Overview and Update of MSR Activities within GIF

Dr. Jiri Krepel, PSI, Switzerland

22 January 2025

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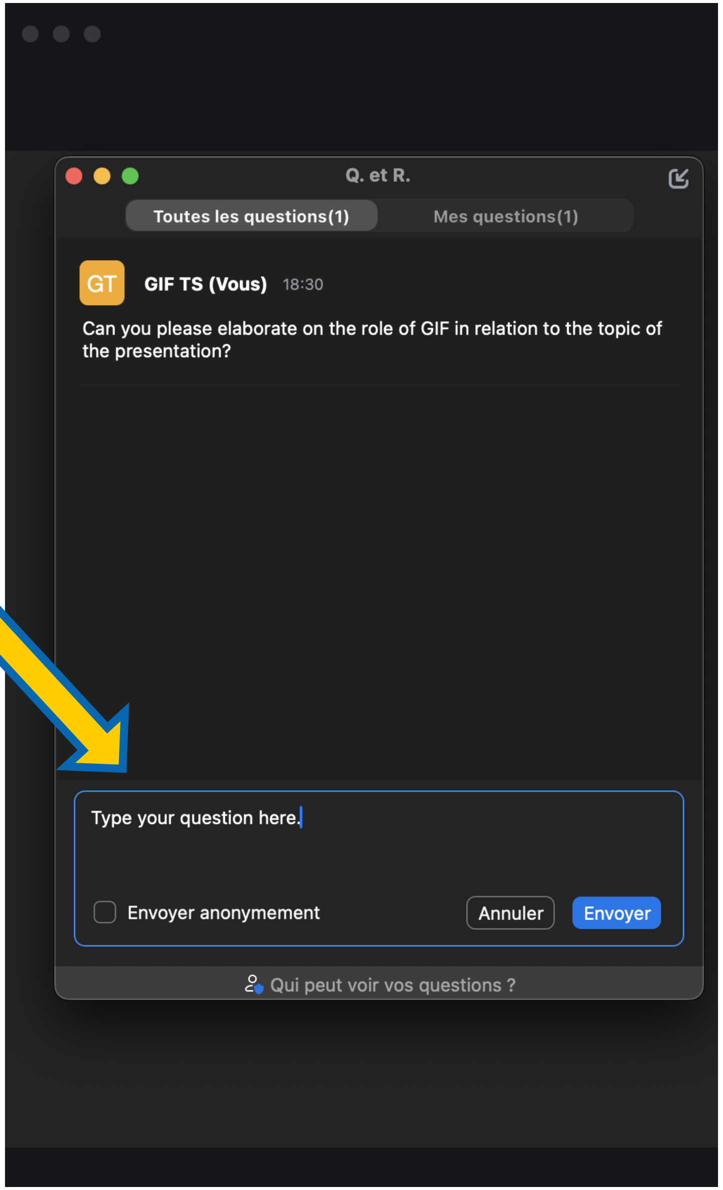

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22 January 2025

Meet the Presenter

Dr. Jiri Krepel is a senior scientist in Advanced Nuclear Systems group of Laboratory for Scientific Computing at Paul Scherrer Institute (PSI) Center for Scientific Computing, Theory and Data in Switzerland.

He earned his Ph.D. in 2006 at the Czech Technical University in Prague and Helmholtz-Zentrum Dresden-Rossendorf in Germany for his thesis entitled "*Dynamics of Molten Salt Reactors*".

Dr. Krepel is the coordinator of the PSI MSR research at PSI and is responsible for fuel cycle analysis and related safety parameters of Gen IV reactors.

He is also the chair of the provisional System Steering Committee of GIF MSR project and co-developer of the IAEA MSR taxonomy.

Dr. Krepel has experience in the neutronics of liquid-metal and gas-cooled fast reactors and in neutronics and transient analysis of thermal and fast MSRs.

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Content

- ***Introduction:***
  - GIF MSR role and position
  - MSR Taxonomy development (IAEA TRS No. 489)
  - Brief history of MSR
  - MSR issues in a nutshell
- ***Members' and observers' activities:***
  - Australia
  - Canada
  - EURATOM
  - France
  - Russia
  - Switzerland
  - USA
  - China
  - Korea

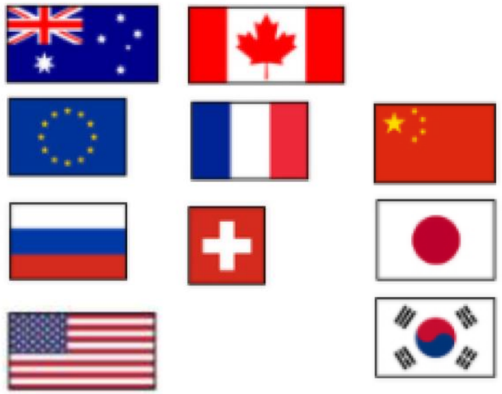
GIF MSR project introduction

GIF MSR project introduction

- **MSR as well as LFR systems**
  are still organized only by Memorandum of Understanding.
- **In 2025 new GIF framework agreement is expected to be signed.**
  - New MOU should be signed also for the MSR project.
  - Korea may join the MOU.
- **Signing MSR system arrangement?**
  The GIF as a platform for states and state/private cooperation may need a general redefinition:
  - Research organizations are often financed from public money and required to publish openly.
  - Private start-up prefer bilateral cooperation with commercial contracts.

MOU signatories

Australia
Canada
Euratom
France
Russia
Switzerland
USA



Observers

China
Japan
Korea

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PARTIES TO GIF FRAMEWORK AGREEMENT AND SYSTEM ARRANGEMENTS

Member	Framework Agreement	System Arrangements				Memoranda of Understanding (MOU)	
		GFR	SCWR	SFR	VHTR	LFR	MSR
Argentina							
Australia	X				X		X
Brazil							
Canada	X		X		X		X
Euratom[1]	X	X	X	X	X	X	X
France	X	X		X	X		X
Japan	X	X	X	X	X	X	
People's Republic of China	X		X	X	X	X	
Republic of Korea	X			X	X	X	
Republic of South Africa	X						
Russian Federation	X		X	X		X	X
Switzerland[2]	X				X		X
United Kingdom[3]	X			X	X		
United States	X			X	X	X	X

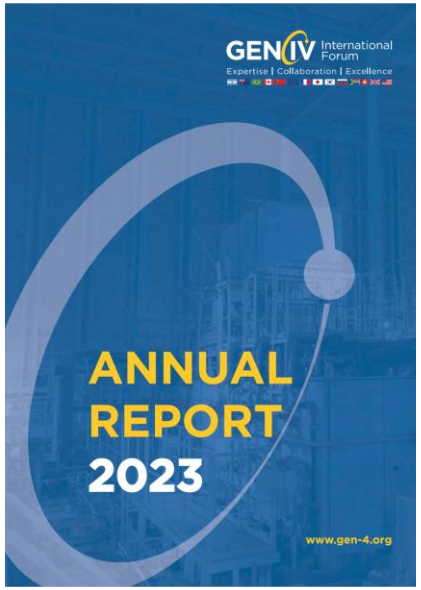
* Among the signatories to the Charter, twelve Members (Australia, Canada, Euratom, France, Japan, the People's Republic of China, the Republic of Korea, the Republic of South Africa, Russian Federation, Switzerland, United Kingdom and the United States) have signed or acceded to the Framework Agreement (FA) as shown in the table above, other signatories to the Charter (Argentina and Brazil) are Non-Active Members.

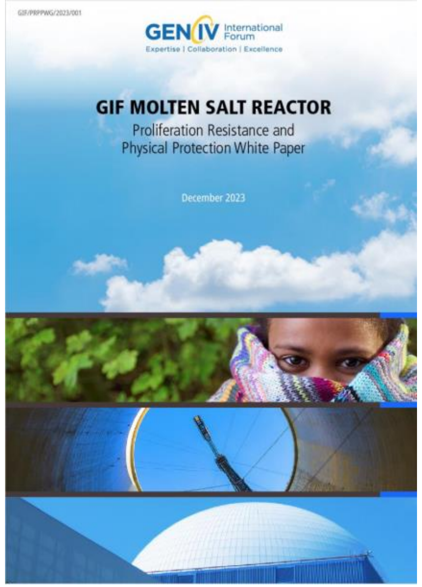
1. The European Atomic Energy Community (Euratom) is the implementing organisation for development of nuclear energy within the European Union.
2. Switzerland was a signatory to the GFR System Arrangement from 11/2006 to 11/2015.
3. United Kingdom ratified the Framework Agreement in October 2018.

https://www.gen-4.org/gif/jcms/c_9342/framework-agreement

GIF MSR activities

- Organizing bi-annual project meeting.
- Contribution to GIF annual progress report.
- Together with PRPPWG published MSR PRPP white paper.
- Discussing with RSWG the preparation/finishing of MSR white paper and system safety assessment.
- Representing GIF MSR project at IAEA technical meetings.





1st Initiative	March 24, 2005	Cadarache (France)
2nd Initiative	September 9, 2005	Prague (Czech Republic)
1st pSSC	February 22–23, 2006	Paris (France)
2nd pSSC	July 11–12, 2006	Karlsruhe (Germany)
3rd pSSC	December 14–15, 2006	NEA (France)
4th pSSC	May 15, 2007	Nice (France)
5th pSSC	October 2–3, 2007	Prague (Czech Republic)
6th pSSC	March 3, 2008	NEA (France)
7th pSSC	October 15–16, 2008	Paris (France)
8th pSSC	March 5–6, 2009	Karlsruhe (Germany)
9th pSSC	September 8, 2009	Paris (France)
10th pSSC	March 18–19, 2010	NEA (France)
11th pSSC	September 22, 2010	Oak Ridge (US)
12th pSSC	April 8, 2011	Marcoule (France)
13th pSSC	November 8–9, 2011	Delft (Netherlands)
14th pSSC	May 24–25, 2012	NEA (France)
15th pSSC	November 5, 2012	Karlsruhe (Germany)
16th pSSC	July 2–4, 2013	Dimitrovgrad (Russian Federation)
17th pSSC	November 7–8, 2013	Orsay (France)
18th pSSC	May 28–29, 2014	Shanghai (China)
19th pSSC	December 8–9, 2014	NEA (France)
20th pSSC	August 25–26, 2015	Delft (Netherlands)
21st pSSC	January 26–27, 2016	Karlsruhe (Germany)
22nd pSSC	June 30, 2016	Grenoble (France)
23rd pSSC	January 23–24, 2017	Villigen PSI (Switzerland)
24th pSSC	September 28–29, 2017	Vienna (Austria)
25th pSSC	April 10–11, 2018	Shanghai (China)
26th pSSC	October 30–31, 2018	NEA (France)
27th pSSC	March 12–13, 2019	Sydney (Australia)
28th pSSC	September 16–17 2019	Avignon (France)
29th pSSC	July 24, 2020	Virtual Zoom meeting
30th pSSC	May 11–12, 2021	Virtual Zoom meeting
31st pSSC	Oct 26–27 & Nov 2, 2021	Virtual Zoom meeting
32nd pSSC	May 3–5, 2022	Oakville (Canada)
33rd pSSC	December 6–8, 2022	Copenhagen (Denmark)
34th pSSC	April 4–5, 2023	Virtual Zoom meeting
35th pSSC	Nov 30 & Dec 1, 2023	Avignon (France)

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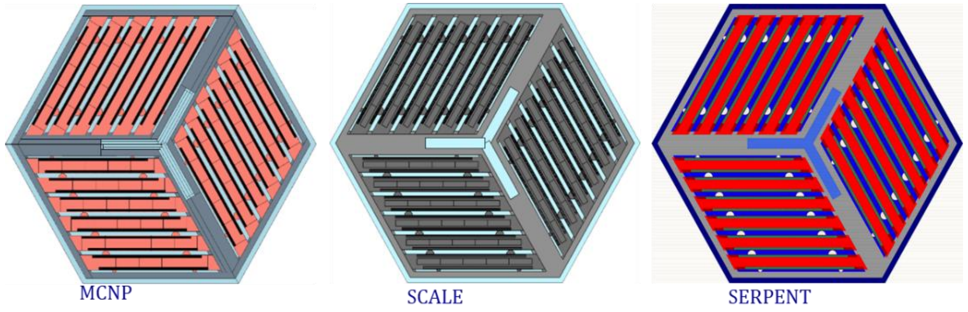
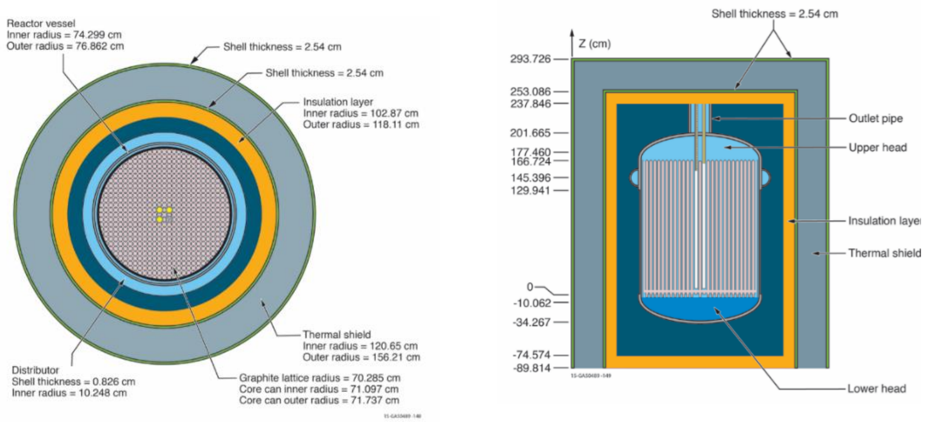
GIF MSR interaction with OECD NEA

- OECD NEA acts as a secretariat for Generation IV international forum and so for GIV MSR project.
- Other way there is no direct cooperation on MSR.
- NEA Working Party on Scientific Issues of Reactor Systems (WPRS) prepared Fluoride-salt High-temperature Reactor (FHR) benchmark.
- NEA International Reactor Physics Experiment Evaluation Project (IRPhEP) included in its handbook of critical experiments the MSRE case.
- 19-23 May 2024, WPRS held its annual Benchmarks Workshops event in Lucca.



Benchmark Specifications for the Fluoride-salt Hightemperature Reactor (FHR) Reactor Physics Calculations, Phase I-A and I-B: Fuel, Element 2D Benchmark, NEA/NSC/R(2020)5, March 2021



Reactor physics benchmark of the first criticalityin the Molten Salt Reactor Experiment, Dan Shen, Germina Ilas, Jeffrey J. Powers, Massimiliano Fratoni, February 2021Nuclear Science and Engineering

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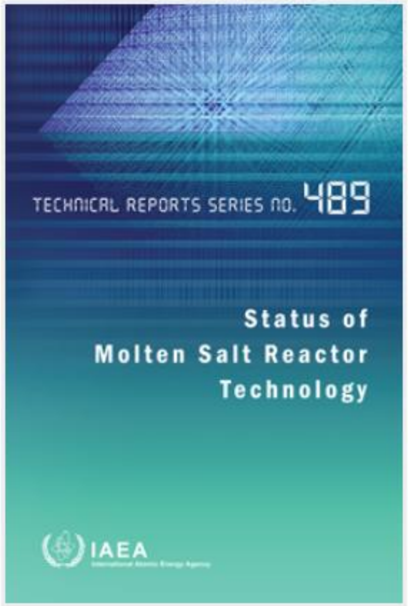
GIF MSR interaction with IAEA

- GIF and IAEA organize regular General Interface Meeting.
- GIF-IAEA Cooperation Matrix for all system inclusive MSR.
- IAEA has several activities, which should in long term result in modifications of selected requirements and guides (e.g. SSR 2/1, SSG-1, SSG-4, SSG-52, SSG-54) for non-water-cooled reactors.
- The work on MSR was intensified in 2024 and will continue in 2025, considering GIF MSR, RSWG & IAEA cooperation.
- Individual experts' participation on IAEA activities.
- Example of past IAEA documents with GIF MSR expert involvement:
  - 2013: Challenges Related to the Use of Liquid Metal and Molten Salt Coolants in Advanced Reactors (IAEA-TECDOC-1696)
  - 2020: Considerations for the Back End of the Fuel Cycle of Small Modular Reactors (IAEA-TECDOC-2040)
  - 2021: Status and Trends in Pyroprocessing of Spent Nuclear Fuels (IAEA-TECDOC-1967)
  - 2022: Near Term and Promising Long Term Options for the Deployment of Thorium Based Nuclear Energy (IAEA-TECDOC-2009)
  - 2023: **Status of Molten Salt Reactor Technology** (Technical Reports Series No. 489)
  - 2023:Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors (Safety Reports Series No. 123)

MSR Taxonomy from the IAEA TRS No. 489

Status of Molten Salt Reactor Technology



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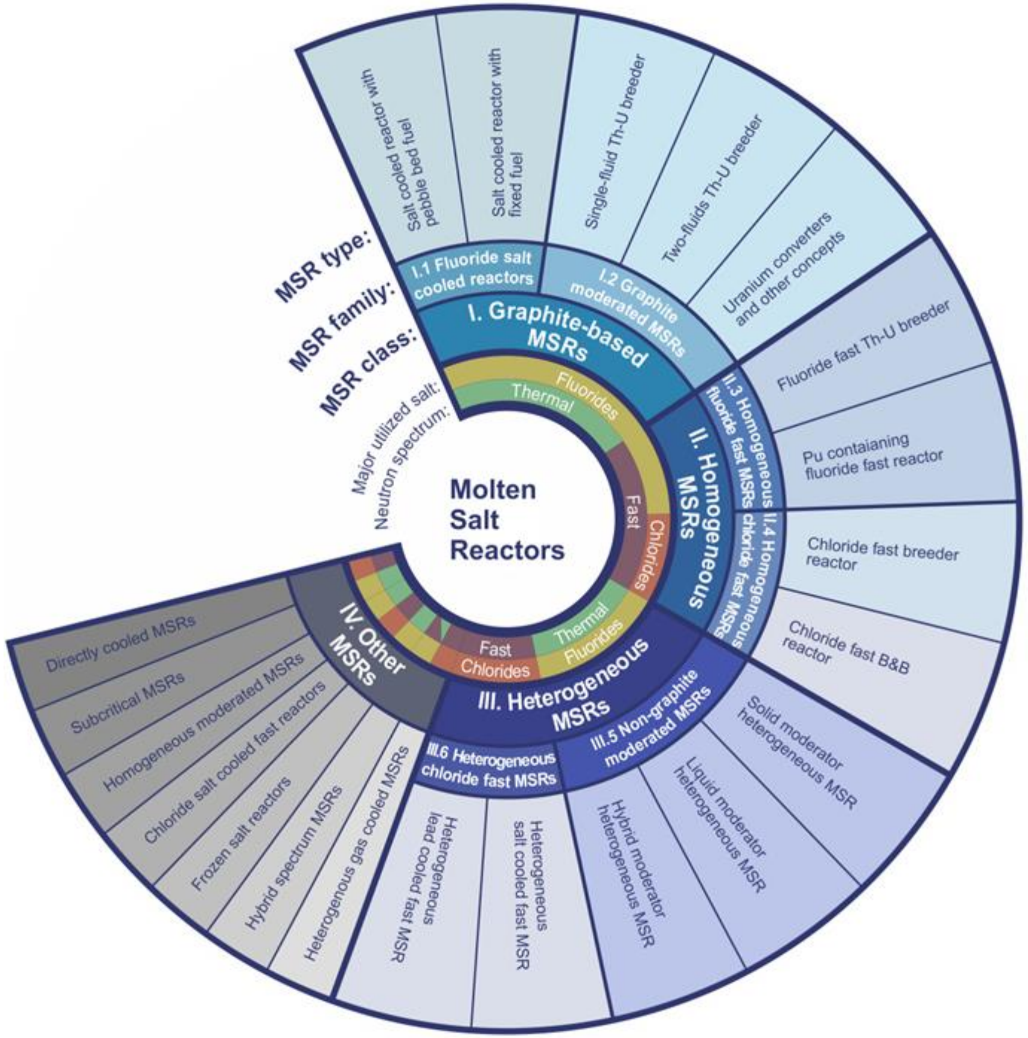


https://www.iaea.org/publications/14998/status-of-molten-salt-reactor-technology

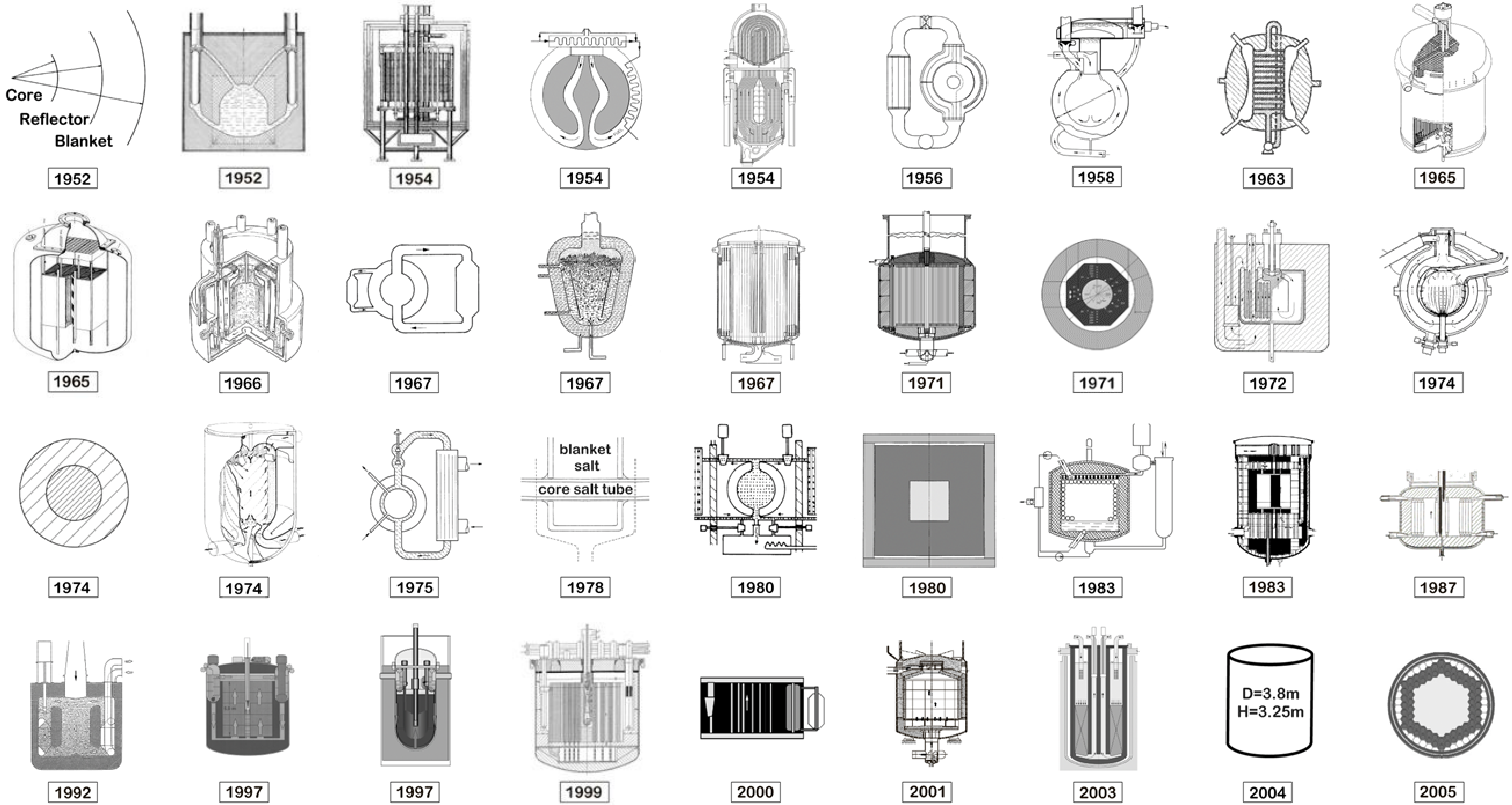
IAEA TRS No. 489
MSR Taxonomy development

First step: MSR definition

MSR is any reactor where a molten salt has a prominent role in the reactor core (i.e., fuel, coolant, and/or moderator).

… accordingly, it includes salt-cooled reactors.

Second step: MSR concepts collection (past)



Second step: MSR concepts collection (recent)

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.

Third step: existence of past taxonomy..?

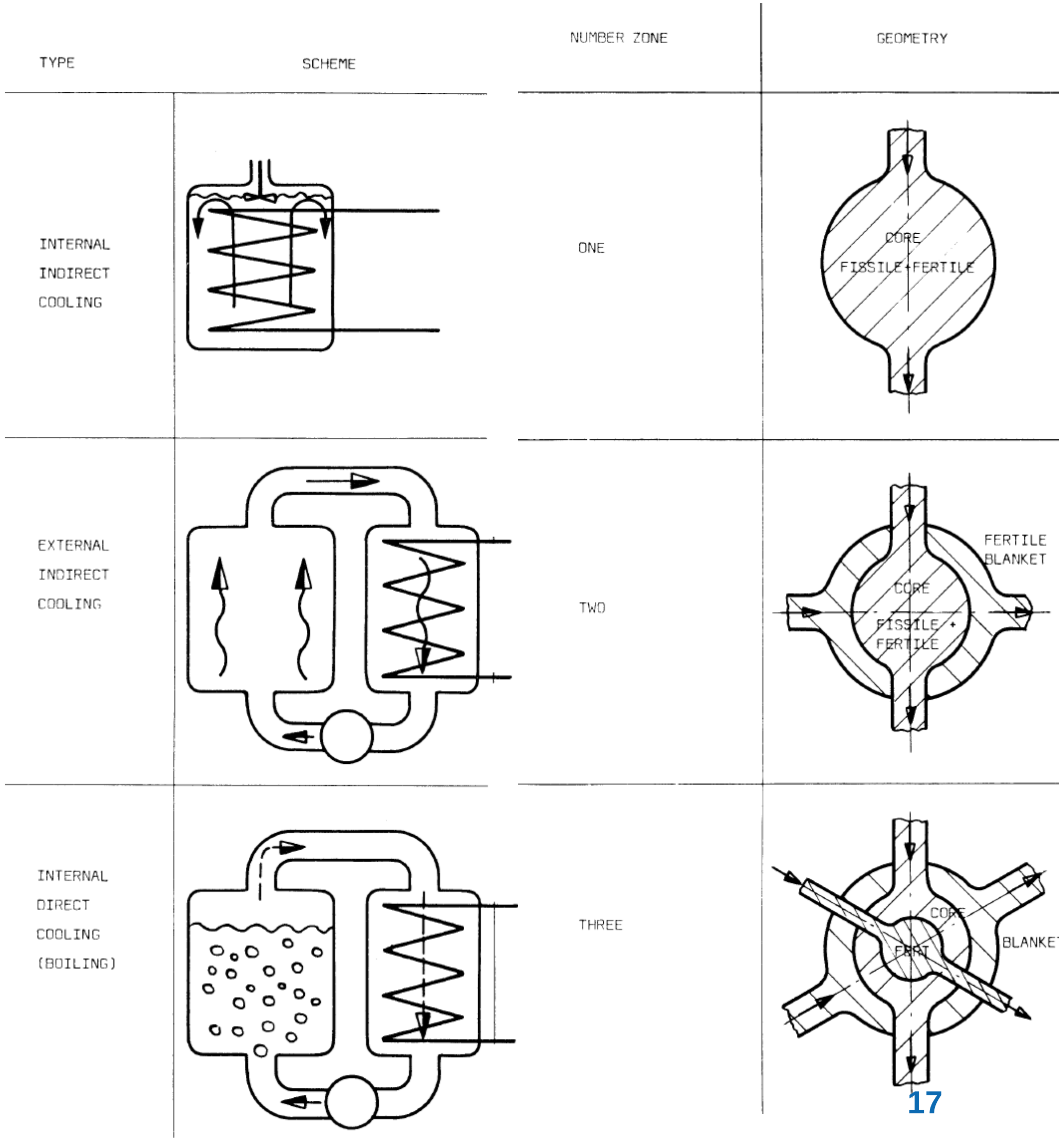
In 1978 EIR (PSI) final report was published with MSR classification based predominantly on cooling method. It was biased towards fast MSR and strongly included directly cooled MSR.

1.1 Methods of classification

There are many ways of classifying a reactor type. One such possibility is shown here.

a) Method of cooling
b) Flux intensity related also to specific power density
c) Number of zones in the reactor
d) Kind of fissile nuclides and fuel cycles
e) Neutron energy
f) Purpose of the reactor
g) Dilutent for the molten salt

It is clear that such an arbitrary classification is not necessarily internally compatible and not all reactor types fall easily into the scheme chosen.



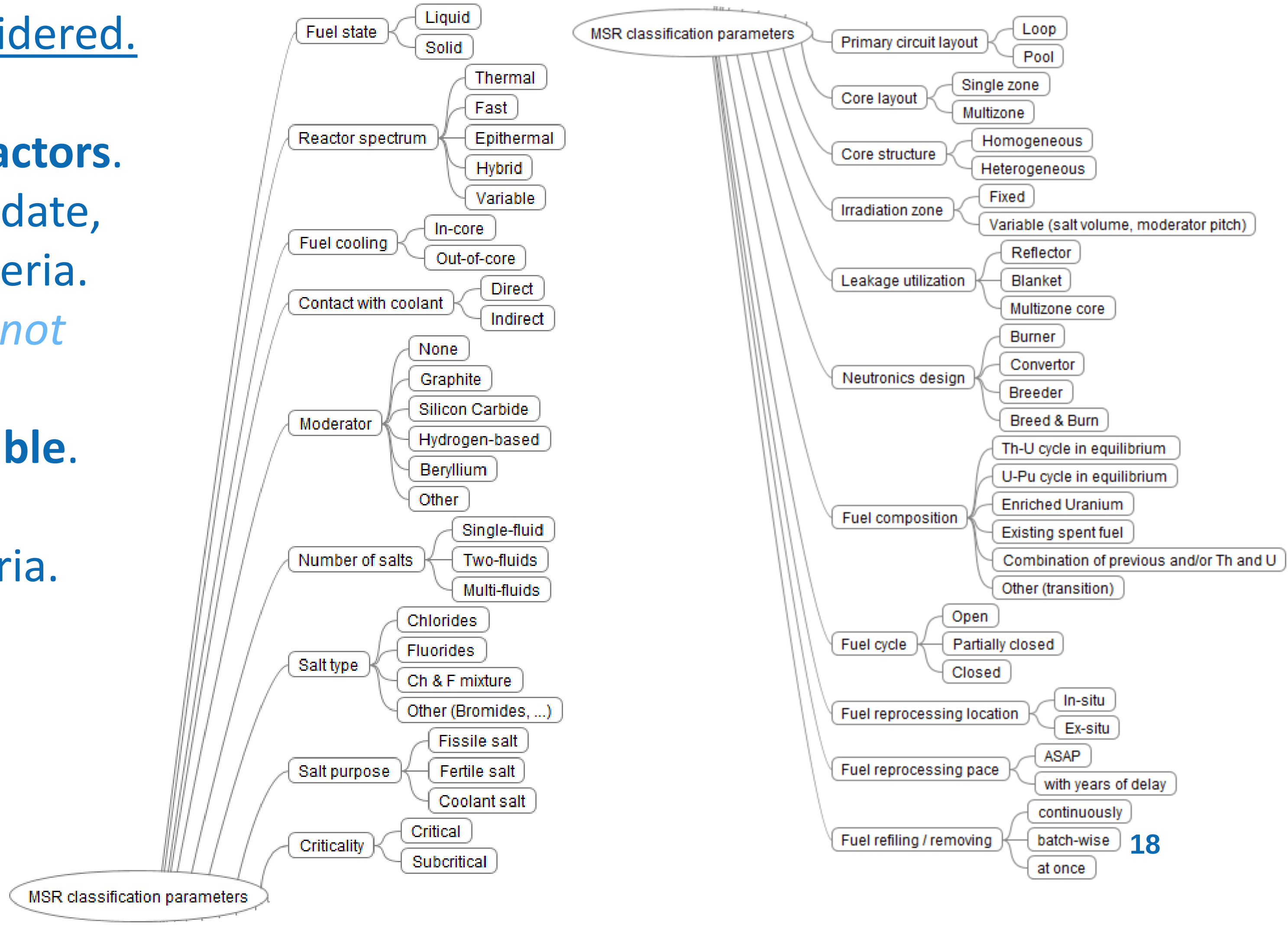
TAUBE, M., Fast Reactors Using Molten Chloride Salts as Fuel — Final Report (1972–1977), Rep. EIR-332, Eidg. Institut für Reaktorforschung, Würenlingen, Switzerland (1978).

Initial brainstorming and possible parameters

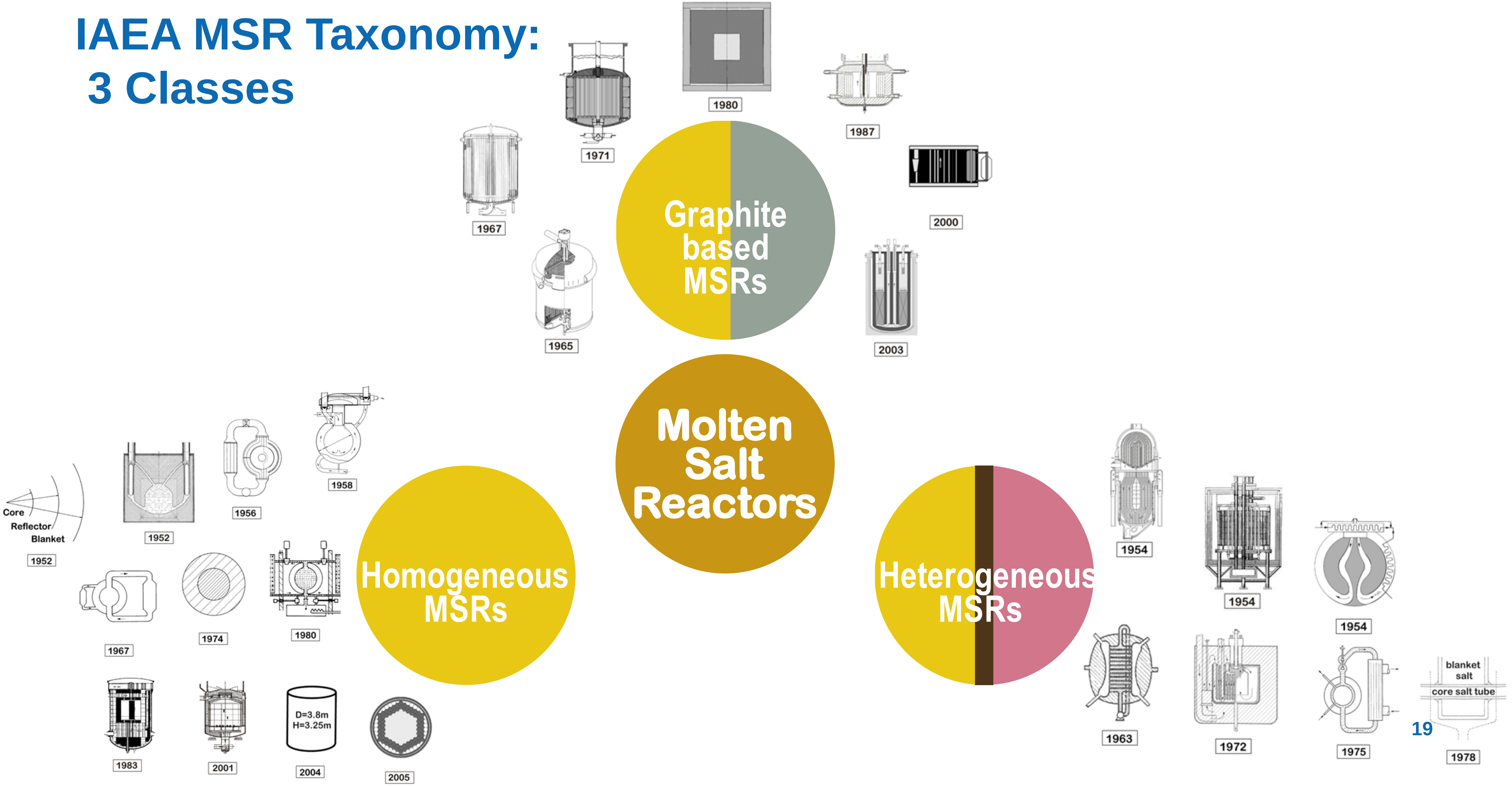
First technical Meeting on the Status of Molten Salt Reactor Technology at IAEA Headquarters in Vienna took place on 31.10-3.11.2016.

Many classification options have been considered.

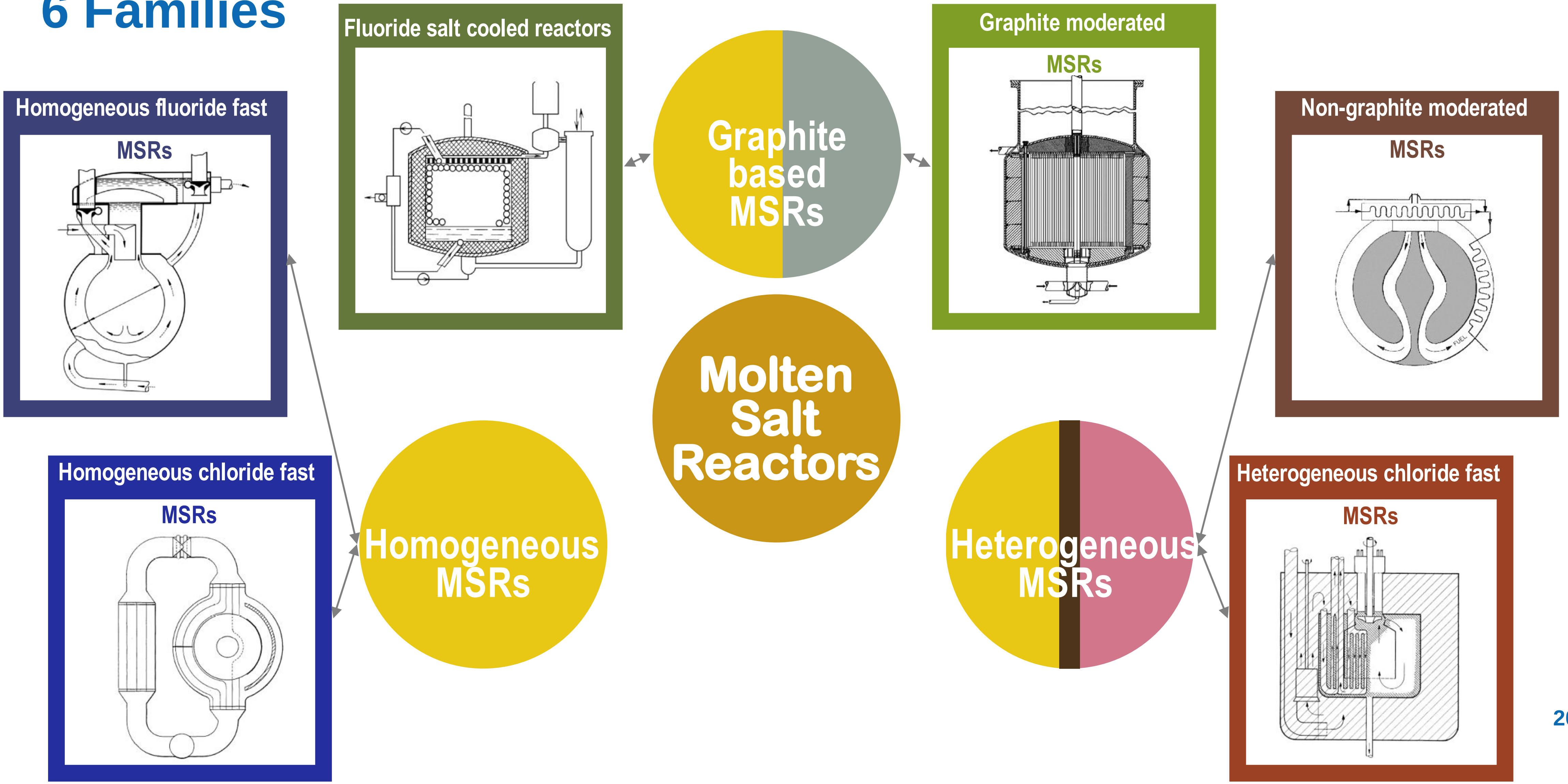
- **Taxonomy** was developed for **"large" reactors**.
- **Neutrons spectrum**, as a tempting candidate, **was not selected** as the highest rank criteria. *(similarly, like terrestrial or aquatic does not play a role in animal taxonomy)*
- Also **salt or fuel cycle type** was **not suitable**.
- Finally, the **number of materials** in the **active core** acts as the highest rank criteria.
- TRS No. 489 taxonomy with 3 classes:
  - 1 material *(fuel salt)*
  - 2 materials *(salt and graphite)*
  - 3 materials *(fuel salt, barrier, and dedicated coolant or moderator)*



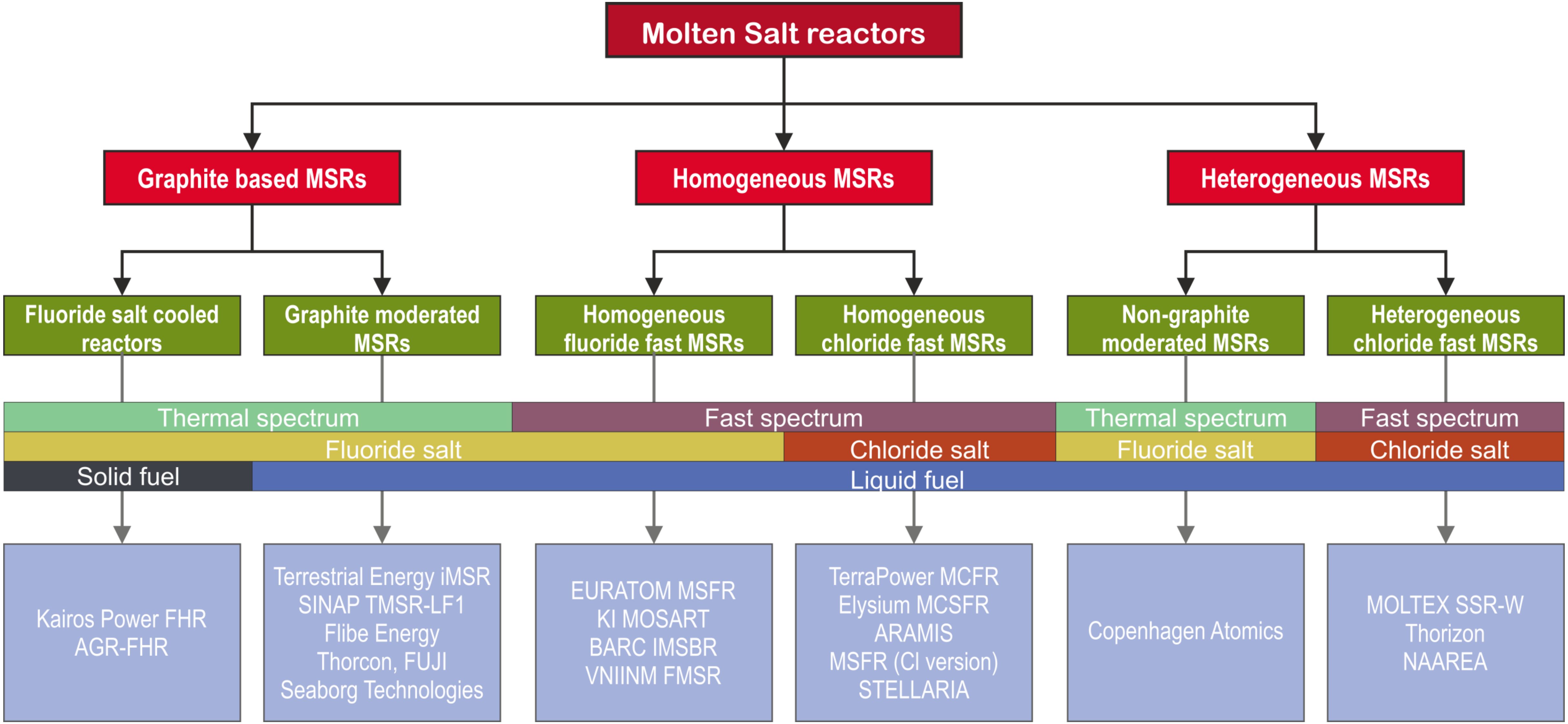
IAEA MSR Taxonomy: 3 Classes



IAEA MSR Taxonomy:
6 Families



IAEA taxonomy as adopted in GIF



IAEA taxonomy, GIF annual report 2024

Brief history of MSR

Aircraft Nuclear Propulsion program (1947-1961)

Spectrum: *Fast reactors have been excluded (size and shielding issues)*

Moderation options: *Solid fuel in the core cooled by liquid moderator (LiOH, NaOH) or liquid fuel passing through solid moderator in the core (Be, BeO)*

Fuel: *Enriched uranium*

Fuel form: *All possible uranium compounds have been considered.*

Major option: *Uranium fluoride diluted by fluoride carrier salt*

Major engineering challenges valid till now:

- *Minimizing melting temperature*
- *Compatibility with materials*
- *Minimizing core/shielding size/weight*

TABLE 12

Uranium Compounds

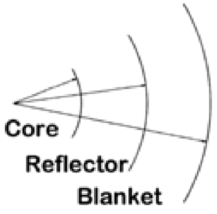
COMPOUND	MELTING POINT (°C)	BOILING POINT (°C)
UO_2	2700	-
UO_3	-	dec. 650
U_3O_8	-	dec. 1700
UF_3	1425	2300
UF_4	1036	1417
UF_6	65	56
UCl_3	835	1725
UCl_4	590	787
UCl_5	-	dec.
UCl_6	179	277
UBr_3	752	1567
UBr_4	519	766
UI_3	757	1427
UI_4	502	759
UN	2600	dec.
UC	2275	dec.
US	1800	-
U_2S_3	-	dec. 1800
US_2	-	dec. 1600
UOS	-	Probably unstable
UO_2F_2	-	dec.
UO_2Cl_2	-	dec.
$UOCl_2$	-	750
UP_2O_7	m.p. of porcelain	vol.
$UO_2P_2C_7$	-	
UC_2EO_2	called "stable" (most perborates explode)	
$3UO_3B_2O_3$		
$UO_3 \cdot 7SiO_2$	easily melted	
Na_2UO_4 (and polyuranates, other alkali uranates)	stable—not melted at 800°	

ELLIS, C.B.,THOMPSON, W.E., The Aircraft Nuclear Propulsion Project, quarterly progress report for period ending August 31, 1950, Rep. ORNL-0858, Oak Ridge Natl Lab., TN (1950).

1950th Early time of ORNL MSR pioneering

- Ongoing military project (small moderated cores)
- Students looking on fast chloride and fluoride breeder (faster in publishing?).

Year	Class	Family	Type	Concept	Author
1952	II. Class	4. Family	Chloride fast breeder reactor	**Fast Converter**	MIT
	GOODMAN, C., et al., Nuclear Problems of Non-aqueous Fluid Fuel Reactors, Rep. MIT-5000, Massachusetts Institute of Technology, Cambridge, MA (1952).				
1952	II. Class	3. Family	Fluoride fast Th-U breeder	**Fused Salt (Fast) Breeder Reactor (FSBR)**	ORNL
	WEHMEYER, D.B., et al., Study of a fused salt breeder reactor for power production, Rep. CF-53-10-25, Oak Ridge School of Reactor Technology, TN (1953).				
1954	III. Class	5. Family	Solid moderator heterogeneous MSRs	**ARE**	ORNL
	FRAAS, A.P., SAVOLAINEN, A.W., ORNL Aircraft Nuclear Power Plant Design, Rep. ORNL-1721, Oak Ridge Natl Lab., TN (1954).				
1954	III. Class	5. Family	Solid moderator heterogeneous MSRs	**Fireball**	ORNL
	FRAAS, A.P., SAVOLAINEN, A.W., ORNL Aircraft Nuclear Power Plant Design, Rep. ORNL-1721, Oak Ridge Natl Lab., TN (1954).				
1954	III. Class	5. Family	Liquid moderator heterogeneous MSRs	**ART concept variation**	ORNL
	FRAAS, A.P., SAVOLAINEN, A.W., ORNL Aircraft Nuclear Power Plant Design, Rep. ORNL-1721, Oak Ridge Natl Lab., TN (1954).				
1956	II. Class	4. Family	Chloride fast breeder reactor	**Fused Salt Fast Breeder**	ORNL
	BULMER, J.J., et al., Fused Salt Fast Breeder, Rep. ORNL-CF-56-8-204, Oak Ridge Natl Lab., TN (1956).				
1958	II. Class	3. Family	Fluoride fast Th-U breeder	**Two-region, homogeneous MSR**	ORNL
	MACPHERSON, H. G., Molten-Salt Reactor Program Quarterly Progress Report for Period Ending January 31, 1958, Rep. ORNL-2474, Oak Ridge Natl Lab., TN (1958).				



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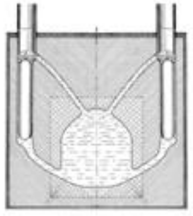
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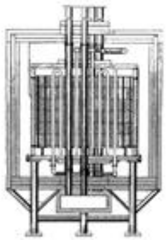
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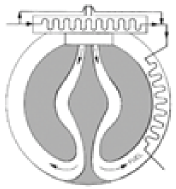
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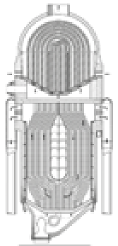
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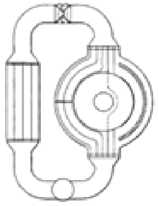
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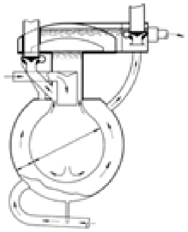
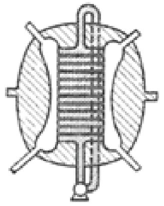

1958

1960th Leaving the military constrains

- No more necessity for compact reactor.
- Focusing on breeding performance.
- Th-U cycle in moderated, U-Pu in fast systems.

Year	Class	Family	Type	Concept	Author
1963	III. Class	6. Family	Heterogeneous salt cooled fast MSRs	**Internally cooled fast molten salt reactor**	ORNL
	Alexander, L. G., 1963, Molten-salt fast reactors, in proceedings of the Conference on Breeding, Economics and Safety in Large Fast Power Reactors, October 7–10.				
1965	I. Class	2. Family	Uranium converters and other concepts	**MSRE**	ORNL
	MACPHERSON, H. G., Molten-Salt Reactor Program Quarterly Progress Report for Period Ending July 31, 1960, Rep. ORNL-3014, Oak Ridge Natl Lab., TN (1960).				
1965	IV. Class	Other	Directly cooled MSRs	**MOSEL**	ORNL
	Kasten P. R., et al., 1965, Design concepts for the core structure of a MOSEL (Molten Salt Experimental) reactor, Nuclear structural engineering 2, (1965) 224-232.				
1966	IV. Class	Other	Directly cooled MSRs	**MSR directly cooled by lead**	Moore and Fawcett
	Moore and Fawcett, 1966, Present and Future Types of Fast Breeder Reactors, Proceedings of the London Conference on Fast Breeder Reactors Organized by the British Nuclear Energy				
1967	II. Class	4. Family	Chloride fast breeder reactor	**Homogeneous chloride-fueled fast reactor**	ANL
	NELSON, P.A., BUTLER, D.K., CHASANOV, M.G., MENEGHETTI, D., Fuel properties and nuclear performance of fast reactors fueled with molten chlorides, Nucl. Technol. 3 9 (1967) 540-547.				
1967	IV. Class	Other	Directly cooled MSRs	**MSR cooled by boiling AlCl3**	Taube et al.
	Taube, M., Mielcarski, M., Poturaj-Gutniak, S., Kowalew, A., 1967, New boiling salt fast breeder reactor concepts, Nuclear Engineering and Design, Volume 5, Issue 2, March 1967, Pages 109-				
1967	I. Class	2. Family	Two-fluids Th-U breeder	**MSBR2f**	ORNL
	ROSENTHAL, M.W., et al., Molten-Salt Reactor Program, Semiannual Progress Report for period ending August 31, 1967, Rep. ORNL-4191, Oak Ridge Natl Lab., TN (1967).				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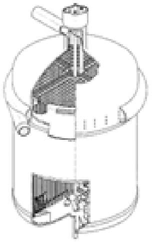
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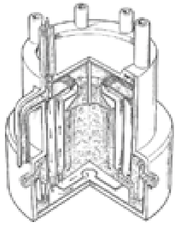
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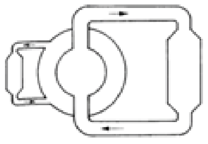
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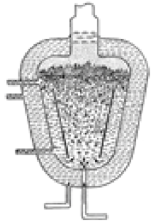
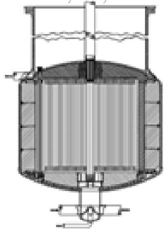

1967


1967

1970th ORNL activity declination

- In 1973 the MSBR project at ORNL was terminated.
- International research continued with some inertia; however, with delay it was also declining.

Year	Class	Family	Type	Concept	Author
1971	I. Class	2. Family	Single-fluid Th-U breeder	**MSBR**	ORNL
	ROBERTSON, R.C., et al., Conceptual Design of a Single-Fluid Molten-Salt Breeder Reactor, Rep. ORNL-4541, Oak Ridge Natl Lab., TN (1971).				
1971	IV. Class	Other	Frozen salt reactor	**Zero power reactor**	SINAP
	ZOU, Y., "Research progress of TMSR design, Shanghai Institute of Applied Physics, CAS", presented at SAMOFAR Final Mtg, Delft, Netherlands, 2019.				
1972	III. Class	6. Family	Heterogeneous salt cooled fast MSRs	**MCFBR**	EIR
	TAUBE, M., LIGOU J., Molten Chlorides Fast Breeder Reactor Problems and Possibilities, Rep. EIR-215, Eidg. Institut fur Reaktorforschung, Wurenlingen, Switzerland (1972).				
1974	II. Class	4. Family	Chloride fast breeder reactor	**Molten chloride Salt Fast Reactor**	Smith et al.
	SMITH, J., et al., An Assessment of a 2500 MWe Molten Chloride Salt Fast Reactor, Rep. AEEW-R956, UK Atomic Energy Authority, Winfrith, UK (1974).				
1974	II. Class	4. Family	Chloride fast breeder reactor	**Thorium-Uranium Fast/Thermal Breeder**	Taube et al.
	TAUBE, M., Thorium-Uranium Fast/Thermal Breeding System with Molten Salt Fuel, Rep. EIR-253, Eidg. Institut fur Reaktorforschung, Wurenlingen, Switzerland (1974).				
1974	IV. Class	Other	Directly cooled MSRs	**MSR directly cooled by lead**	Smith et al.
	SMITH, J., et al., An Assessment of a 2500 MWe Molten Chloride Salt Fast Reactor, Rep. AEEW-R956, UK Atomic Energy Authority, Winfrith, UK (1974).				
1975	II. Class	4. Family	Chloride fast breeder reactor	**High-Flux Fast Molten Salt Reactor**	Taube et al.
	TAUBE, M., OTTEWITTE, E. H., LIGOU, J., A High-Flux Fast Molten Salt Reactor for the Transmutation of Caesium-137 and Strontium-90, Rep. EIR-259, Switzerland (1975).				
1978	II. Class	4. Family	Chloride fast breeder reactor	**Chloride fast thorium breeder**	Ottewitte
	Ottewitte, E., 1978, Fast molten chloride reactor on the thorium cycle, ANS annual meeting; San Diego, CA, USA, 18 Jun.				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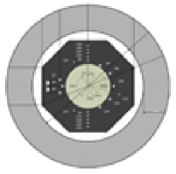
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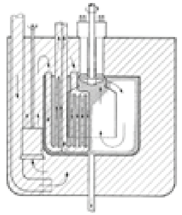
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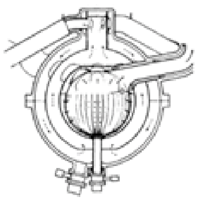
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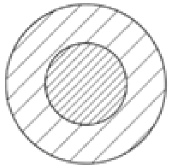
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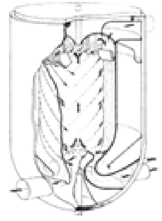
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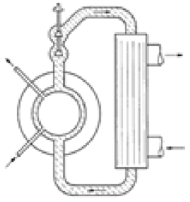
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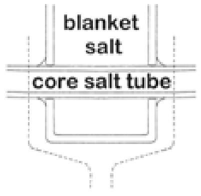
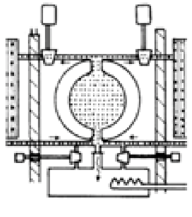


1978

1980th Low interest period

- Advanced reactor research is generally declining.
- LWR technology is dominating.
- Reserves of uranium seems sufficient.

Year	Class	Family	Type	Concept	Author
1980	II. Class	4. Family	Chloride fast breeder reactor	**SOFT**	EIR
	TAUBE, M., HEER, W., Reactor with Very Low Fission Product Inventory, Rep. EIR-411, Eidgenössisches Institut für Reaktorforschung (EIR), Wurenlingen, Switzerland (1980).				
1980	I. Class	2. Family	Uranium converters and other concepts	**DMSR**	ORNL
	ENGEL, J.R., et al., Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling, Rep. ORNL-TM-7207, Oak Ridge Natl Lab., TN (1980).				
1983	I. Class	1. Family	Salt cooled reactor with pebble bed fuel	**FCSR**	Kurchatov Institute
	BELOUSOV, I.G., et al., Features layout of VTRS for technological purpose, VANTS 16 3 (1983) 13-14.				
1983	IV. Class	Other	Directly cooled MSRs	**Concept RSF (lead cooled)**	CEA
	Groupe de Travail CEA-EDF "Concept RSF" (1983). Dossier Concept. Note CEA 002381, Commisariat à l'Énergie Atomique (CEA).				
1987	I. Class	2. Family	Uranium converters and other concepts	**FUJI**	Furukawa et al.
	FURUKAWA, K., et al., Compact molten-salt fission power stations (FUJI-series) and their developmental program, ECS Proceedings Volumes 1987 1 (1987) 896-905.				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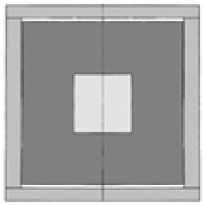
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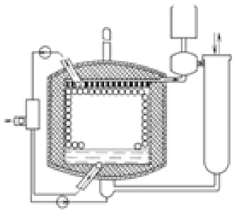
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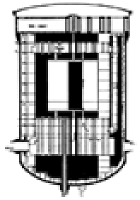
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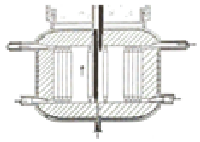
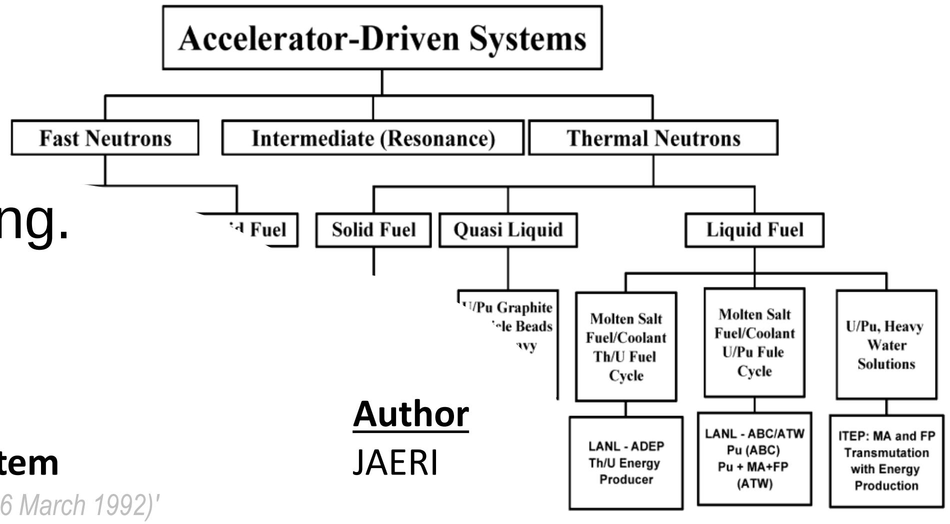
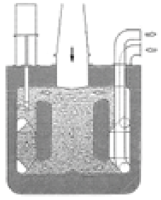

1987

1990th Waster burning time

- Accelerator driven systems considered for waster burning.
- MSR was also considered, but rather like exotic option.



Year	Class	Family	Type	Concept	Author
1992	IV. Class	Other	Subcritical MSRs	**Molten salt target system**	JAERI
	Kato, Y., et al., Accelerator Molten Salt Target System for Transmutation, Meeting on Accerelator Based Tmnsmutation (PSI, 24-26 March 1992)'				
1997	IV. Class	Other	Subcritical MSRs	**ADTT target blanket system**	LANL
	BOWMAN, C.D., "Basis and objectives of the Los Alamos Accelerator Driven Transmutation Technology Project", Status Report, IAEA-TECDOC-985, IAEA, Vienna (1997).				
1997	IV. Class	Other	Subcritical MSRs	**Molten salt ATW burner**	LANL
	VENNERI, F., et al., "The Los Alamos accelerator driven transmutation of nuclear waste (ATW) concept development of the ATW target/blanket system", IAEA-TECDOC-985, IAEA, Vienna				
1999	IV. Class	Other	Subcritical MSRs	**ADTT 700**	Skoda J.S.
	Valenta, V.: „Zadávací podklady pro projekt základní a demonstrační jednotky ADTT systému." Výzkumná zpráva pro Škoda JS s.r.o., Plzeň, 1999				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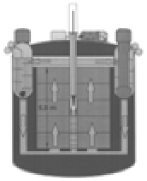
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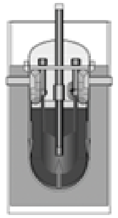
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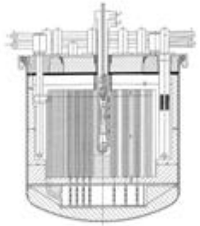
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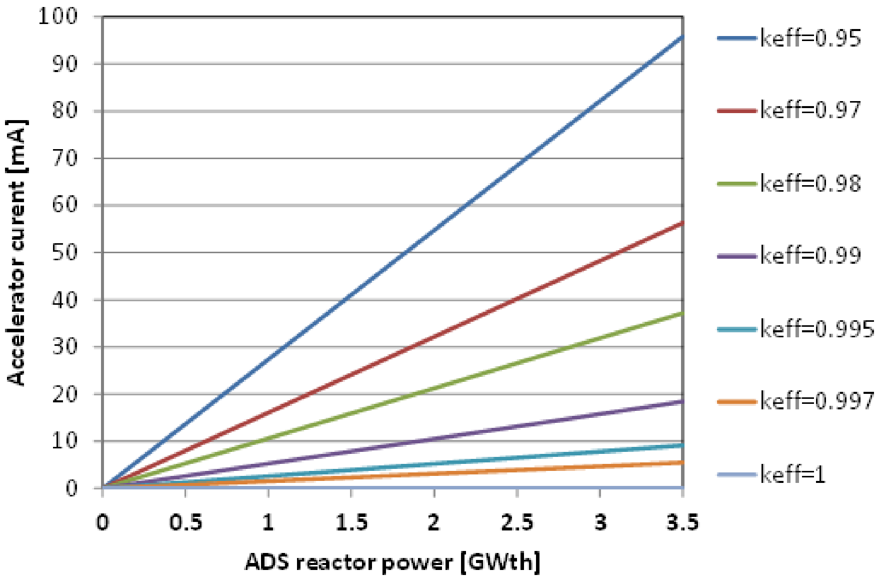
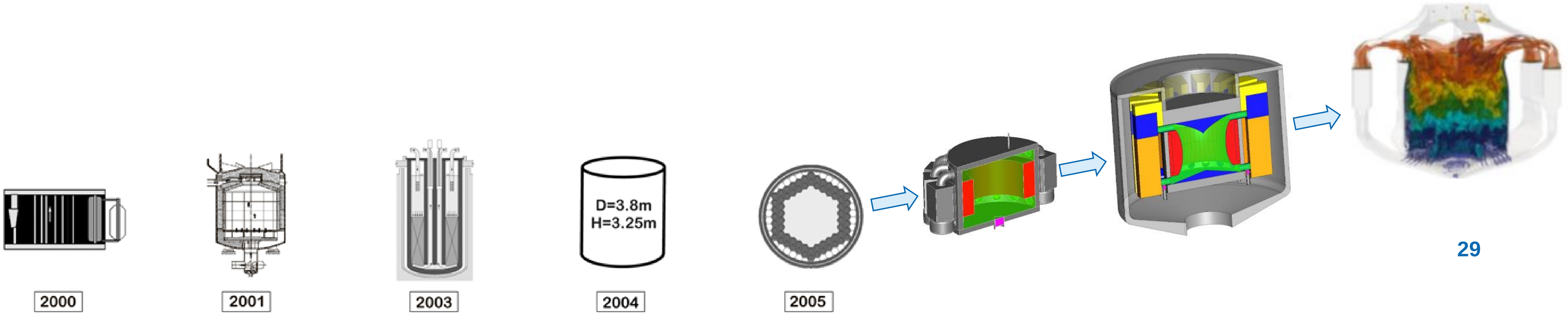


2000th start of Generation IV international forum

- Research of advanced nuclear system is growing.
- GIF defines 6 GIV systems inclusive MSR.
- Research still driven by academic institutions and research centers.

Year	Class	Family	Type	Concept	Author
2000	I. Class	2. Family	Single-fluid Th-U breeder	**AMSTER**	EdF
	VERGNES, J., et al., "The AMSTER Concept", Proc. of the 6th Information Exchange Mtg on Ac. and FPs. Partitioning and Transmutation, Madrid, 2000, OECD, Paris (2001) Session II.				
2001	II. Class	3. Family	Fluoride fast Pu-fuelled reactor	**MOSART**	Kurchatov Institute
	IGNATIEV, V., et al., Progress in Development of Li, Be, Na/F Molten Salt Actinide Recycler and Transmuter Concept, Proc. Int. Congr. Advances in Nuclear Power Plants (ICAPP 2007) (2007).				
2003	I. Class	1. Family	Salt cooled reactor with fixed fuel	**FHR**	UC Berkeley
	Forsberg, C., et al., Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity, Nuclear Technology 144(3), 2003				
2004	II. Class	4. Family	Chloride fast breeder reactor	**REBUS**	EDF
	MOUROGOV, A., BOKOV, P., "Fast spectrum molten salt reactor concept: REBUS-3700", paper presented at CAPRA CADRA Int. Sem., Aix-en-Provence, 2004.				
2005	II. Class	3. Family	Fluoride fast Th-U breeder	**MSFR**	CNRS
	MATHIEU, L., et al., The thorium molten salt reactor: moving on from the MSBR, Prog. Nucl. Energ. 48 7 (2006) 664-679.				



2010-2015 Start-up / brainstorming time

- MSR research is becoming substantial.
- Private start-ups revive many old concepts.
- Often based on one, typically fuel cycle, idea.

Year	Class	Family	Type	Concept	Author
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.				

2016-2020 Start-up / brainstorming time

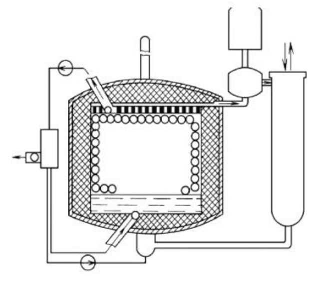
- MSR research is becoming substantial.
- Private start-ups revive many old concepts.
- Often based on one, typically fuel cycle, idea.

Year	Class	Family	Type	Concept	Author	Reference
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.*

MSR concepts as listed in the GIF annual report

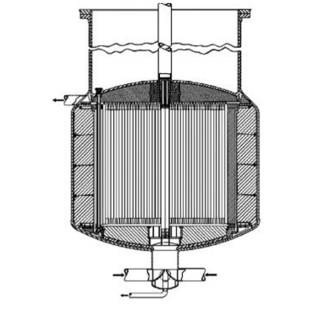
- Several MSR designers are progressing with the development and licensing.
- Often with national support project. However, major development steps are done with private capital.
- Searching for a GIF role: how to profit from this international collaboration, established framework, and collected knowledge...?

Fluoride salt cooled reactors



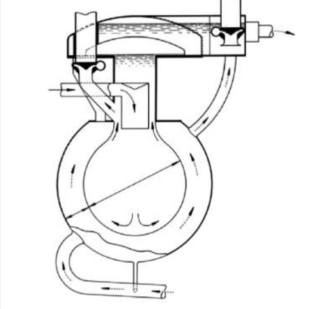
Kairos Power FHR
AGR-FHR

Graphite moderated MSRs



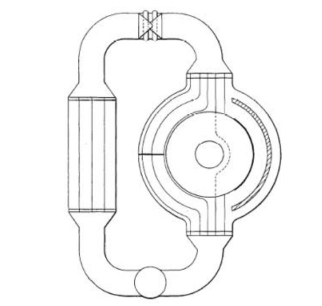
Terrestrial Energy iMSR
SINAP TMSR-LF1
Flibe Energy
Thorcon, FUJI
Seaborg Technologies

Homogeneous fluoride fast MSRs



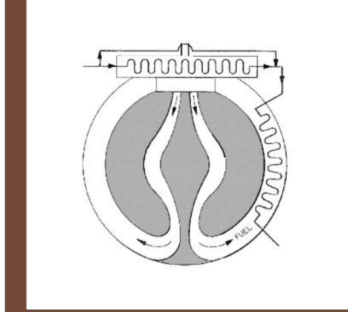
EURATOM MSFR
KI MOSART
BARC IMSBR
VNIINM FMSR

Homogeneous chloride fast MSRs



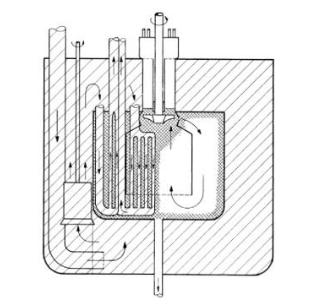
TerraPower MCFR
Elysium MCSFR
ARAMIS
MSFR (Cl version)
STELLARIA

Non-graphite moderated MSRs



Copenhagen Atomics

Heterogeneous chloride fast MSRs



MOLTEX SSR-W
Thorizon
NAAREA

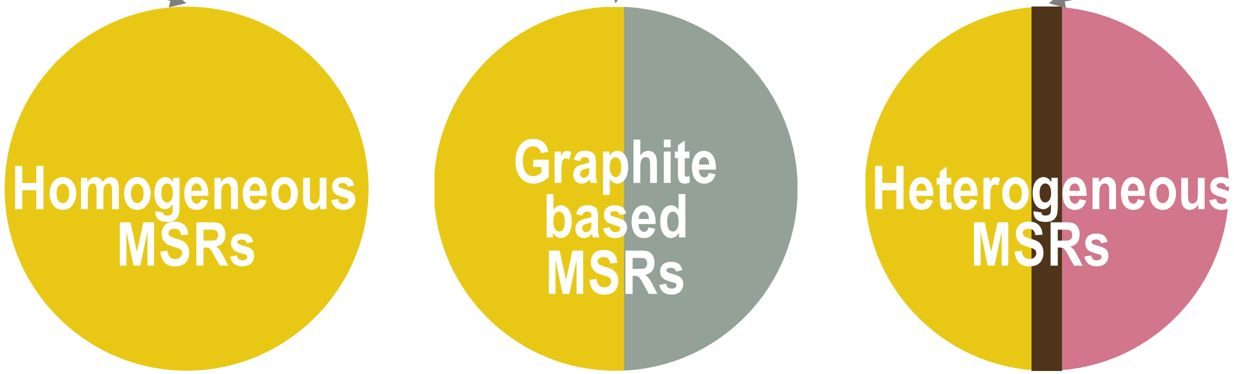
MSR issues in a nutshell

Expertise | Collaboration | Excellence

MSR classes: 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.

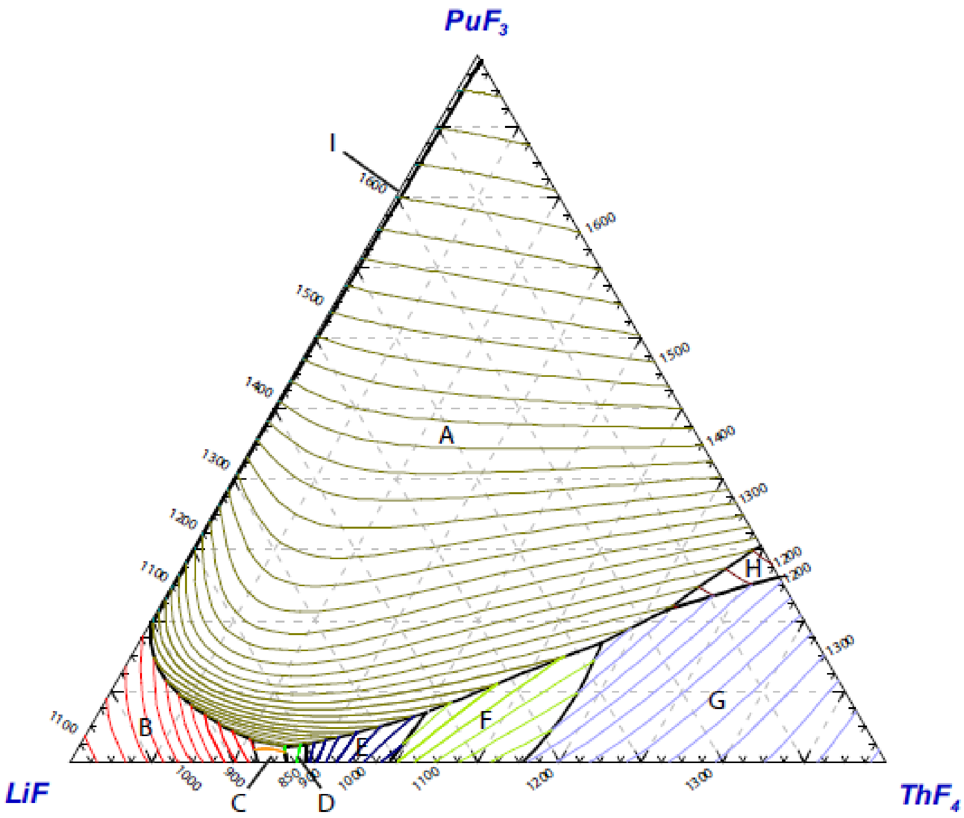
- Fluoride salt. *(high Cl neutron captures)*
- Possibility of Th-U cycle. *(demanding, fast fuel cleaning needed)*
- LEU fuel cycle.
- In case of solid fuel embedded in graphite, only moderating salts, like LiF-BeF_2, provides negative coolant density effect.
- Regular graphite replacement.



- 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.

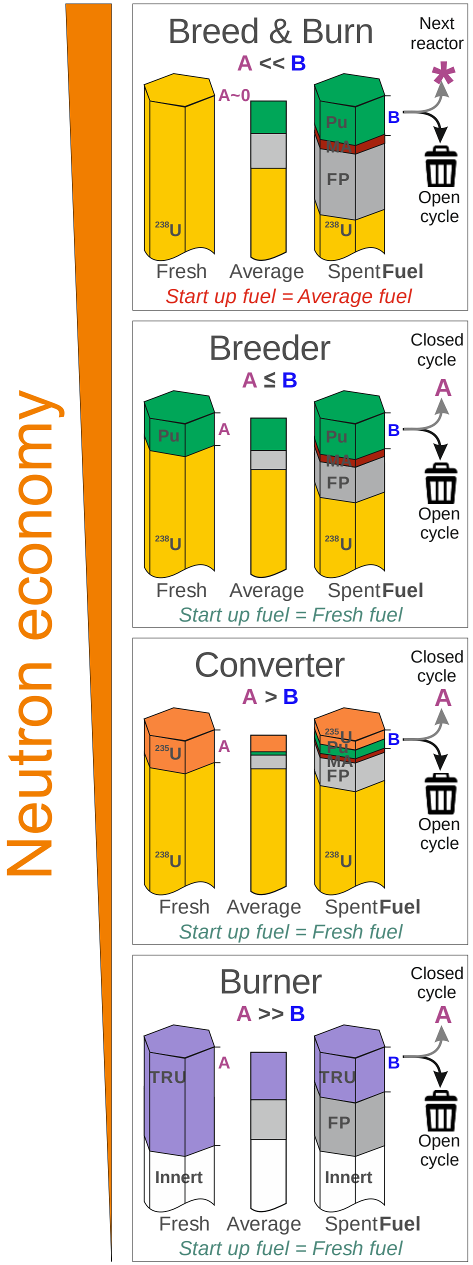
Reasonable temperature window for operation:
interval between salt melting and structural materials failure

- 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

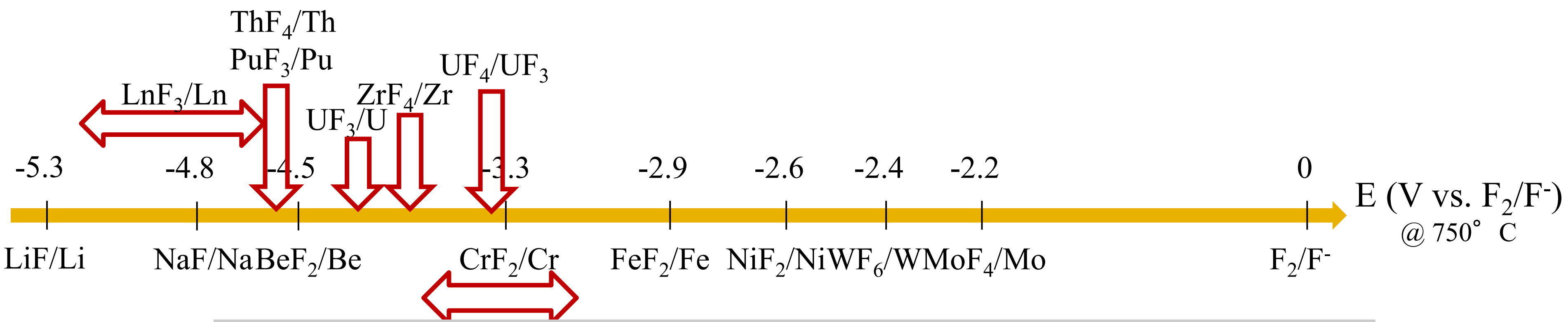
E. CAPELLI et al., "Thermodynamic Assessment of the LiF–ThF4–PuF3–UF4 System," J. Nucl. Mater., ***462****, 43 (2015).*



Reasonable Redox potential window

Salt stability versus structural material corrosion

- 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.
- Redox needs to be controlled and impurities removed (to avoid corrosion and/or precipitation).



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

Salt compatibility with reprocessing method

Reprocessing as "à la carte " choice

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:

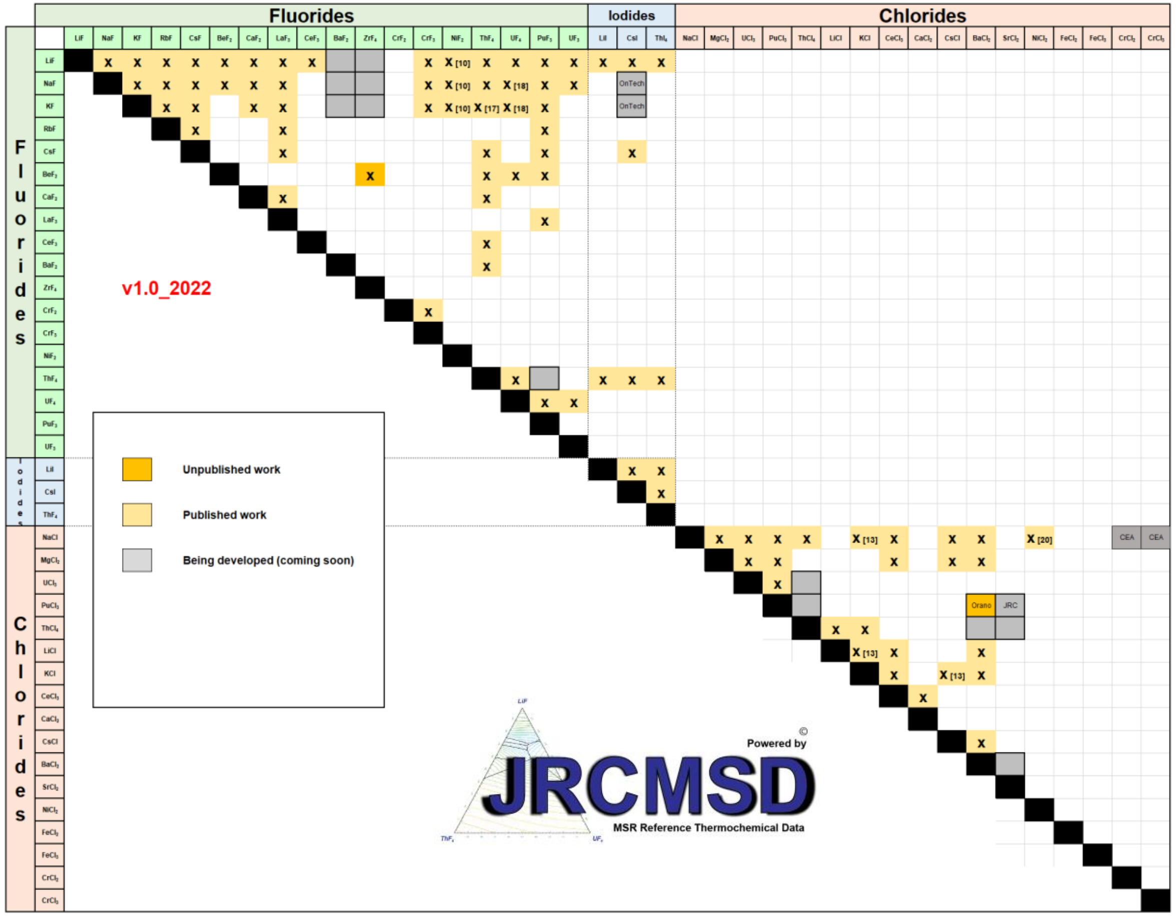
- Gaseous and volatile FPs removal (off-gas system).
- Metallic FPs removal (sponge filter or by off-gas sys.).
- Molten salt / liquid metal reductive extraction.
- Electro-separation processes.
- Compound evaporation or possibly precipitation.
- Fluoride volatilization techniques, fluorination of the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

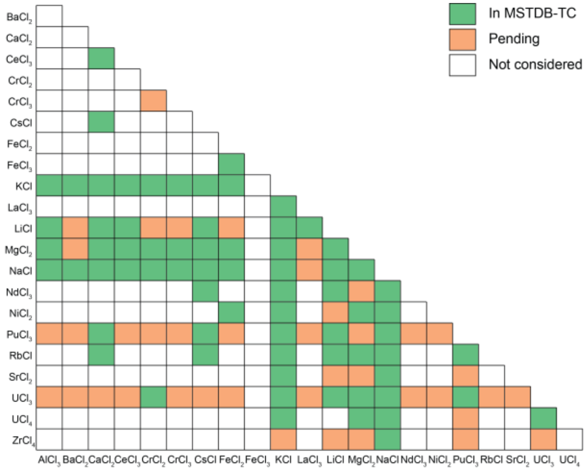
Salt removal from the core	Removed salt share	Fissile fuel recycling	Fissile fuel return after reprocessing	Carrier salt cleaning	Carrier salt return after reprocessing	Reprocessing waste immobilization
Continuous or Batch-wise	From 0.1% to whole salt volume	In-situ or Ex-situ	ASAP or with months or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

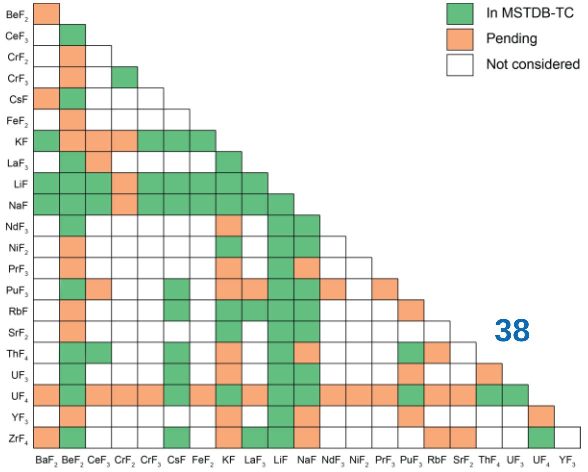
Thermodynamic databases

- **JRCMSD - JRC Thermodynamic database**
  - Started in 2002 by JRC
  - Multi-lateral collaboration TEMOSA Project
  - Open access through EU Science Hub, distribution through FactSage and Thermochimica ongoing

- **MSTDB-TC - Molten Salt Thermal Properties – Thermochemical Database**
  - Started in 2021
  - Collaboration of ORNL, University of South Carolina, NEAMS, and Molten salt Reactor PROGRAM
  - Access through ORNL web page







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Oak Ridge National Laboratory

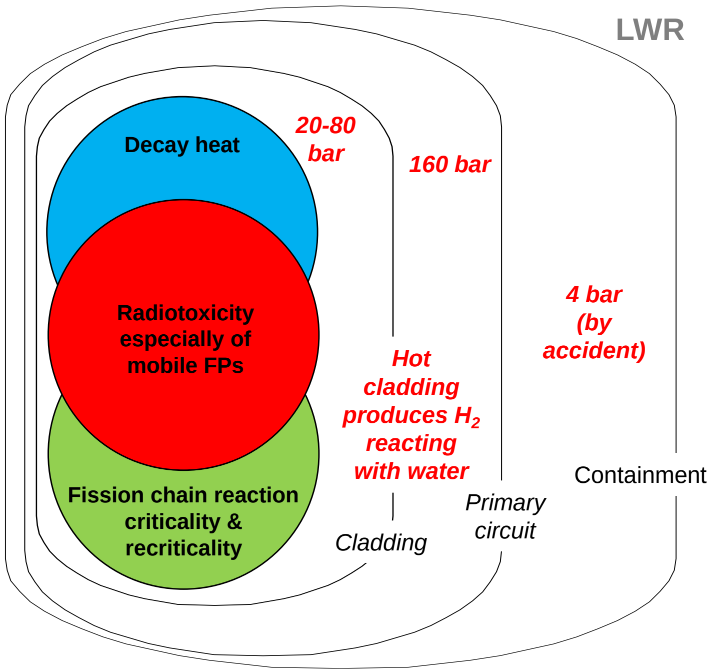
NEAMS

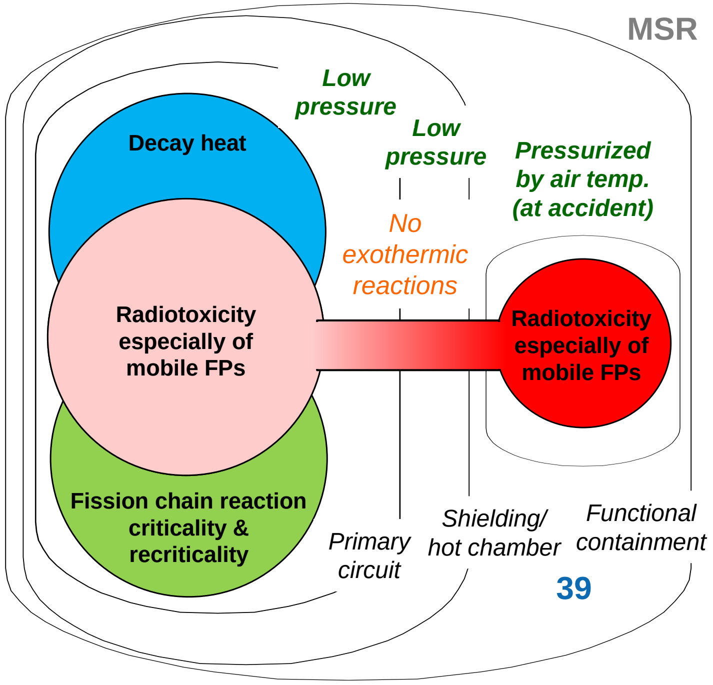
University of South Carolina

Molten Salt Reactor PROGRAM

MSR safety and licensing

- In majority of solid fuel reactors, the reactor core consist of a fuel pin lattice.
- The fuel assemblies/pins (cladding & fuel pellet) form the reactor core, which has three major functions:
  1. It is the location of first confinement barrier.
  2. It is the location of primary heat exchange (pin surface is the heat exchange surface).
  3. Core (fuel pins) are shaping the neutron flux area (criticality safety).
- Core damage thus:
  - represents loss of these three functions and
  - is considered as severe accident (safety threat; irreversible; facility loss).
- In some MSR designs the core is shaped by solid moderator and/or vessel.
- Liquid fuel relocation from core does not always mean severe accident.
- Core damage can thus have different importance in MSR.
- Safety regulations are not necessarily prepared for MSR.





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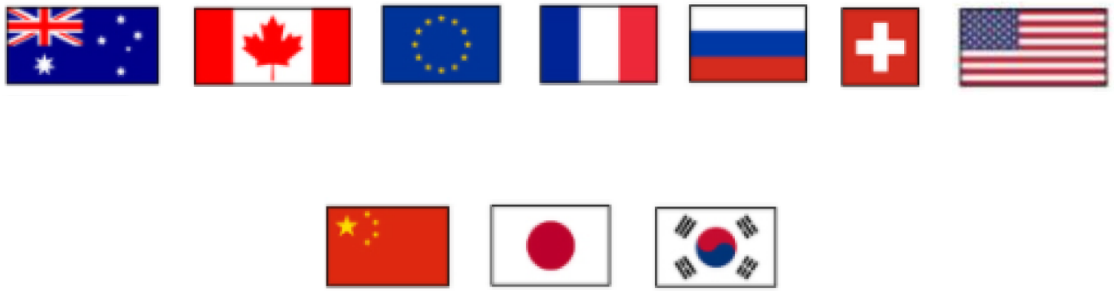
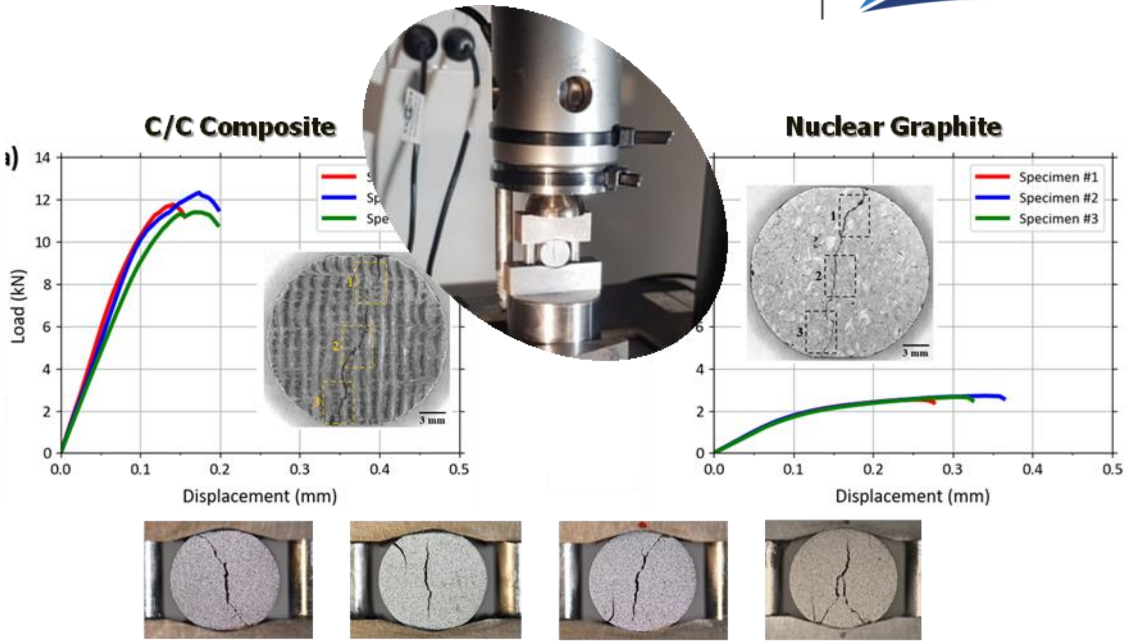
GIF MSR partners

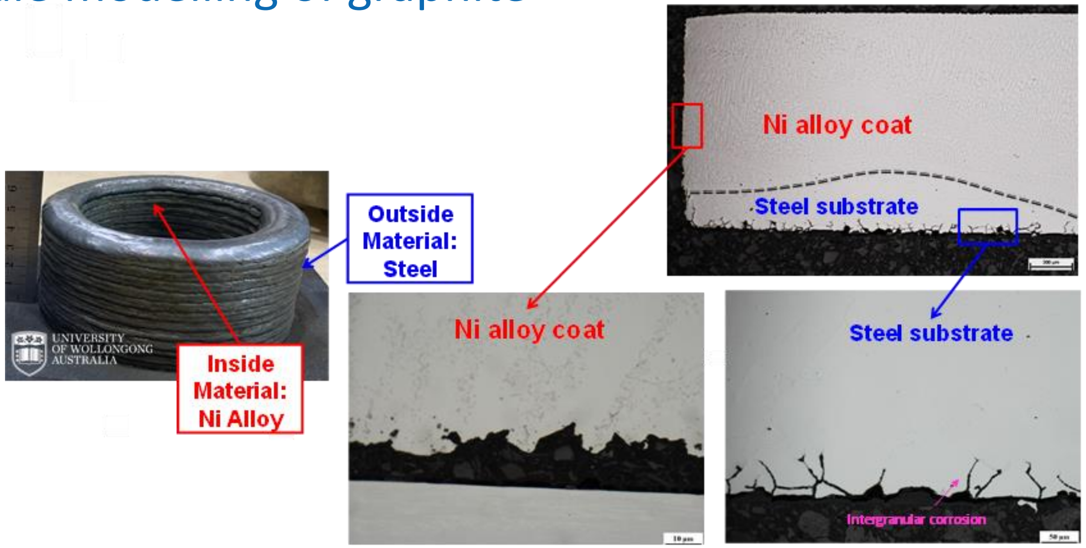


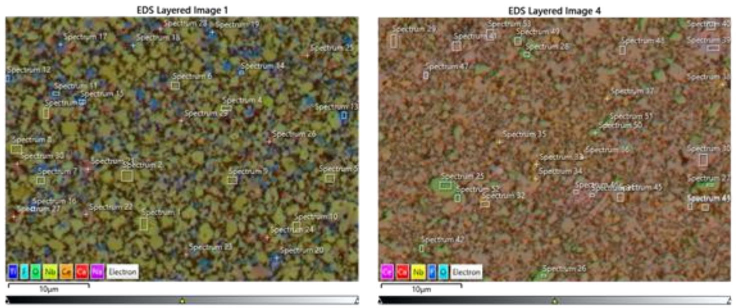
Australia : MSR Landscape

Focus areas:

- Radiation damage of structural nickel alloys
- High temperature creep & molten salt corrosion of structural alloys
- Development of Synroc-type waste forms for fluoride molten salt immobilisation
- Testing and multiscale modelling of graphite and C/C composite







Ti balancing
Green: Pyrochlore
Blue: Titania
Red: CaF_2 fluorite

Vacancy balancing
Orange/red: Pyrochlore
Green: $NaNbO_3$

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Canada: MSR Landscape

Stream 1: On-Grid, ~300 MW_e

- Ontario Power Generation & SaskPower select GE-Hitachi BWRX-300
  - Darlington 4 units (2028 first)
  - SK 4 units (2034-2042)
- Alberta
  - SMART MOU
  - OPG & Capital Power

Stream 2: Advanced Reactors

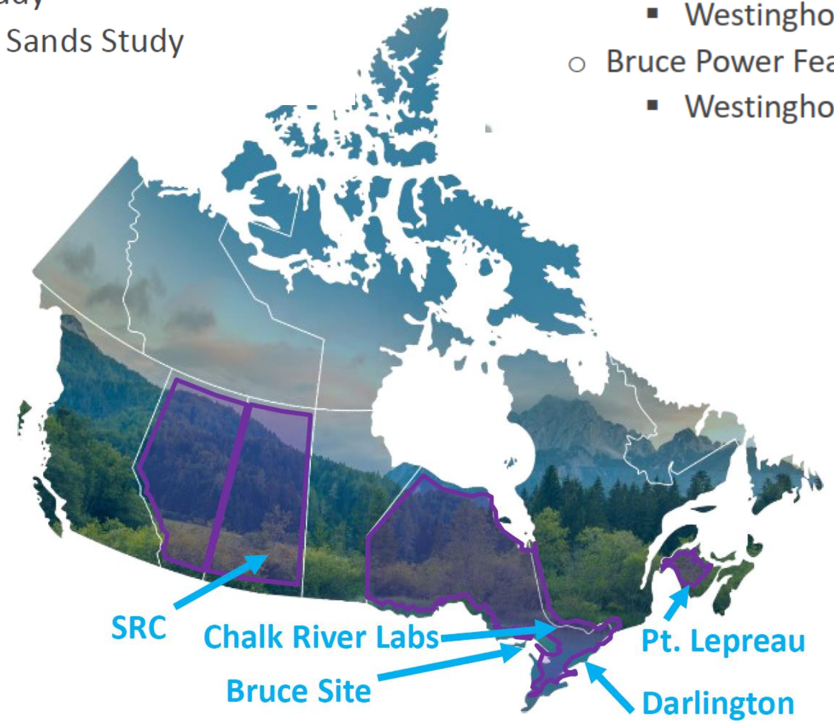
- New Brunswick Power, Point Lepreau
  - ARC Nuclear ARC-100, LTPS submitted
  - Moltex SSR-W
- OPG + X-Energy framework agreement
- Alberta
  - Terrestrial Energy MOU
  - X-Energy Study
  - Cenovus Oil Sands Study

Stream 3: Off-Grid, <15 MW_e

- Development of a pan-Canadian Framework to inform the safe deployment of SMR microreactors
  - CNL's Siting Invitation Process
    - Hosting a clean energy demonstration on a CNL-managed site (e.g. GFP MMR)
  - McMaster's Net Zero Community Project
    - USNC/GFP MOU
  - Saskatchewan Research Council (SRC) Nuclear
    - Westinghouse eVinci
  - Bruce Power Feasibility Study
    - Westinghouse eVinci

Large Nuclear

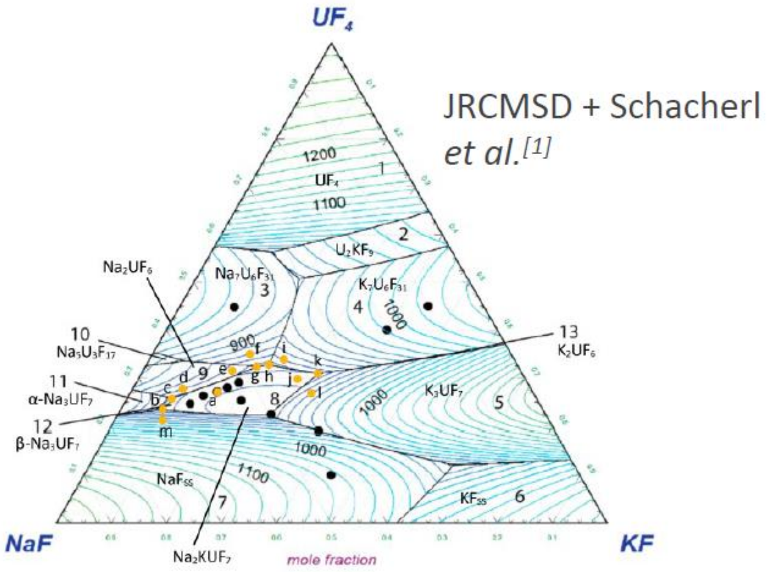
- Refurbs ahead of plan
- Pickering refurb
- Bruce Site 4800MWe pre-development
- AtkinsRéalis 1,000 MW CANDU® MONARK™



Canada: MSR Landscape

Fuel and coolant salt properties

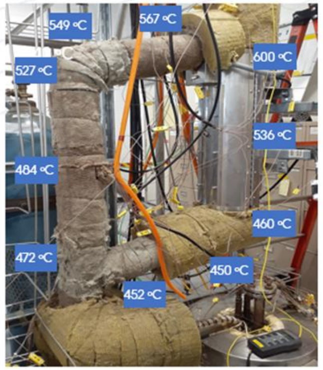
- Performing DSC measurements on selected compositions of NaF-KF-UF_4 fuel salt system to map low-liquidus temperatures and benchmark with JRC.
- Developed and applied polarizable interatomic potentials and ab-initio molecular dynamics to study several systems: Nitrates, KCl-$MgCl_2$, NaCl-UCl_3, NaCl-UCl_4
- And thermophysical properties measurements of molten salts (thermal conductivity, melting point, heat of fusion, heat capacity)



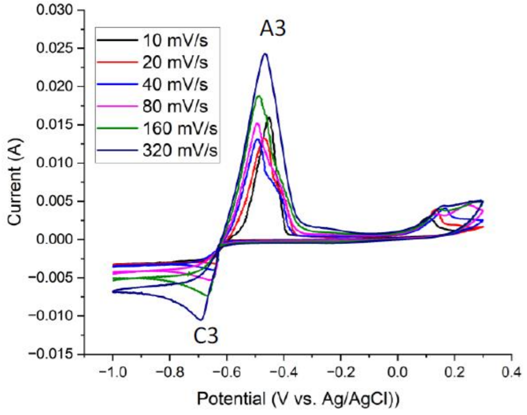
NaF-KF-UF_4 phase diagram

Materials and Components

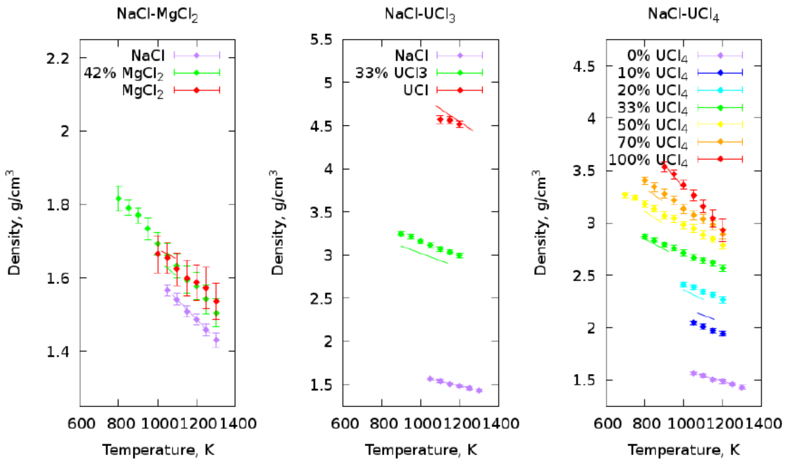
- Corrosion experiment of SS 316 under flowing molten chloride salt conditions
- Developing reference electrodes for molten salts
- Exploring methods for redox potential control in molten salts
- Exploring electrochemical processes and mass transport of corrosion products in molten salts
- Investigating impact of fission products formation and neutron activation on redox potential



Corrosion loop



Cyclic voltammetry scan of $FeCl_2$-containing salt



Temperature dependent densities of chloride salt mixtures computed using polarizable interatomic potentials

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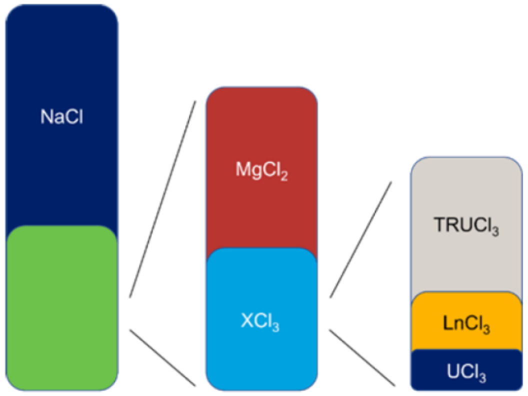
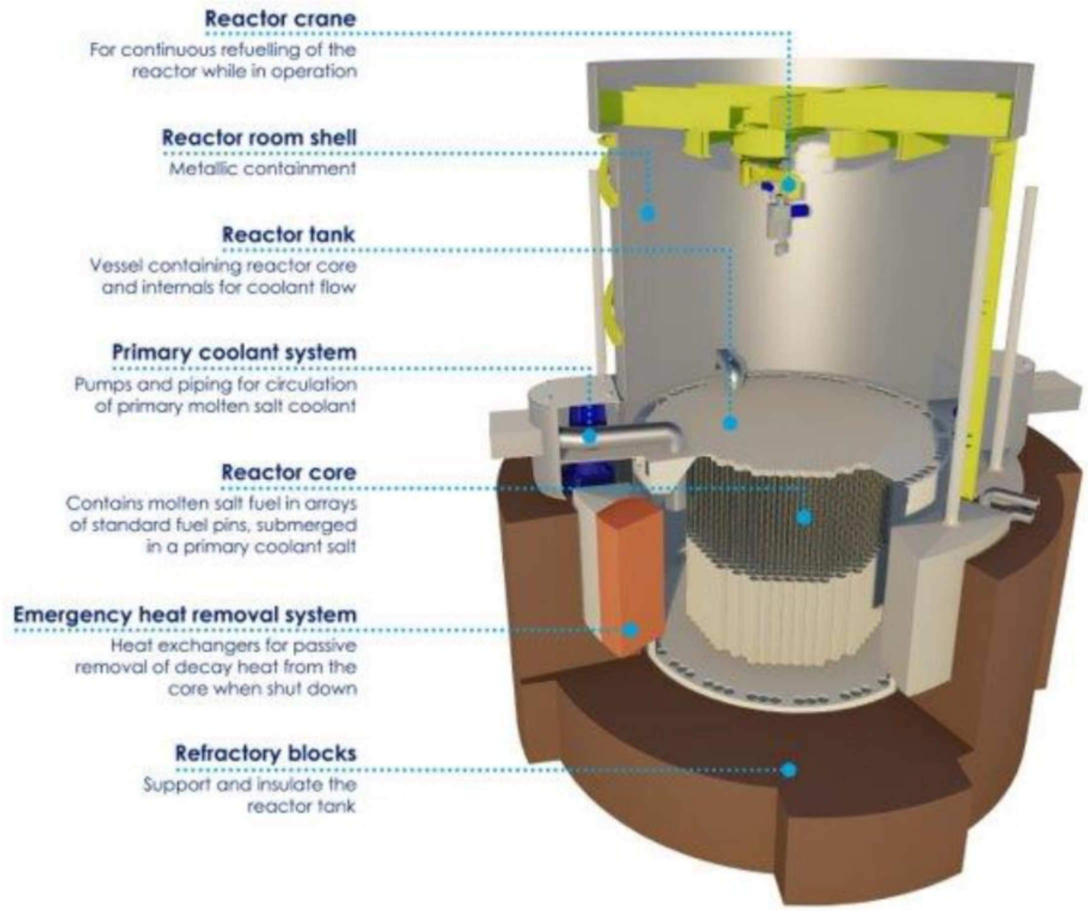
MOLTEX: Stable Salt Reactor Waste burner (SSR-W)

- High temperature (575ºC), fast neutron, molten chloride reactor
- 300-500 MWe per reactor
- Uses recycled nuclear waste as fuel
- Fuel salt confined to pins, grouped in fuel assemblies
- Refuelling by removing/replacing individual assemblies





Source: https://www.moltexenergy.com/

EURATOM: MSR Landscape – Horizon projects

SAMOSAFER

- Successful 4 years project.
- Ended at the end of 2023
- https://samosafer.eu/

MIMOSA

- Orano is the Project coordinator
- Launched in summer 2022 (4 years, ~6M€)
- Feasibility study of MSR (Cl based) as potential option for actinide incinerator
- MultI-recycling strategies of LWR SNF focusing on MOlten SAlt technology
- https://www.mimosa-euratom.eu/

ENDURANCE

- 4 years project
- Informal Follow up of SAMOSAFER
- Launch date 1.10.2024
- To bring MSR to higher TRL's
- Supported by most of EU MSR SME's

EURATOM: MSR Landscape – SME's (excluding France)

Copenhagen Atomics (DK)

- Completion of FLiNaK reactor prototype
- New 11000 m2 site for salt handling and future reactor production
- Microreactor test site selected at PSI

Seaborg Technologies (DK)

- Seaborg leads CMSR design.
- Consortium Agreement with Samsung HI (barge) and Korea H & NP (operation).
- Fuel change from HALEU to LEU, MoU with Kepco Nuclear Fuels and GS Engineering & Construction (fuel production process).
- MoU with Pertamina Power Indonesia to explore deployment of the CMSR Power Barge in Indonesia.

Dual-Fluid (DE)

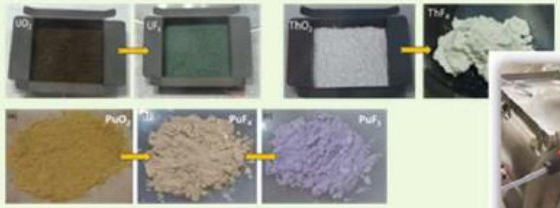
- After the concept revision it is not anymore MSR system.
- Liquid salt fuel was replaced by liquid metal fuel.

Thorizon (NL)

- Chloride fast MSR.
- Reactor core based on fuel cartridges.
- Individual cartridge looks like homogeneous reactor.
- The actual reactor core is, however, heterogeneous.

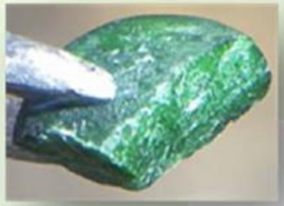
EURATOM: MSR Landscape – JRC & MSR R&D

Synthesis & Electrochemistry



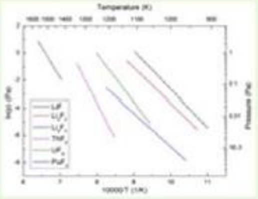
UF_4, UF_3, PuF_3, ThF_4, $PuCl_3$
Ongoing: UCl_3, NpF_3

Irradiation of MS & PIE MS



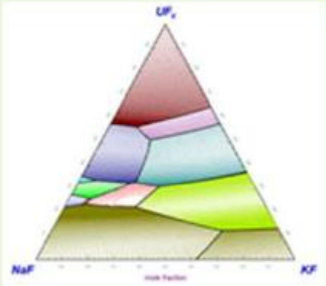
Thermo-physical Properties

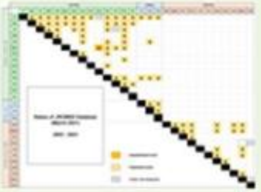
- Melting point
- Thermal conductivity
- Heat capacity
- Fission product behaviour
- Vapour pressure
- Transition enthalpy
- Phase diagrams
- Density, Viscosity
- Corrosion studies



JRC Competences in MSR
R&D Safety Studies

Thermodynamic Database development

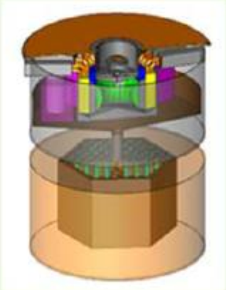


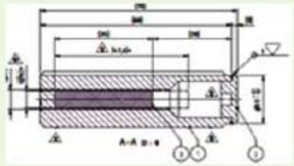


73 systems

JRCMSD

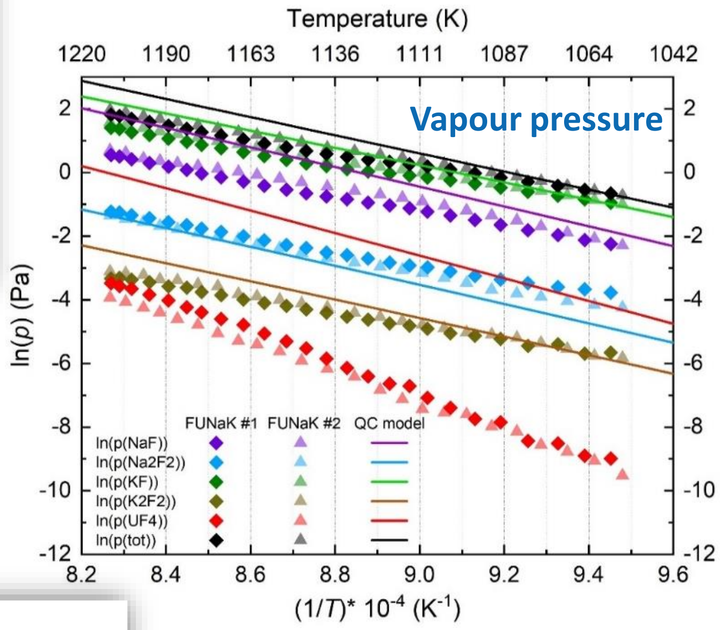
Reactor Safety

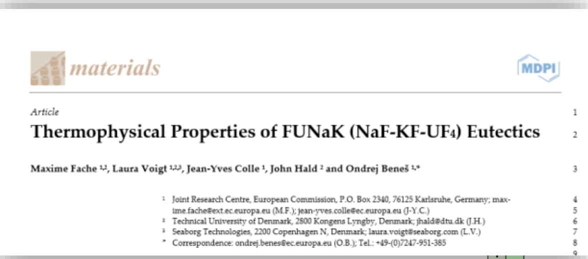




EURATOM: Highlights

- Organization of PSIS workshop (Putting Science Into Standards) on MSR technology (>100 international participants, high recognition) as a side event to the Nuclear Summit in Brussels (2024)/
- Novel Experimental Data on ThF_4, PuF_3, $PuCl_3$- containing systems within SAMOSAFER and MIMOSA EU Projects (incl. corrosion studies)
  - **Highlight:** Experimental identification of 2 lowest FUNaK eutectics and extensive evaluation of their properties (paper submitted)
- Synthesis of high pure $PuCl_3$ (for properties measurements)
- Extension of the JRCMSD Thermodynamic Database by novel assessments
  - Collaboration JRC-TU Delft-CEA-Orano (TEMOSA project signed in January 2024)
  - Today over 120 binary sub-systems





materials MDPI

Article

Thermophysical Properties of FUNaK (NaF-KF-UF4) Eutectics

Maxime Fache [1,2], Laura Voigt [1,2,3], Jean-Yves Colle [1], John Hald [2] and Ondrej Beneš [1,*]

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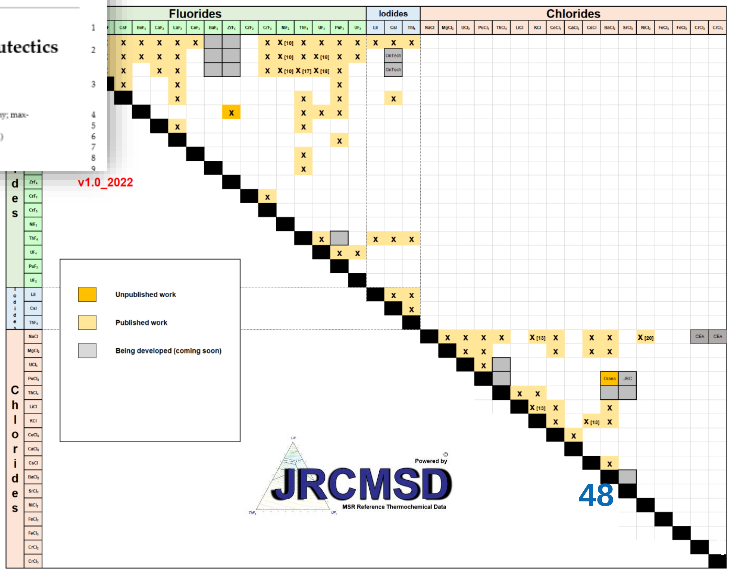


- **Highlight:** Studies on Fission Product influence on thermo-physical properties of MSR fuels
- Participation to high level IAEA-NEA meeting (WP lead)
- ENDURANCE project has been granted (2 EU MSR projects in parallel)

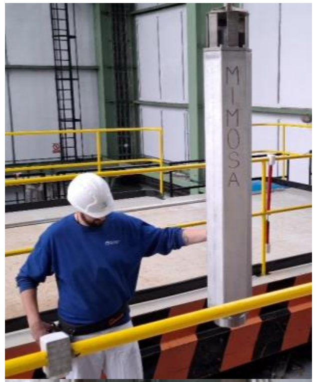
EURATOM: individual countries

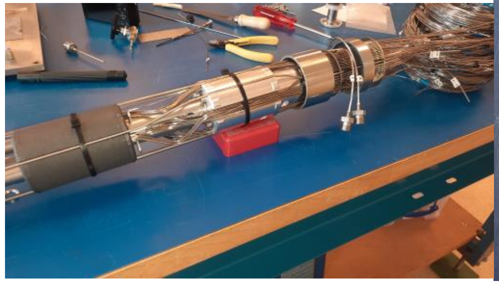
Czechia: CV Řež

- Research Centre Řež is involved in the EC project MIMOSA. Here the main activities were focused on the measurement of neutronic properties of chloride salts NaCl, MgCl2 and CaCl2. The measurements are carried out on the LR-0 reactor.
- Since October 2024, the Research Centre Řež is participating in the new EC project ENDURANCE (continuation of the SAMOSAFER project).
- Within the national activities, MSR material research is mainly focused on surface thermomechanical processing of reactor components for fluoride media (Laser Shot Peening, Hot Isostatics Pressing, ...). Several Czech research organizations are involved in the research.

The Netherlands: NRG

- SAGA-2, the second round of gamma irradiation of salt granulate at ~50°C, has finished; samples (LiF, BeF_2, ThF_4, UF_4, LiF-BeF_2-UF_4, NaCl) transported to labs for post-irradiation examination. SAGA-3 (chloride salts and grain size effects) is in preparation for start in Q3 2025.
- Successful chemical conversion of chloride salt to borosilicate glass was carried out in the context of MIMOSA.
- High-temperature creep (HITEC) experiment on tensile creep of stainless steels at 650°C is in preparation within the FIDES-2 irradiation program (OECD/NEA); concept design completed. Post-irradiation examination of Hastelloy N and similar alloys irradiated at 650°C: tensile tests completed, low-cycle fatigue and microscopy to be done.
- Salt capsule irradiation containing LiF-ThF_4-Uf_x-PuF_3 in Hastelloy N capsules (SALIENT-03) is scheduled to start in summer of 2025.





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EURATOM: individual countries

The Netherlands: TU Delft

- PhD thesis of B. Kaaks on melting and solidification in molten salt reactors. https://resolver.tudelft.nl/uuid:c566870e-e503-4b37-a7d8-93fbca9488c1
- PhD thesis of T. Dumaire on the chemistry of molten salt fuels with fission products and corrosion products. https://research.tudelft.nl/en/publications/advanced-in-the-chemistry-of-molten-salt-fuels-with-emphasis-on-f
- Ongoing study on maximizing the recovery of fission particles in molten salt reactors as part of the MIMOSA project. The tests based on the design with water have been finalized, the experimental facility with molten salt is currently under construction.
- Experimental study and thermodynamic modelling of the key fission products systems in chloride fuels: BaCl2-NdCl3 and SrCl2-NdCl3 & BaCl2-CeCl3
- Experimental study and thermodynamic modelling of the corrosion products system in fluoride fuel salts: LiF-ThF4-CrF2. https://www.sciencedirect.com/science/article/pii/S0364591624000646
- Thermodynamic assessment of the fission product system LiF-BaF2-ZrF4 in fluoride fuel salt. https://www.sciencedirect.com/science/article/pii/S0378381224001249
- Study of key corrosion systems in chloride fuel salts in the MIMOSA project, e.g. NaCl-CrCl2, NaCl-FeCl2, CrCl2-NdCl3 (PhD Nick ter Veer)
- Static corrosion experiments of various selected alloys in contact with NaCl-MgCl2-CeCl3 salt mixtures (PhD Ana Sacristan)
- Per October 1 2024, the new project ENDURANCE will commence (follow-up of SAMOSAFER).

EURATOM: individual countries

Italy: PoliMi

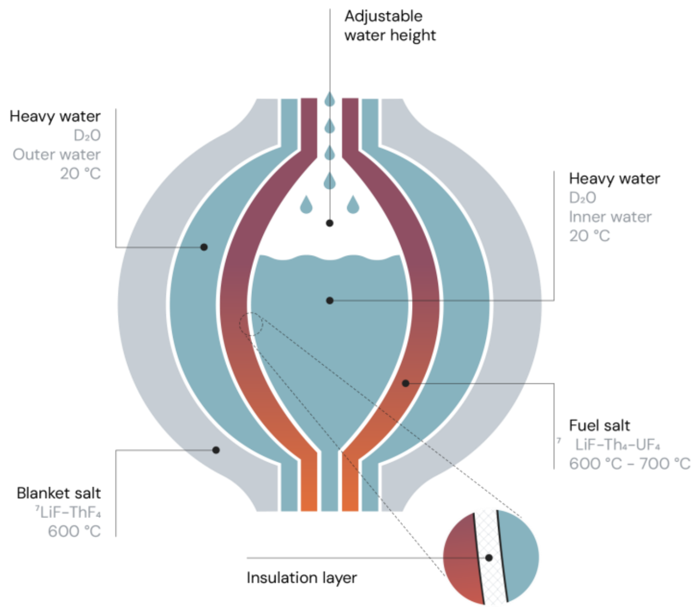
- S. Lorenzi (Polimi) project coordinator of the 4 years project ENDURANCE (kick-off meeting on 03.10.2024).
- new model for particle deposition in collaboration with Naarea (Phd student funded)
- simulation on freeze plug melting and draining, study of fuel blockage in MSBR-like channel
- developing OpenFOAM/Modelica coupling through Functional Mockup Interface

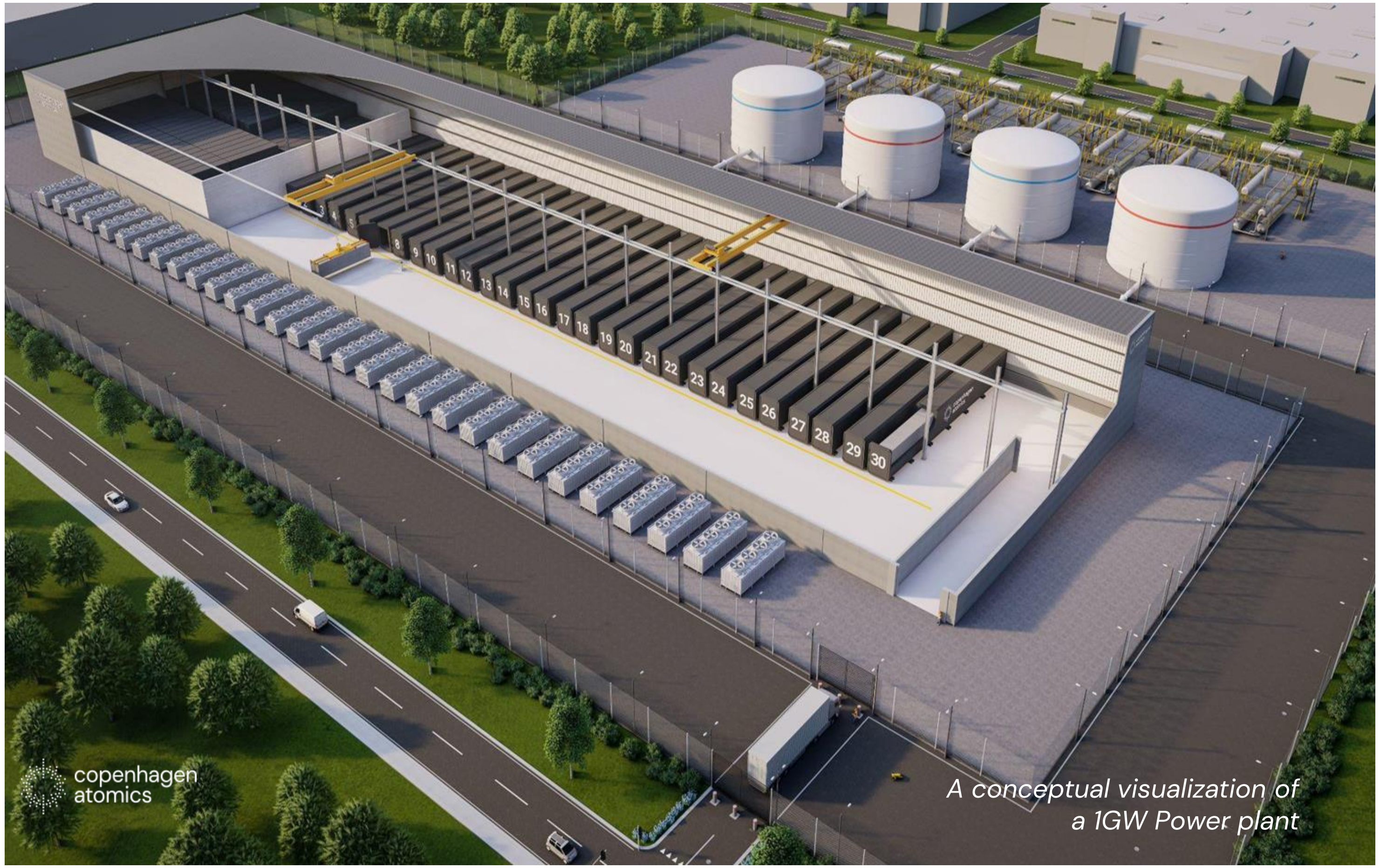
Denmark: DTU

- Startup of the Centre for Nuclear Energy Technology (as of 1.1.2024)
- Completion of one PhD (Birgitte Stoffersen) and funding for two new PhD's (to be recruited)
- New laboratory equipment at DTU Construct and DTU Energy (see attached slides)
- Collaboration project with DTU, Seaborg and JRC completed (Maxime Fache)

EURATOM: Copenhagen Atomics (DK)

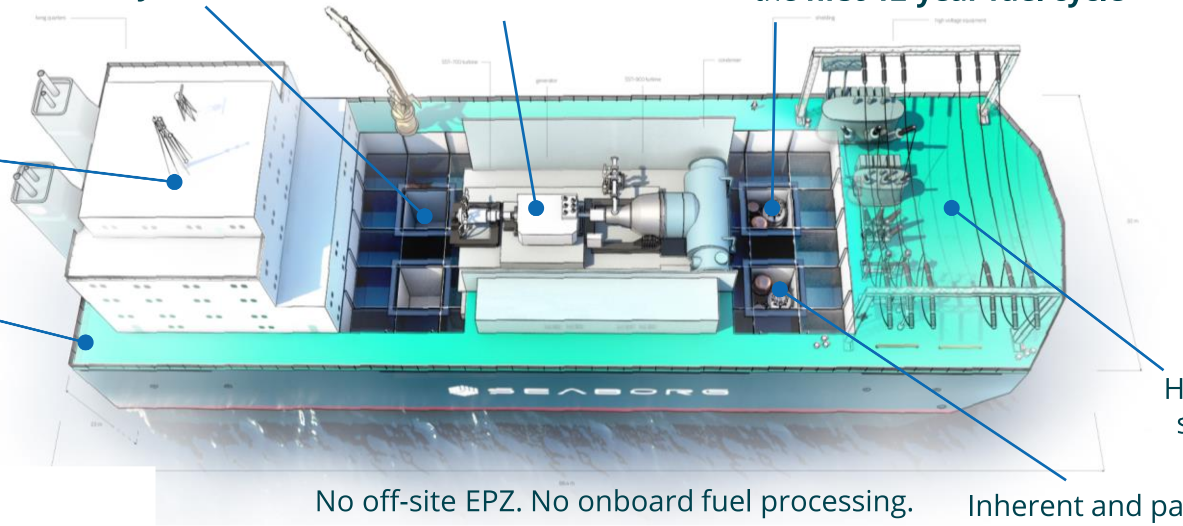
- Molten fluoride thermal breeder reactor
- Burn-then-breed (Th-U fuel cycle)
- 100 MWt per reactor
- 40ft container sized, mass manufactured on an assembly line
- Reactivity control adjusting water level
- No online refueling for the life of the reactor

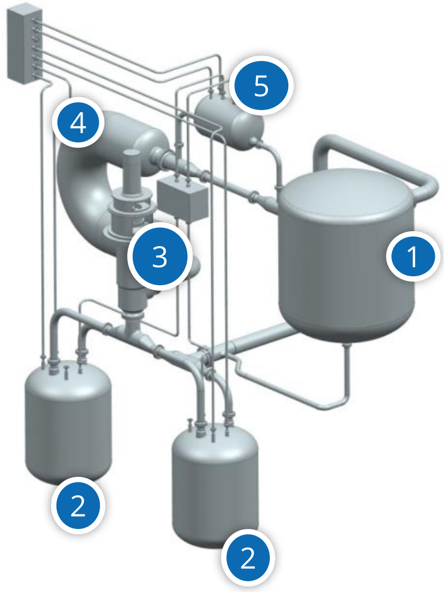




EURATOM: Seaborg Technologies (DK)

Seaborg develops the CMSR – a graphite moderated molten salt reactor to be integrated on a barge for worldwide deployment





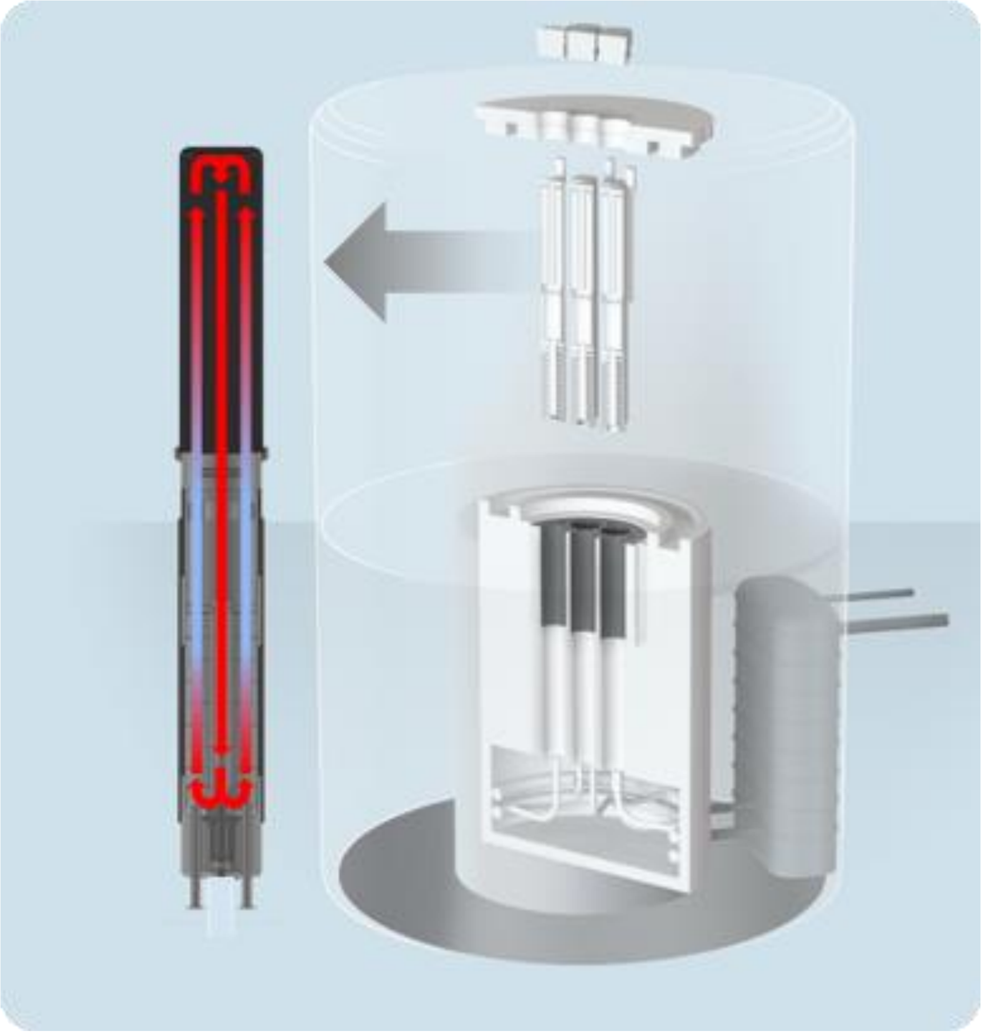
1. Reactor Vessel
2. Fuel Salt Drain Tank
3. Primary Pump
4. Primary Heat Exchanger
5. High Point Tank

POWER BARGE KEY CHARACTERISTICS

Parameter	Value
Reactor Type	**Molten Salt Reactor**
Neutron spectrum	Thermal
Moderator	**Graphite**
Thermal/electric capacity	$250MW_t/100MW_e$ per CMSR
Fuel type	**FUNaK LEU**
Initial enrichment	= approx. 2%
Fuel cycle	**144 months once through Online addition of fuel**
Power conversion process	Superheated steam driven turbine (Rankine cycle)
Design life (target)	**12 y per CMSR/ 24 y per Power Barge**
Design status	**Conceptual design**

EURATOM: Thorizon (NL)

- Cartridge based-core.
- Salt is contained in cartridges that are replaced every 5 to 10 years.
- Containment materials are already qualified for nuclear use.
- Fuel volume is compartmented in modular cartridges.
- Cartridges allow for transport and handling of fuel.



Thorizon's patented concept:

Exchangeable molten salt cartridges that together form a critical reactor core

France: MSR Landscape

Project France Relance ISAC (2022-2026) IN PROGRESS
dedicated to assess the opportunity of actinide transmutation in fast chloride MSR. Include experimental programs on material behavior and molten salt chemistry as well as design and simulation activities (leader **CEA** – partners CNRS, ORANO, FRAMATOME, EDF)

Project France Relance MOSARWASTE (2023-2026) IN PROGRESS
dedicated to the management of waste from molten salt reactors – linked to the ISAC project (leader **CEA**, partners ORANO, CNRS)

Project France Relance PORTHOS (2022-2025) IN PROGRESS
dedicated to the synthesis of $ThCl_4$ and purification of molten chloride salts (leader **ORANO**, partners: SOLVAY, CNRS)

Project Horizon/Europe SAMOSAFER (2019-2023)

Dedicated to safety operation of MSR and preliminary regulations issues (leader **TUDelft** - partners CNRS, CEA, FRAMATOME, IRSN, EDF)

Project Horizon/Europe MIMOSA (2022-2026) IN PROGRESS
implication on neutronic and coupled calculations, on scenarios, on chemistry and valorization of FPs (leader **ORANO** - partners CNRS)

Call Horizon/Europe ENDURANCE (2024-2028) NEW

Next EURATOM call 2023 - dedicated to MSR technological development and operation
(leader **POLITECNICO**, partners CEA, CNRS, FRAMATOME, NAAREA)

Startup NAAREA (2021-) Selected in 06/22 as part as the France 2030 call NEW

Fast chloride micro MSRs using actinides (1 to 40 Mwe)

Startup STELLARIA (2023-)

Fast chloride small MSRs using actinides (150 to 300 Mwe)

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France: Overview of CEA R&D activities on MSR

CODE DEVELOPMENT & SIMULATION ACTIVITIES

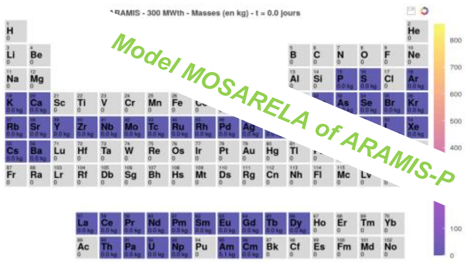
Development of **MOSARELA** (MOlten SAlt REactor Life-cycle Assessment) for fuel salt composition evolution and fission products assessement

Coupling **MOSARELA/OPENCALPHAD** to assess salt thermodynamical state (@Post Doc TIWARI V.)

Extension of **CATHARE 3** system code to MSR physics (calculation of ARE tests …)

Development of multiphysics calculation schemes :

- **APOLLO3/TRIO CFD, TRUST-NK** N/TH coupling (RANS/LES)
- **APOLLO3/EUROPLEXUS** fluid dynamics and neutron coupling



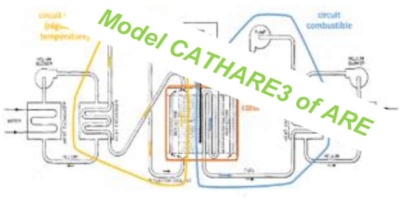
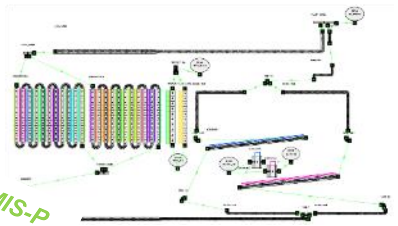
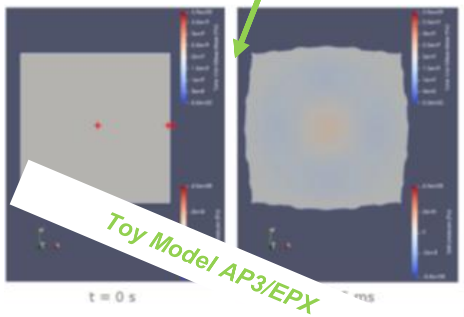


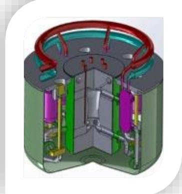
Fig. 2.1. Schematic Diagram of the Aircraft Reactor Experiment.





DESIGN ACTIVITIES

ARAMIS-P : Pre-design a 300 MWth fast MSR for plutonium conversion (ORANO/CEA)



Preliminary analysis of an experimental reactor to assess MSR physics (@Post Doc METHIVIERS L.)

EUROPEAN & NATIONAL PROJECT

Contribution on **SAMOSAFER** project (CAO, safety, operating conditions)

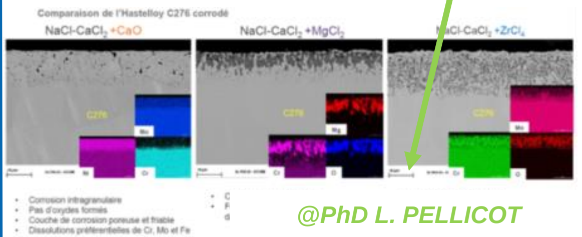
Involved in the **ENDURANCE** call (safety, transient analysis, expert design review)

Contribution to **MOSARWASTE** projet (review of final waste of MSR cycle)

CHEMISTRY

PuCl3 synthesis and salt processing studies in ATALANTE (**CEA Marcoule - 2021**)

Material corrosion screening in MESCAL (2021) (**CEA Saclay**)



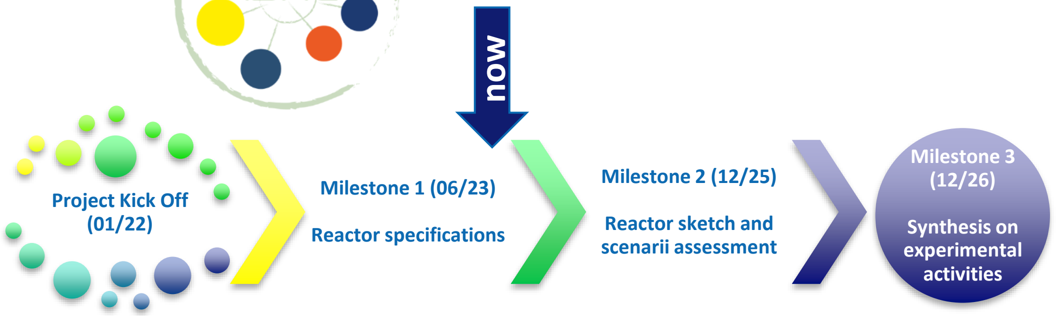
@PhD L. PELLICOT

SUPPORT FOR FRENCH MSR STARTUPs

Startups support in the framework of France 2030 call

- Design review
- Code development activities (coupling schemes, CATHARE or MSR, MOSARELA …)
- Safety and operation activities (PIRT analysis, ISAM methodology …)
- Material corrosion experiments
- Molten salt chemistry experiments

France: Focus on ISAC activities at CEA / CNRS

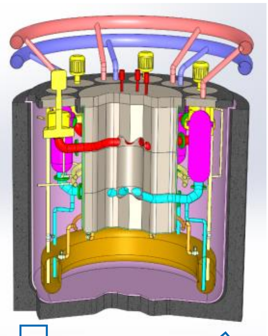


ISAC Project (2022-2026) – 26 M€ in 5 years

- Preliminary specifications of actinide burner ARAMIS-A (FRAMATOME et al.)
- Preliminary assessment of incineration capacities (CEA et al.)

DESIGN & SIMULATION

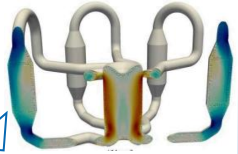
2023



Preliminary design of fuel circuit and neutron core (CEA, CNRS, FRA, ORA)

Preliminary maintenance specifications (FRA, ORA)

Salt depletion evaluation using MOSARELA (CEA)



@CNRS, T. SORNAY

1st coupled neutron/thermalhydraulic simulations (CNRS, FRA, CEA, EDF)

CHEMISTRY & MATERIALS

06/2023 : Milestone on preliminary material review for MSR (CEA, ORA)

Corrosion facilities in chloride salts

MESCAL glove box (CEA Saclay)
MESCAL 2 planned in S2/2023 (CEA Saclay)
CNRS facilities (Lille, Toulouse, Orléans)

2023 : Common salt purification protocol
2023 : Start of extensive corrosion screening tests

Actinides and salt synthesis & property measurements

Molten salt lab in ATALANTE
Molten salt lab in JRC

2023 : $AmCl_3$ synthesis
2024 (early) : Fuel salt density measurements

Basic actinide and FP chemistry & fuel cycle processes

Molten salt inactive lab (CEA Cadarache)
Active labs (Atalante)
CNRS facilities (Lille, Toulouse, Orléans)

2023 : $PuCl_3$ extraction tests by pyro

ISAC PhD (8 PhD at CEA / 6 at CNRS)

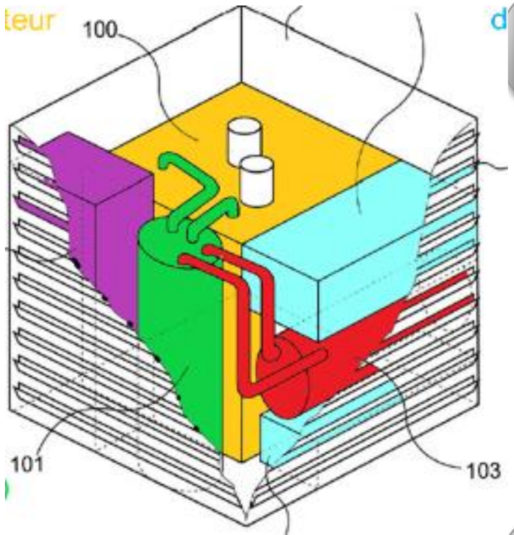
Subject		Place	Date
MSR neutronic calculations	CEA	Cadarache	2022/2025
MSR operation margins	CEA	Cadarache	2021/2024
Fission product nucleation	CEA	Cadarache	2022/2025
AmCl3 properties	CEA	Cadarache	2022/2025
Actinides chemistry	CEA	Marcoule	2021/2024
Corrosion	CEA	Saclay	2021/2024
Nickel based ODS	CEA	Saclay	2022/2025
Interaction irradiation/corrosion	CEA	Saclay	2023/2026
MSR scenarii studies	CNRS	LPSC	2022/2025
MSR operation and design	CNRS	LPSC	2021/2024
Fission producs chemistry	CNRS	??	2023/2026
Salt thermophysical properties	CNRS	??	2022/2025
Salt loops	CNRS	LPSC	??
??	CNRS	??	??

France: NAAREA, a molten-salt micro-reactor

Local authorities, Ultra-fast recharging station, Plants, Generators, Desalination, Smart grid, Support for renewable energy ...

Solutions for deploying decentralised production resources

naarea



A fast-spectrum MSR (fluoride or chloride)

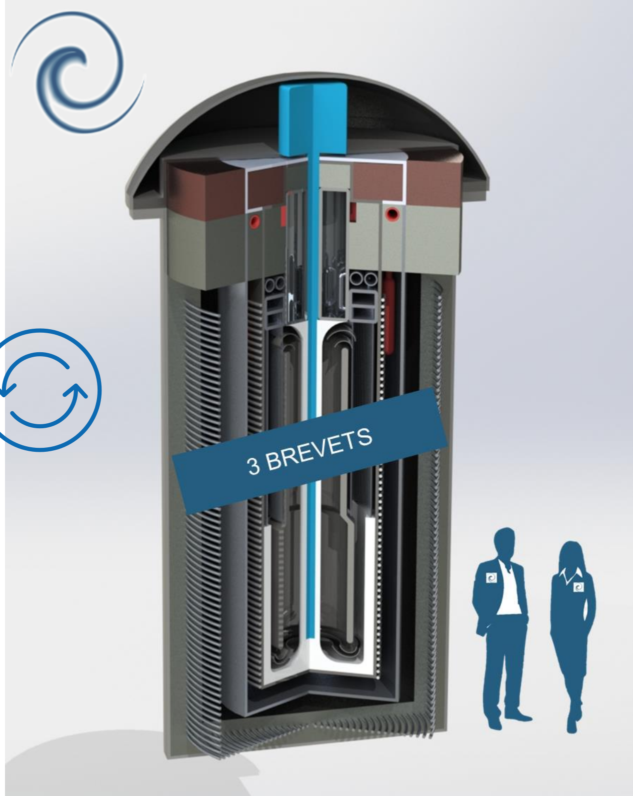
- Transportable / Modules can be reused
- Remote operation - Simplified maintenance
- Safety by design for social acceptance
  Target cost < gas
- Native ultra-silotability
  Support for ENR

2,5 to 100 MWth	690°C	>30%PN/min	Industrial Alliance	Fuel cycle
1 to 80 MWe	5y of autonomy	MA burning	Transportable	Safety

France: STELLARIA, a molten salt SMR for heavy industry

Data centres, semi-conductors, mining, petrochemicals, molecules, steel industries

Energy-intensive customers looking for low-carbon solutions on a global scale

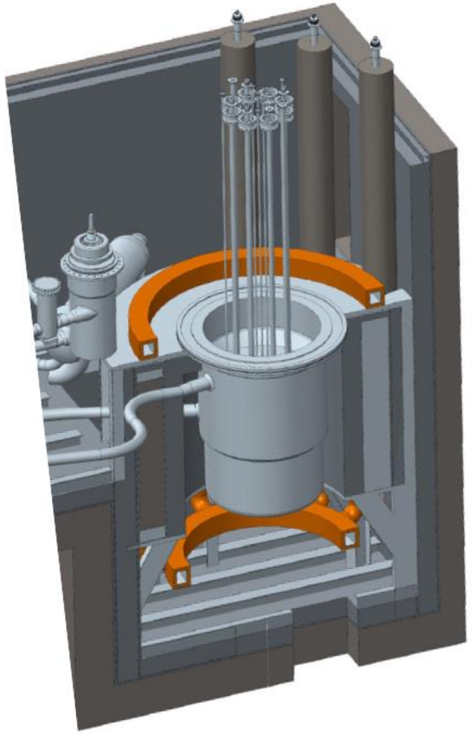


A fast spectrum MSR (chloride)

- Fuel regeneration and materials recovery
- Simplified maintenance for competitive costs
- Safety by design for social acceptance
- natively controllable

400 MWth	570°C	>30%PN/min	Industrial Alliance	Fuel cycle service
200 MWe	20 y of autonomy	Breed & Burn	Natural convection	Safety

Russia: MSR Landscape



Rosatom, vendor

Kurchatov, scientific leader

RDIPE, design

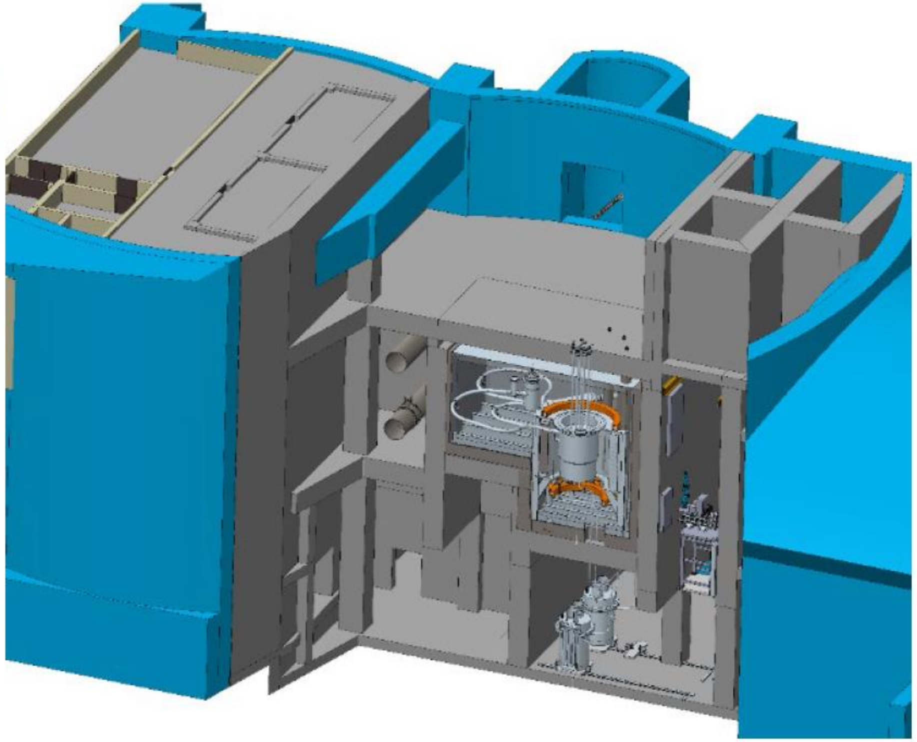
MCC, operator

VNIINM, salt processing

RIAR, in-reactor testing

IHTE, salt properties

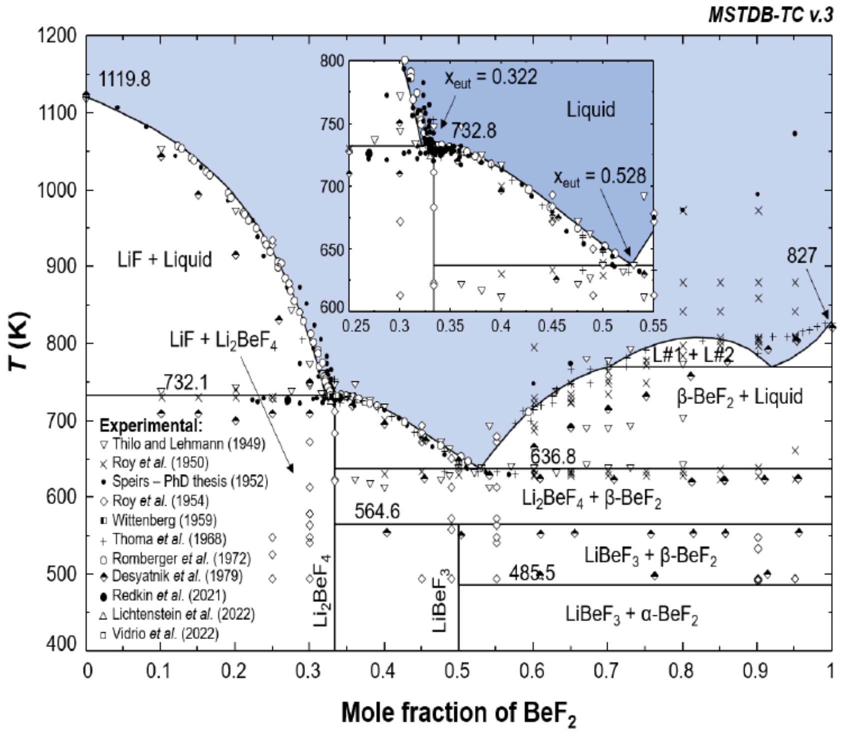
UralFU, materials compatibility

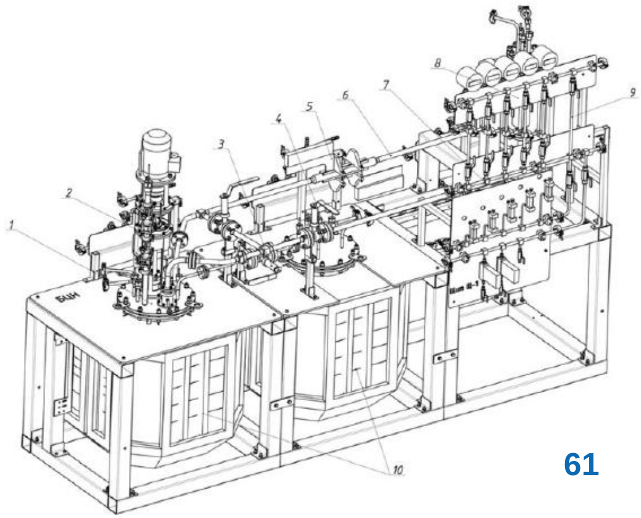


Implementation within the framework of the Federal project (FP-4) “New materials and technologies” of the Comprehensive program “Development of equipment, technologies and scientific research in the field of use of atomic energy in the Russian Federation for the period until 2024” (extendeduntil2030)

Russia: Highlights

- Experimental effort was done to test the technological operations for purification and conditioning of the fuel LiF-BeF_2-Pu(Am)F_3 salt mixture.
- Two methods have been developed to determine oxygen impurities in the molten FLiBe based mixtures.
- A sensor for measuring the Redox potential in the molten FLiBe based mixtures with a dynamic reference electrode was tested.
- Compatibility of SS as well as Ni and Mo based alloys with molten LiF-BeF_2-salt mixture fueled by PuF_3 CeF_3 and UF_4 was tested.
- Additional efforts are required on scale production and welding technologies.
- Thermal properties of the fuel LiF-BeF_2-PuF_3 salt mixture are measured.





Switzerland: Landscape & Highlights

MSR Landscape

- Focus safety and fuel cycle sustainability, no strong MSR system preference.
- PSI as implementing agent cooperates with ETH Zurich and EPFL Lausanne
- There are four research areas, where the assessment of MSR safety is the central ultimate objective. The other three areas address:
  - MSR sustainability from fuel cycle perspective.
  - Transient analysis and decay heat removal.
  - Fuel salt chemistry for nominal and accidental conditions.

Highlights

- Participation in EU project ENDURANCE (started 01.10.2024).
- PSI and Copenhagen Atomics signed a large-scale experimental collaboration agreement.

Copenhagen Atomics Onion Core™, with which the novel critical experiments are carried out in collaboration with the department Hotlab at PSI. The partnership between PSI and Copenhagen Atomics aims to conduct a thorium molten salt critical experiment in 2026. © Copenhagen Atomics

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USA: MSR Landscape – Government, Industry, and Regulatory Activities

- Department of Energy (DOE)-Office of Nuclear Energy (NE) activities remain focused on enabling MSR industry and building supporting infrastructure
  - Largest fraction of DOE support is via the Advanced Reactor Demonstration Program (ARDP)
- DOE-NE continues to support MSRs via multiple mechanisms
  - MSR technical campaign, regulatory development activities, advanced materials and manufacturing campaign
  - Advanced fuel cycle campaign
  - Nuclear Energy Advanced Modeling and Simulation (NEAMS) tool development
  - Nuclear Energy University Program (NEUP), small business opportunities, Gateway for Accelerated Innovation in Nuclear (GAIN) vouchers, and direct industry awards
- Advanced Research Projects Agency (ARPA-E) reactor initiatives include MSRs
- Nuclear Regulatory Commission is developing a technology-neutral, performance-based, risk-informed regulatory framework

*MSR support includes both solid (aka FHRs) and liquid fueled concepts

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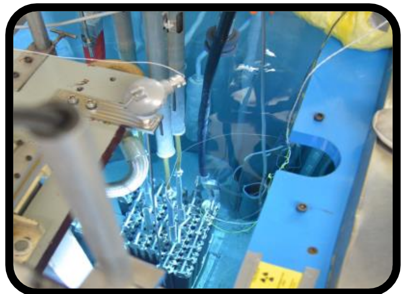
USA: MSR Landscape – DOE-NE MSR campaign

Develop the technological foundations to enable MSRs for safe and economical operations while maintaining a high level of proliferation resistance.

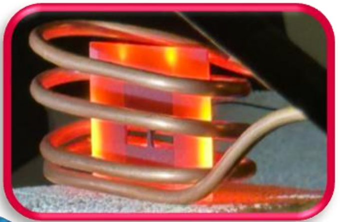
Thermophysical and Thermochemical Properties of Molten Salts – Experimentally and Computationally

Salt Chemistry



Irradiation

Advanced Materials



Development of Materials Surveillance Technology Graphite/Salt & Materials/Salt Interaction

Argonne NATIONAL LABORATORY

INL Idaho National Laboratory

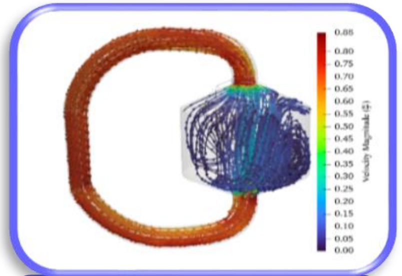
The DOE-NE MSR campaign serves as the hub for efficiently and effectively addressing, in partnership with other stakeholders, the technology challenges for MSRs to enter the commercial market.

Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

Off-Gas Management Radionuclide Release Monitoring, Sensors & Instrumentation LSTL & FASTR

Technology Development



Mod & Sim

MSR Radioisotopes

Developing new Technologies to separate Radioisotopes of Interest to the MSR Community

Molten Salt Reactor PROGRAM

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

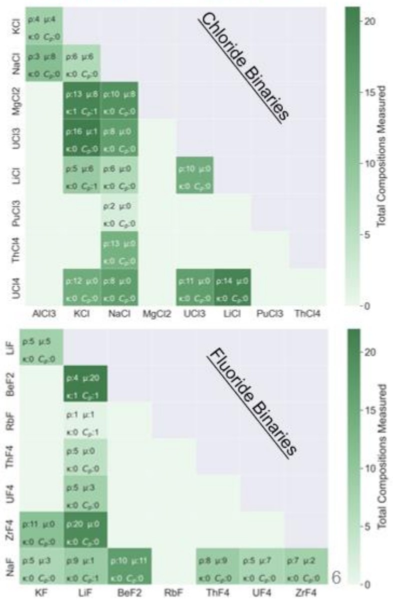
USA: Highlights

- Multiple companies are pursuing deployment in the 2020s and early 2030s
- Regulator is preparing capabilities to efficiently evaluate reactor safety adequacy
- Advancement of multiple MSR supportive technologies from modeling and simulation to electrochemistry to materials science has substantially decreased the technical difficulty of implementing MSRs
- Pressing need for safe, reliable, efficient energy production driving MSR development faster than at any time in the past half century
- No MSR has yet reached the market, and no developer has openly committed the funds necessary to complete MSR development and deployment

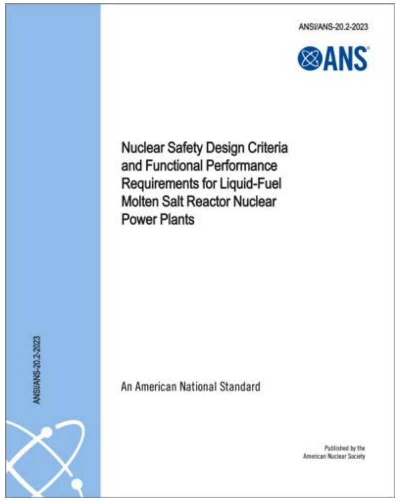
Oak Ridge National Laboratory | NEAMS | University of South Carolina | Molten Salt Reactor Program

MSTDB-TP v 3.1 Released
MSTDB-TC v 4.0 Released

Available @ mstdb.ornl.gov



Facility to Alleviate Salt Technology Risks (FASTR)


ANSI/ANS-20.2-2023

ANS

Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid-Fuel Molten Salt Reactor Nuclear Power Plants

An American National Standard

Published by the American Nuclear Society

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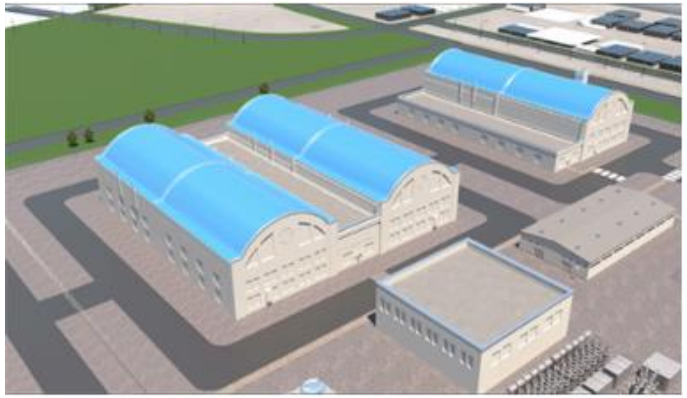
USA: Highlights - MSR Advanced Reactor Demonstration Projects Jointly Funded by Government and Industry Transitioning to Commercial Phase

Kairos Power



Hermes 2 next to Hermes 1

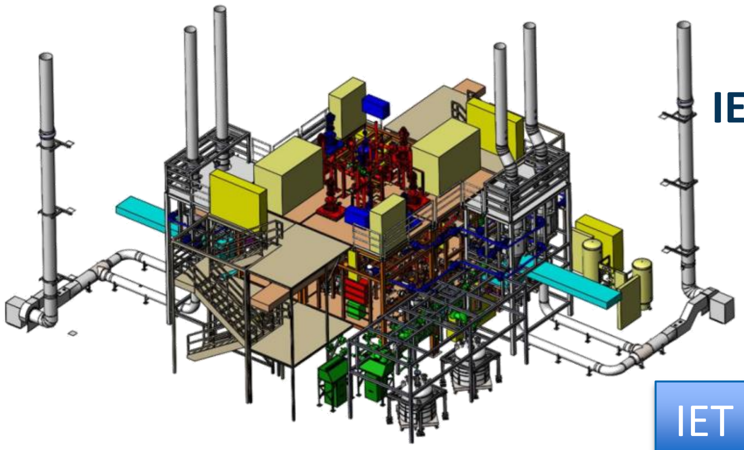
Milestones	
Final Safety Evaluation Issued for Hermes 2	July 19, 2024
Final Environmental Assessment Issued with a finding of no significant impact	August 30, 2024
Kairos Power breaks ground on salt production facility to produce high-purity molten salt coolant includes proprietary process to separate lithium isotopes	October 2, 2024
Google and Kairos Power Partner to Deploy 500 MW of Clean Electricity Generation	October 14, 2024

USA: Highlights - MSR Advanced Reactor Demonstration Projects Jointly Funded by Government and Industry Continue to Progress

TerraPower Southern Company

MCRE

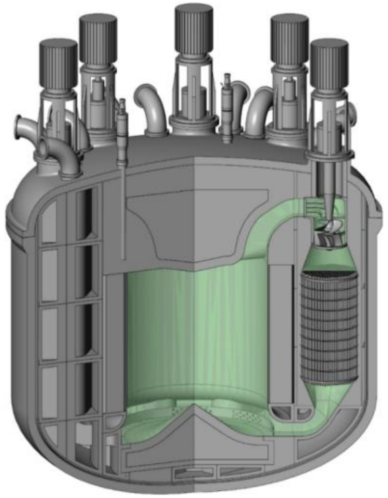
- TerraPower describes methodology to extrapolate high temperature material properties of Inconel 617 for molten chloride reactor experiment applications
- IET > 250 documented lessons learned
- Began construction of MCRE mock-up (LOTUS test cell compared to building reactor in a bottle)



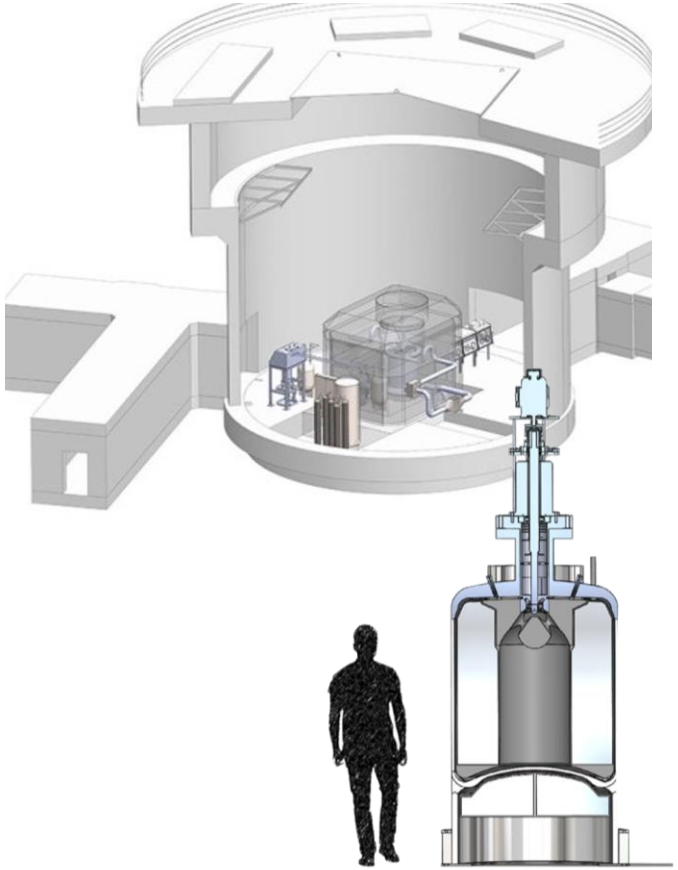
IET

IET overview video

https://www.youtube.com/watch?v=JQR_b19lZGE



MCFR



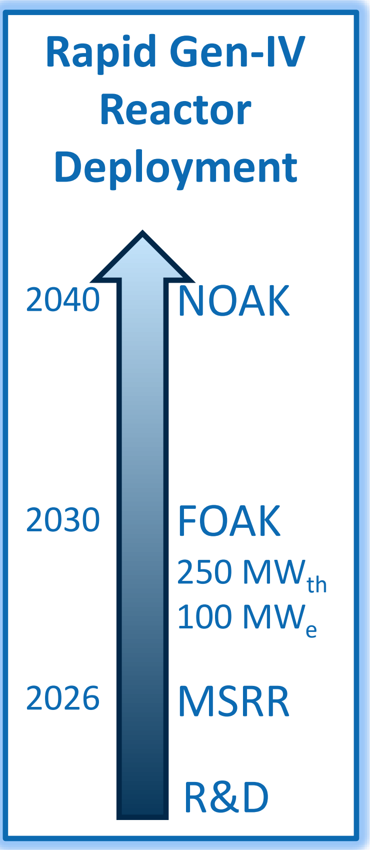
USA: Highlights - Abilene Christian University Research Reactor Underway

Natura Resources SUSTAINABLE ENERGY — NEXTRA Nuclear Energy eXperimental Testing Research Alliance — ABILENE CHRISTIAN UNIVERSITY

- Natura Resources is sponsoring a collaboration between University of Texas at Austin, Texas A&M University, Abilene Christian University, and Georgia Tech University to construct a non-power MSR at ACU
- Natura Resources receives construction permit for MSR-1 at ACU (September 16th, 2024)
- Partnership with Texas Produced Water Consortium to investigate deployment of liquid-fueled MSRs to power the Permian Basin (July 24th, 2024)

Cut-away showing reactor in trench

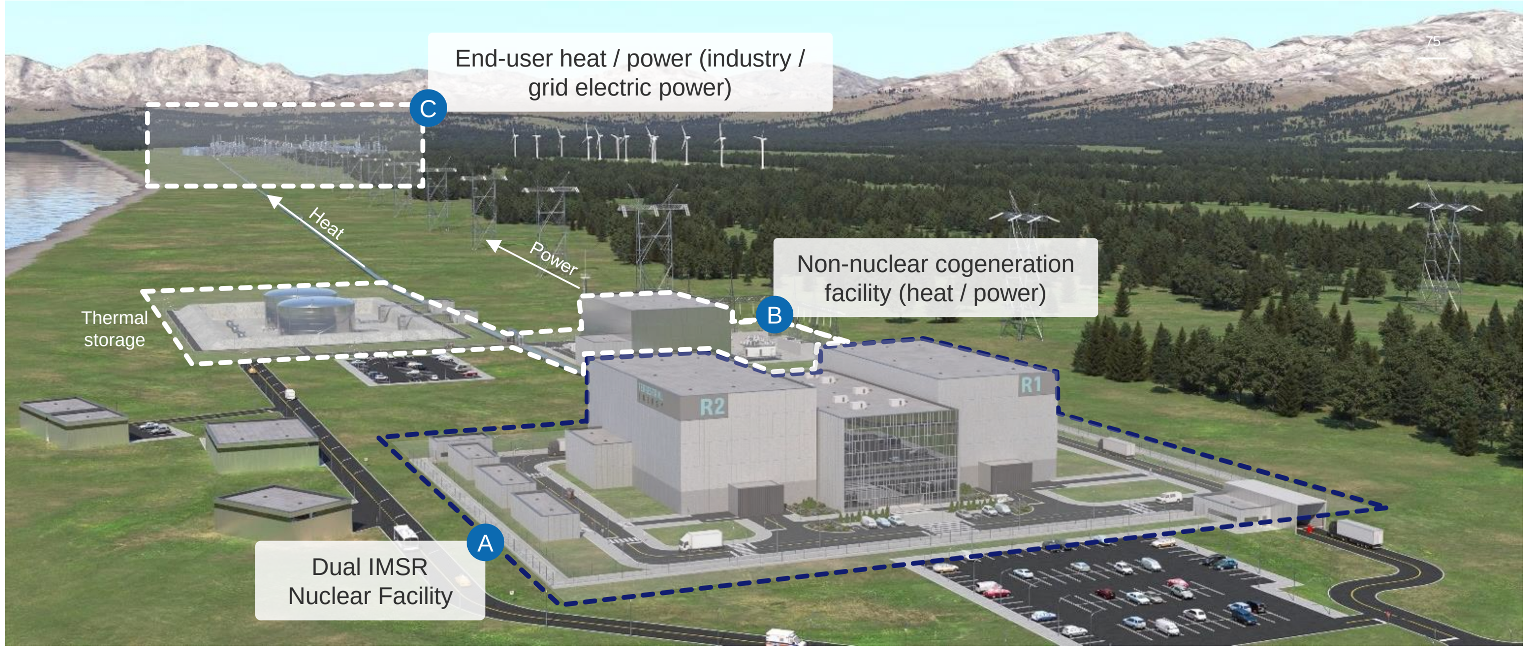
Gayle and Max Dillard Science and Engineering Research Center - completed



Images courtesy Abilene Christian University

USA: Highlights – TERRESTRIAL ENERGY Redomiciles to the USA

By design, the IMSR Plant of TERRESTRIAL ENERGY is uniquely flexible to deliver – "behind the fence" – customized cogeneration of heat and power to industry with a GEN IV reactor that avoids the need for High Assay LEU



A Standardized dual IMSR Nuclear Facility

- Subject to nuclear regulation
- Standardized, simplifying design and saving costs
- 884 MW (gross) thermal energy production for 585°C supply

B Customized non-nuclear Thermal and Electrical facility

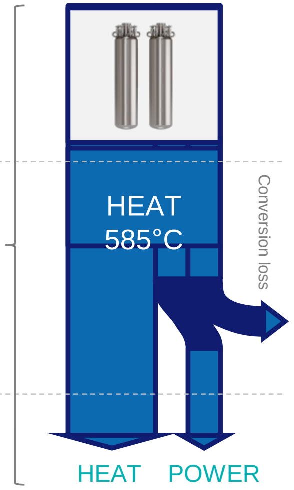
- Converts 884 MW (gross) thermal energy from two IMSRs to 585°C 822 MW (net) thermal or 390 MW (net) electric power for commercial supply – or any heat/electric power mix in between
- Can include molten-salt thermal energy storage and buffering to enhance its inherent strong load-following capability for commercial advantage
- Separate nuclear island and non-nuclear balance-of-plant allows for safe harbor of incentives past 2035

C Industrial cogeneration off-takers

- Chemical and petrochemical plant
- Hydrogen / ammonia / fertilizer plant
- Other industrials requiring clean heat & power

Municipal off-takers

- Electric grid
- Desalination



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Note: Example is for a dual reactor core IMSR Plant. Scaling up is possible.

USA: Highlights – other startups

- Fast spectrum MSR – homogeneous plutonium eliminating reactor (hope® reactor)
  - Safeguards- and security-by-design
  - Reactor core homogeneous MSR – fast spectrum
  - Designed for efficient burning of transuranics
  - Thermal spectrum in blanket region

  https://curio.energy/#tech

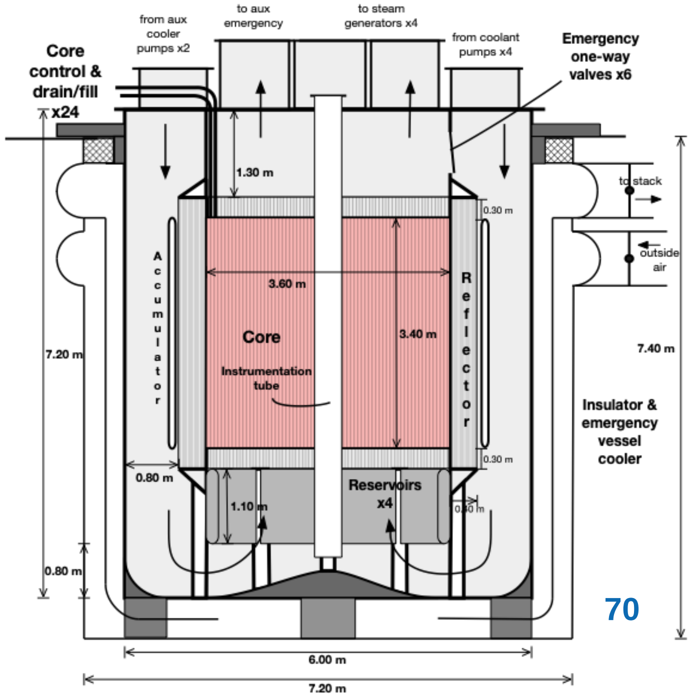
CURIO

- Wielenga Innovation static salt reactor (WISSR)
  - Non-profit corporation
  - Working with University of Michigan nuclear engineering department

Wielenga Innovation Foundation, Inc.

- Fast-spectrum chloride salt, waste-burner
  - Potassium chloride eutectic salt

  https://www.wifound.org/nuclear-reactor



China: MSR landscape

TMSR Reactors and Applications

Th Energy: Long-Term Supply of Nuclear Fuel

MSR: Elevated Safety, Efficiency, Nonproliferation

TMSR-SF(Solid-Fuel):

Optimized for high-temperature based hybrid nuclear energy application.

TMSR-LF(Liquid-Fuel):

Optimized for utilization of Th with Pyroprocess.

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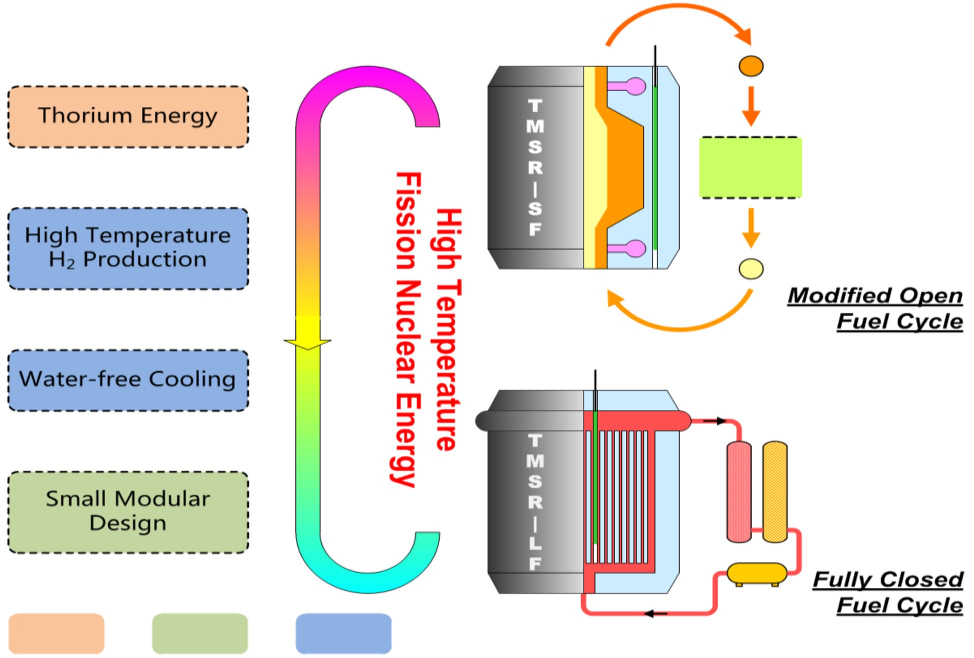
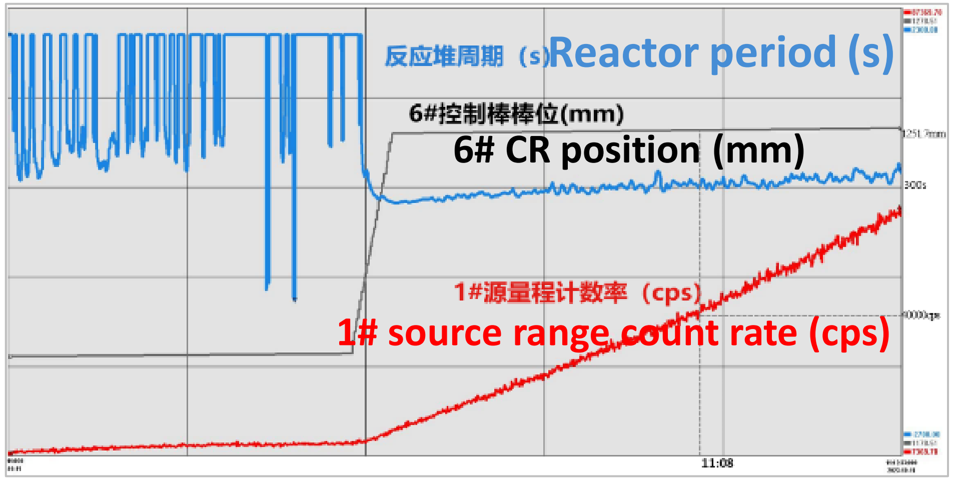
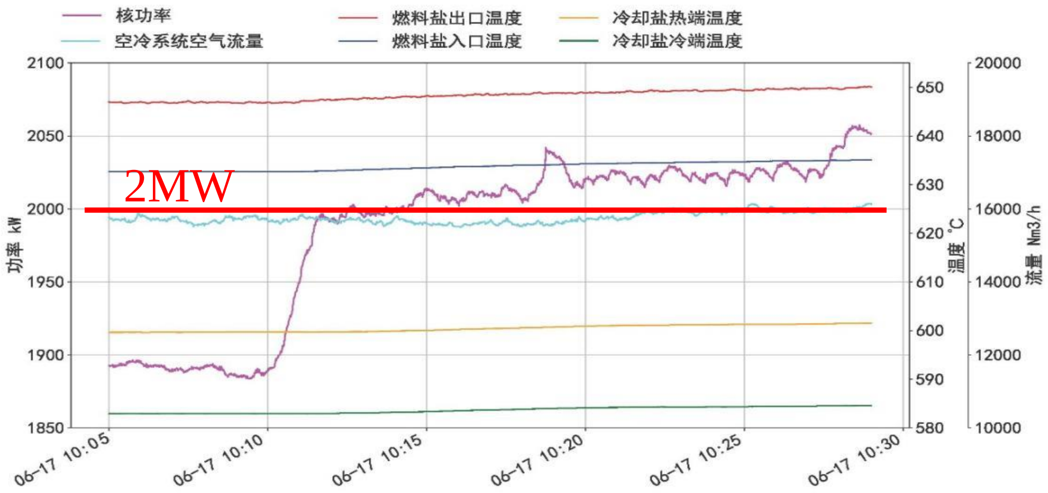


Strategy of TMSR R&D

China: Highlights - TMSR-LF1 achieved full power operation of 2MWt

- SINAP started to build TMSR-LF1 in 2018.
- **At 11:08 on October 11, 2023,** TMSR-LF1 achieved first criticality.
- **At 12:10 on June 17, 2024,** 2MWt full power operation was achieved.
- **On October 8, 2024,** TMSR-LF1 operated at full power for 10 days with thorium fuel, and Pa-233 was detected





Schematic diagram of TMSR-LF1 parameter adjustment for reactor criticality and full power

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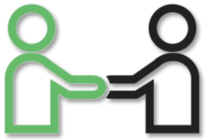
Korea: MSR landscape

Ministry of Science and ICT

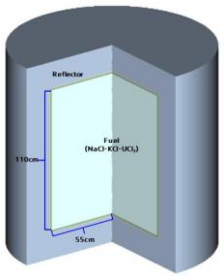
- Strategic Alliance for Promoting Public-Private Cooperation in Next-generation SMRs
  - The domestic 8 leading EPC companies and the Government completed MOU signing. (March 20th, 2024). Field of cooperation:
    - Collaborative design of the nuclear island, BOP (AE), and licensing response
    - Operating a public-private consultative body for Advanced Non-water-cooled Reactors



현대엔지니어링
DAEWOO E&C
posco E&C
DOOSAN Enerbility
SAMSUNG HEAVY INDUSTRIES
HD KOREA SHIPBUILDING & OFFSHORE ENGINEERING
HYUNDAI ENGINEERING & CONSTRUCTION
Century

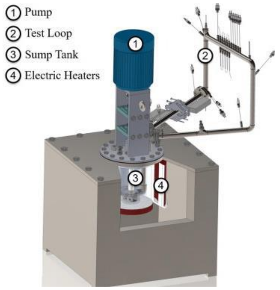
- HYUNDAI ENGINEERING & CONSTRUCTION
  - as the head of a private partnership organization, is responsible for MSR concept design, managing coordination among various specialized fields, nurturing companies with core technologies, and securing equipment supply chains. Additionally, it oversees future standard designs and domestic and international nuclear regulatory approvals.

① Core Design



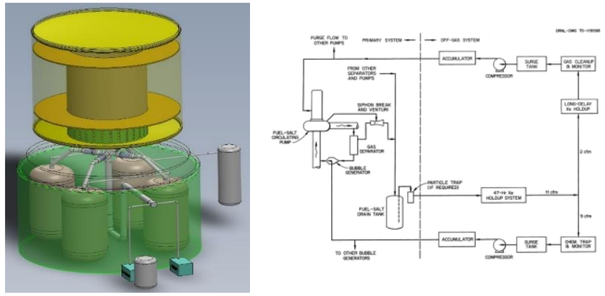
Geometry of Conceptual MSR

② Fuel and Materials



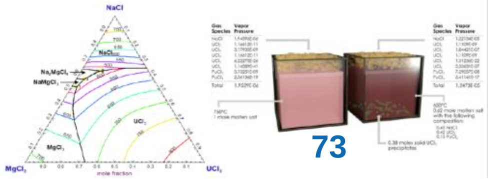
Experimental Loops

③ Safety and Auxiliary Systems



Fuel salt drain system & off-gas system

④ Safety Assessment



Evaluation of Fission Product Release

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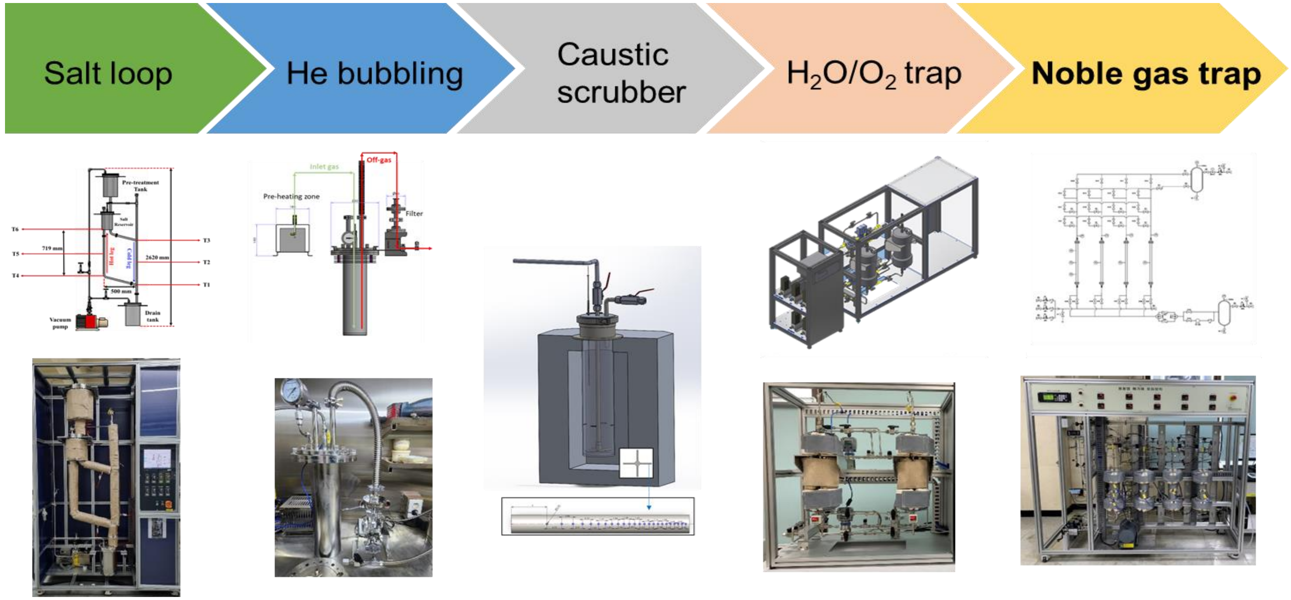
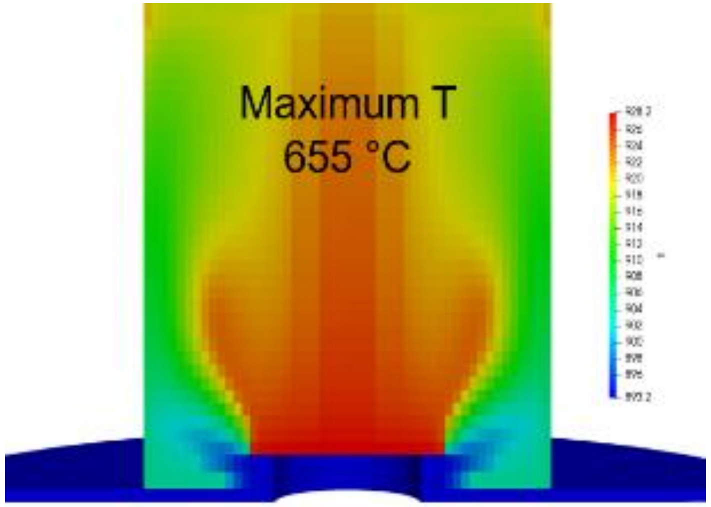
Korea: Highlights



- Fuel/Coolant salt properties
  - ✓ > 300 g/batch scale UCl_3 production
  - ✓ Development of determining phase-transition temperatures based on the electrical conductivity
  - ✓ Completion of design/fabrication and commissioning of molten salt loops
  - ✓ Performed preliminary experiments for off-gas unit processes
- Materials and components
  - ✓ Corrosion rate evaluation on candidate alloys and potential clad material
- Reactor physics modelling & simulation
  - ✓ MC code improvements for MSR design and neutronics analysis
  - ✓ Coupling of MC and CFD codes for MSR in progress



CUPID-MSR Simulation of a MSR

Thank you for your attention

Upcoming Webinars

Date	Title	Presenter
19 February 2025	Overview and Update of VHTR activities within GIF	Gerhard Strydom, INL, USA
27 March 2025	Nuclear power: electricity and beyond the grid. Data-driven insights from IAEA's Power Reactor Information System (PRIS).	Marta Gospodarczyk, IAEA
15 April 2025	Advanced manufacturing supporting Gen IV reactor systems	Isabella Van Rooyen, PNNL, USA

2025 Pitch your Gen IV Research Competition

- Are you a PhD student, post-doctoral fellow, or junior engineer with a PhD working on Generation IV nuclear energy systems? *(Completion of the PhD must be after Jan1, 2023)*
- The GIF Education and Training Working Group (ETWG) invites you to participate in the 2025 edition of the "Pitch Your Generation IV Research" competition (PYG4RC).
- This competition provides a platform for you to showcase your research and gain recognition within the nuclear energy community.

https://www.gen-4.org/resources/events/pitch-your-generation-iv-research-competition-2025