PSI Center for Scientific Computing, Theory and Data

Molten Salt Reactors Taxonomy and Fuel Cycle Performance

Joint IAEA-NEA-EC/JRC Workshop on the Taxonomy and Related Terminology of Fuel Cycles for Molten Salt Reactors

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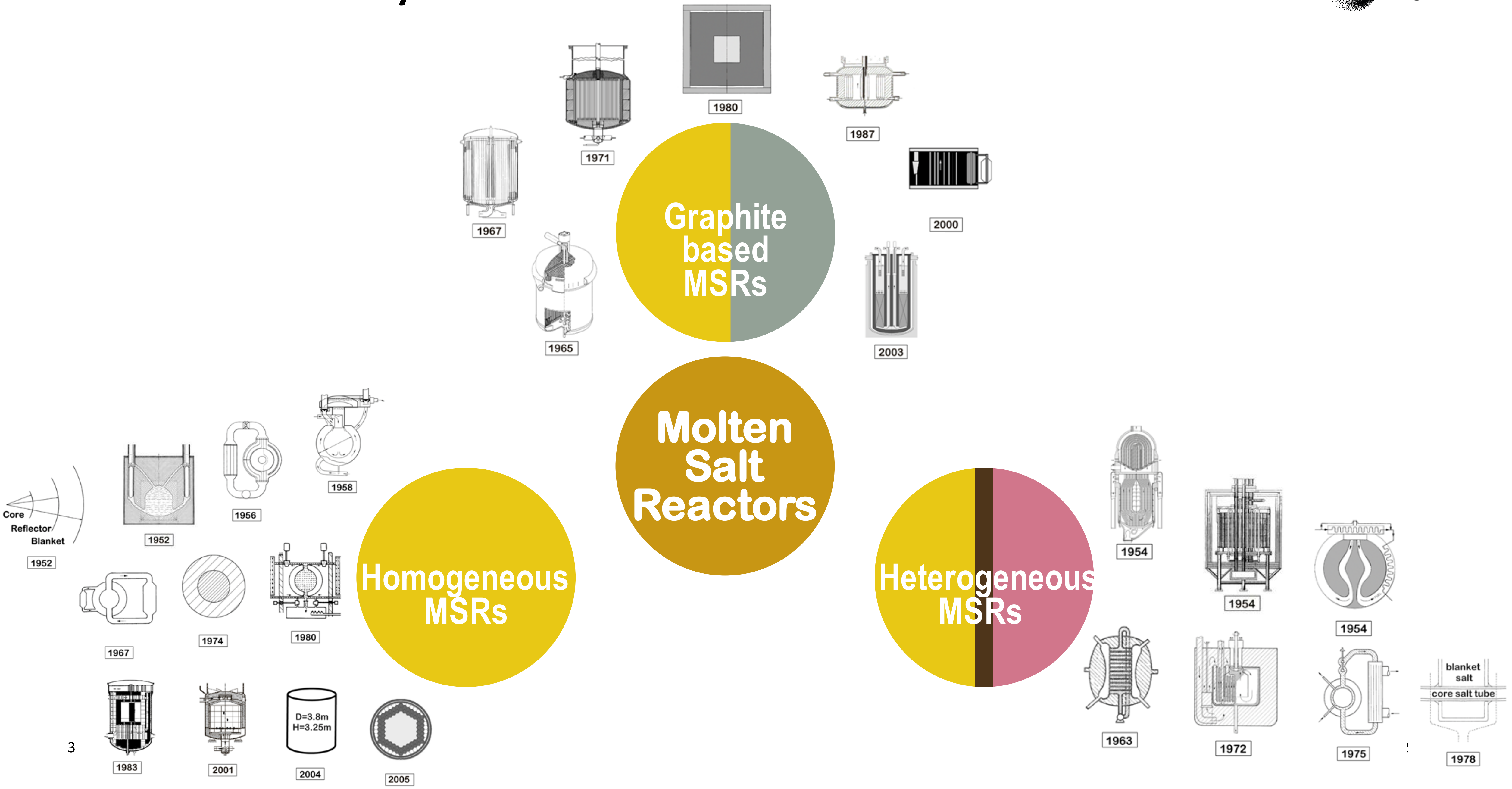
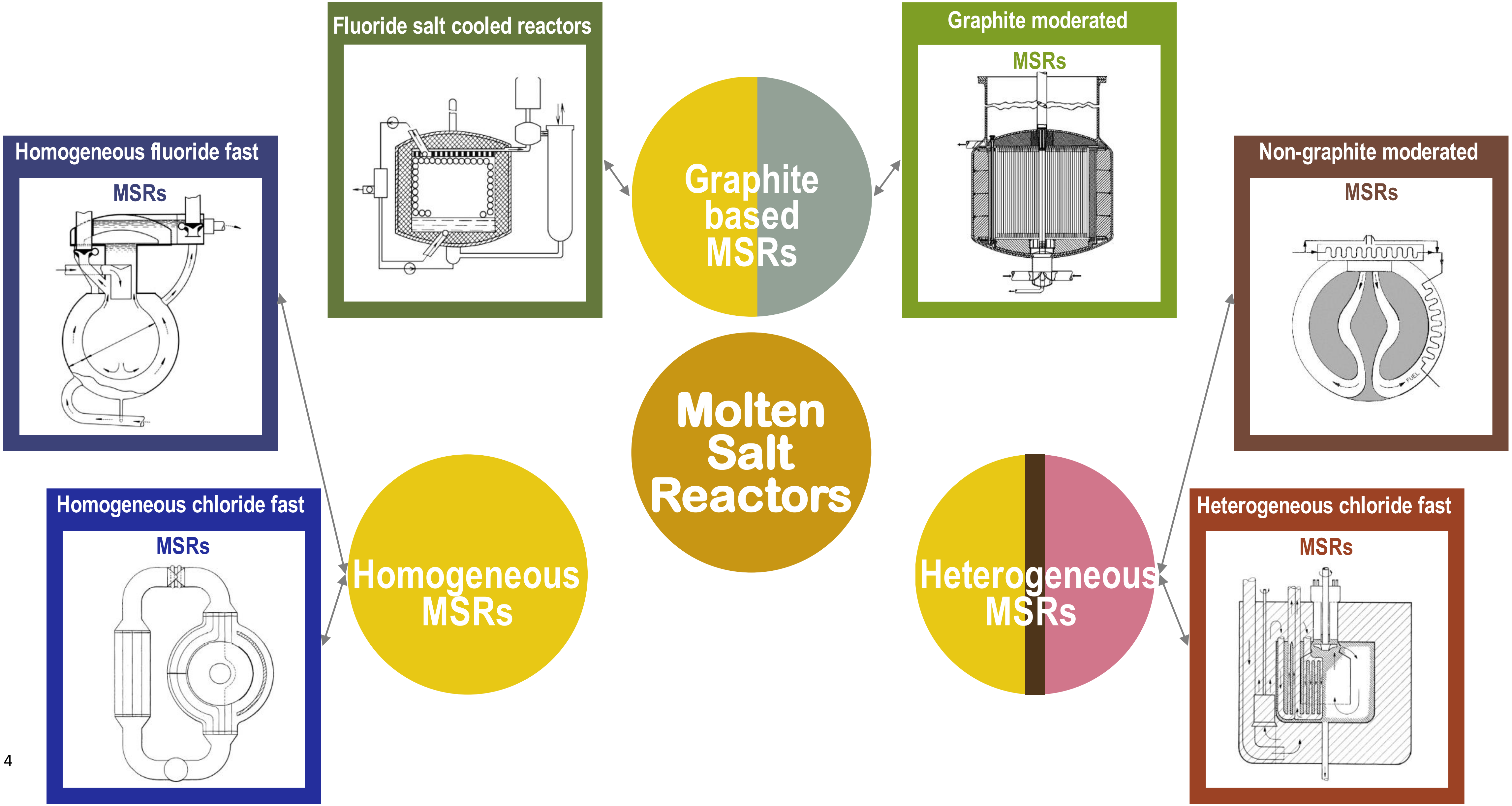
3 – 7 November 2025, IAEA, Vienna

MSR Taxonomy

IAEA MSR Taxonomy: 3 Classes



IAEA MSR Taxonomy: 6 Families



Example of MSR designs

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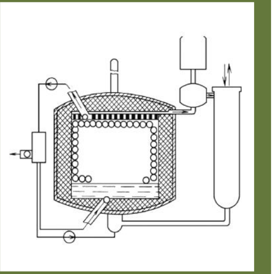
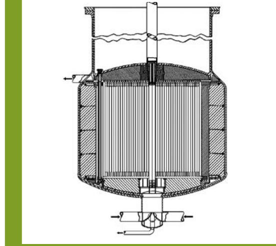
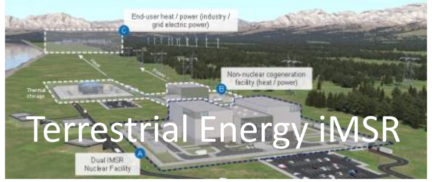
Fluoride salt cooled reactors

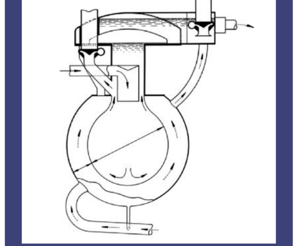


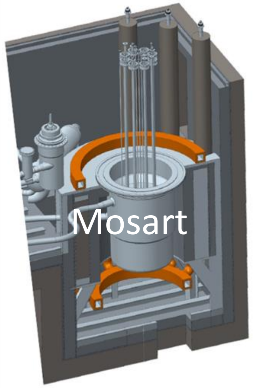
Graphite moderated MSRs

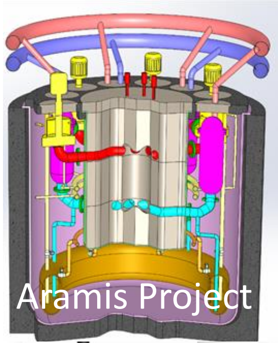


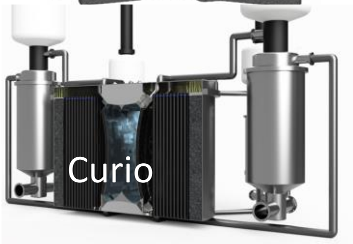


Homogeneous fluoride fast MSRs

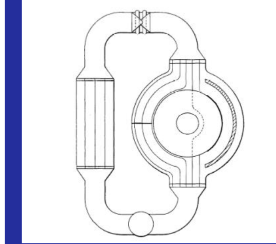


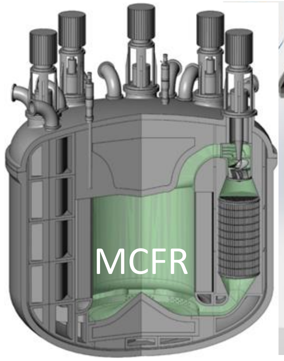


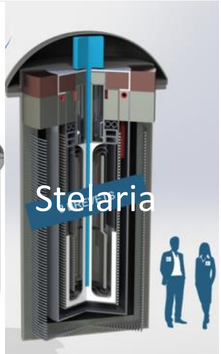


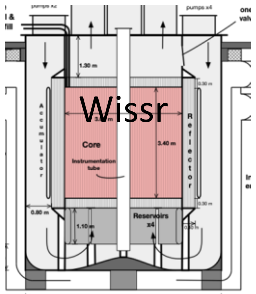


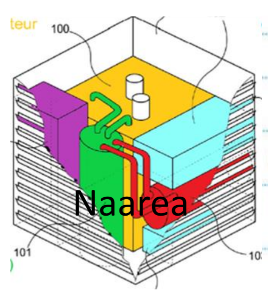
Homogeneous chloride fast MSRs

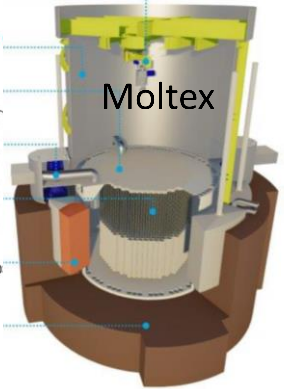




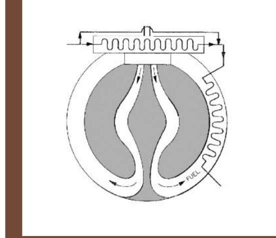




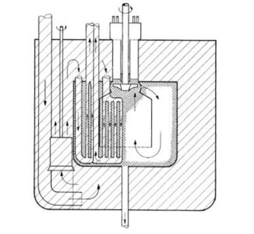




Non-graphite moderated MSRs



Heterogeneous chloride fast MSRs



F.I.1. Fluoride salt cooled reactors

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Salt cooled reactor with pebble bed fuel

Salt cooled reactor with fixed fuel

Types definition: *By fuel form (pebble bed vs. prismatic or compacts)*

Primary heat exchange: *In core*

Heat convection by fuel: *No, dedicated coolant **LiF-BeF_2** (Li is enriched to ^7Li)*

Fuel form: *Triso-particles in graphite matrix*

Struct. material in core: *No, graphite moderator and coolant salt are compatible*

Neutronic performance: *Converter*

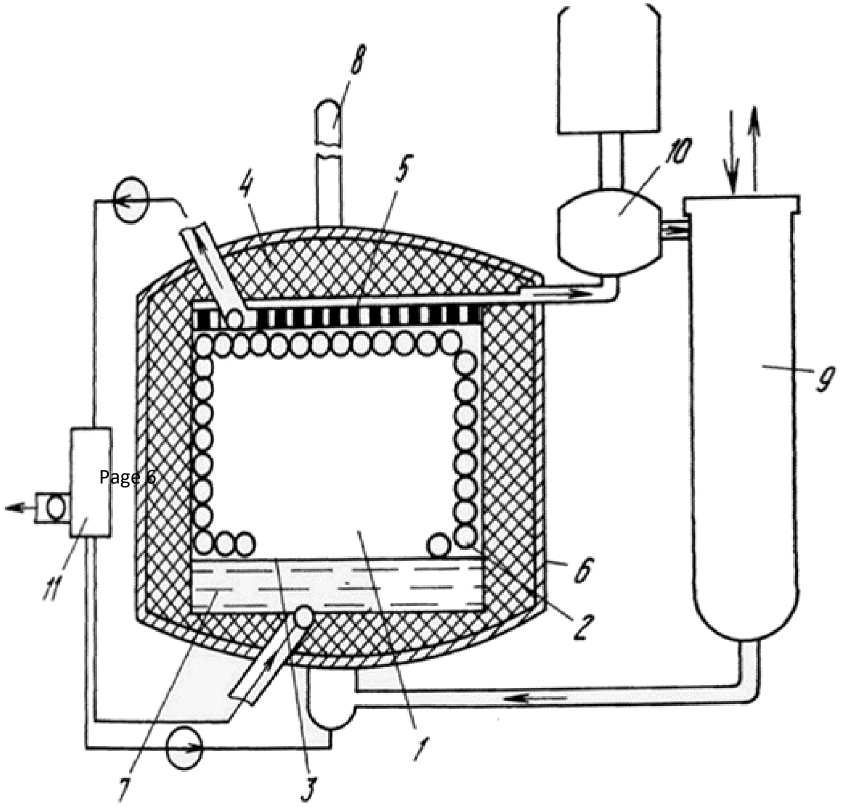
Self-sustaining breeding: *Can not be achieved*

Major fuel cycle: *Enr. U converter*

Leakage utilization: *Reflector*

Characteristic:

- ***^7LiF-BeF_2** has certain moderation power, hence it has **negative density effect** on reactivity.*
- *Very low specific fuel density in some designs:*
  - → *Unprocessed **spent fuel is volumetric**.*
  - → *Increased non-fuel parasitic neutron captures.*
  - → *Core transparency for neutrons (neutron leakage).*



BELOUSOV, I.G., et al., Features layout of VTRS for technological purpose, VANTS 16 3 (1983) 13–14

F.I.2. Graphite moderated MSRs

Types definition: *By fuel cycle type (Th-U breeder or enr. U converter)*

Primary heat exchange: *Ex core*

Heat convection by fuel: *Yes*

Fuel form: *Ac. diluted in fluorides salts, for breeders it is exclusively* ^{7}**LiF-BeF$_2$** *(^{7}LiF?)*

Struct. material in core: *No, graphite moderator and coolant salt are compatible*

Neutronic performance: *Breeder or converter*

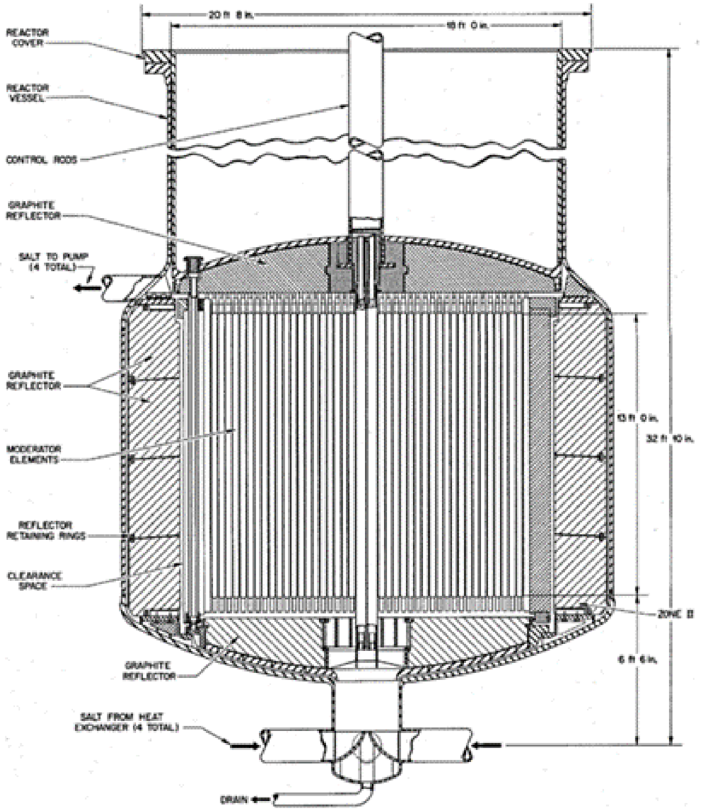
Self-sustaining breeding: *Can be achieved, is demanding*

Major fuel cycle: *Closed Th-U or enr. U converter*

Leakage utilization: *Reflector, multi-zone core, blanket*

Characteristic:

- *Specific fuel density is higher than in Fluoride salt cooled reactors.*
- *Limited graphite life-span as the only reason for its exchange.*
- *Hastelloy vessel protected by graphite reflector.*
- *Need of fast FPs removal and/or ^{233}Pa separation to achieve self-sustaining breeding.*



R. C. Robertson, Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor. ORNL-4541, **(1971)**

F.II.3. Homogeneous fluoride fast MSRs

PSI

Fluoride fast Th-U breeder

Pu containing fluoride fast rector

Types definition: *By fuel cycle type (Th-U breeder, enr. U converter, burner)*

Primary heat exchange: *Ex core*

Heat convection by fuel: *Yes*

Fuel form: *Ac. diluted in fluorides salts, for breeders it is typically ^{7}**LiF** (FLiNa, FNaK?)*

Struct. material in core: *No, homogeneous salt-filled core*

Neutronic performance: *Breeder, converter, dedicated burner*

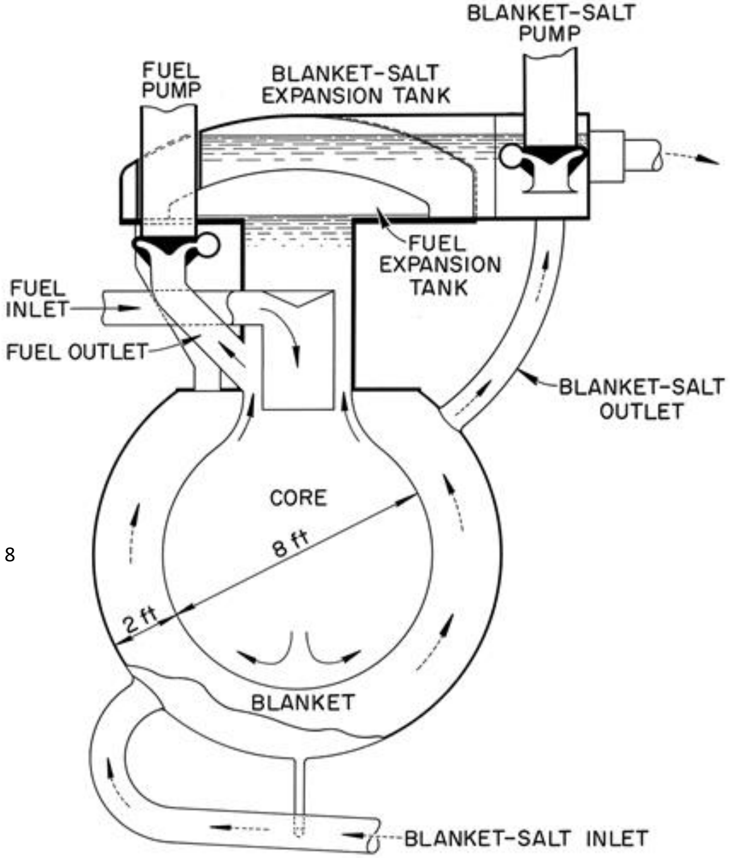
Self-sustaining breeding: *Can be achieved*

Major fuel cycle: *Closed Th-U (U-Pu), enr. U converter, burner*

Leakage utilization: *Blanket, Reflector (Hastelloy)*

Characteristic:

- *Hastelloy vessel is exposed to neutron flux and should be regularly replaced.*
- *Moderation power of ^{7}LiF:*
  - → *Softest fast spectra.*
  - → *Low transparency for neutrons.*
  - → *Possibility of compact cores.*



MACPHERSON, H. G., Rep. ORNL-2474, Oak Ridge Natl Lab., TN (1958)

F.II.4. Homogeneous chloride fast MSRs

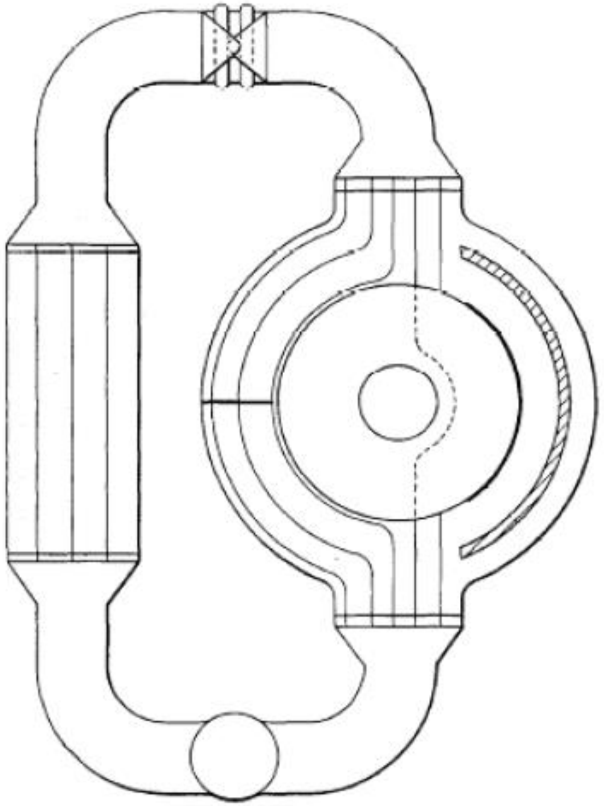
PSI

Chloride fast breeder reactor

Chloride fast breed & burn reactor

Types definition: *By fuel cycle type (U-Pu breeder or breed & burn cycle)*
Primary heat exchange: *Ex core*
Heat convection by fuel: *Yes*
Fuel form: *Ac. diluted in chloride salts, for breeders it is typically* ***$Na^{37}Cl$***
Struct. material in core: *No, homogeneous salt-filled core*
Neutronic performance: *Breeder, Breed and Burn*
Self-sustaining breeding: *Can be achieved*
Major fuel cycle: *Closed U-Pu or Breed-and-Burn U-Pu*
Leakage utilization: *Blanket, Reflector (lead?)*
Characteristic:

- *Reactor vessel is exposed to neutron flux and should be regularly replaced.*
- *Absence of scattering / moderation power:*
  - → *Transparent for neutrons.*
  - → *Hardest spectra from all fast reactors.*
  - → *Large reactor cores, unsuitable for Th-U cycle.*



Bulmer J, et al., Fused Salt Fast Breeder. ORNL, CF-56-8-204, (**1956**)

F.III.5. Non-graphite moderated MSRs

Solid moderator heterogeneous MSR

Liquid moderator heterogeneous MSR

Types definition: *By moderator state (solid or liquid moderator)*

Primary heat exchange: *Ex core**

Heat convection by fuel: *Yes**

Fuel form: *Ac. diluted in fluorides salts, for breeders it is exclusively* $^7LiF\text{-}BeF_2$ *(*^7LiF*?)*

Struct. material in core: *Yes, for separation of fuel salt and moderator*

Neutronic performance: *Converter, burner*

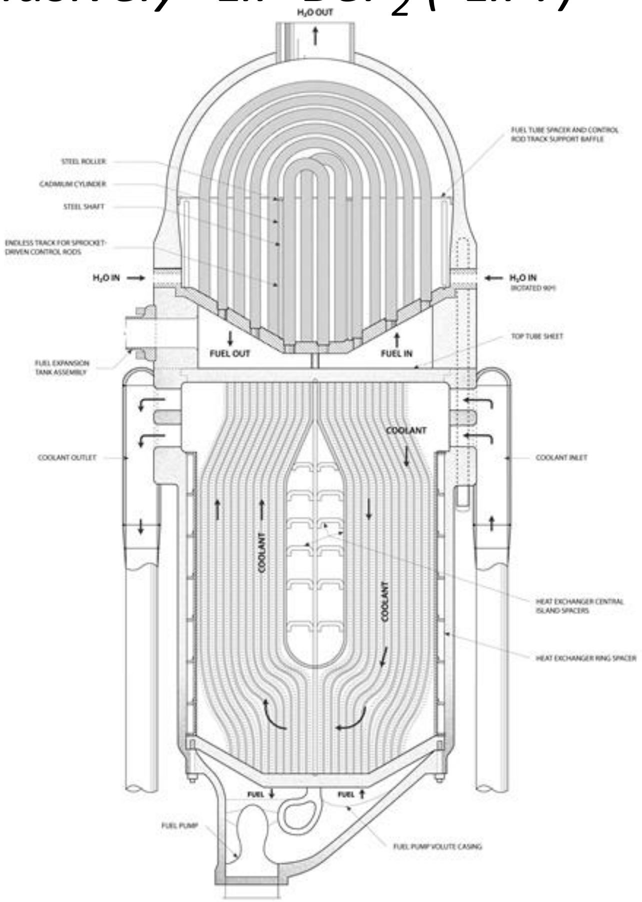
Self-sustaining breeding: *Impossible or very demanding***

Major fuel cycle: *Closed Th-U**, enr. U converter, burner*

Leakage utilization: *Reflector (moderator)*

Characteristic:

– *Moderator requires structural material for separation:*
  - → *Limited life-span of separation material.*
  - → *Determination of neutronic performance.*



* *Unless if liquid moderator acts as coolant.*

** *Relying on low capture structural material (SiC?).*

FRAAS, A.P., SAVOLAINEN, A.W., Rep. ORNL-1721, Oak Ridge Natl Lab., TN (**1954**)

F.III.6. Heterogeneous chloride fast MSRs

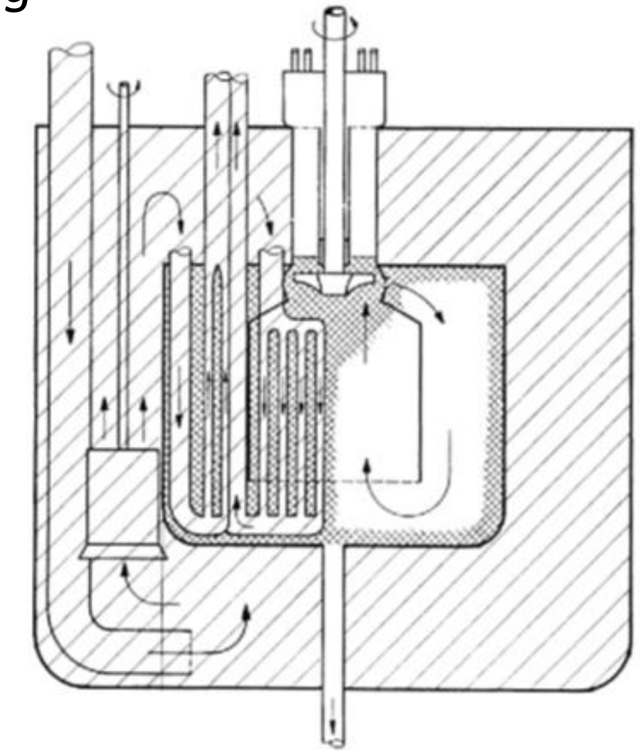
PSI

Heterogeneous salt cooled fast MSR

Heterogeneous lead cooled fast MSR

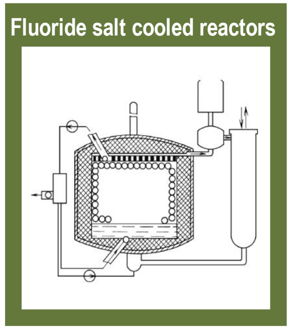
Types definition: *By dedicated coolant type (salt or lead cooled)*
Primary heat exchange: *In core*
Heat convection by fuel: *Usually no, dedicated coolant*
Fuel form: *Ac. diluted in chloride salts, for breeders it is typically* ***Na^{37}Cl***
Struct. material in core: *Yes, for separation of fuel salt and dedicated coolant*
Neutronic performance: *Converter, Breeder, Breed and Burn is demanding*
Self-sustaining breeding: *Can be achieved*
Major fuel cycle: *Closed U-Pu or enr. U burning*
Leakage utilization: *Blanket, Reflector (lead?)*
Characteristic:

– *Coolant requires structural material for separation:*
  → *Limited life-span of separation material.*
  → *Reduced neutronic performance.*
  → *It provides additional scattering XS.*
  → *Possibly smaller cores that homogeneous chloride fast MSRs.*

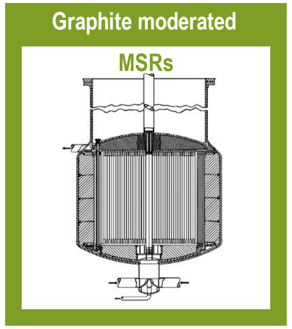


Taube M and Ligou J, Report EIR-215 Wurenlingen, Switzerland (**1972**).

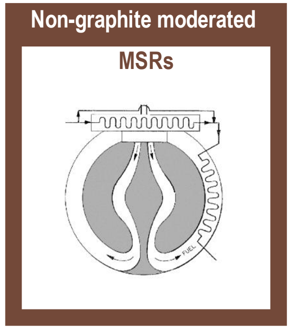
Salts for 6 MSR families



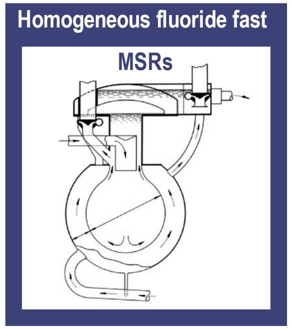
*^{7}**LiF-BeF$_2$** has certain moderation power, hence it has **negative density effect** on reactivity. Therefore, it is exclusively used as a dedicated coolant in FHR.*



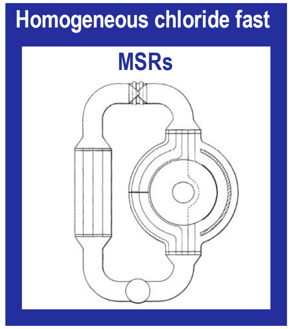
*^{7}**LiF-BeF$_2$** or ^{7}**LiF** are the only two carrier salts, which can be used to achieve breeding in Th-U cycle. For other cycles other cations like Mg, Na or K can be used.*



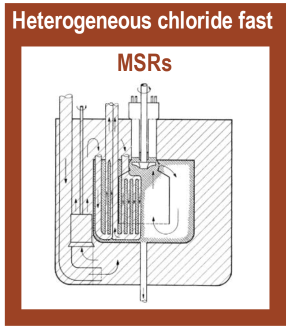
*Other moderators than graphite needs cladding or coating, which can increase neutron capture. Breeding is achievable with ^{7}**LiF-BeF$_2$** or ^{7}**LiF** salts and SiC based cladding for moderators based on Be and D_2O.*



*Be has certain moderation power, ^{7}**LiF-BeF$_2$** or **NaF-BeF$_2$** should be avoided in breeders.*
*^{7}**LiF** can be used to achieve Th-U breeding.*
***LiF-NaF** or **KF-NaF** have lower performance.*
U-Pu cycle in fluorides is possible, but the performance suffers by softer neutron spectrum.



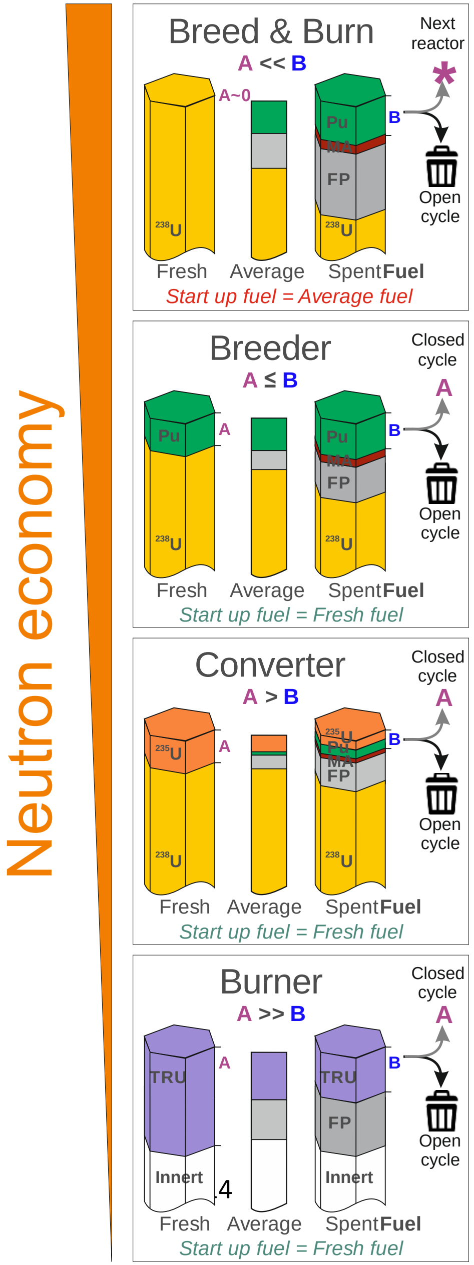
*Fast moderating power of Chlorine is 1/5 of theone for Fluorine and it does not have strong scattering resonances. Hence the spectrum in chlorides is much harder. Many **different cations can be used** for closed U-Pu cycle. **Na^{37}Cl** salt has one of the best performance and can be used also in breed-and-burn cycle (or Th-U closed cycle).*



*Hard spectrum of chlorides provides neutron excess and U-Pu breeding can be achieved also in reactors with dedicated coolant and separation material in the core. **Na^{37}Cl** salt could be needed to compensate the other neutron losses.*

Fuel cycle

MSR fuel cycle choices and options



- The carrier salt (liquid fuel solvent) is an ionic liquid and can be irradiated without a limit.
- No matter the fuel cycle, it is always good to keep actinides as long as possible in the reactor (high burnup).
- At best only Fission Products (FPs) should leave the core.
- Unfortunately, FPs (Lanthanides) tends to leave the fuel salt as last.
- In any fuel cycle, core with higher actinides load could be designed as smaller.
- Actinides density collides with salt melting temperature and potentially also with solubility limits (solidus – liquidus temperature gap?).
- Concept capable to operate in Breed-and-burn cycle can be also designed as breeder, converter or burner.
- Concept designed as burner or converter are not necessarily capable of breeding or breed-and-burn operation mode.

Salts reprocessing method

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Fuel salts components:

1. Carrier salt (LiF, NaCl,…)
2. Fertile actinides (^{232}Th and ^{238}U).
3. Fissile actinides (^{233}U and ^{239}Pu).
4. Minor actinides (MA).
5. FPs.

Salt treatment / reprocessing techniques:

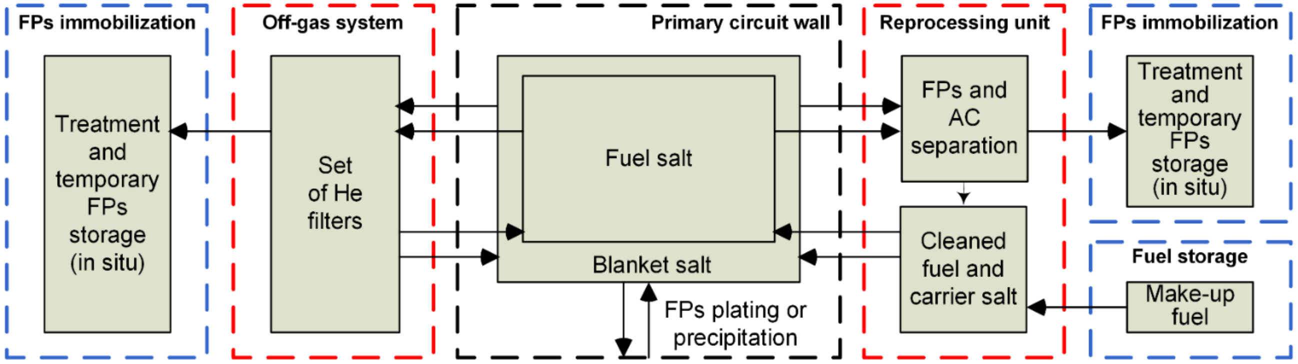
- Gaseous and volatile FPs removal (off-gas system).
- Metallic FPs removal (sponge filter or by off-gas sys.).
- Molten salt / liquid metal reductive extraction.
- Electro-separation processes.
- Compound evaporation or possibly precipitation.
- Fluoride volatilization techniques, fluorination of the molten salt mixture.

Salt removal from the core	Removed salt share	Fissile fuel recycling	Fissile fuel return after reprocessing	Carrier salt cleaning	Carrier salt return after reprocessing	Reprocessing waste immobilization
Continuous or Batch-wise	From 0.1% to whole salt volume	In-situ or Ex-situ	ASAP or with months or years of delay	In-situ or Ex-situ	ASAP or with months or years of delay	In-situ or Ex-situ

FPs mass evolution in MSFR systems

Top 15 decay chains (the same A) according to ingestion radiotoxicity.

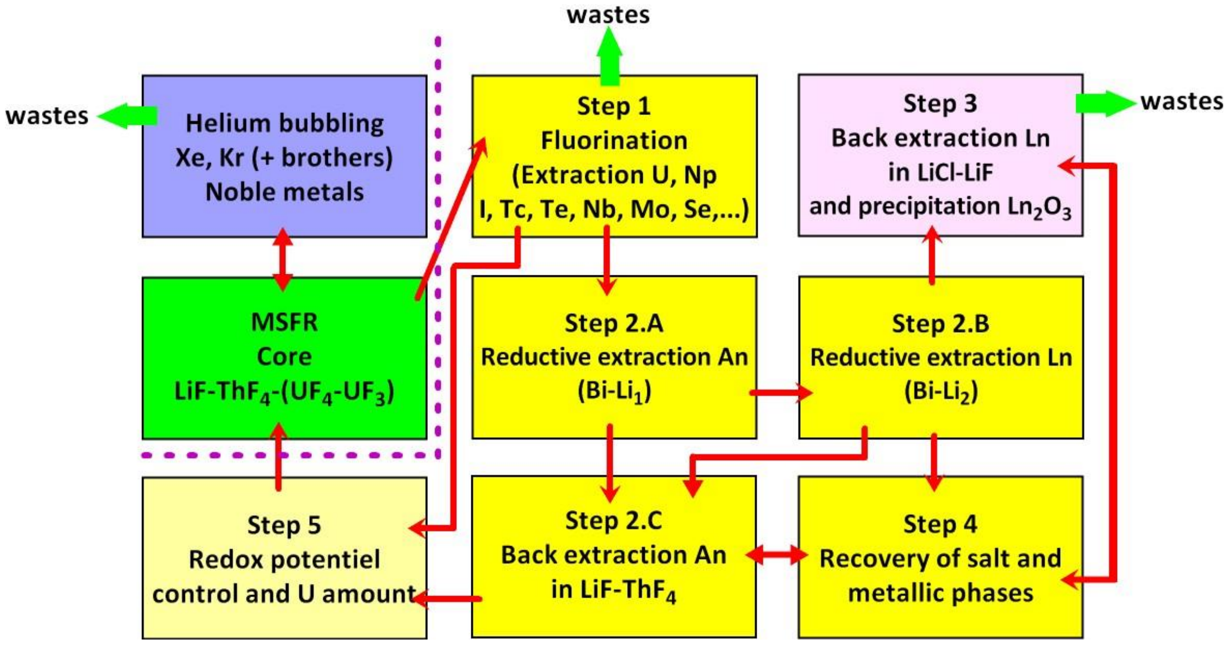
The off-gas system dominates in many cases.

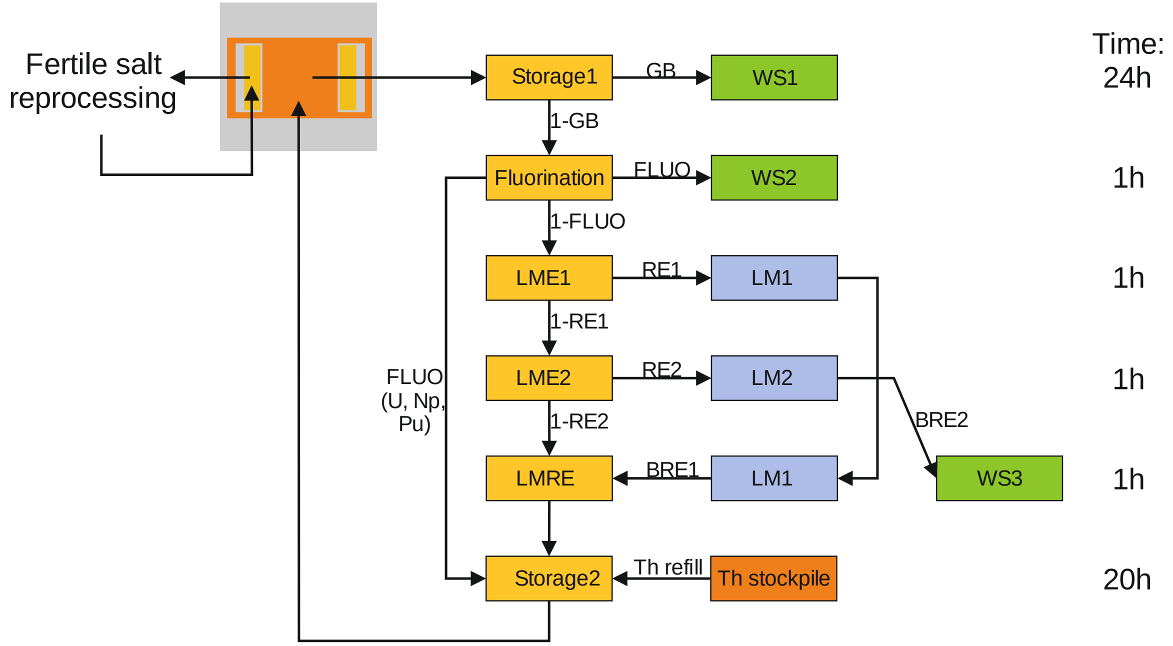


Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Atomic number	233	131	90	137	140	133	144	91	132	89	143	97	95	93	141
Nuclides	233Th 233Pa	131Cd 131In 131Sn 131Sb 131Te-m 131Te 131I 131Xe-m	90Se 90Br 90Kr 90Rb-m 90Rb 90Sr 90Y	137Sn 137Sb 137Te 137I 137Xe 137Cs 137Ba-m	140Te 140I 140Xe 140Cs 140Ba 140La	133In 133Sn 133Sb 133Te-m 133Te 133I 133Xe-m 133Xe	144Xe 144Cs 144Ba 144La 144Ce 144Pr-m 144Pr 144Nd	91Se 91Br 91Kr 91Rb 91Sr 91Y	132In 132Sn 132Sb-m 132Sb 132Te 132I 132Xe 132Cs	89As 89Se 89Br 89Kr 89Rb 89Sr 89Y-m	143Xe 143Cs 143Ba 143La 143Ce 143Pr 143Nd	97Kr 97Rb 97Sr 97Y 97Zr 97Nb-m 97Nb	95Kr 95Rb 95Sr 95Y 95Zr 95Nb-m 95Nb 95Mo	93Br 93Kr 93Rb 93Sr 93Y 93Zr 93Nb-m	141I 141Xe 141Cs 141Ba 141La 141Ce
Half-lives	22m 27d	0.106s 0.28s 39s 23.0m 1.35d 25.0m 8.040d 11.9d	0.427s 1.9s 32.3s 4.3m 2.6m 29.1y 2.67d	- 0.478s 2.5s 24.5s 3.82m 30.17y 2.552m	0.894s 0.86s 13.6s 1.06m 12.75d 1.678d	0.18s 1.44s 2.5m 55.4m 12.4m 20.8h 2.19d 5.243d	1.2s 1.01s 11.4s 40.7s 284.6d 7.2m 17.28m 15.32l	0.27s 0.54s 8.6s 58.0s 9.5h 58.5d	0.20s 40s 2.8m 4.2m 3.26d 2.28h stable 6.475d	0.121s 0.41s 4.37s 3.15m 15.4m 50.52d 15.7s	0.30s 1.78s 14.3s 14.1m 1.38d 13.57d stable	0.1s 0.169s 0.42s 3.76s 16.8h 58.1s 1.23h	0.78s 0.377s 25.1s 10.3m 64.02d 3.61d 34.97d stable	0.176s 1.29s 5.85s 7.4m 10.2h 1.5e6y 12y	0.45s 1.72s 24.9s 18.3m 3.90h 32.50d
Total ingestion radiotoxicity (Sv)	**9.2E+10**	**7.7E+10**	**7.3E+10**	**3.0E+10**	**2.8E+10**	**2.5E+10**	**2.4E+10**	**1.9E+10**	**1.8E+10**	**1.6E+10**	**1.3E+10**	**1.1E+10**	**9.5E+09**	**7.9E+09**	**6.9E+09**
Off-gas system (%)	0.0	**67.0**	**38.3**	**82.1**	**11.0**	**37.7**	0.0	**9.6**	**98.6**	**75.4**	0.0	**89.5**	**97.2**	0.2	0.6
Fuel in core (%)	**90.7**	**32.1**	**20.6**	2.1	**88.1**	**61.9**	**66.2**	**87.7**	1.4	**23.8**	**98.2**	**10.5**	2.8	**99.4**	**95.7**
Reprocessing unit (%)	0.1	0.8	**40.9**	**15.8**	0.5	0.2	**33.4**	2.3	0.0	0.8	1.4	0.0	0.0	0.0	3.4
Fuel in blanket (%)	**9.2**	0.1	0.2	0.1	0.3	0.2	0.4	0.3	0.0	0.1	0.4	0.0	0.0	0.4	0.4

Reprocessing scheme of MSFR fuel salt

(chemical versus physical perspective)

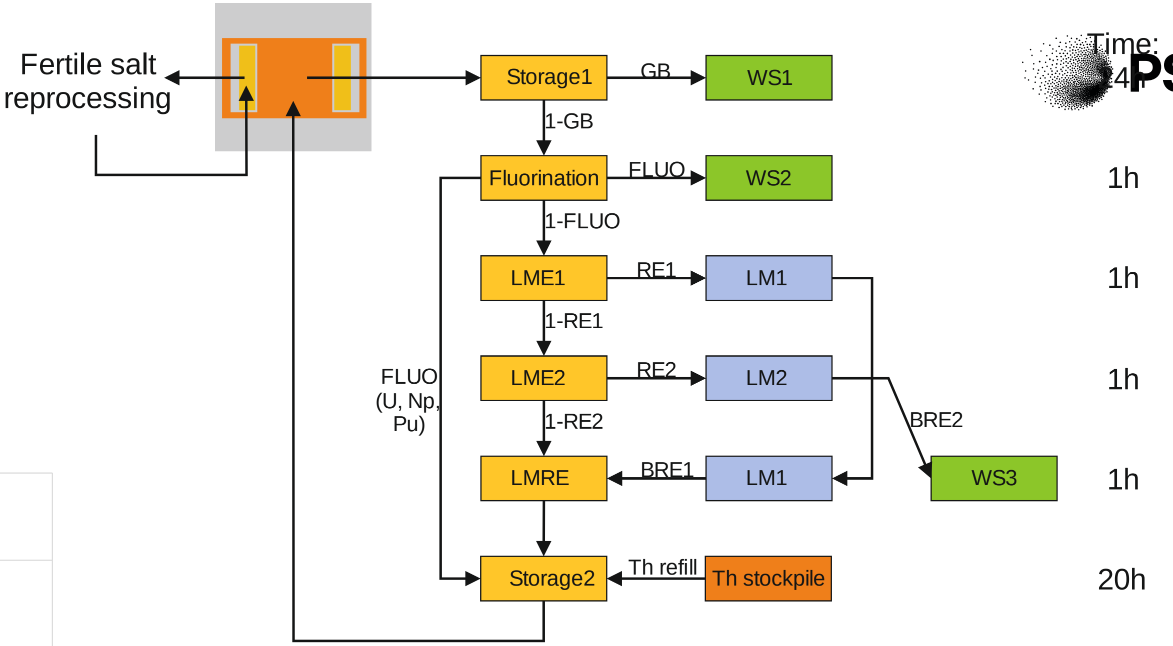


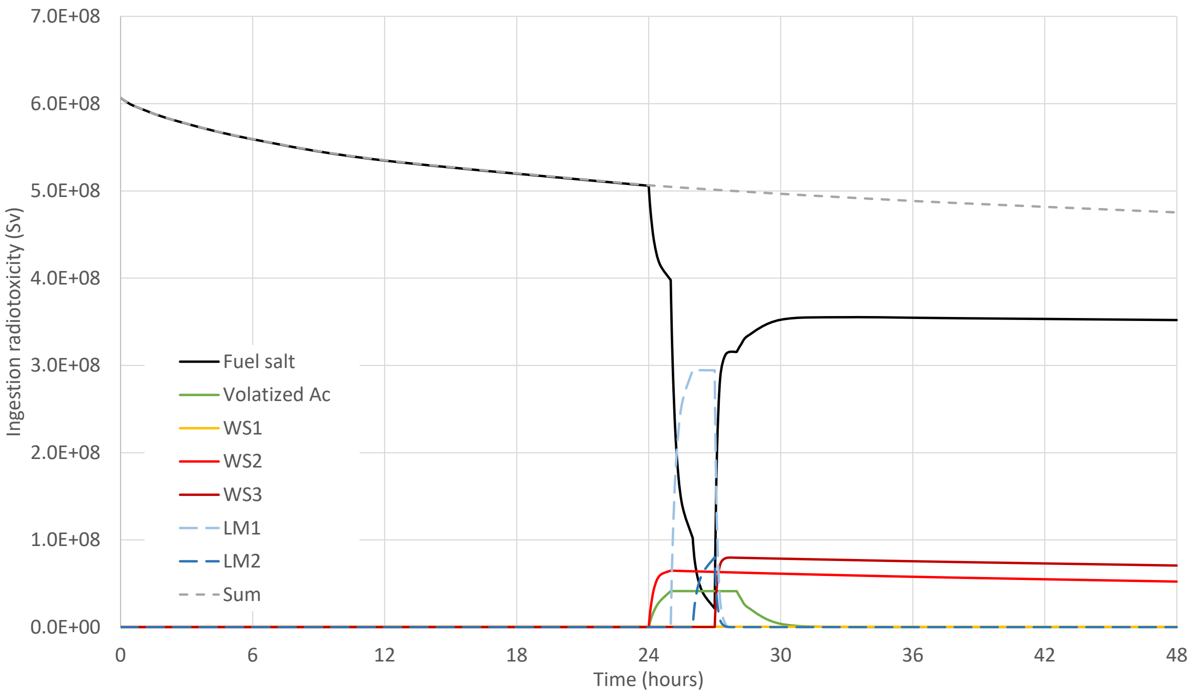


Alexis de Villepin, Internship Report, PSI, 2024

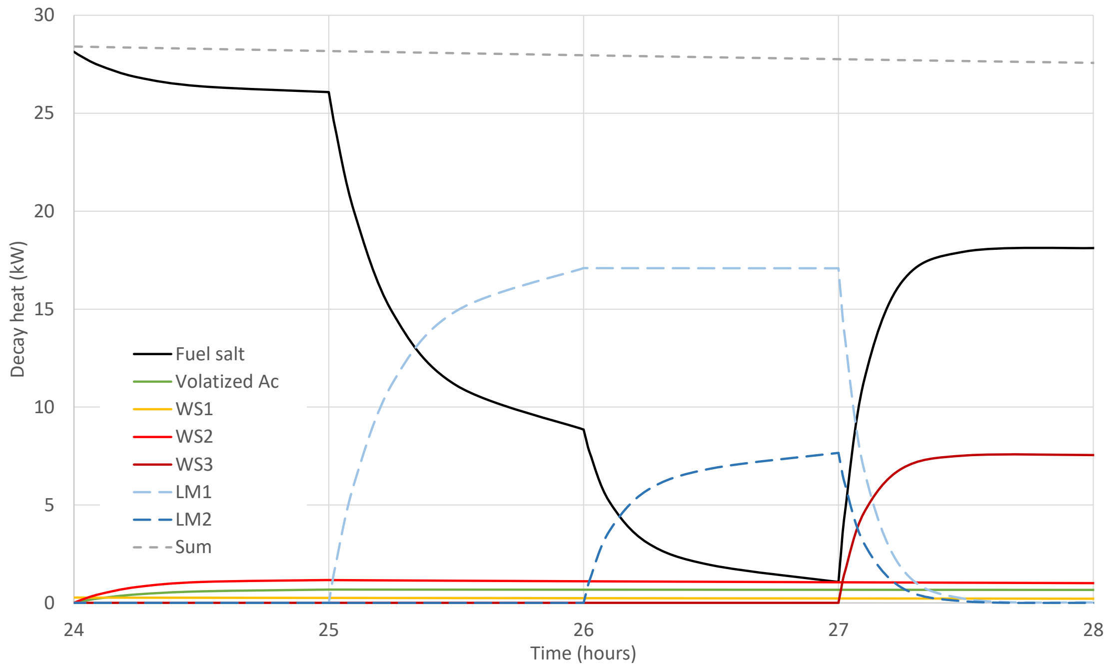
FPs mass evolution in reprocessing systems

- Decay heat and radiotoxicity distribution in the MSFR reprocessing system.





Distribution of ingestion radiotoxicity during the 48 hours of salt residence time in reprocessing unit.



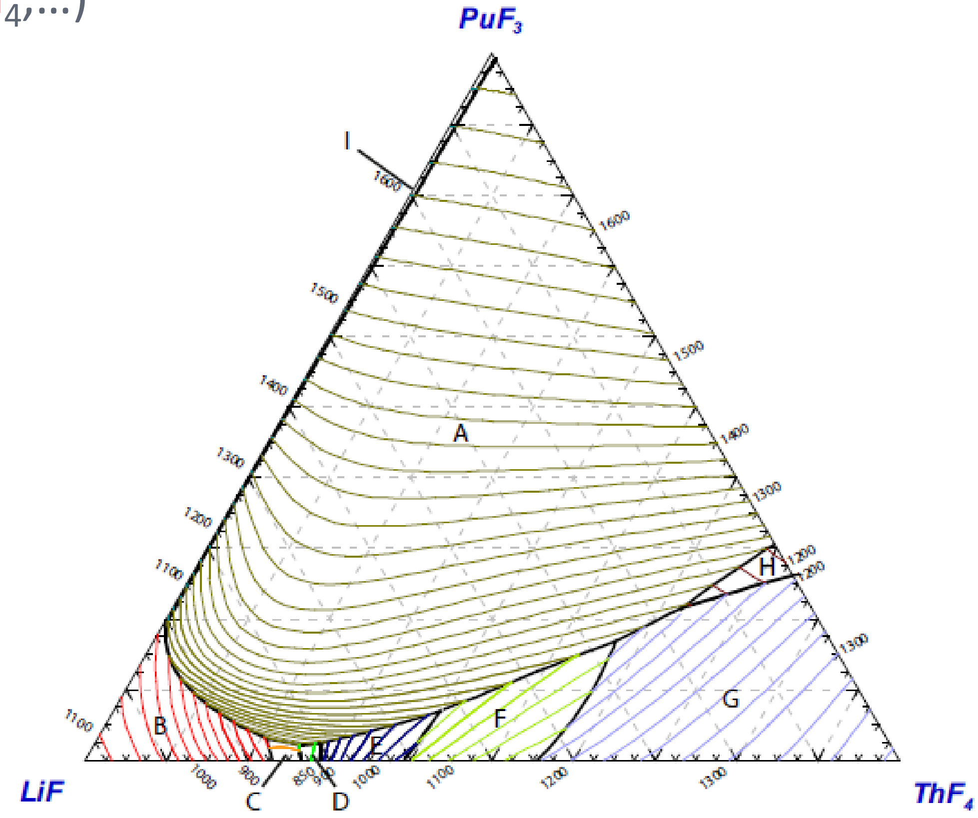
Distribution of decay heat during the 4 hours of salt processing.

Actinides content versus liquidus temperature

Reasonable temperature window for operation:

interval between salt melting and structural materials failure

- Typically eutectic mixture of carrier salts (LiF, BeF_2, NaF, LiCl, NaCl,…) and actinides salts (ThF_4, UF_4, PuF_3, $PuCl_3$, UCl_3, $ThCl_4$,…)
- **MSRE** salt, **$T_{melt.}$=432°C**
  65%LiF - 29.1BeF_2 - 5%ZrF_4 - 0.9%UF_4
- **MSBR** , Th-U equilibrium cycle, **$T_{melt.}$=500°C**
  71.7%LiF - 16%BeF_2 - 12%ThF_4 - 0.3%UF_4
- **MSFR**, Th-U equilibrium cycle, **$T_{melt.}$=560°C**
  78%LiF - 17.6%ThF_4 - 4%UF_4 - 0.2%PuF_3
- **MSFR**, Pu started Th-U cycle, **$T_{melt.}$=625°C**
  78%LiF - 16%ThF_4 - 6%PuF_3
- **MCFR**, Pu started U-Pu cycle, **$T_{melt.}$=565°C**
  60%NaCl - 35%UCl_3 - 5%$PuCl_3$
- **MCFR**, Pu started Th-U cycle, **$T_{melt.}$=425°C**
  55%NaCl - 39%$ThCl_4$ - 6%$PuCl_3$
- Generally **solubility limits** (e.g. PuF_3) and **actinides density** compete with **melting temperature**.

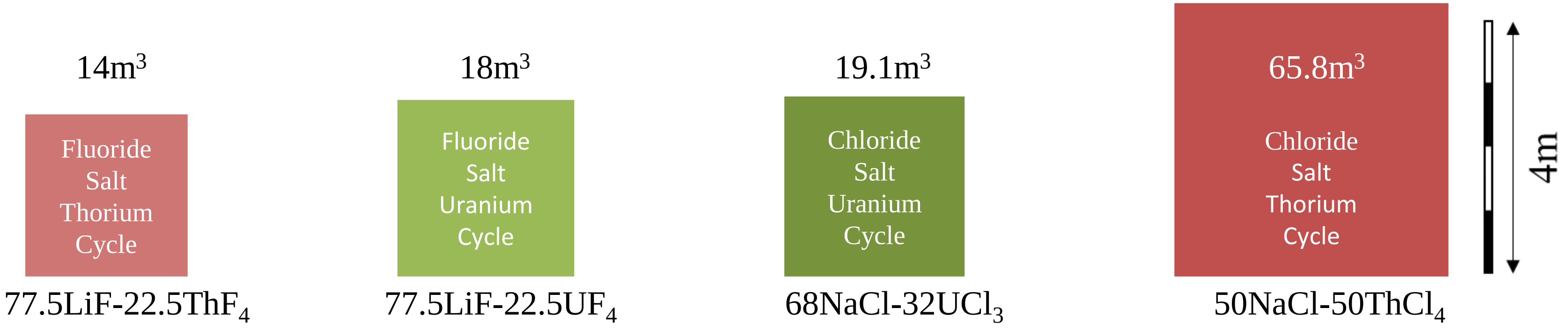


LiF-ThF_4-PuF_3 ternary phase diagram w/ fixed 1% mol UF_4 concentration

*E. CAPELLI et al., "Thermodynamic Assessment of the LiF–ThF4–PuF3–UF4 System," J. Nucl. Mater., **462**, 43 (2015).*

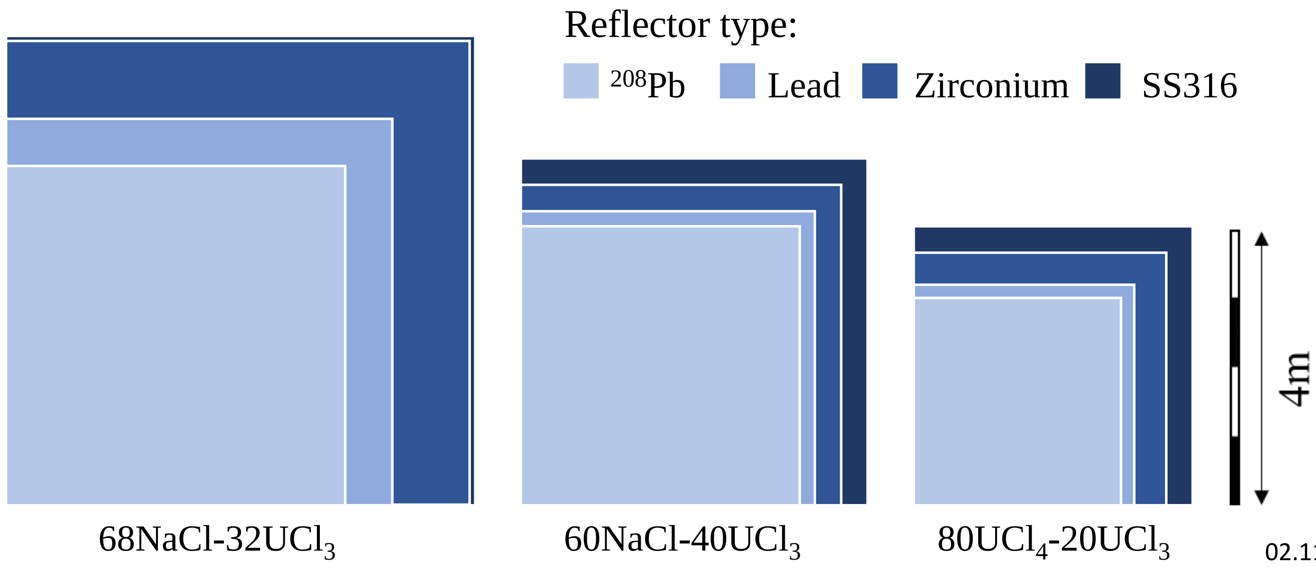
Core size comparison for closed and open B&B cycle

- Closed cycle



- Breed and burn open cycle

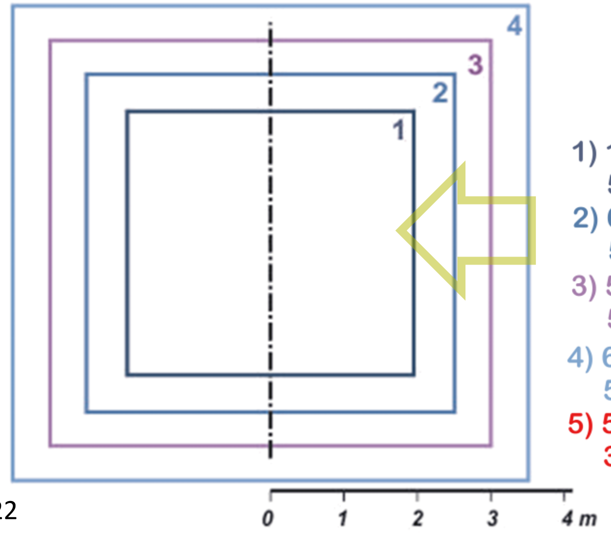
Critical core sizes



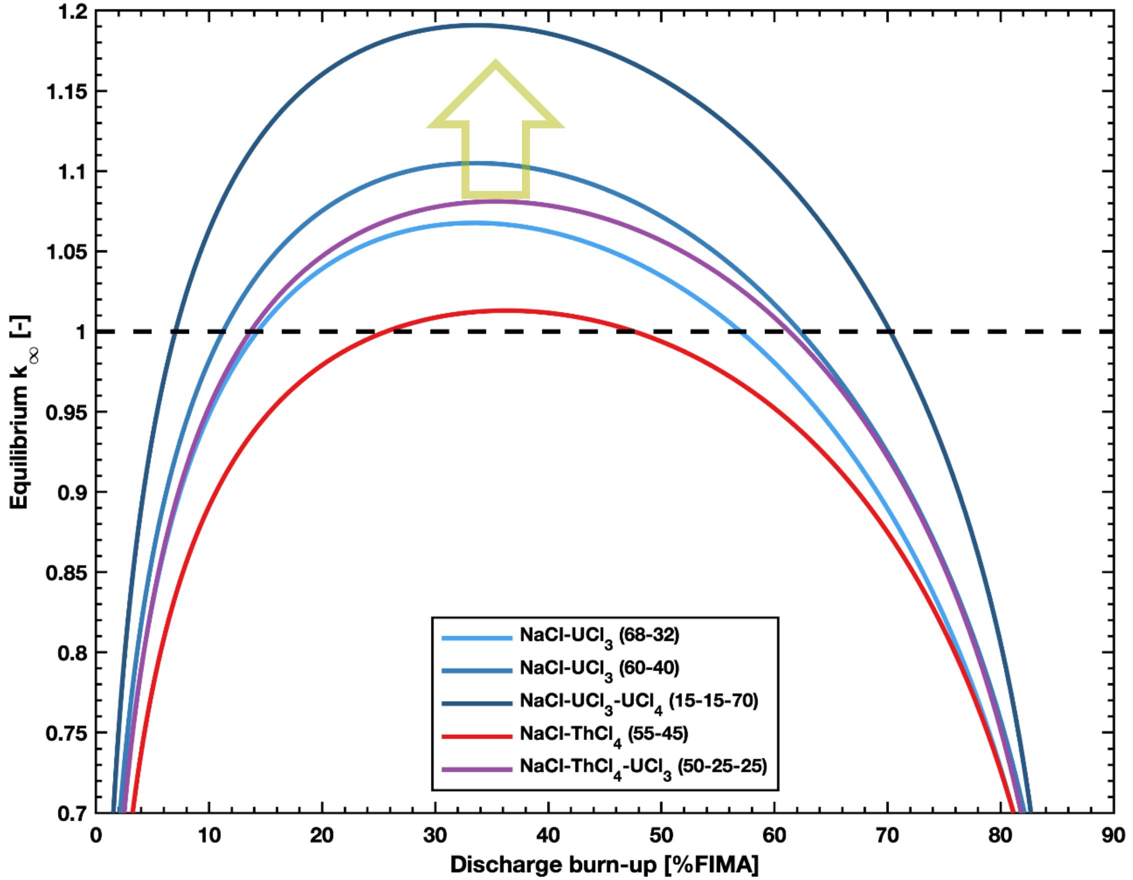
Hombourger, B.A., 2018. Ph.D. Thesis. EPFL Lausanne, Switzerland.

Self-sustaining breeder in open cycle (B&B)

- B&B is practically not possible in Th-U cycle.
- It is only possible in mixed U-Pu & Th-U cycle.
- B&B cores are bulky (chlorides = hard spectrum, but also high Migration area).
- The performance increases with growing actinides share in the core.



1) 15%NaCl-15%UCl3-70%UCl4
500°C
2) 60%NaCl-40%UCl3
590°C
3) 50%NaCl-25%UCl4-25%ThCl3
500°C
4) 68%NaCl-32%UCl3
520°C
5) 55%NaCl-45%ThCl4
375°C - not critical



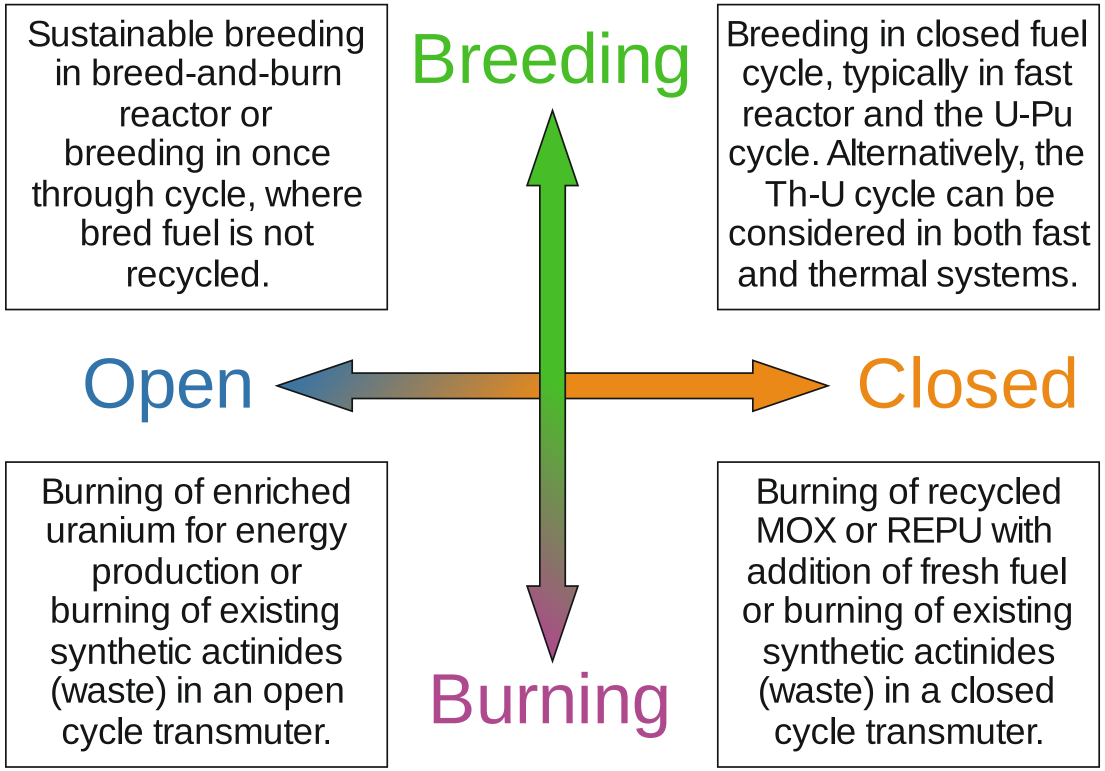
There exist **temperature window** for MSR operation determined by:

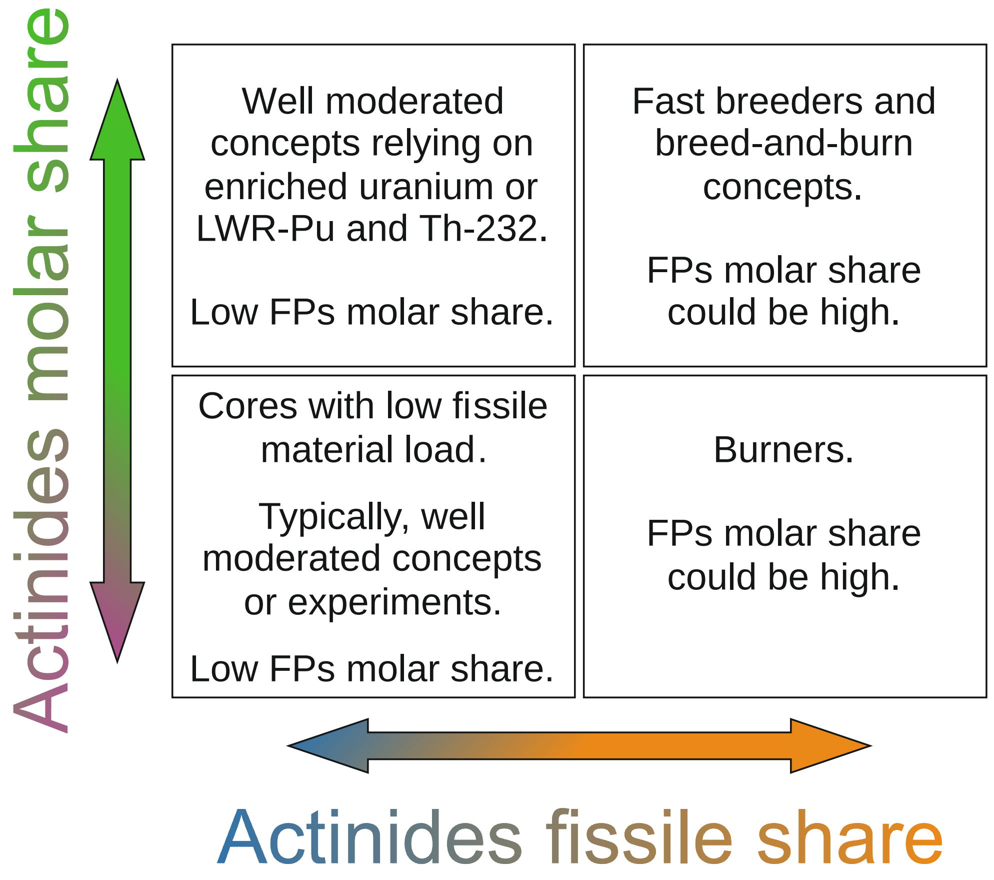
1. Salt liquidus temperature
2. Material structural integrity

!

Hombourger, B. et al., 2019. Breed-and-Burn Fuel Cycle in Molten Salt Reactors. Submitted to special MSR edition of The European Physical Journal

Two independent crosses for salt classification

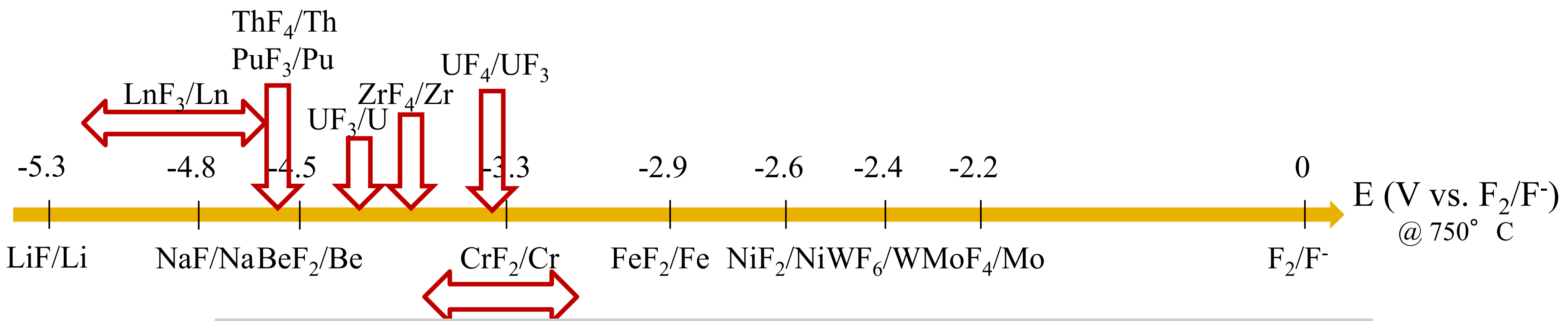




Salt redox (&reprocessing)
versus source term retention retention

Redox window for operation

- Similarly, like the temperature window for MSR, there is Redox window.
- It is determined by salt species reduction on one side and structural materials and salt species oxidation on the other side.
- Redox control is important for limiting the structural materials corrosion.
- It is also important in accidental conditions to limit the source term mobility.



Relative stability of redox couples, Gibbs energy : $\Delta E\ (V) = -\Delta_r G(J/mol)/nF$, $E°(F_2/F^-) = 0$ V

Adopted from: Laurent Cassayre, LGC.CNRS.FR, Corrosion in molten salt reactors, EVOL Winter School, 4-6 November 2013, IPNO, France

Redox window: volatilization

- Speciation of elements in the core for $UF_4/UF_3 \in [10, 100]$ $E\ (V) \in [-3.44, -3.24]$

H2(g)					No data	gaz	solid	salt	liquid								He(g)
LiF	BeF2											BF3(g)	C(-IV)	N2(g)	O(-II)	F(-I)	Ne(g)
NaF	MgF2											AlF3	SiF4(g)	PF3(g)	S2(g)	Cl(-I)	Ar(g)
KF	CaF2	ScF3	TiF3	VF2	CrF2	MnF2	FeF2	Co(s)	Ni(s)	Cu(s)	Zn(l)	Ga(l)	Ge(l)	As4(g)	Se2(g)	Br(-I)	Kr(g)
RbF	SrF2	YF3	ZrF4	Nb(s)	Mo(s)	Tc(s)	Ru(s)	Rh(s)	Pd(s)	Ag(l)	Cd(l)	In(l)	Sn(l)	Sb(l)	Te(l)	I(-I)	Xe(g)
CsF	BaF2	LaF3	HfF3	Ta(s)	W(s)	Re(s)	Os(s)	Ir(s)	Pt(s)	Au(s)	Hg(s)	Tl(s)	Pb(l)	Bi(l)	Po(l)	At2(g)	Rn(g)
FrF	RaF4	AcF3															
			CeF3	PrF3	NdF3	PmF3	SmF3	EuF3	GdF3	TbF3	DyF3	HoF3	ErF3	TmF3	YbF3	LuF3	
			ThF4	PaF4	UF4-UF3	NpF3	PuF3	AmF3	CmF3	BkF3	CfF3	EsF3	FmF3	MdF3	NoF3	LrF3	

- Speciation of elements in the volatilization unit.

HF(g)				·	No data	gaz	solid	salt	liquid	fluorinated							He(g)
LiF	BeF2											BF3(g)	CF4(g)	N2(g)	O(-II)	F2(g)	Ne(g)
NaF	MgF2											AlF3	SIF4(g)	PF5(g)	SF6(g)	Cl(-I)	Ar(g)
KF	CaF2	ScF3	TiF4(g)	VF4(g)	CrF6(g)	MnF4(g)	FeF2(g)	CoF3	NiF2	CuF2	ZnF2	GaF3(g)	GeF4(g)	AsF5(g)	SeF6(g)	BrF5(g)	Kr(g)
RbF	SrF2	YF3	ZrF4	NbF5(g)	MoF6(g)	TcF6(g)	RuF5(g)	RhF4(g)	PdF3(g)	AgF(g)	CdF2	InF3	SnF4(g)	SbF5(g)	TeF6(g)	IF5(g)	Xe(g)
CsF	BaF2	LaF3	HfF4	TaF5(g)	WF6(g)	ReF7(g)	OsF6(g)	IrF4(g)	PtF4(g)	AuF3	HgF2(g)	TlF3	PbF4(g)	BiF3(g)	PoFx	At2(g)	Rn(g)
FrF	RaF4	AcF3															
			CeF4(g)	PrF3	NdF3	PmF3	SmF3	EuF3	GdF3	TbF3	DyF3	HoF3	ErF3	TmF3	YbF3	LuF3	
			ThF4	PaF4	UF6(g)	NpF6(g)	PuF6(g)	AmF3	CmF3	BkF3	CfF3	EsF3	FmF3	MdF3	NoF3	LrF3	

Redox window: volatilization

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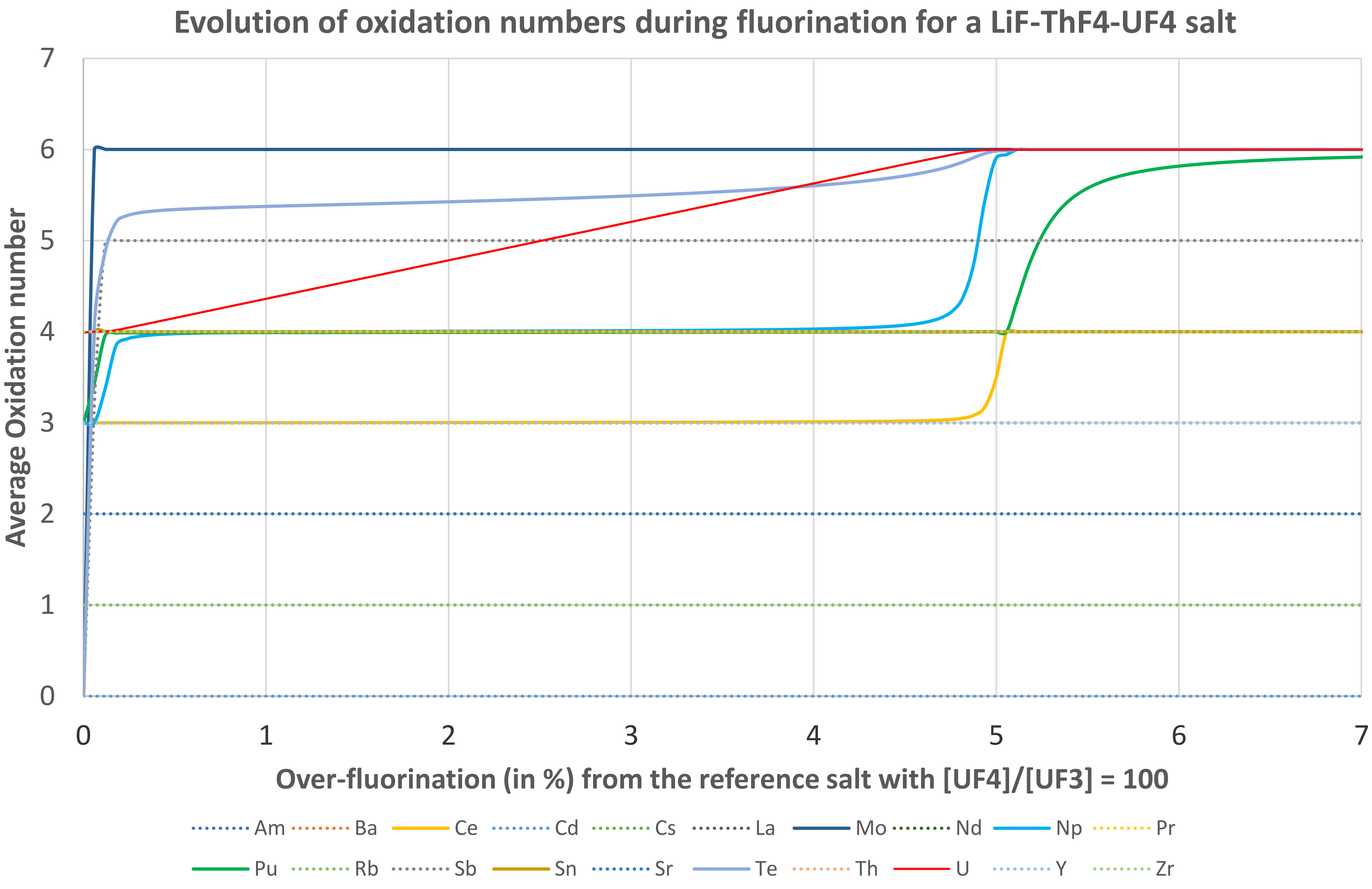
- Evolution of the oxidation number of the nuclides during fluorination



Alexis de Villepin, Internship Report, PSI, 2024

Summary

- High salt density (actinides molar share) can result in smaller reactor cores.
- It however compete with liquidus temperature.
- Density is thus limited to ranges close to eutectic composition.

- There exist temperature design window between liquidus temperature and material structural integrity.
- There exist redox design window between salt species reduction and structural material oxidation.

- Redox change can be used as separation technique.
- Reprocessing strategy during nominal operation influences source term during accident.

Center for Scientific Computing, Theory and Data

Thank you

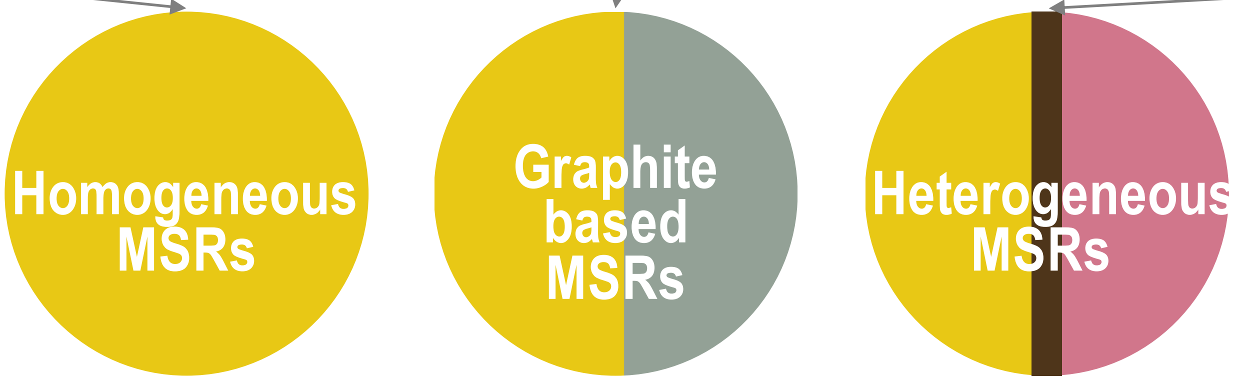
Jiri Krepel, Sergii Nichenko, Mateusz Malicki, Alexis de Villepin
21 July – 25 July 2025, IAEA, Vienna

IAEA MSR Taxonomy: basic features

- Fluoride or Chloride salts acting as fuel and coolant.
- Fast spectrum
  (epithermal with Be)
- Chlorides:
  U-Pu, hard spectrum, transparent for neutrons.
- Fluorides:
  Th-U, softer spectrum, scattering neutrons.
- F and Cl mixture or other salts/halides usually not considered.
- Regular vessel replacement.

- Fluoride salt. *(high Cl neutron captures)*
- Possibility of Th-U cycle.
  (demanding, fast fuel cleaning needed)
- LEU fuel cycle.
- In case of solid fuel embedded in graphite, only moderating salts, like LiF-BeF_2, provides negative density effect.
- Regular graphite replacement.

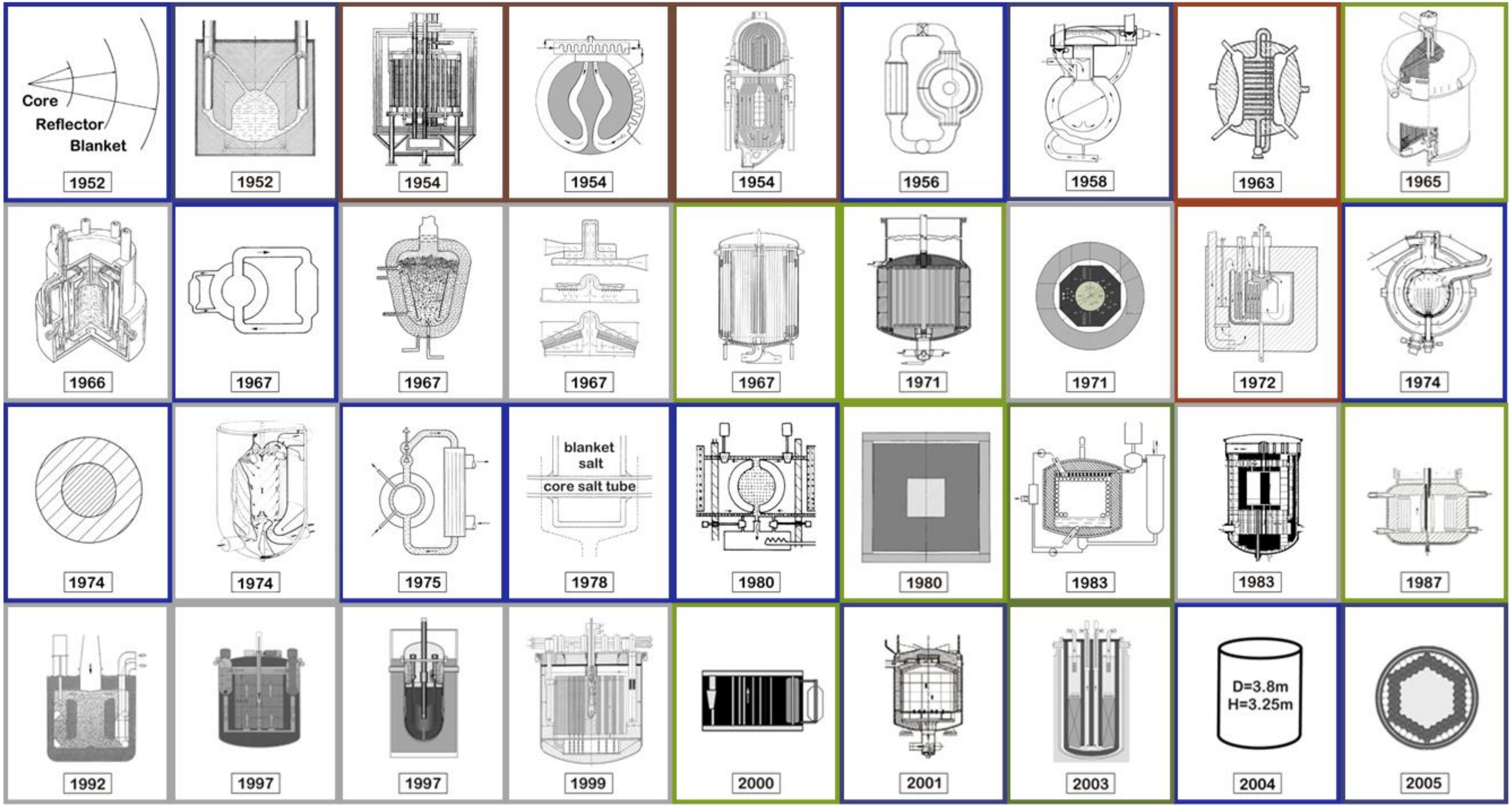
- Parasitic neutron capture of separating material. *(composites?)*
- Material choice determines breeding capability.
- Fluoride salt for moderated systems. *(high Cl neutron captures)*
- Chloride salts for fast systems. *(reactivity excess needed)*
- In case of two liquids, cooling can be distributed.
- Regular structural material replacement.



Past concepts

PSI

	I. 1. Fluoride salt cooled reactors	I. 2. Graphite moderated MSRs	II. 3. Homogeneous fluoride fast MSRs	II. 4. Homogeneous chloride fast MSRs	III. 5. Non-graphite moderated MSRs	III. 6. Heterogeneous chloride fast MSRs	IV. Other MSRs
Number of concepts (1950-2010):	2	6	4	9	3	2	10



Recent concepts

	I. 1. Fluoride salt cooled reactors	I. 2. Graphite moderated MSRs	II. 3. Homogeneous fluoride fast MSRs	II. 4. Homogeneous chloride fast MSRs	III. 5. Non-graphite moderated MSRs	III. 6. Heterogeneous chloride fast MSRs	IV. Other MSRs
Number of concepts (2010-2020):	3	6	3	5	4	4	0

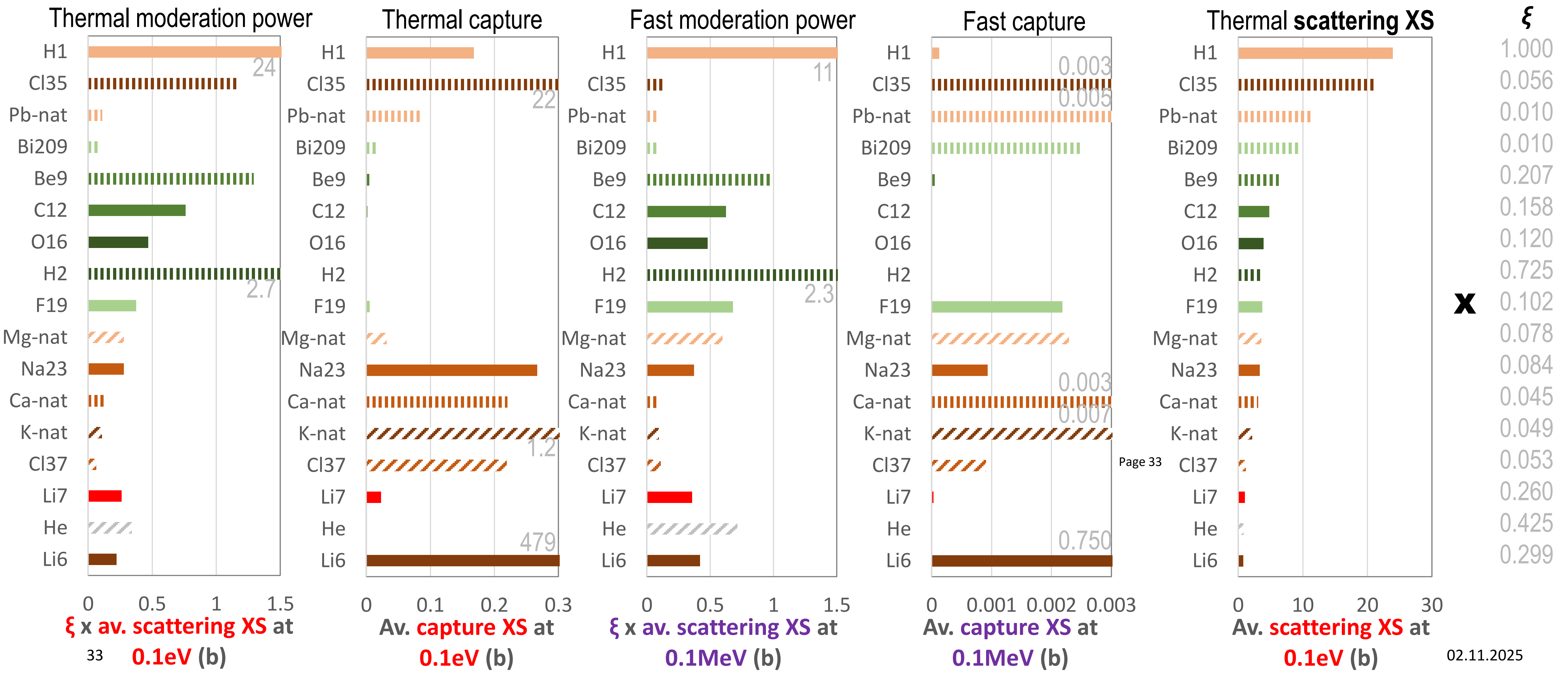
Year	Class	Family	Description	Concept	Developer
2010	I. Class	1. Family	Salt cooled reactor with fixed fuel	**AHTR, SmAHTR**	ORNL
			GREENE, S. R., et al., Pre-Conceptual Design of a Small Modular Fluoride Salt-Cooled High Temperature Reactor (SmAHTR), Rep. ORNL/TM-2010/199, Oak Ridge Natl Lab., TN (2010).		
2011	I. Class	2. Family	Two-fluids Th-U breeder	**LFTR**	Flibe Energy
			SOWDER, A., et al., Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design, The Liquid-Fluoride Thorium Reactor (LFTR), Rep. EPRI-3002005460 (2015).		
2013	III. Class	5. Family	Solid moderator heterogeneous MSRs	**TAP**	Transatomic Power
			MASSIE, M., DEWAN, L.C., Nuclear Reactors and Related Methods and Apparatus, U.S. Patent Office, US 20130083878 A1, April 4, 2013.		
2013	I. Class	2. Family	Single-fluid Th-U breeder	**TMSR**	SINAP
			XU, H., Status and Perspective of TMSR in China, Molten Salt Reactor Workshop, Paul Scherrer Institut, Switzerland (2017), https://www.gen-4.org/gif/jcms/c_82829/workshops		
2013	I. Class	2. Family	Uranium converters and other concepts	**IMSR**	Terrestrial Energy
			CHOE, J., et al., "Fuel Cycle Flexibility of Terrestrial Energy's Integral Molten Salt Reactor (IMSR®)" 38th Annual Conf. of the Canadian Nuclear Society, Saskatoon, 2018.		
2014	III. Class	6. Family	Heterogeneous salt cooled fast MSRs	**SSR-W300**	Moltex
			SCOTT, I., et al., Stable Salt Reactor Design Concept, Thorium Energy Conf. 2015 (ThEC15), Mumbai, India (2015).		
2015	III. Class	5. Family	Liquid moderator heterogeneous MSRs	**Copenhagen Atomics Waste Burner**	Copenhagen Atomics
			PEDERSEN, T.J., A walkthrough of the Copenhagen Atomics Waste Burner design, Proc. Int. Thorium Energy Conference, Mumbai, India (2015).		
2015	II. Class	4. Family	Chloride fast breed-and-burn reactor	**B&B MCFR**	Hombourger et al.
			HOMBOURGER, B.,et al., "Fuel cycle analysis of a molten salt reactor for breed-and-burn mode", ICAPP 2015, Nice, France, 2015		
2015	II. Class	4. Family	Chloride fast breed-and-burn reactor	**MCFR**	TerraPower
			LATKOWSKI, J., TerraPower and the Molten Chloride Fast Reactor, MSR - 2015 Workshop on Molten Salt Reactor Technologies, Oak Ridge Natl Lab., TN (2015).		
2015	II. Class	3. Family	Fluoride fast Th-U breeder	**IMSBR**	BARC
			VIJAYAN, P.K., et al., Conceptual design of Indian molten salt breeder reactor, PRAMANA - J. Phys. 85 3 (2015) 539-554.		
2015	II. Class	3. Family	Fluoride fast Pu-fuelled reactor	**FMSR**	VNIINM
			DEGTYAREV, A, MYASNIKOV, A., PONOMAREV, L., Molten salt fast reactor with U-Pu fuel cycle, Prog. Nucl. Energ. 82 (2015) 33-36.		
2015	I. Class	2. Family	Uranium converters and other concepts	**ThorCon**	ThorCon
			JORGENSEN, L., "ThorCon reactor", Molten Salt Reactor and Thorium Energy (DOLAN, T.J., Ed.), Woodhead Publishing, Duxford, UK (2017) Ch. 19.		
2015	III. Class	6. Family	Heterogeneous lead cooled fast MSRs	**DFR**	IFK Berlin
			HUKE, A., et al., The Dual Fluid Reactor - A novel concept for a fast nuclear reactor of high efficiency, Ann. Nucl. Energy 80 (2015) 225-235.		
2016	II. Class	3. Family	Fluoride fast Pu-fuelled reactor	**Molten Salt Fast Breeder Reactor (MSFBR)**	Hirose et al.
			HIROSE, Y., MITACHI, K., SHIMAZU, Y., Operation Control of Molten Salt U-Pu Fast Breeder Reactor, Proc. 2016 Int. Congr. Advances in Nuclear Power Plants (ICAPP 2016), San Francisco, CA (2016).		
2016	I. Class	1. Family	Salt cooled reactor with pebble bed fuel	**PB-FHR, KP-FHR**	UCB, Kairos Power
			ANDREADES, et al., Design summary of the Mark-I Pebble-Bed, Fluoride salt-cooled, High-temperature Reactor commercial power plant, Nucl. Technol. 195 3 (2016) 223-238.		
2016	III. Class	6. Family	Heterogeneous salt cooled fast MSRs	**SSR-B&B**	Kasam and Shwageraus
			KASAM, A., SHWAGERAUS, E., Neutronic Feasibility of a Breed & Burn Molten Salt Reactor, Serpent User Group Mtg 2016, Milan (2016).		
2017	II. Class	4. Family	Chloride fast breed-and-burn reactor	**Molten Chloride Salt Fast Reactor (MCSFR)**	Elysium Industries
			PHEIL, E., "Elysium Molten Chloride Salt Fast Reactor (MCSFR)", presented at 8th Thorium Energy Alliance Conf., St. Louis, MO, 2017.		
2017	III. Class	5. Family	Liquid moderator heterogeneous MSRs	**CMSR**	Seaborg Technologies
			SCHÖNFELDT, T., et al., Molten Salt Reactor, AWA Denmark patent WO2018229265, PCT/EP2018/065989, Copenhagen (2018).		
2017	I. Class	2. Family	Two-fluids Th-U breeder	**SSR-Th***	Moltex
			SCOTT, I., "Stable salt fast reactor", Molten Salt Reactors and Thorium Energy (DOLAN, T.J., Ed.), Woodhead Publishing, Duxford, UK (2017) Ch. 21.		
2017	I. Class	2. Family	Uranium converters and other concepts	**SSR-U***	Moltex
			SCOTT, I., "Stable salt fast reactor", Molten Salt Reactors and Thorium Energy (DOLAN, T.J., Ed.), Woodhead Publishing, Duxford, UK (2017) Ch. 21.		
2018	III. Class	6. Family	Heterogeneous lead cooled fast MSRs	**HSR**	Aristos power
			ANDREI, A., HSR - Hard Spectrum Reactor http://www.thoriumenergyworld.com/uploads/6/9/8/7/69878937/aristos_power_thec18_slides.pdf		
2019	III. Class	5. Family	Liquid moderator heterogeneous MSRs	**HW-MSR**	SINAP
			WU, J., et al., A novel concept for a molten salt reactor moderated by heavy water, Ann. Nucl. Energy 132 (2019) 391-403.		
2019	I. Class	1. Family	Salt cooled reactor with fixed fuel	**AGR-FHR**	Forsberg
			FORSBERG, C., et al., Fluoride-salt-cooled High-Temperature Reactor (FHR) using British Advanced Gas-Cooled Reactor (AGR) refueling technology and decay heat removal systems that prevent salt freezing, Nucl. Technol. 205 9 (2019) 1127-1142.		
2020	II. Class	4. Family	Chloride fast breed-and-burn reactor	**B&B MCFR in multizone**	Raffuzzi and Krepel
			RAFFUZZI, V., KREPEL, J., "Simulation of breed and burn fuel cycle operation of Molten Salt Reactor in batch-wise refueling mode", Proc. Physics of Reactors (PHYSOR) 2020, Cambridge, UK, Nuclear Energy Group, Cambridge (2020) 1185.		
2020	II. Class	4. Family	Chloride fast breed-and-burn reactor	**B&B MCFR with baffles for flow direction**	De Oliveira
			DE OLIVEIRA, R. G., HOMBOURGER, B.A., "Fuel tap: a simplified breed-and-burn MSR", Proc. Physics of Reactors (PHYSOR) 2020, Cambridge, UK, Nuclear Energy Group, Cambridge (2020) 1547.		

Neutronics properties: Moderation power and capture XS

Logarithmic decrement of energy ξ describes neutron energy loss by scattering.

Product of ξ and **scattering XS** is used here as a **moderation power*** criteria.

It is not a standard definition, because it uses microscopic instead of macroscopic XS.



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Actinides content versus
liquidus-solidus temperatures gap
Transition to closed Th-U and U-Pu cycle

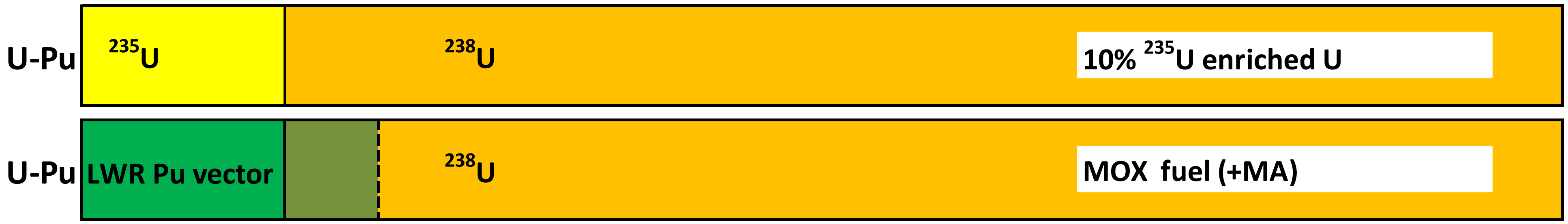
5 major fissile materials to start the Th-U cycle

Material	RG_Pu	LEU	HEU	U233	WG_Pu
Fissile isotope(s)	^{239}Pu, ^{241}Pu	^{235}U	^{235}U	^{233}U	^{239}Pu
Fissile isotope share	~60%	1-20%	21-95%	60-100%	>93%
"Availability"	medium	high	high	low	medium
Proliferation risk	medium	medium	high	high	high

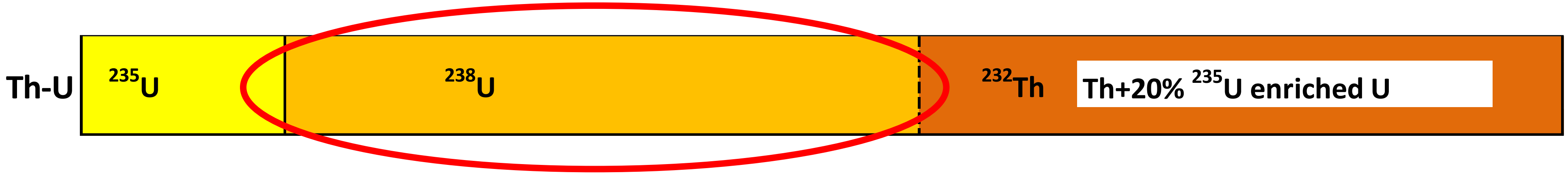
RG_Pu and LEU as initial fuel load

- Both **RG_Pu** and **LEU** are very natural option to start the **U-Pu** cycle.

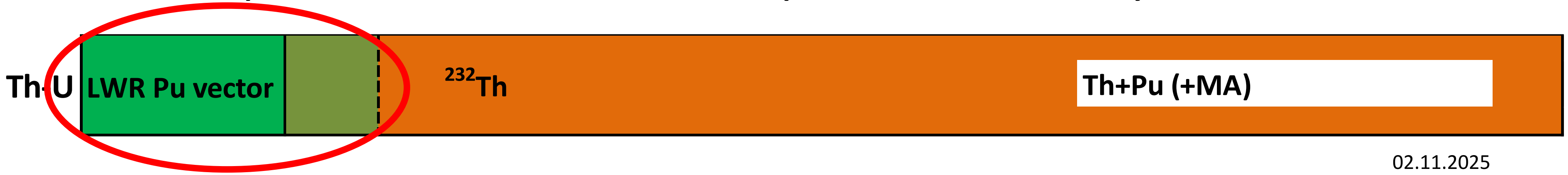
Fuel composition - initial cycles (10% ^{235}U equivalent)



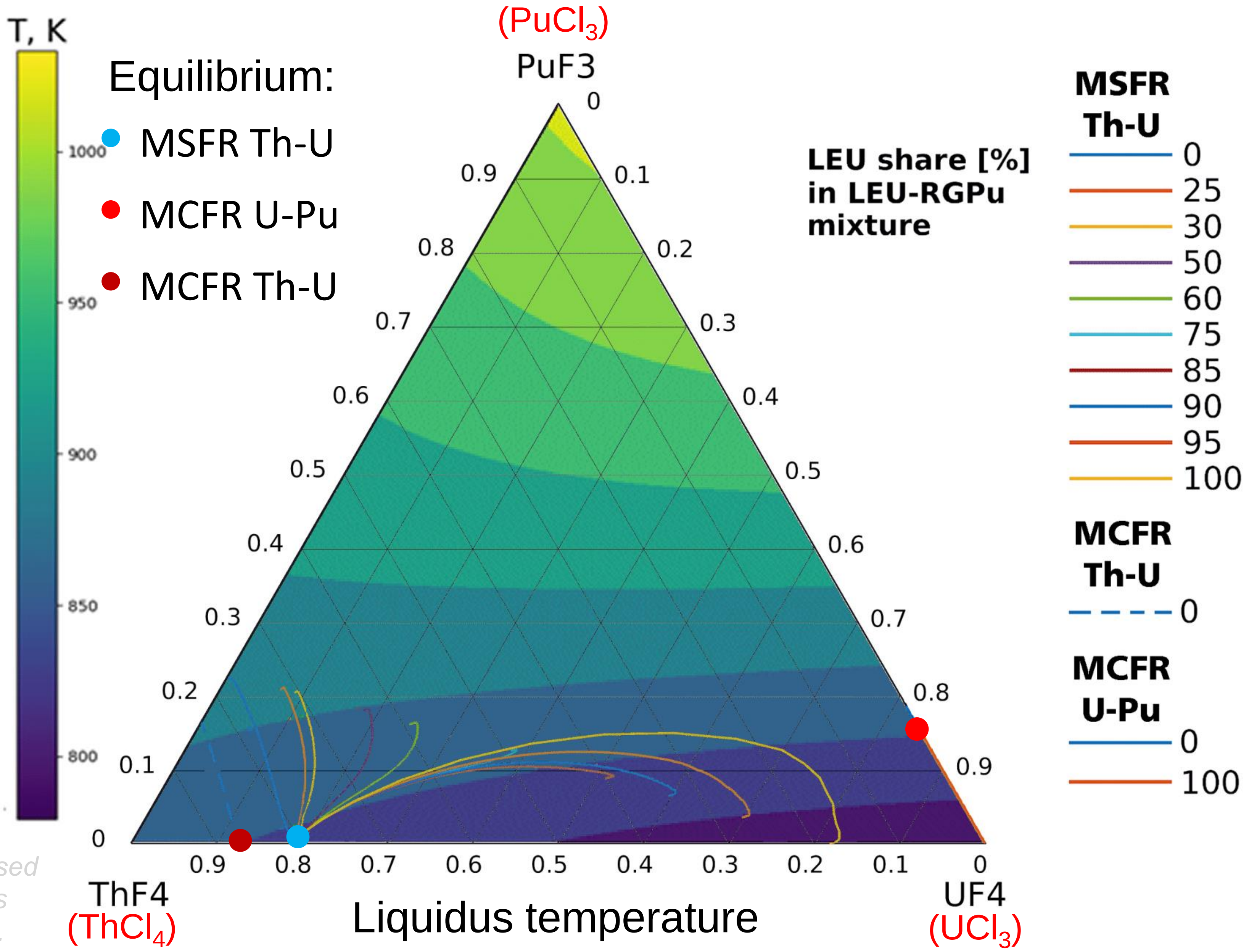
- Starting **Th-U** cycle with **LEU** induces **^{238}U presence** in the core.



- Starting **Th-U** cycle with **RG_Pu, LEU** or their mixture introduces strong **perturbation**.
- Pu and $^{235 \& 238}U$ are not presented in the salt at equilibrium Th-U cycle.



Transition to Th-U cycle in MSFR (and U-Pu MCFR)



Křepel, J. et al., Transition to closed Th-U fuel cycle in fluoride salts based fast MSR. ICAPP 2019.

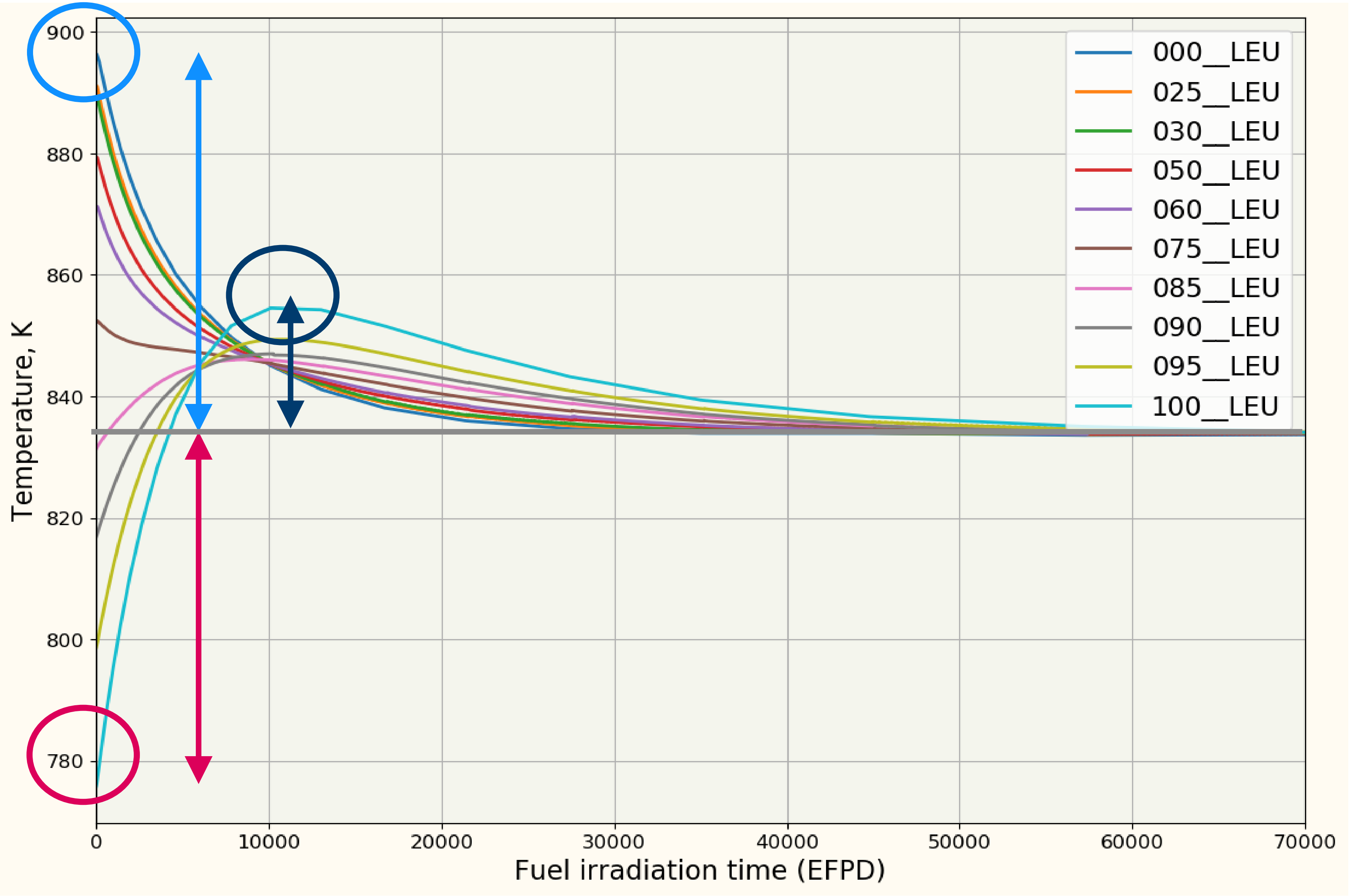
Evolution of the liquidus temperature

PSI

- **PuF_3** presence increases the liquidus temperature.
- **UF_4** presence decreases the liquidus temperature.
- The temperature for equilibrium Th-U cycle is cca **835K.**
- The difference is:

  up to **-55K** and **+60K** or **+20K**.

LiF-ThF4-UF4-PuF3 (at **76.6%** LiF).

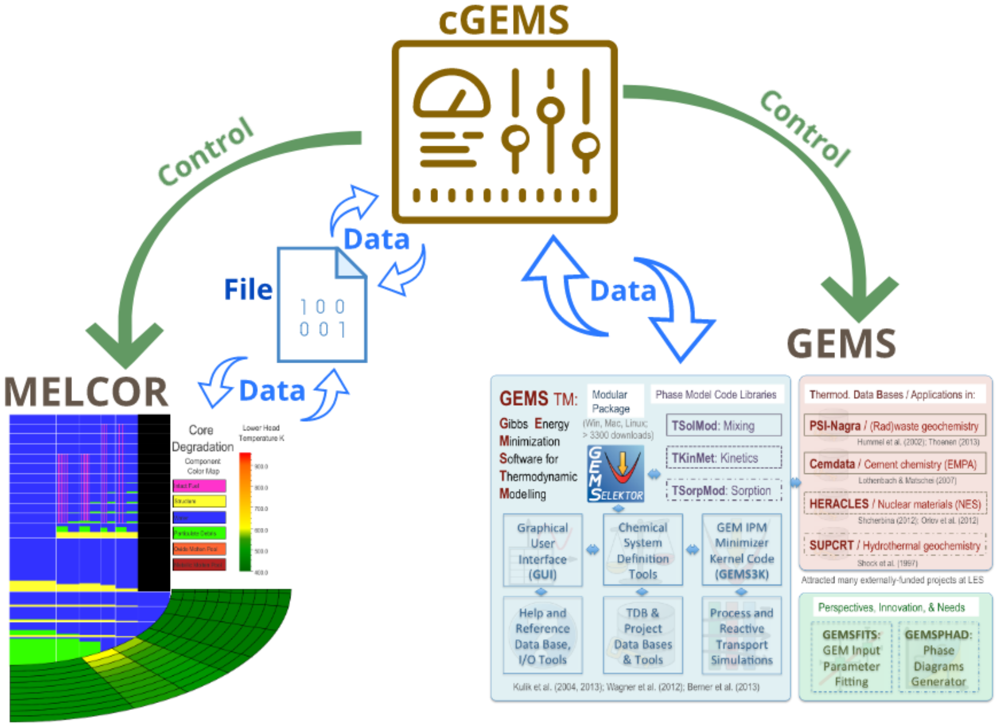


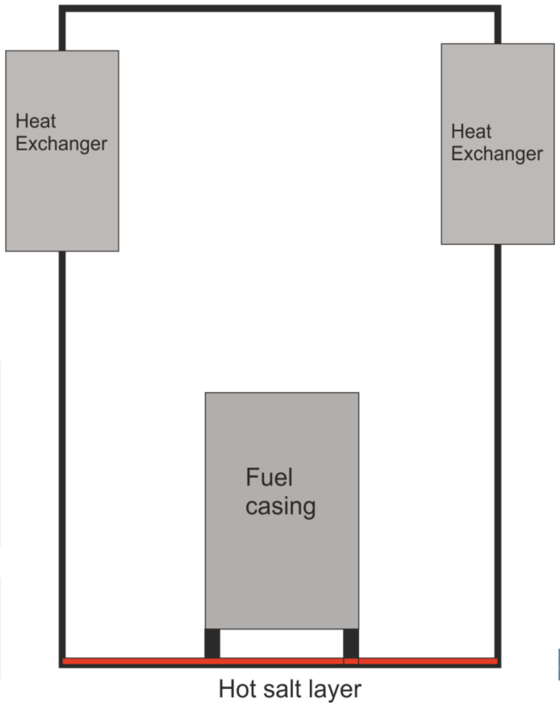
Křepel, J. et al., Transition to closed Th-U fuel cycle in fluoride salts based fast MSR. ICAPP 2019.

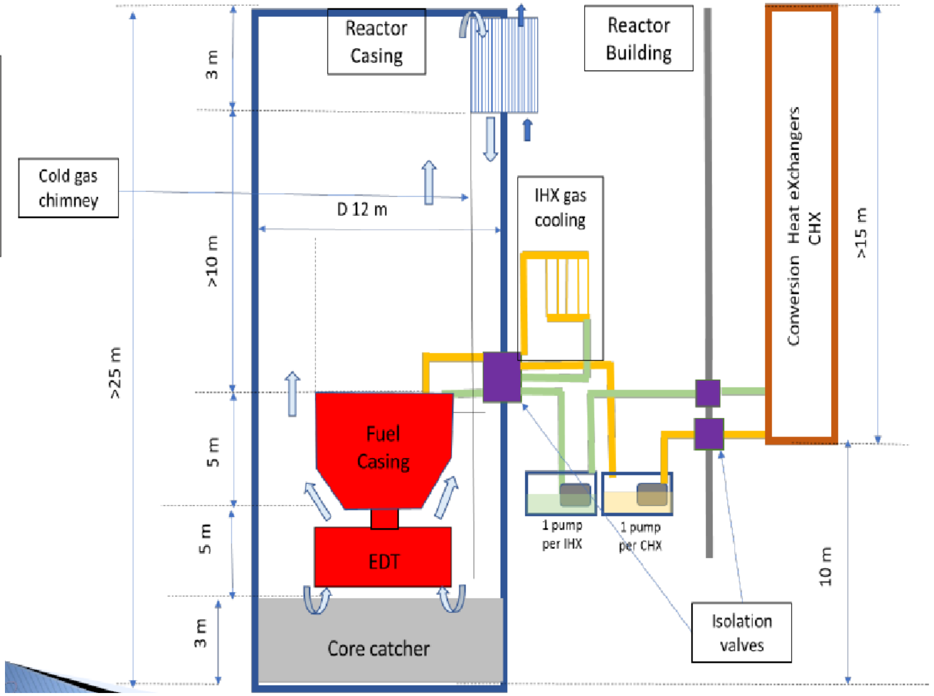
cGEMS application to severe accident in MSFR

Within EU project SAMOSAFER the deliverable: **Aerosols formation and filtration in accidental conditions** was resealed. It is not public, but the results have been also in Journal of Nuclear Materials:
J. Kalilainen, S. Nichenko, J. Krepel:
"**Evaporation of materials from the molten salt reactor fuel under elevated temperatures**"
https://doi.org/10.1016/j.jnucmat.2020.152134

Simple salt spilling scenario in cylindrical containment with salt heat up from 800°C to 1500°C.



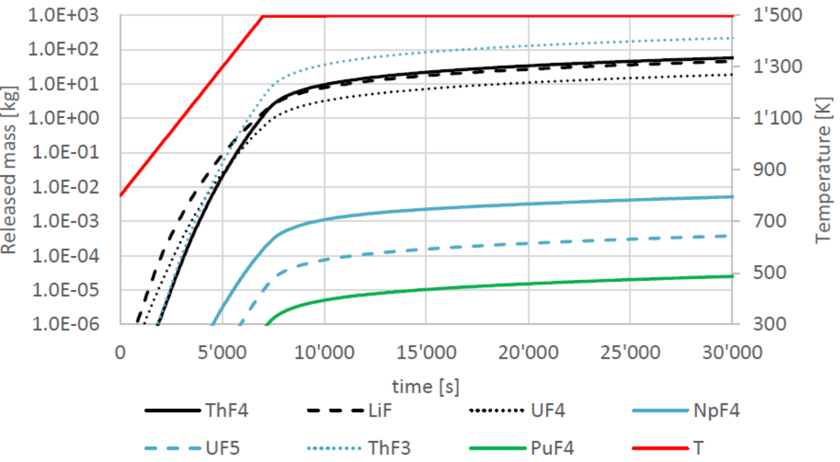


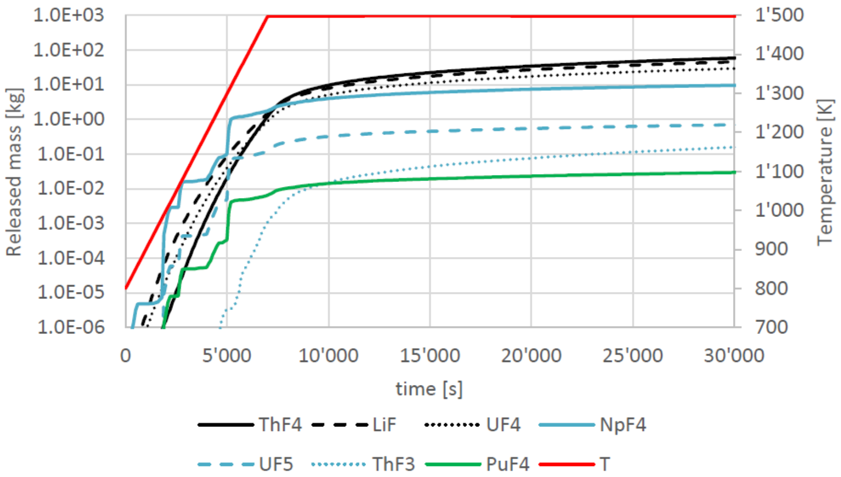


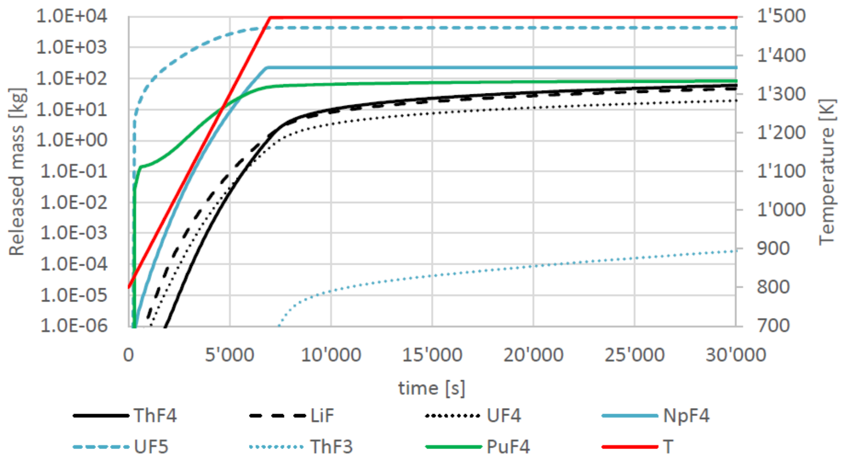
From the SAMOFAR Final meeting, E. Merle et al.

Released mass sensitivity to redox

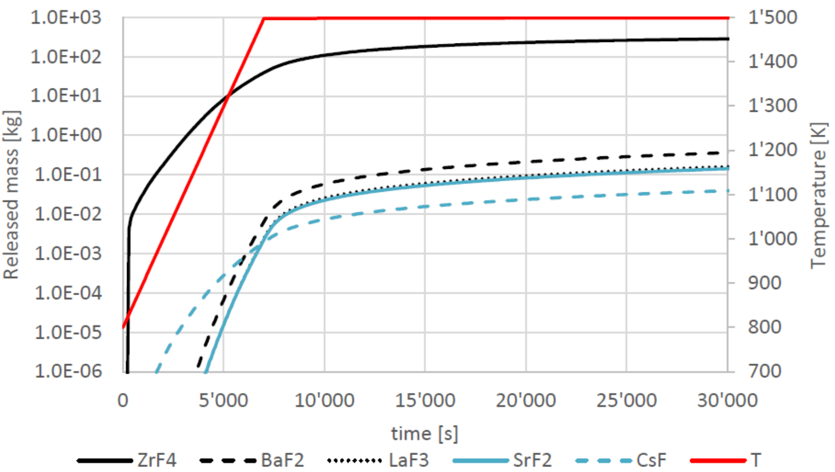
Fluorine: -1% mol. | Stoichiometric | +1% mol.

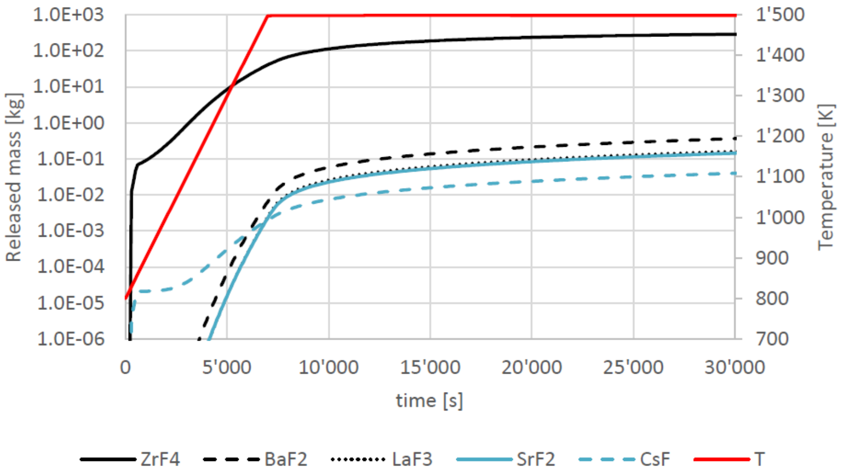


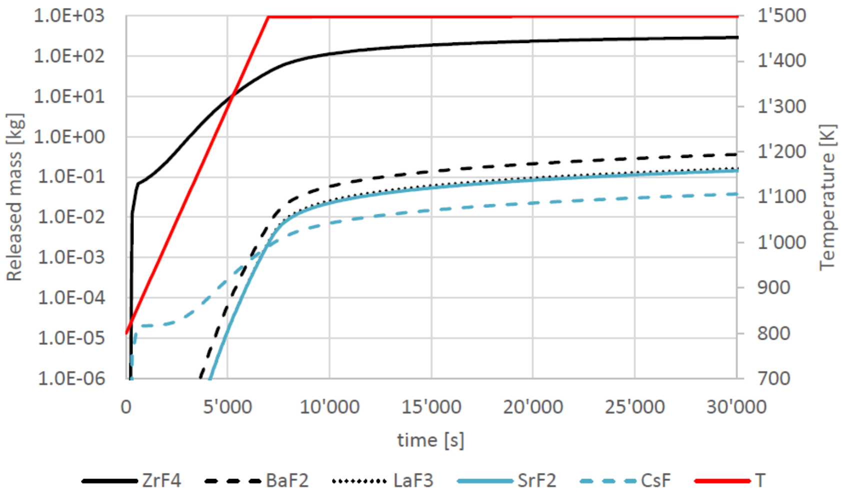




Actinides and salt species





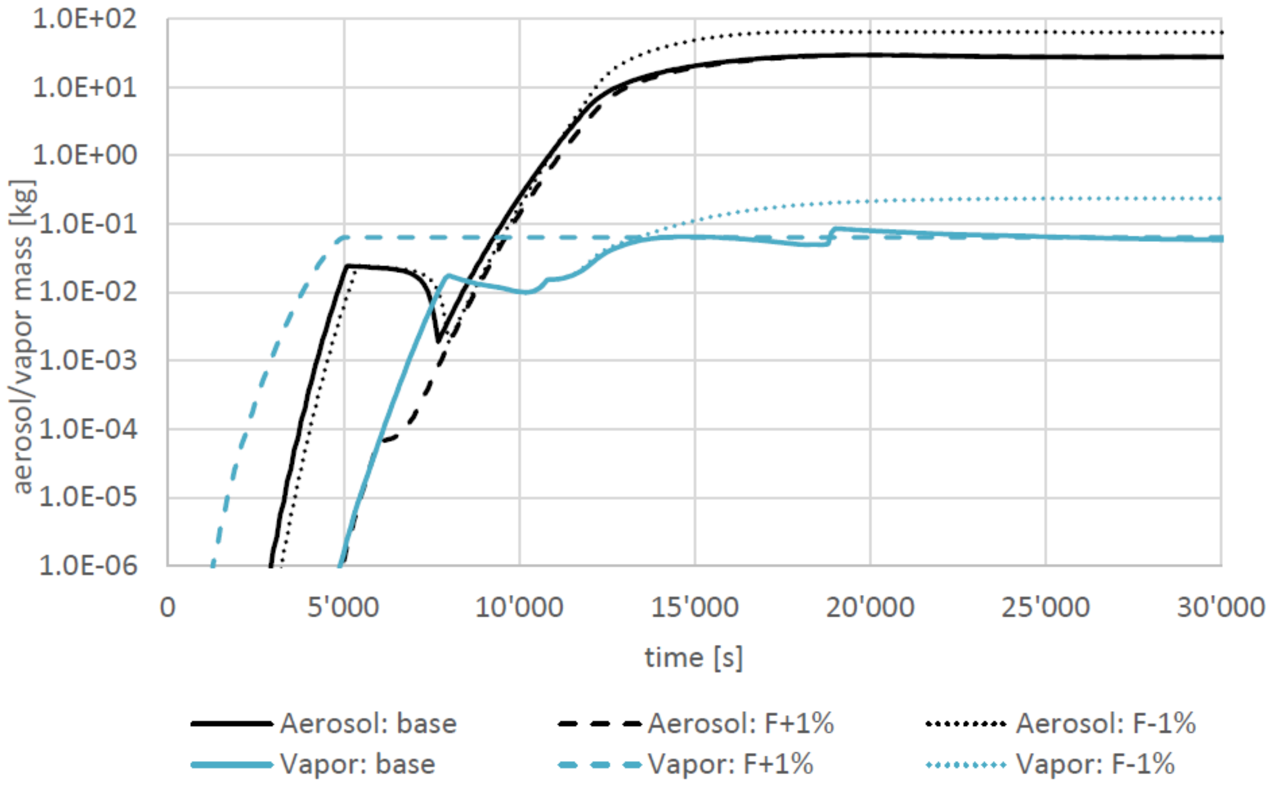


Fission products species

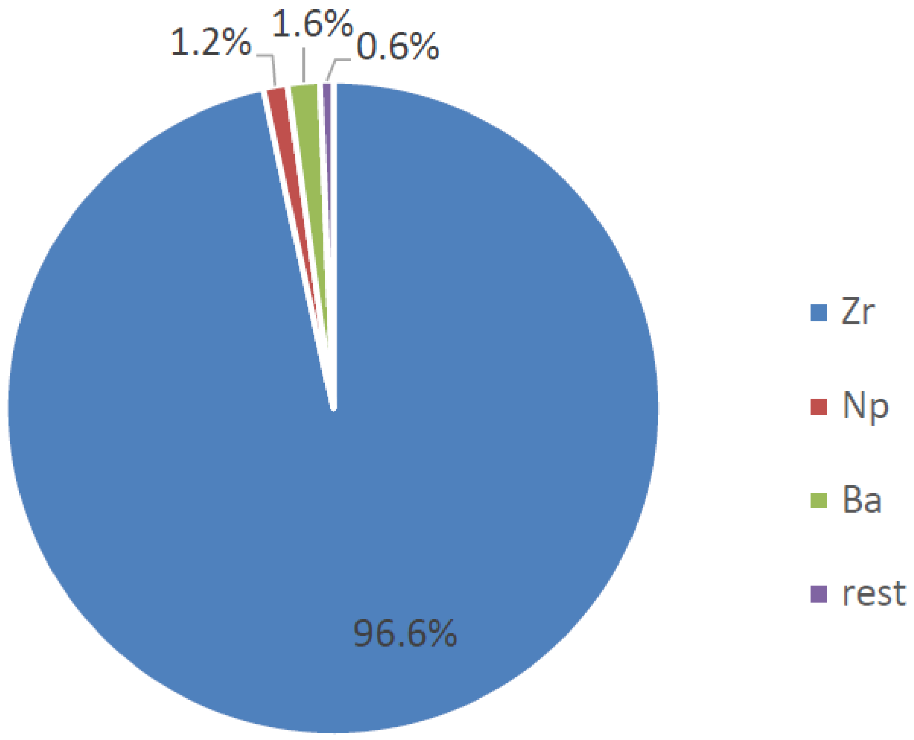
Total released mass during the accident (salt heat up from 800°C to 1500°C)

ZrF_4 as the major component?

Based on the applied reprocessing scheme, ZrF_4 in form of aerosols seems to be the major activity carrier during the postulated accident.



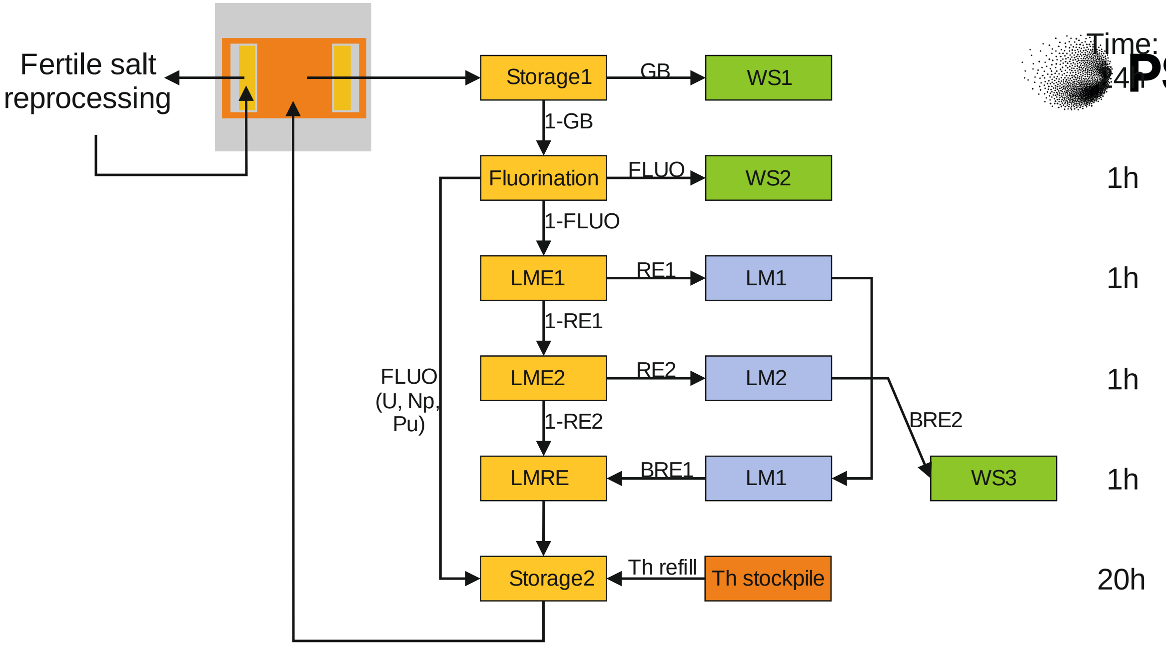
Total released activity in form of aerosols and vapors during the accident (salt heat up from 800°C to 1500°C)

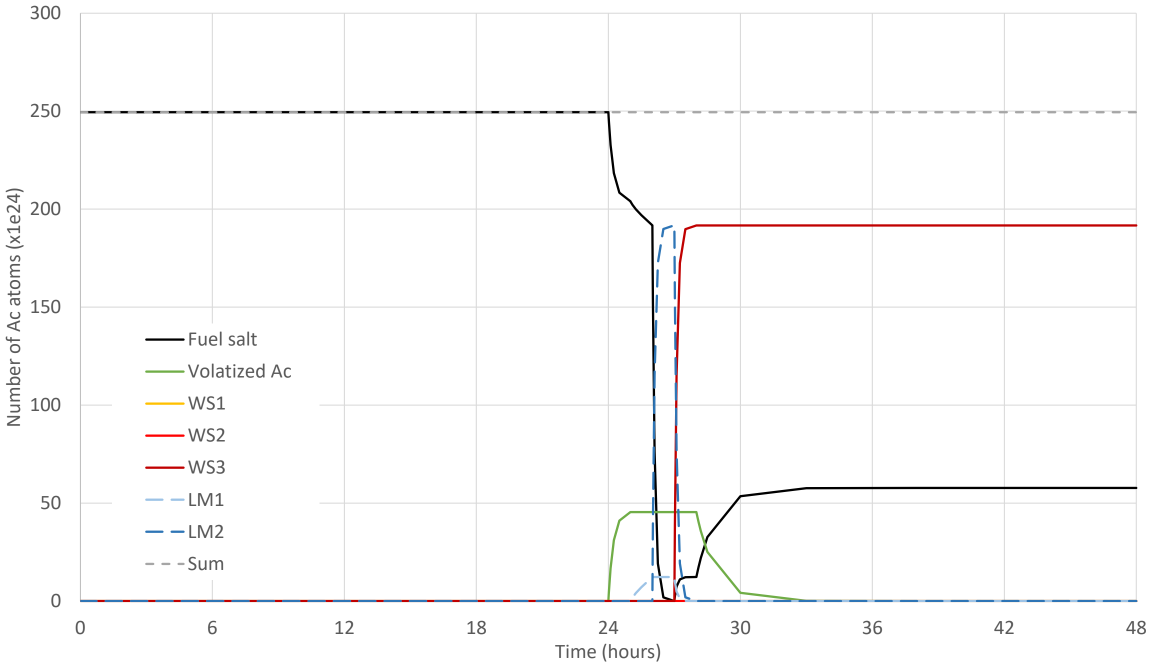


Activity break-down at the end of simulation (t=30'000s) of the accident (salt heat up from 800°C to 1500°C)

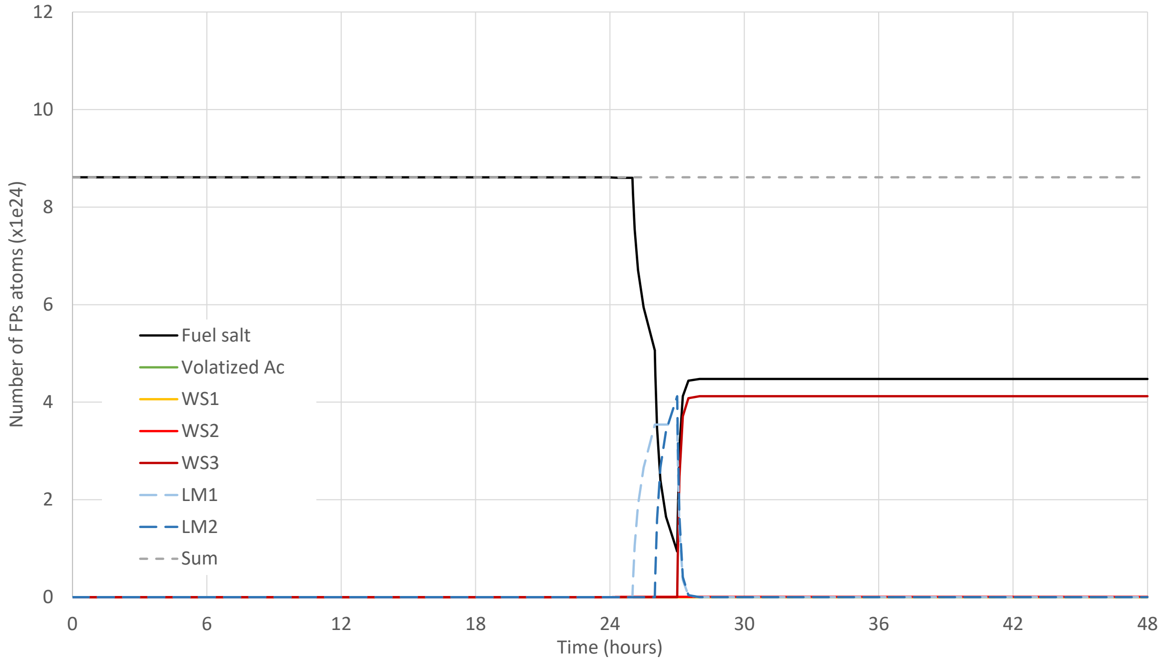
FPs mass evolution in reprocessing systems

- Ac and FPs flow through the reprocessing unit.
- Th fully removed, whereas many FPs only partially.





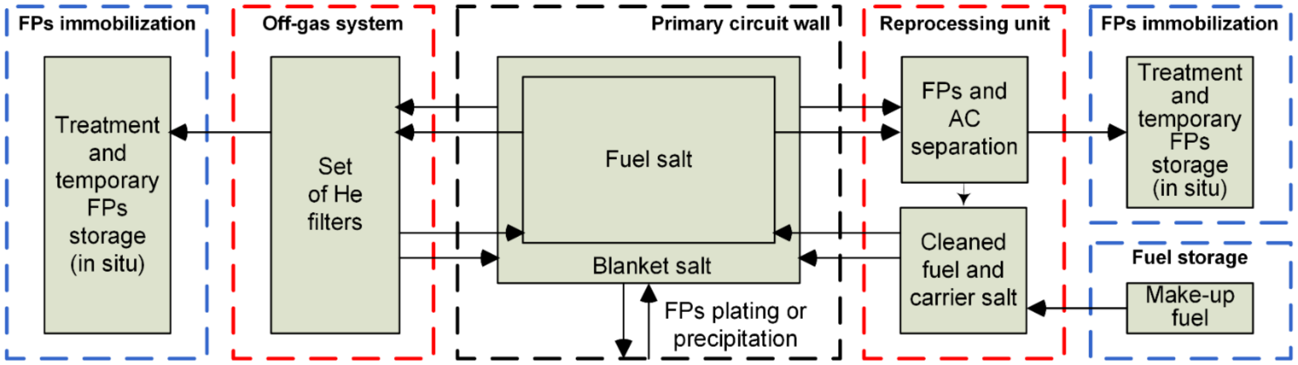
Distribution of Ac during the 48 hours of salt residence time in in reprocessing unit.

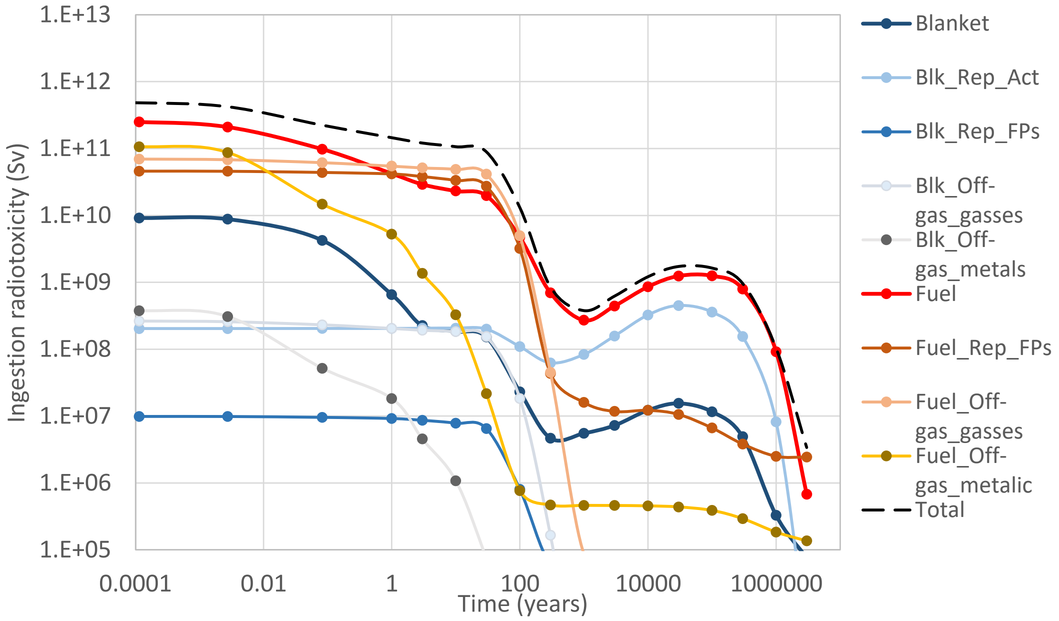


Distribution of FPs during the 48 hours of salt residence time in in reprocessing unit.

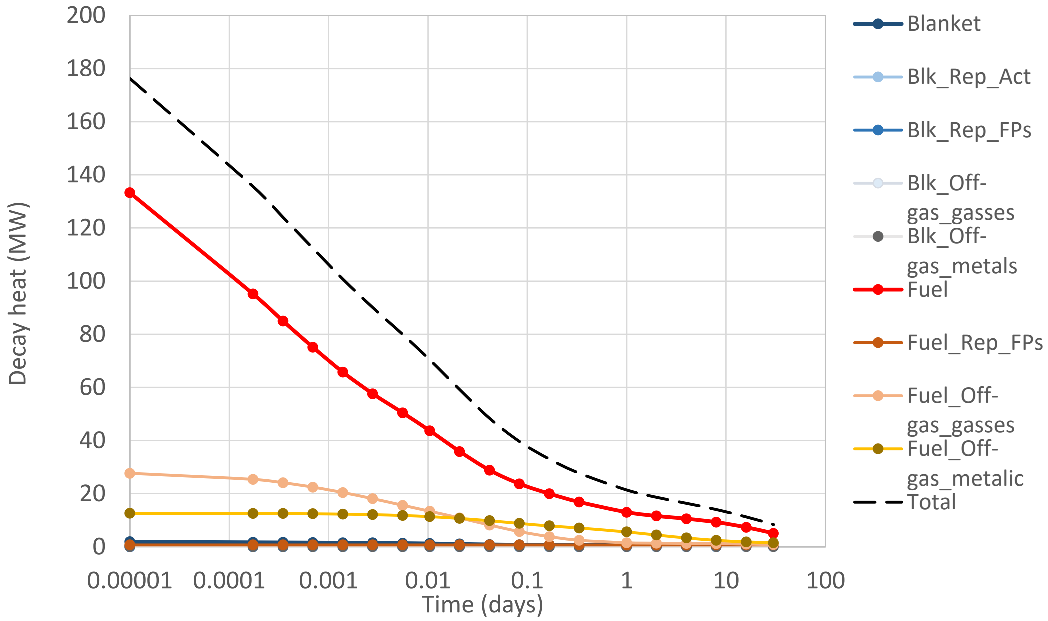
FPs mass evolution in MSFR systems

Radiotoxicity and decay heat distribution after 20 EFPY of operation.





Distribution of ingestion radiotoxicity between several locations (Blk. – blanket salt, Fuel – fuel salt, Rep. –reprocessing unit) after 20 EFPY of irradiation.



Distribution of decay heat between several locations (Blk. – blanket salt, Fuel – fuel salt, Rep. –reprocessing unit) after 20 EFPY of irradiation.