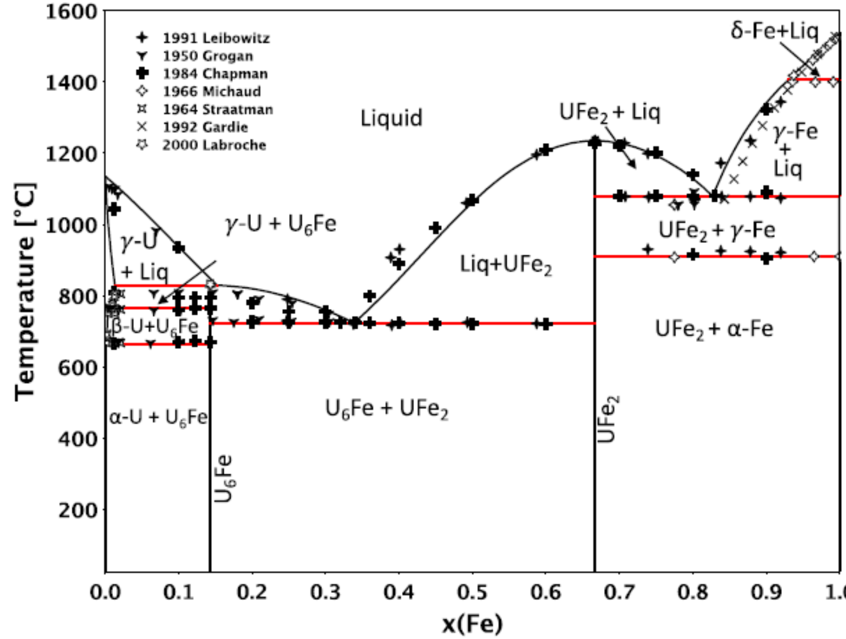
$$\rho(T) = A - BT$$

Metal	A	B
Fe	8.618	8.83e-4
U	19.520	1.601e-3

– Density for mixture: Ideal Liquid Model

$$\frac{1}{\rho} = \sum_i \left(\frac{w_i}{\rho_i}\right)$$

U-Fe phase diagram



- Moore, E. E., Turchi, P. E., Landa, A., Söderlind, P., Oudot, B., Belof , J. L., ... & Perron, A. (2019). Development of a CALPHAD thermodynamic database for Pu-U-Fe-Ga alloys. Applied Sciences, 9(23), 5040.

- Grosse, A. V., & Kirshenbaum, A. D. (1963). The densities of liquid iron and nickel and an estimate of their critical temperature. *Journal of Inorganic and Nuclear Chemistry*, *25*(4), 331-334.
- Rohr, W. G., & Wittenberg, L. J. (1970). Density of liquid uranium . *The Journal of Physical Chemistry*, *74*(5), 1151-1152.

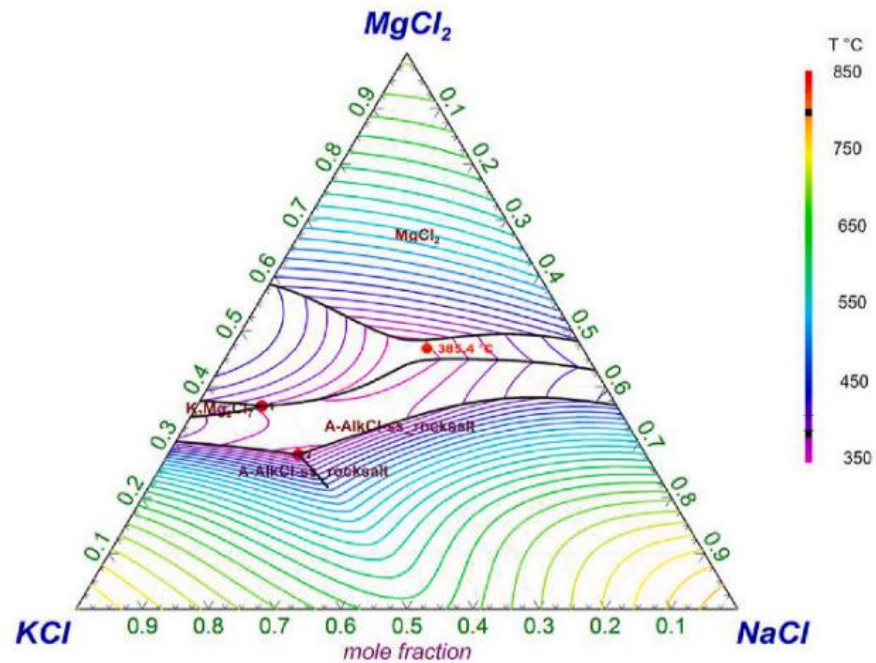
Concept and Modelling of MSMR (3/4)

Molten salt coolant ($NaCl$-KCl-$MgCl_2$)

– Eutectic composition: 30.2-22.7-47.1 (mol)
  - Melting temperature: 385℃
– Density
  - Linear approximation of each component
  - Ideal Liquid Model

$$\rho(t) = \rho_m - k(t - t_m)$$

Formula	t_m/°C	ρ_m/g cm^{-3}	k/g cm^{-3} °C^{-1}
NaCl	800.7	1.556	0.000543
KCl	771	1.527	0.000583
$MgCl_2$	714	1.68	0.000271



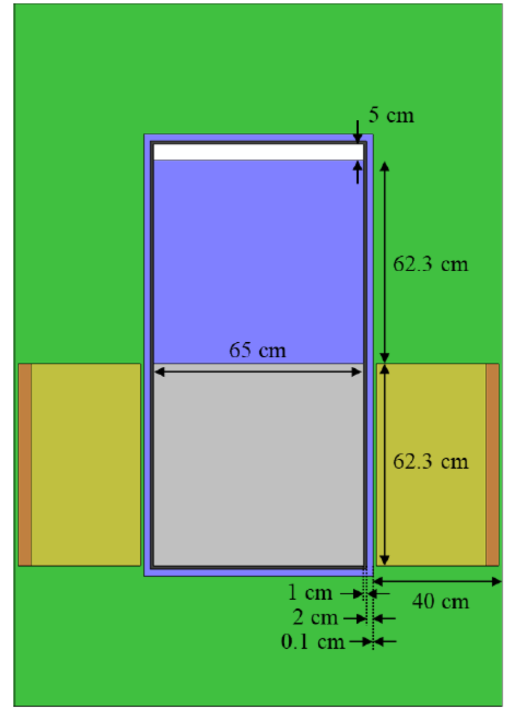
Haynes, W. M., Lide, D. R., & Bruno, T. J. (2016). CRC handbook of chemistry and physics. CRC press.

Villada, C., Ding, W., Bonk, A., & Bauer, T. (2021). Engineerin g molten MgCl2–KCl–NaCl salt for high-temperature thermal e nergy storage: Review on salt properties and corrosion control s trategies. Solar Energy Materials and Solar Cells, 232, 111344.

Concept and Modelling of MSMR (4/4)

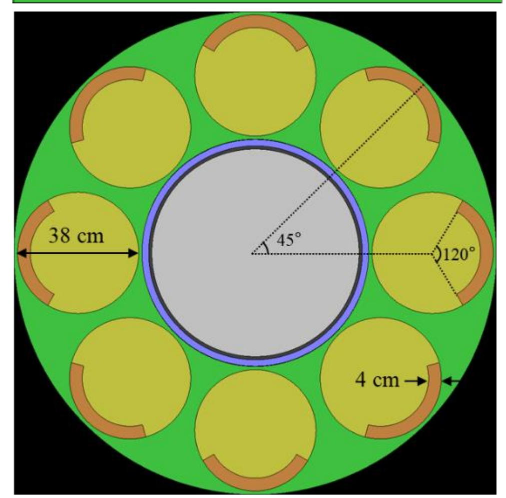
Reactor Layout

- Fuel zone
  - Diameter = 65 cm, Height = 62.3 cm
  - Uranium enrichment = 12 wt.%
  - Fuel inventory: 2,818 kg
- Upper molten salt zone: Same as Fuel zone
  - Chloride enrichment = 99 at.% Cl-37
- Gas plenum: 5 cm
- Reactor vessel: 1 cm
- Secondary system: 2 cm thickness gap molten salt-filled
- Reflector: 40 cm SS304



Drum-shaped reactivity control device

- Located in the reflector region and surrounding the active core
- Drum body: SS304 (same as a reflector)
  - The number of drums: 8
  - Height: 62.3 cm
  - Diameter: 38 cm
- Pad: B_4C (98% of theoretical density, 90wt.% of B-10)
  - Pad thickness: 4 cm
  - Arc angle: 120°

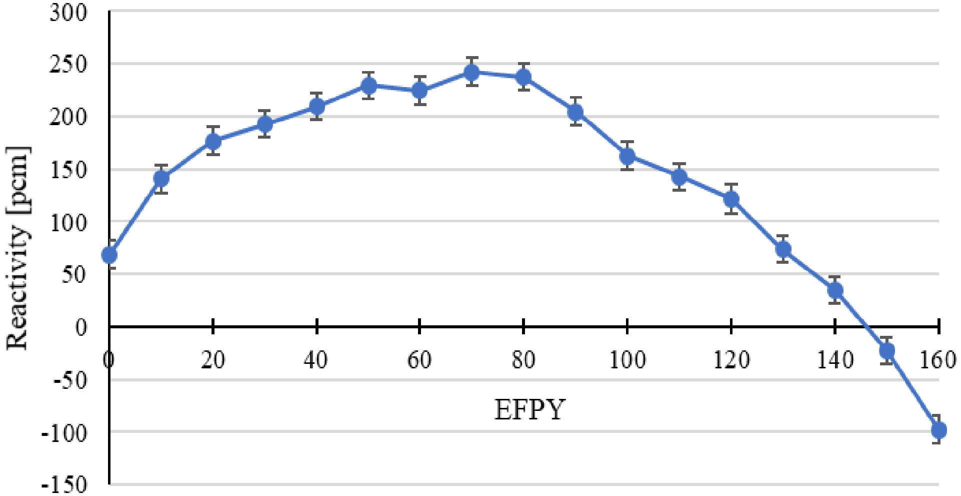


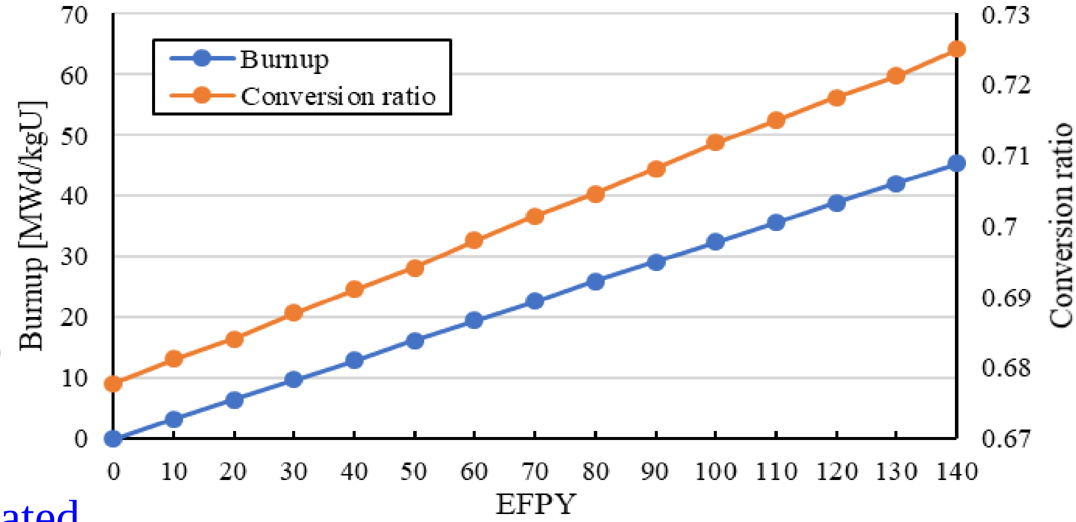
Numerical Results (1/6)

Reactivities and conversion ratios .vs. Full-power operation time (2.5 MWth)

– Program: Serpent 2.2.0

– Samples: (History: 100,000, inactive cycle: 100, active cycle: 300)





250 pcm of maximum reactivity can be estimated.
140 years of lifetime and 45 MWd/kg of discharge burnup can be estimated.
The worth of the reactivity control drum has been estimated to 2,629 ± 20 pcm

Fuel Temperature Coefficient

Temperature range [C]	800 - 900	900 - 1000	1000 - 1100	1100 - 1200
Temperature coefficient [pcm/K]	-2.48 ± 0.06	-2.48 ± 0.06	-2.51 ± 0.06	-2.67 ± 0.06

Numerical Results (2/6)

Fission Product Information

- Three types of fission products
  - Noble gas, noble metal, others
- Fission products at 45 MWd/kg burnup
  - Total mass: 131.2 kg

Noble gas	gaseous fission products that do not dissolve in liquid fuel and molten salt
Noble metal	non-gaseous fission products that do not dissolve in molten salt
Salt seeker (Others)	fission products can be dissolved in molten salt

Element	Type	Mass fraction [%]	Element	Type	Mass fractio n [%]	Element	Type	Mass fraction [%]
Xe	Noble gas	12.58606	**Hf**	Noble metal	4.52E-17	**Pm**	Others	0.038028
Kr	Noble gas	1.163383	**Hg**	Noble metal	1.41E-24	**Sm**	Others	2.675983
Rn	Noble gas	8.42E-14	**Tl**	Noble metal	4.64E-14	**Gd**	Others	0.123585
Zr	Noble metal	12.44069	**Pb**	Noble metal	7.71E-07	**Dy**	Others	0.002517
Nb	Noble metal	0.002414	**Bi**	Noble metal	8.63E-11	**Ho**	Others	8.84E-05
Mo	Noble metal	9.971559	**Te**	Noble metal	1.446093	**Er**	Others	0.000111
Tc	Noble metal	2.471687	**Se**	Noble metal	0.192263	**Tm**	Others	7.55E-06
Ru	Noble metal	5.93603	**Po**	Noble metal	1.80E-12	**Yb**	Others	4.25E-06
Rh	Noble metal	1.767941	**I**	Noble metal	0.693799	**Y**	Others	1.481246
Pd	Noble metal	2.280483	**At**	Noble metal	3.78E-21	**Rb**	Others	1.226256
Ag	Noble metal	0.124034	**La**	Others	3.629297	**Cs**	Others	8.660187
Cd	Noble metal	0.214767	**Ce**	Others	6.794389	**Sr**	Others	1.629292
In	Noble metal	0.034521	**Pr**	Others	3.39548	**Ba**	Others	6.435432
Sn	Noble metal	0.325362	**Nd**	Others	12.10858	**Br**	Others	0.066805
Sb	Noble metal	0.081617						

Fission Product Information

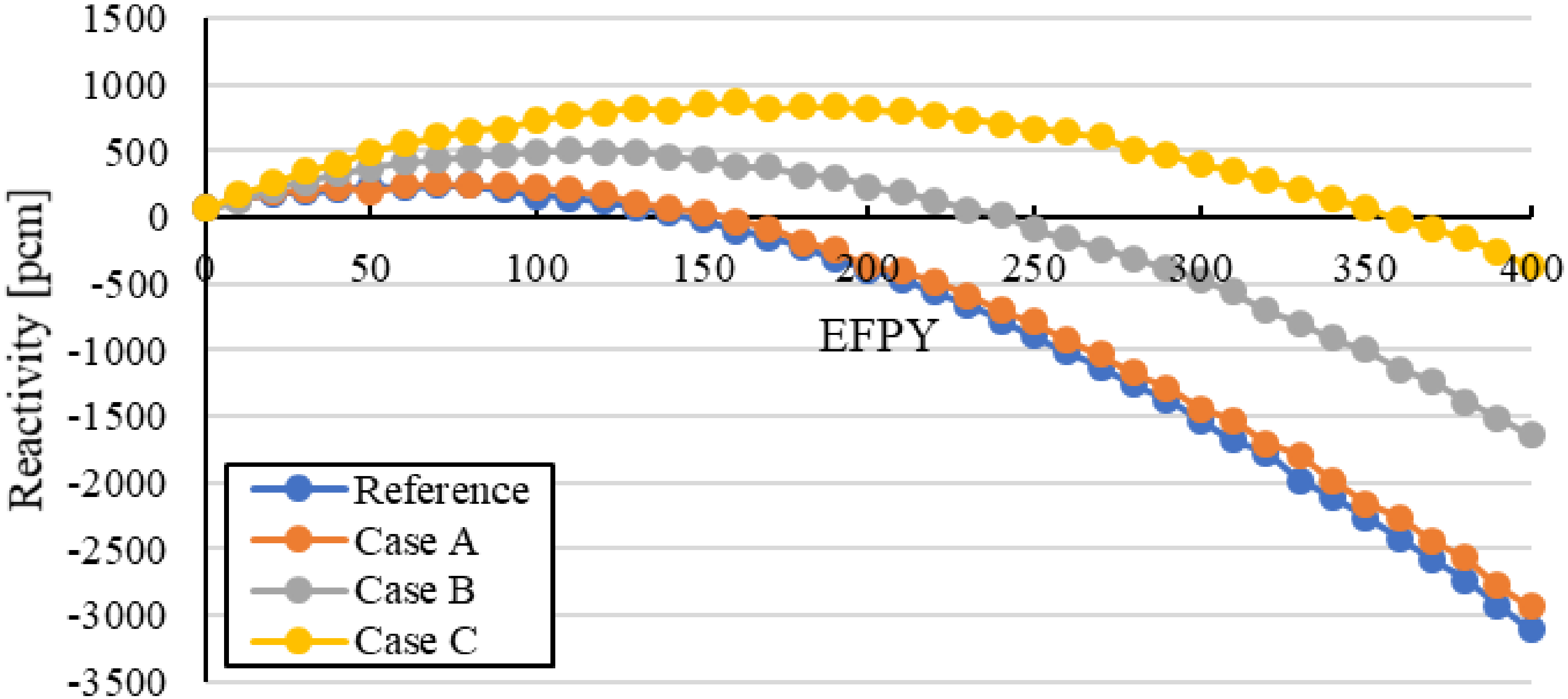
- Three types of fission products
  - Noble gas: gaseous fission products that do not dissolve in liquid fuel and molten salt
  - Noble metal: non-gaseous fission products that do not dissolve in molten salt
  - Salt seeker (Others): fission products that can be dissolved in molten salt
- Assumptions and scenarios of fission product behavior
  - All noble gases are completely removed from the fuel
  - All noble metals remain in the fuel
  - Some of the salt-seekers in the fuel migrate to the molten salt

	Noble gas	Noble metal	Salt-seeker elements
Reference	Not removed	Remains in fuel	Not removed
Case A	Completely removed	Remains in fuel	Not removed
Case B	Completely removed	Remains in fuel	50% removed*
Case C	Completely removed	Remains in fuel	100% removed

* Removal ratios of all elements are identical

Reactivities .vs. Full-power operation time (dependent on three scenarios)

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



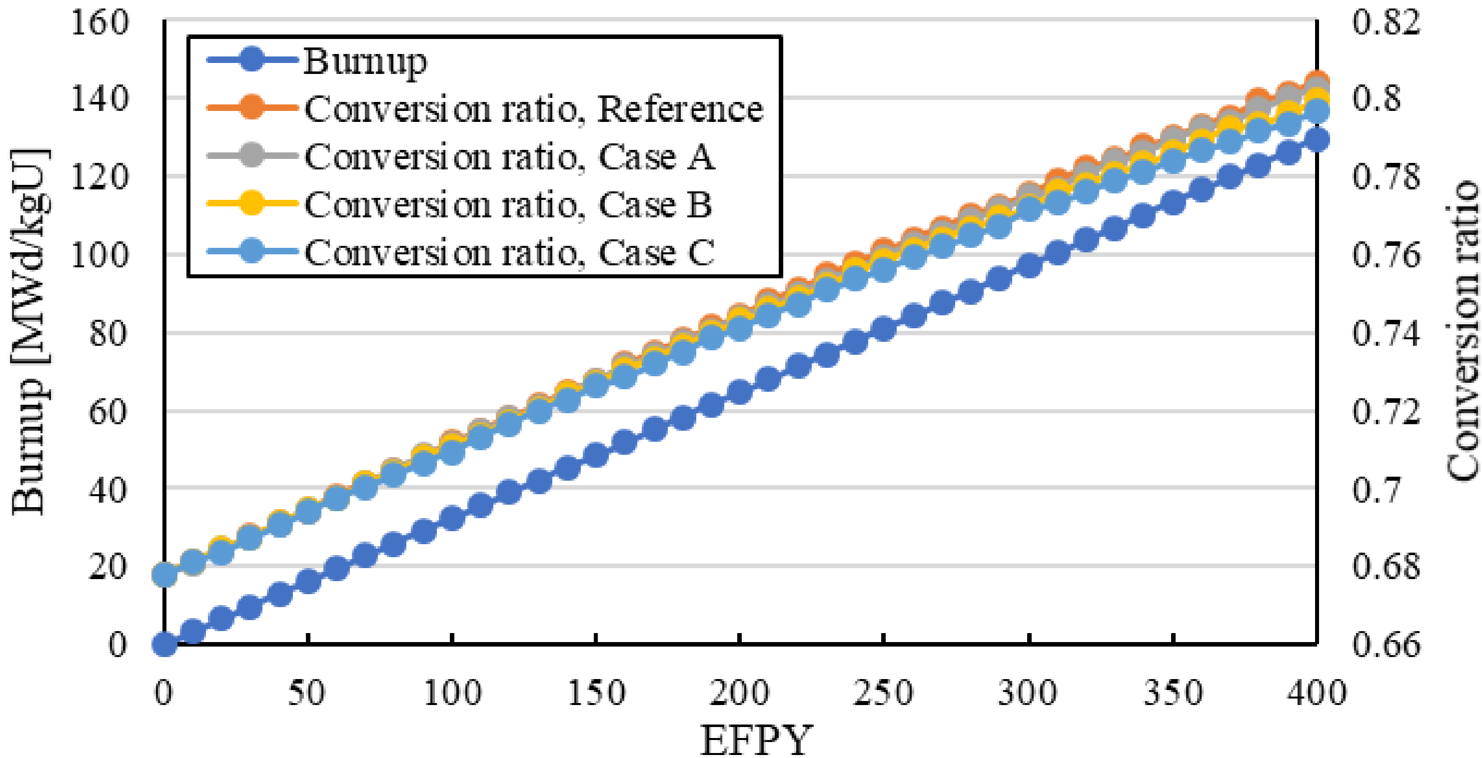
Reactivity and reactor lifetime can reach up to 870 pcm and 350 years repectively.

Numerical Results (5/6)

Burnup and Conversion ratios .vs. Full-power operation time

– Program: Serpent 2.2.0, library: ENDF/B-VII.1

– History: 100,000, inactive cycle: 100, active cycle: 300

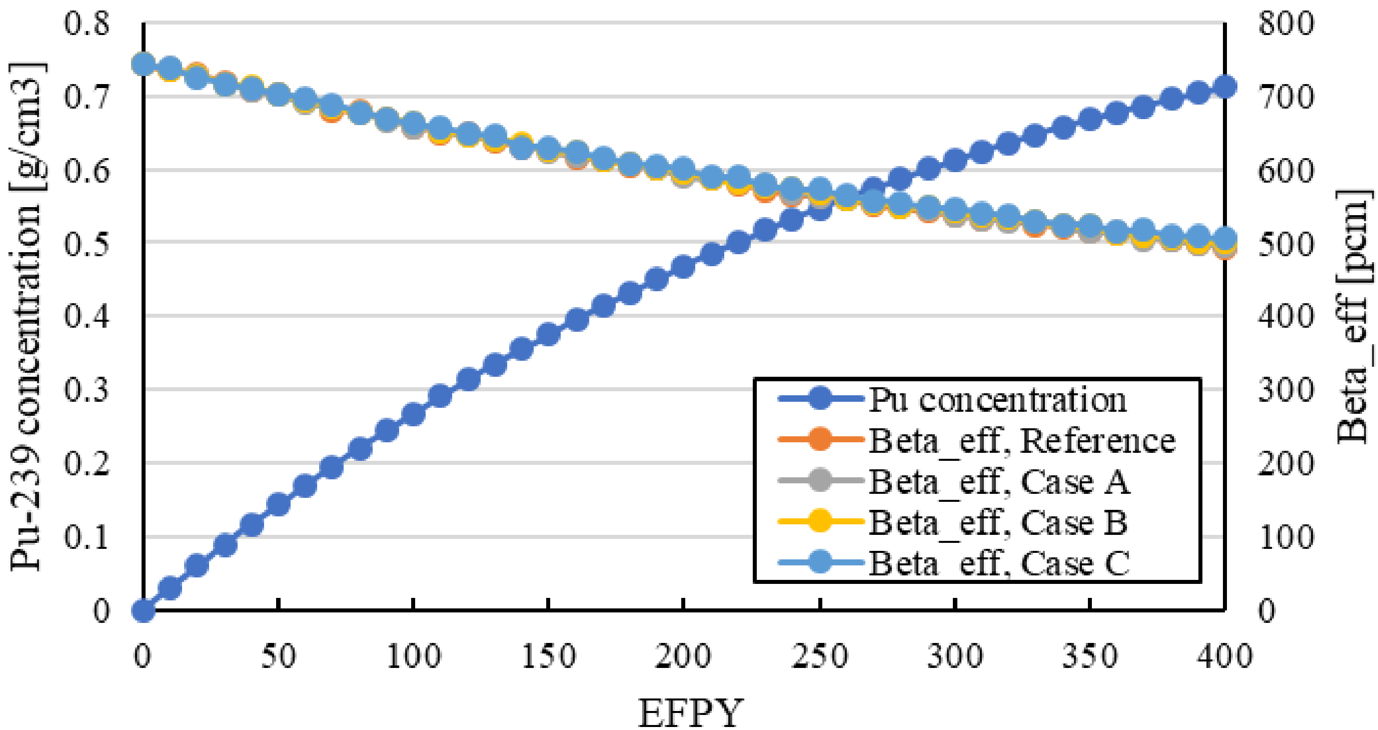


Conversion ratios rise with increasing burnup due to accumulation of Pu
Migration of fission products hardly affects the conversion ratio

Numerical Results (6/6)

Pu concentration and delayed neutron fraction .vs. Full-power operation time

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



Plutonium is accumulated and β_{eff} decreases with increment of burnup
Plutonium accumulation rate dwindles due to utilization of plutonium
Migration of fission products hardly effects β_{eff}

Summary & Conclusions

The effect of fission product removal on the neutronics behavior of MSMR has been investigated

- Expected reactor lifetime can be expanded up to 2.5 times
- Maximum reactivity can rise up to 3 times
- The evolution trends for discharge burnup, conversion ratio, and delayed neutron fraction are similar to each other

	Reference	Case A	Case B	Case C
Expected reactor lifetime	140 years	150 years	240 years	350 years
Maximum reactivity	240 pcm	260 pcm	510 pcm	820 pcm
Discharge burnup	45 MWd/kg	49 MWd/kg	78 MWd/kg	113 MWd/kg
Conversion ratio	0.67-0.73	0.67-0.73	0.67-0.76	0.67-0.78
Delayed neutron fraction	630-743 pcm	624-743 pcm	573-743 pcm	524-743 pcm

- Case A) Noble gas removed, Noble metal remains, Salt-seeker elements not removed
- Case B) Noble gas removed, Noble metal remains, Salt-seeker elements 50% removed
- Case C) Noble gas removed, Noble metal remains, Salt-seeker elements 100% removed

Summary & Conclusions

The MSMR can be utilized as an ultramicro-miniaturized reaactor

- The diameter of MSMR is estimated at about 65 cm
- Fuel mass of the reactor is about 2.8 tons
- Its life is estimated to be about 140 years with 2.5 MWth
- Normal operation is guaranteed in aspect of temperature coefficient and reactivity worth

Behavior of fission products can alter several properties of MSMR

- Lifetime and maximum reactivity can rise up to about 2.5 times and 3 times
- Removal of fission products can be advantage in terms of lifetime but challenges in terms of excess reactivity
- For more precise of assessment and optimization, chemical properties of fission products should be more investigated

Thank you for your attentions

Any Questions?