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MSRs: Entire Category of Reactors

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中核集团
CNNC

Interregional Workshop on Advances in Design of Generation-IV Small and Medium Sized or Modular Reactors (SMRs)

Outline

I. MSR definition and taxonomy (IAEA TRS No. 489)

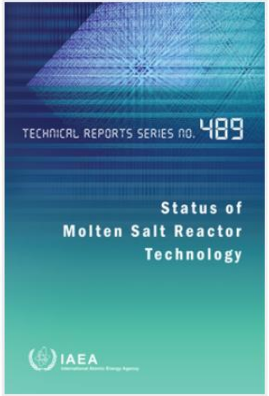
II. Brief MSR history

III. Neutronics properties on applied materials

IV. Characterization of 6 major MSR families

IAEA TRS No. 489

Status of Molten Salt Reactor Technology



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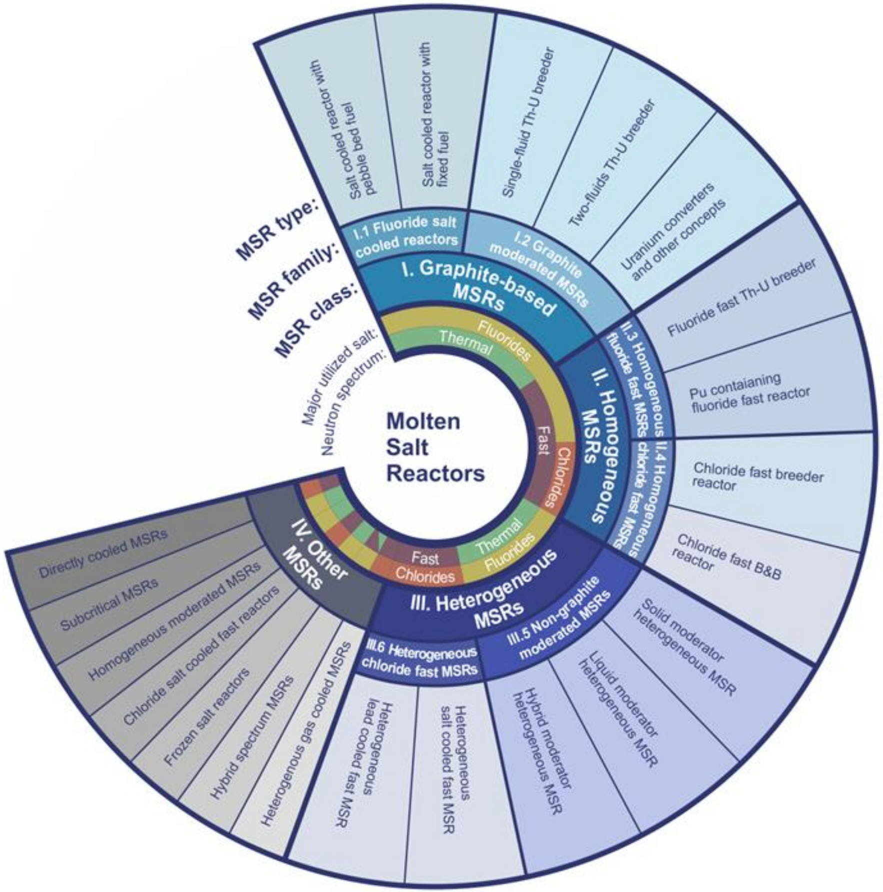
IAEA Technical Report Series, Status of Molten Salt Reactor Technology, document in preparation, International Atomic Energy Agency, 2023.

MSR Taxonomy

- Major aim of this presentation is to illustrate the variety of MSR concepts.
- Explain the IAEA MSR taxonomy and its structure.
- Characterize the major MSR families.



IAEA Technical Report Series, Status of Molten Salt Reactor Technology, document in preparation, International Atomic Energy Agency, 2023.

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Definition of MSRs:

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

IAEA Technical Report Series, Status of Molten Salt Reactor Technology, document in preparation, International Atomic Energy Agency, 2023.

1978 one of the first MSR classification attempt

- In 1978 EIR 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

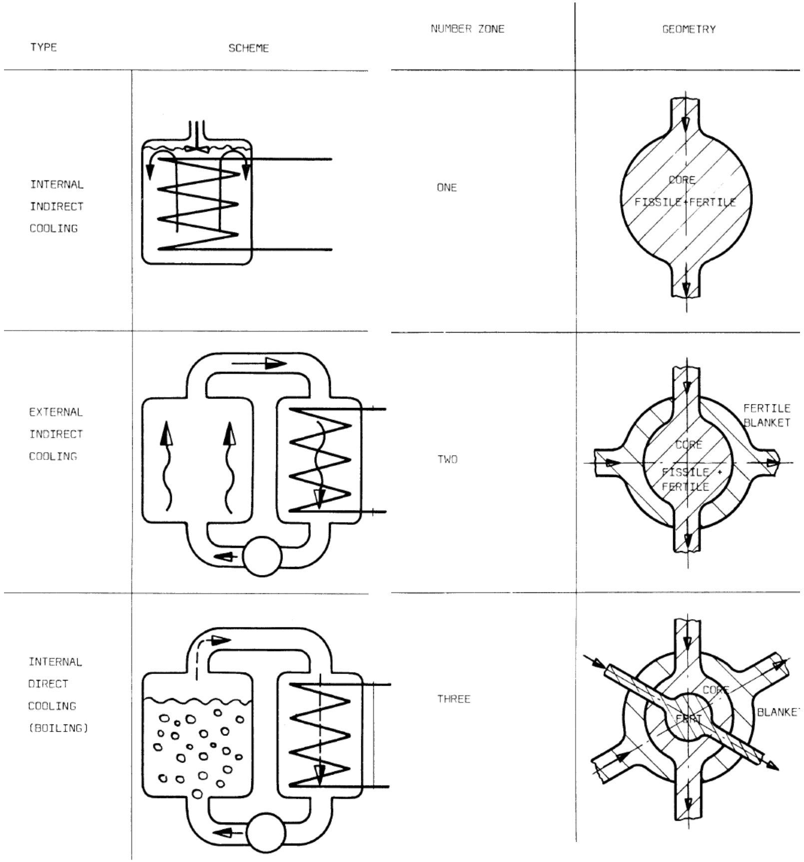
d) Kind of fissile nuclides and fuel cycles

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).

2016 initial brainstorming about the taxoonmy

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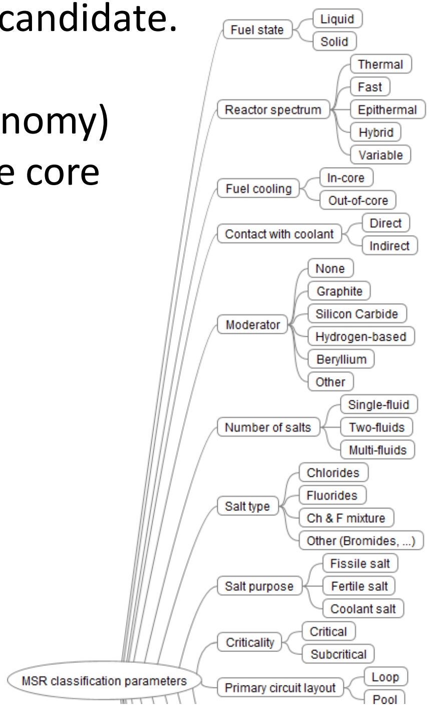
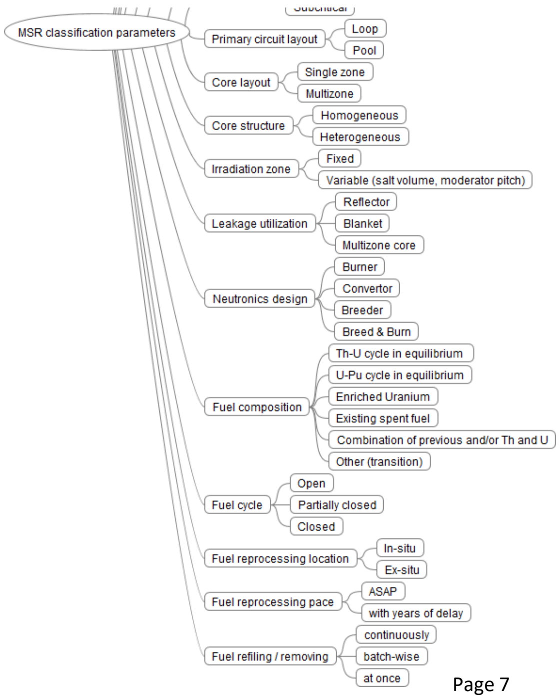
- Technical Meeting on the Status of Molten Salt Reactor Technology
  IAEA Headquarters, Vienna, 31.10-3.11.2016
- Many classification options have been considered.

- The neutrons spectrum was first obvious candidate.
- However, it was not selected.
  (similarly, like count of legs in animal taxonomy)
- Finally, the count of materials in the active core acts as the highest rank criteria:
  - **I. Class:** 2 materials
    (graphite and salt)
  - **II. Class:** 1 material
    (fuel salt)
  - **III. Class:** 3 materials
    (fuel salt, structural material, and dedicated coolant or moderator)





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Taxonomy

Category: Molten Salt Reactors

Classes:

- I. Graphite based MSRs
  - **Families:** I. 1. Fluoride salt cooled reactors
    - **Types:** Salt cooled reactor with pebble bed fuel
    - Salt cooled reactor with fixed fuel
  - I. 2. Graphite moderated MSRs
    - Single-fluid Th-U breeder
    - Two-fluid Th-U breeder
    - Uranium converters and other concepts
- II. Homogeneous MSRs
  - II. 3. Homogeneous fluoride fast MSRs
    - Fluoride fast Th-U breeder
    - Pu containing fluoride fast rector
  - II. 4. Homogeneous chloride fast MSRs
    - Chloride fast breeder reactor
    - Chloride fast breed & burn reactor
- III. Heterogeneous MSRs
  - III. 5. Non-graphite moderated MSRs
    - Solid moderator heterogeneous MSR
    - Liquid moderator heterogeneous MSR
  - III. 6. Heterogeneous chloride fast MSRs
    - Heterogeneous salt cooled fast MSR
    - Heterogeneous lead cooled fast MSR
- IV. Other MSRs
  - Directly cooled MSRs
  - Subcritical MSRs
  - Hybrid moderator MSRs
  - Chloride salt cooled fast reactors
  - Frozen salt MSRs
  - Hybrid spectrum MSRs
  - Heterogeneous gas cooled MSRs

Adopted from: IAEA Technical Report Series, Status of Molten Salt Reactor Technology, document in preparation, International Atomic Energy Agency, 2023.

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

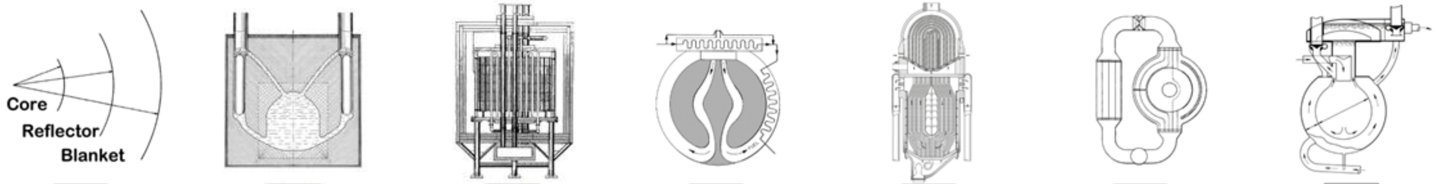
COMPOUND	MELTING POINT (°C)	BOILING POINT (°C)
UO_2	2700	-
UO_3	-	dec. 650
U_3O_8	-	dec. 1700
UF_3	1425	2300
UF_4	1036	1417
UF_6	65	56
UCl_3	835	1725
UCl_4	590	787
UCl_5	-	dec.
UCl_6	179	277
UBr_3	752	1567
UBr_4	519	766
UI_3	757	1427
UI_4	502	759
UN	2600	dec.
UC	2275	dec.
US	1800	-
U_2S_3	-	dec. 1800
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_2BO_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 breeder (faster in publishing?)
- Considerations about fluoride fast breeder

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).				



1952 1952 1954 1954 1954 1956 1958

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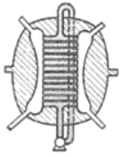
1960th Leaving the military constrains

- 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).				
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 Society.				
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 109-112.				
1967	IV. Class	Other	Directly cooled MSRs	**MOSEL**	Gat
	Gat, U., 1967, Cooling concepts for a compact MOSEL (molten salt) reactor, Nuclear engineering and design 5, 113-122.				
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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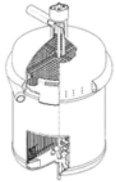
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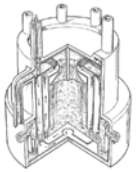
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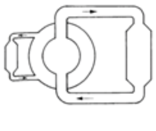
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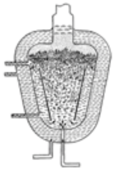
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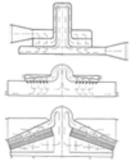
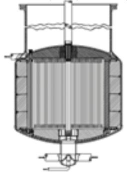

1967


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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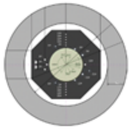
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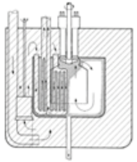
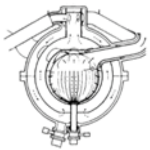

1972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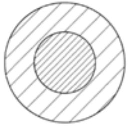
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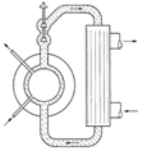
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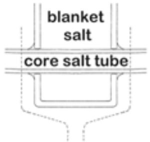
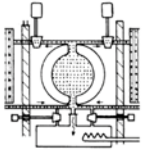


1978

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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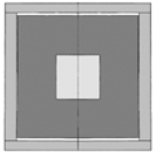
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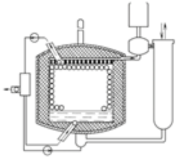
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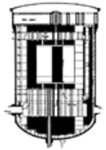
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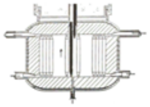
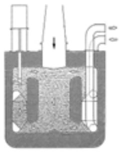

1987

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 (1997).				
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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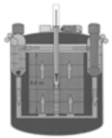

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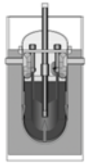

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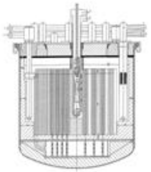

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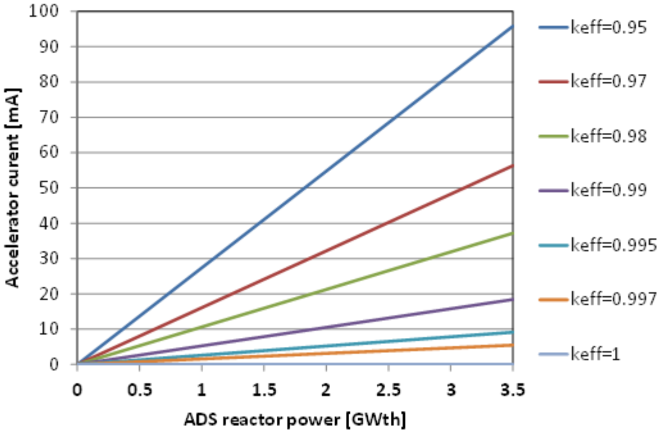
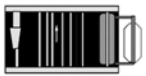


2000th start of Generation IV international forum

- 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	Salt cooled reactor with fixed fuel	**MSFR**	CNRS
	MATHIEU, L., et al., The thorium molten salt reactor: moving on from the MSBR, Prog. Nucl. Energ. 48 7 (2006) 664-679.				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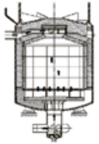
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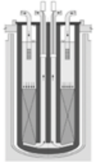
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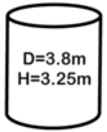

2004


2005

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2010-2020 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
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.				

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2010-2020 Start-up / brainstorming time

- Research of advanced nuclear system is growing.
- GIF defines 6 GIV systems inclusive MSR.ng re-considered.

Year	Class	Family	Type	Concept	Author
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.				

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Neutronics properties on applied materials

4 major coolant types

Water (light & heavy): ^{1}H, ^{2}H, ^{16}O

Liquid metals (sodium, lead, lead-bismuth): ^{23}Na, ^{nat}Pb, ^{209}Bi

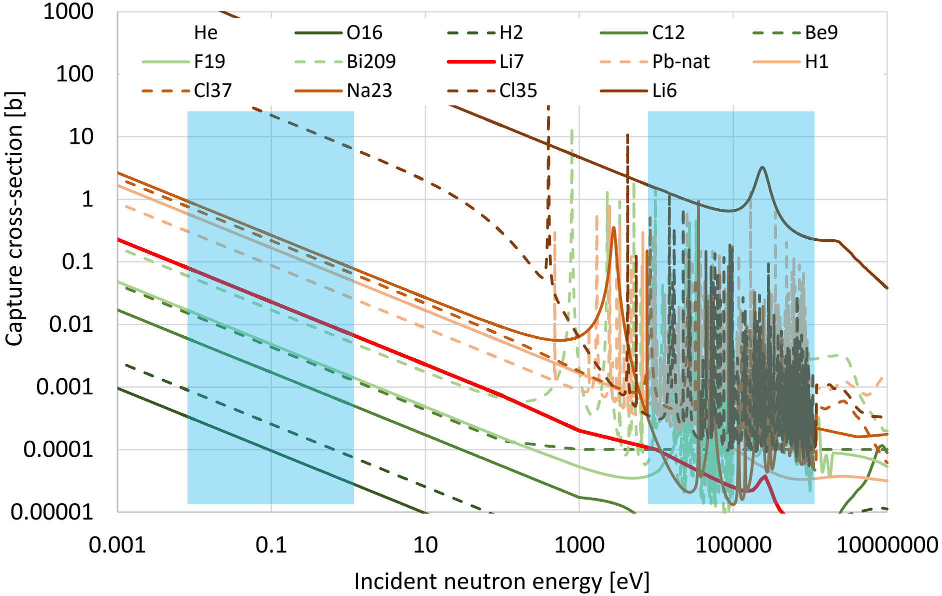
Gases (helium, CO_2): ^{4}He, ^{12}C, ^{16}O

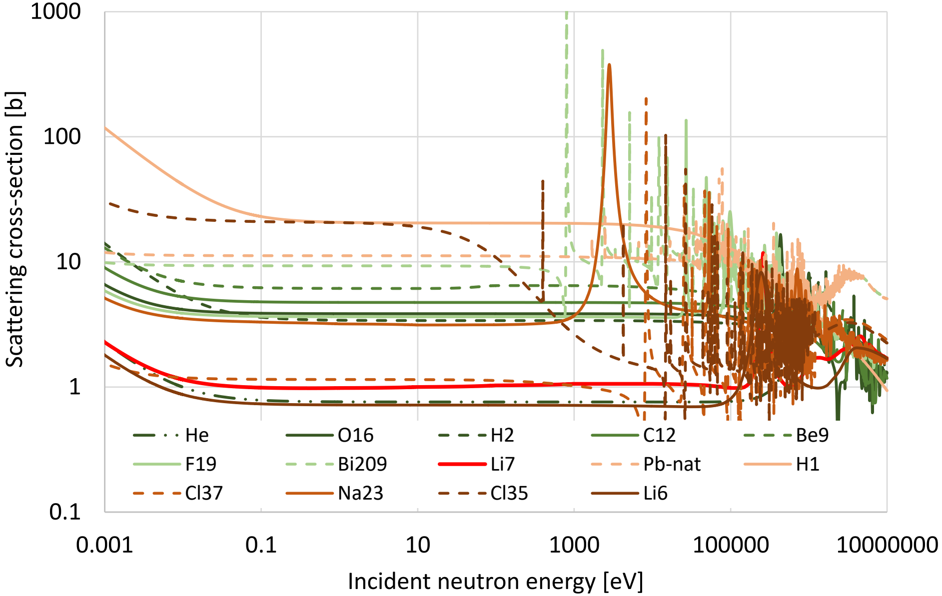
Salts (fluorides, chlorides): ^{6}Li, ^{7}Li, ^{9}Be, ^{19}F, ^{nat}Mg, ^{35}Cl, ^{37}Cl, ^{nat}K, ^{nat}Ca

BTW:

***Capture XS:** 1/v rule, i.e. capture chance depends on the time, which neutrons and nuclei spend together.*

***Scattering XS** is rather flat and based on "geometrical" interaction.*





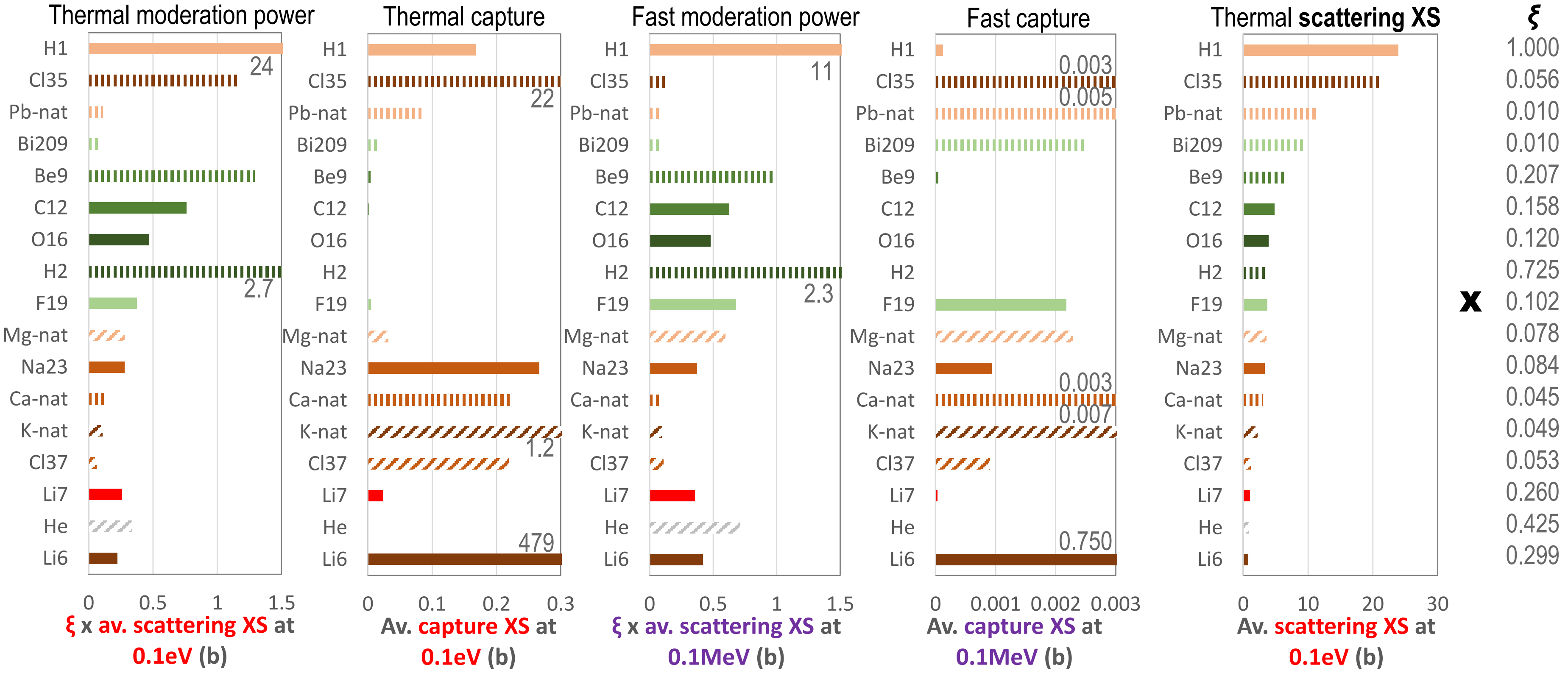
Range for averaging around 0.1ev and 0.1MeV.

Data from ENDF/B VII.0 library

Moderation power and capture XS

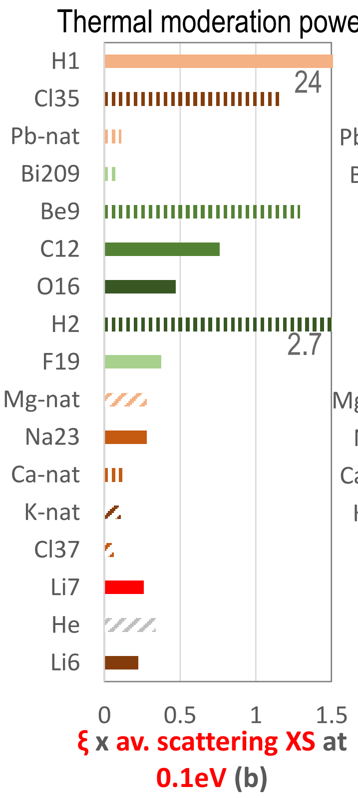
- **Logarithmic decrement of energy ξ** describes neutron energy loss by scattering.
- Product of **ξ** and **scattering XS** is used here as a **moderation power*** criteria.

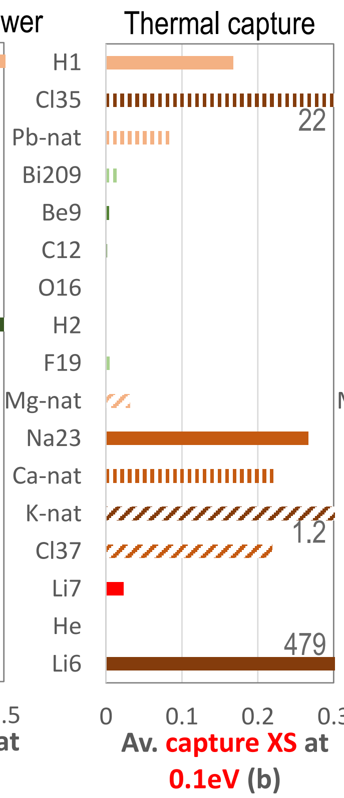
*It is not a standard definition, because it uses microscopic instead of macroscopic XS.

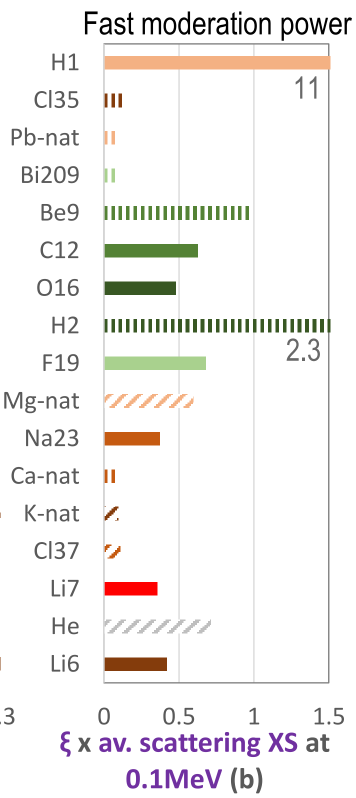


4 coolant nuclides characteristics

Based on the moderation power and capture XS, 4 coolant nuclides performance characteristics can be defined:







	Moderator:	Suppressing fast neutrons:	Breeding in thermal spectrum:	Breeding in fast spectrum:
H1	Yes*	Yes	No	No
Cl35	No	No	No	No
Pb-nat	No	No	No	Yes
Bi209	No	No	No	Yes
Be9	Yes	Yes	Yes	No
C12	Yes	Yes	Yes	No
O16	No	No	Yes	Yes
H2	Yes	Yes	Yes	No
F19	No	Yes**	Yes	Yes***
Mg-nat	No	Yes**	Yes	Yes
Na23	No	No	No	Yes
Ca-nat	No	No	No	Yes
K-nat	No	No	No	Yes
Cl37	No	No	No	Yes
Li7	No	Yes**	Yes	Yes
He4	No	Yes	Yes	Yes
Li6	No	Yes**	No	No

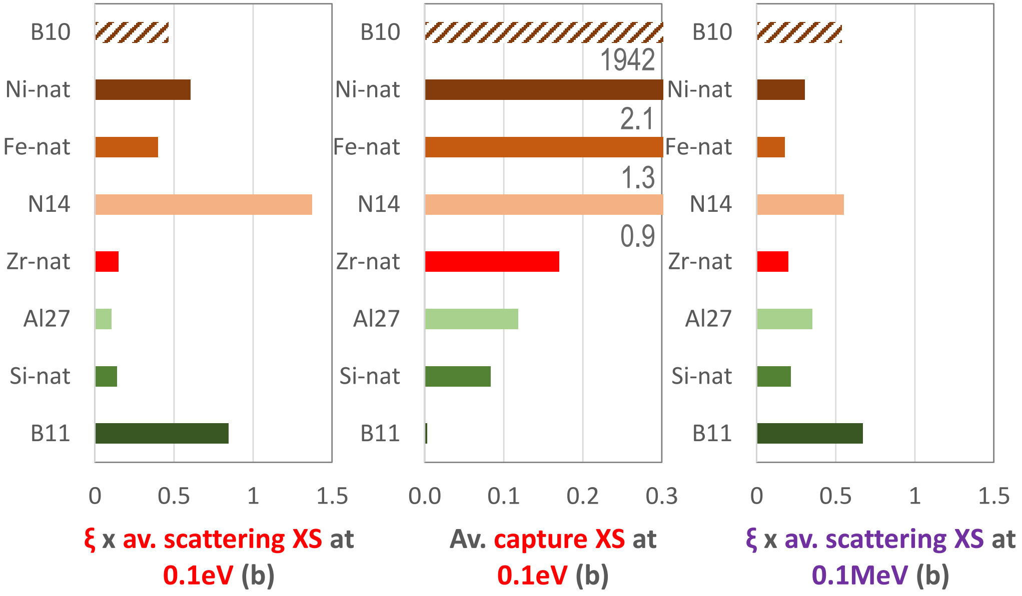
*Substantial capture XS

**Broad Scattering resonances around 0.1MeV

***However the spectrum is quite soft.

Performance of structural materials

- **Boron** (^{10}B, ^{11}B) as an absorber,
- ^{14}**N** as ^{16}O alternative.
- **Si** as part of SiC,
- **Aluminum**, **Zirconium**, **Iron** and **Nickel**.



- **Zirconium:** similar capture XS as ^{1}H.
- **Silicon:** similar capture XS as lead. *(big hope for many MSR concepts)*
- **Aluminum:** some times used as metallic fuel matrix for research reactors.
- **Iron (steel)** can be used in fast reactors, but should be avoided in thermal spectrum.
- **Nickel (alloys)** foreseen for MSRs because of chemical resistance have **2x higher capture XS** than iron.
- Presence in the core, as a fuel cladding:
  1) Should be avoided in thermal systems.
  2) Reduce performance of fast systems.

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Characterization of 6 major MSR families

Taxonomy

Category:

Molten Salt Reactors

Classes:

- I. Graphite based MSRs
- II. Homogeneous MSRs
- III. Heterogeneous MSRs
- IV. Other MSRs

Families:

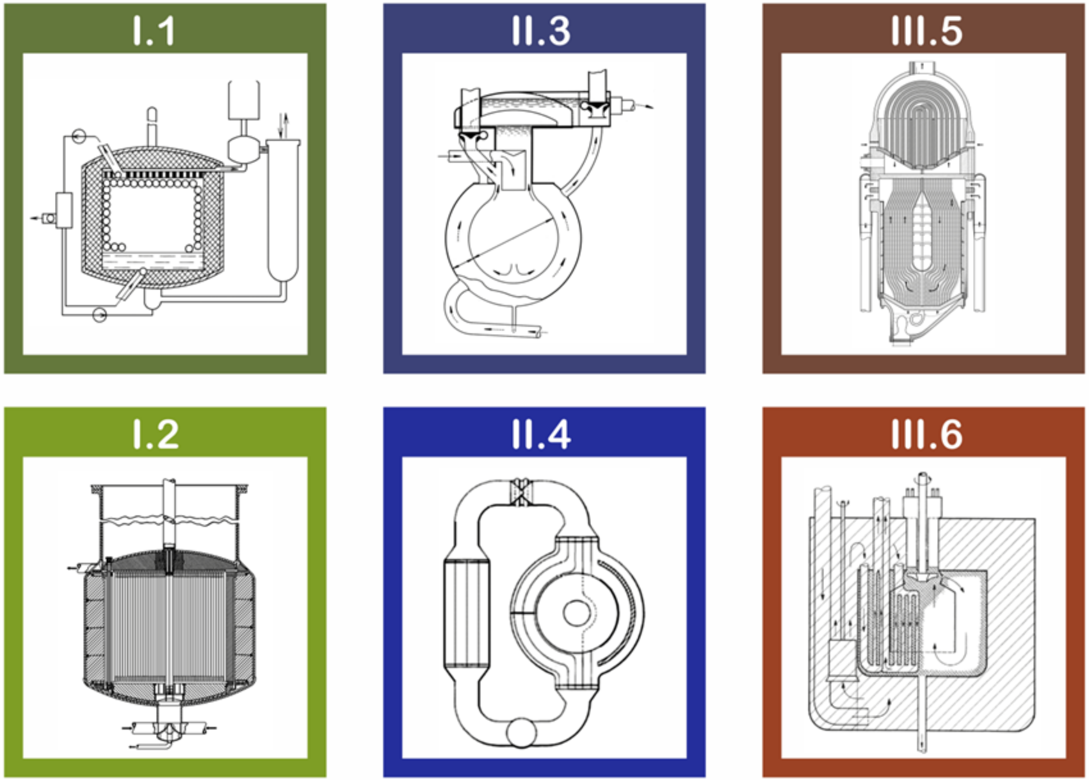
- I. 1. Fluoride salt cooled reactors
- I. 2. Graphite moderated MSRs
- II. 3. Homogeneous fluoride fast MSRs
- II. 4. Homogeneous chloride fast MSRs
- III. 5. Non-graphite moderated MSRs
- III. 6. Heterogeneous chloride fast MSRs

Types:

- I. 1. Fluoride salt cooled reactors:
  - Salt cooled reactor with pebble bed fuel
  - Salt cooled reactor with fixed fuel
- I. 2. Graphite moderated MSRs:
  - Single-fluid Th-U breeder
  - Two-fluid Th-U breeder
  - Uranium converters and other concepts
- II. 3. Homogeneous fluoride fast MSRs:
  - Fluoride fast Th-U breeder
  - Pu containing fluoride fast rector
- II. 4. Homogeneous chloride fast MSRs:
  - Chloride fast breeder reactor
  - Chloride fast breed & burn reactor
- III. 5. Non-graphite moderated MSRs:
  - Solid moderator heterogeneous MSR
  - Liquid moderator heterogeneous MSR
- III. 6. Heterogeneous chloride fast MSRs:
  - Heterogeneous salt cooled fast MSR
  - Heterogeneous lead cooled fast MSR
- IV. Other MSRs:
  - Directly cooled MSRs
  - Subcritical MSRs
  - Hybrid moderator MSRs
  - Chloride salt cooled fast reactors
  - Frozen salt MSRs
  - Hybrid spectrum MSRs
  - Heterogeneous gas cooled MS

Adopted from: IAEA Technical Report Series, Status of Molten Salt Reactor Technology, document in preparation, International Atomic Energy Agency, 2023.

6 Major MSR families



Krepel, J., Ragusa, J., Molten salt reactor physics: characterization, neutronic performance, multiphysics coupling, and reduced-order modeling, chapter 4 in a book: Molten Salt Reactors and Thorium Energy, 2nd Edition - June 1, 2023

F.I.1. Fluoride salt cooled reactors

Salt cooled reactor with pebble bed fuel

Salt cooled reactor with fixed fuel

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

Primary heat exchange: *In core*

Heat convection by fuel: *No, dedicated coolant* ***LiF-BeF$_2$*** *(Li is enriched to ^{7}Li)*

Fuel form: *Triso-particles in graphite matrix*

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

Neutronic performance: *Converter*

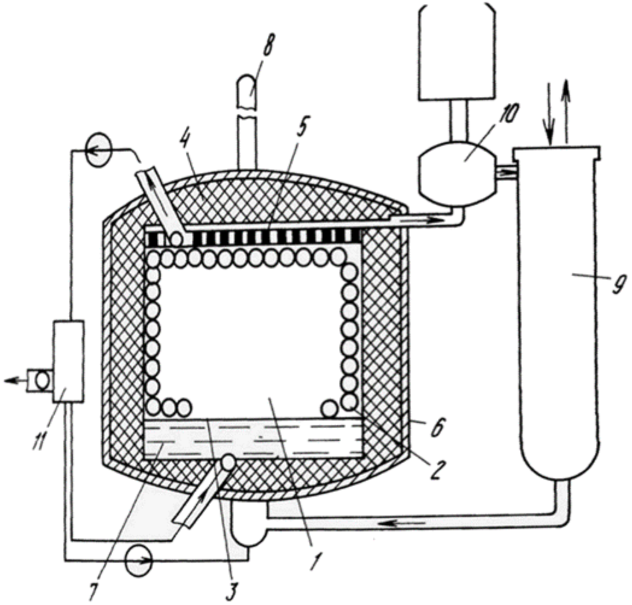
Self-sustaining breeding: *Can not be achieved*

Major fuel cycle: *Enr. U converter*

Leakage utilization: *Reflector*

Characteristic:

- *^{7}**LiF-BeF$_2$** has certain moderation power, hence it has **negative density effect** on reactivity.*
- *Very low specific fuel density in some designs:*
  - → *Unprocessed **spent fuel is volumetric**.*
  - → *Increased non-fuel parasitic neutron captures.*
  - → *Core transparency for neutrons (neutron leakage).*



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

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F.I.2. Graphite moderated MSRs

Single-fluid Th-U breeder

Two-fluid Th-U breeder

Uranium converters and other concepts

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

Primary heat exchange: *Ex core*

Heat convection by fuel: *Yes*

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

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

Neutronic performance: *Breeder or converter*

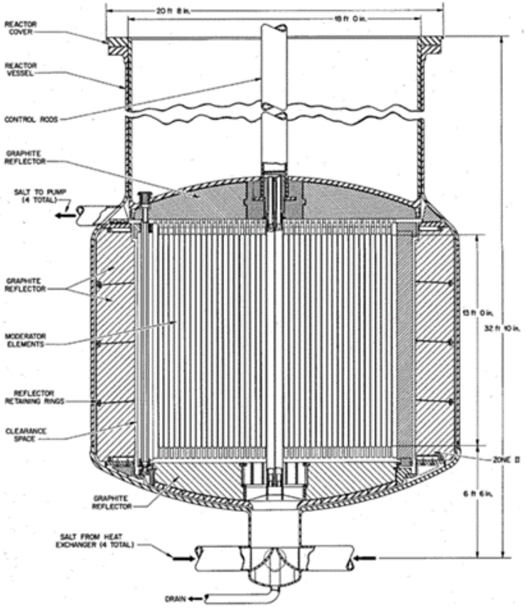
Self-sustaining breeding: *Can be achieved, is demanding*

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

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

Characteristic:

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



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

F.II.3. Homogeneous fluoride fast MSRs

Fluoride fast Th-U breeder

Pu containing fluoride fast rector

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

Primary heat exchange: *Ex core*

Heat convection by fuel: *Yes*

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

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

Neutronic performance: *Breeder, converter, dedicated burner*

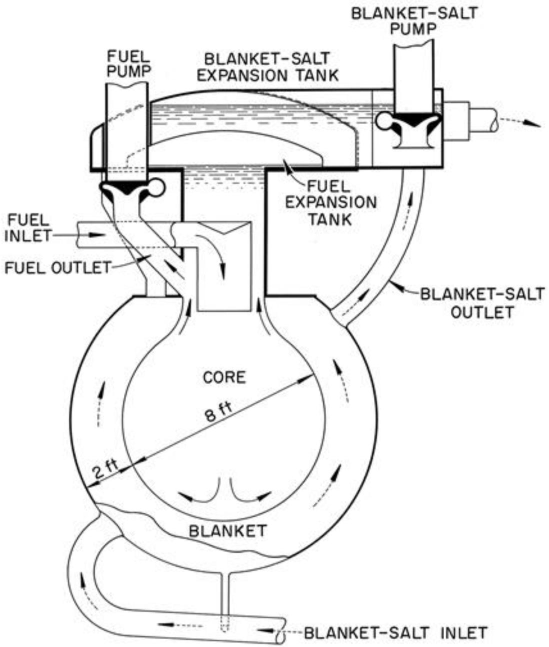
Self-sustaining breeding: *Can be achieved*

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

Leakage utilization: *Blanket, Reflector (Hastelloy)*

Characteristic:

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



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

F.II.4. Homogeneous chloride fast MSRs

Chloride fast breeder reactor

Chloride fast breed & burn reactor

Types definition: *By fuel cycle type (U-Pu breeder or breed & burn cycle)*

Primary heat exchange: *Ex core*

Heat convection by fuel: *Yes*

Fuel form: *Ac. diluted in chloride salts, for breeders it is typically **$Na^{37}Cl$***

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

Neutronic performance: *Breeder, Breed and Burn*

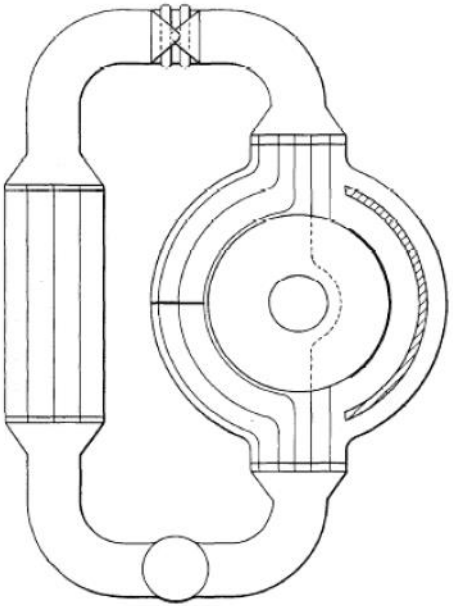
Self-sustaining breeding: *Can be achieved*

Major fuel cycle: *Closed U-Pu or Breed-and-Burn U-Pu*

Leakage utilization: *Blanket, Reflector (lead?)*

Characteristic:

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



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

F.III.5. Non-graphite moderated MSRs

Solid moderator heterogeneous MSR

Liquid moderator heterogeneous MSR

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

Primary heat exchange: *Ex core**

Heat convection by fuel: *Yes**

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

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

Neutronic performance: *Converter, burner*

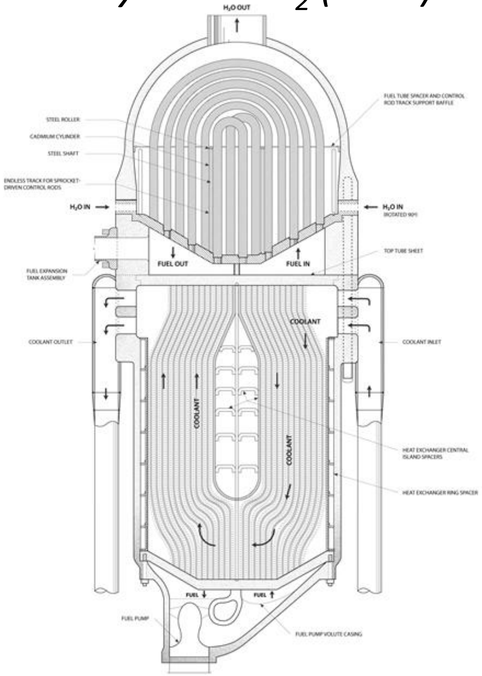
Self-sustaining breeding: *Impossible or very demanding***

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

Leakage utilization: *Reflector (moderator)*

Characteristic:

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



* Unless if liquid moderator acts as coolant.

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

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

F.III.6. Heterogeneous chloride fast MSRs

Heterogeneous salt cooled fast MSR

Heterogeneous lead cooled fast MSR

Types definition: *By dedicated coolant type (salt or lead cooled)*

Primary heat exchange: *In core*

Heat convection by fuel: *Usually no, dedicated coolant*

Fuel form: *Ac. diluted in chloride salts, for breeders it is typically* ***$Na^{37}Cl$***

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

Neutronic performance: *Converter, Breeder, Breed and Burn is demanding*

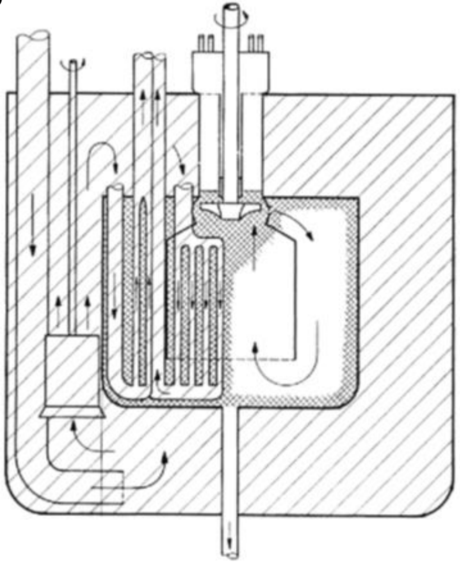
Self-sustaining breeding: *Can be achieved*

Major fuel cycle: *Closed U-Pu or enr. U burning*

Leakage utilization: *Blanket, Reflector (lead?)*

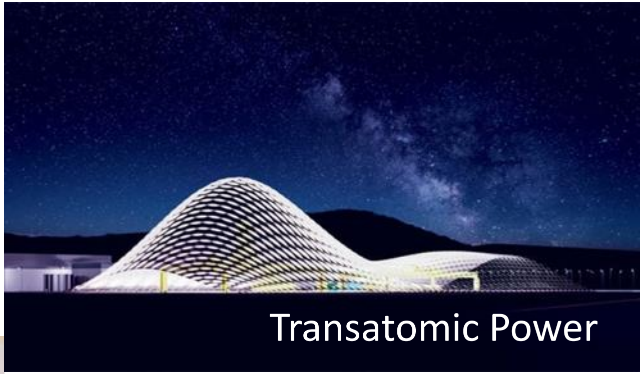
Characteristic:

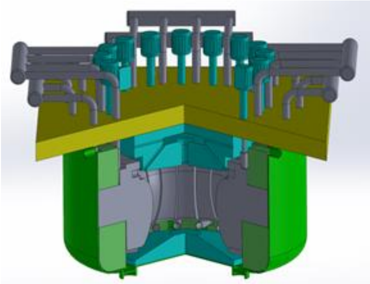
- *Coolant requires structural material for separation:*
  - → *Limited life-span of separation material.*
  - → *Reduced neutronic performance.*
  - → *It provides additional scattering XS.*
  - → *Possibly smaller cores that homogeneous chloride fast MSRs.*



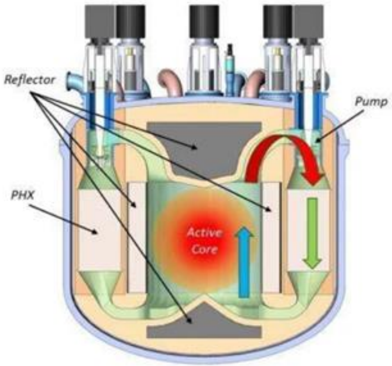
Taube M and Ligou J, Report EIR-215 Wurenlingen, Switzerland (1972).

MSR illustrative startups


Transatomic Power


CNRS's MSFR


Copenhagen Atomics



Terrapower's MCFR


Terrestrial Energy

Thank you.
Questions?