ESFR-SMART SPRING SCHOOL

OVERVIEW ON MOLTEN SALT REACTORS

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CEA Cadarache

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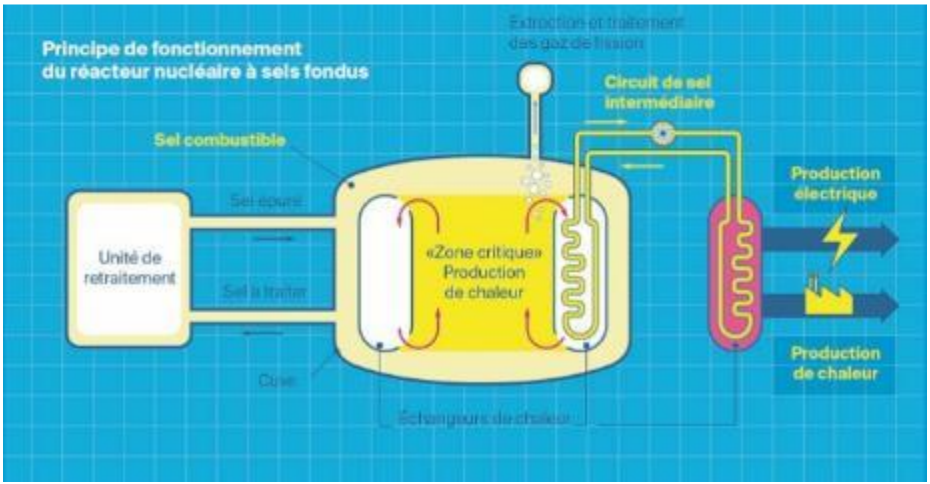
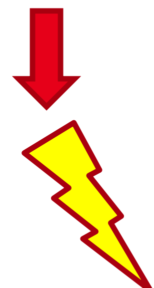
- What is a molten salt reactor ?
- International overview
- Assets and limits of the concept
- Salt selection
- Quick look on the french R&D program
- Conclusion

Reactors with a liquid fuel used also as a coolant

- Fast or thermal concepts
- Uranium/Thorium or Uranium/Plutonium fuel cycles
- Fluorides or chlorides





MSR HISTORY : ARE & MSRE

- **MSR concepts are imagined in the 50's**
- Développed in USA for military needs
- Propulsion of bomber aircrafts
- Interests : very long flight time, power density, power variations

- One prototype : **ARE (Aircraft Reactor Experiment)**

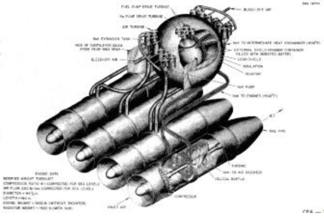
Developped and built

Operating from 3 to 12 november 1954 … = 9 days

Corrosion issues on the Inconel steel

→ **In parallel, development of long shot balistic missiles and submarines**

→ **Stop of the military use for MSR but continuous effort for power generation : MSRE**



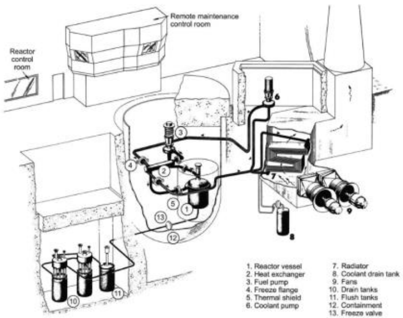
MSRE (Molten Salt Reactor Experiment)

Experimental reactor (7,4 MWth)
Operating form 1965 to 1970 at Oak Ridge National Laboratory
→ New material / ARE : Hastelloy N

- On this MSRE basis, a power reactor has been developed (MSBR)

Key Features	ARE	MSRE	MSBR (Design)
Name and Dates	Aircraft Reactor Experiment 1954	Molten Salt Reactor Experiment 1965-1970	Molten Salt Breeder Reactor (design) 1970-1976
Peak Power Output (MWt)	~2.5*	~8*	n/a
Peak Temperature (°C)	860	650	705
Solid Moderator	BeO	Graphite	Graphite
Fuel-Salt Composition (% mol)	$NaF-ZrF_4-UF_4$ (53-41-6)	$^7LiF-BeF_2-ZrF_4-UF_4$ (65-30-5-0.1)	$^7LiF-BeF_2-ThF_4-UF_4$ (72-16-12-0.4)
Secondary Coolant	Na metal	$^7LiF-BeF_2$	$NaF-NaBF_4$

235U, then 233U then 239Pu
(no thorium inside)



Development stopped in the 70s : PWR & SFR development

MSR operational feedback is limited to ARE & MSRE
No other MSR has been built, especially no fast MSR or chloride MSR

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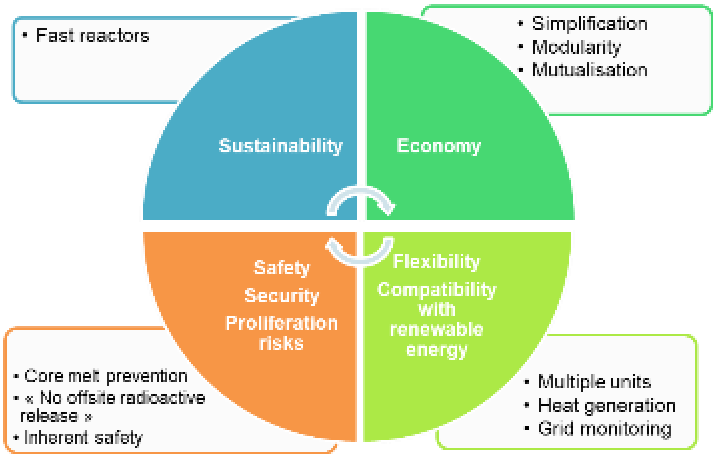
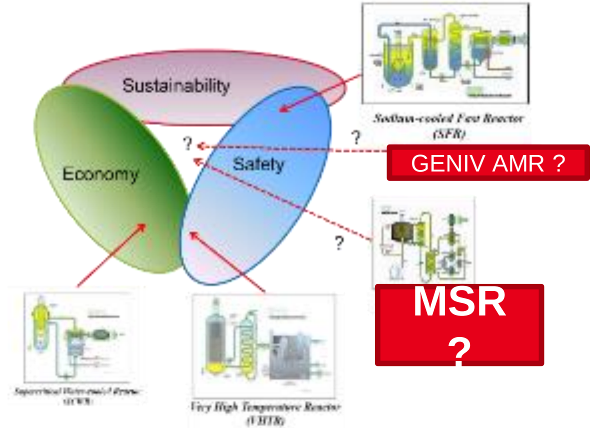
Objectives of GenIV reactors

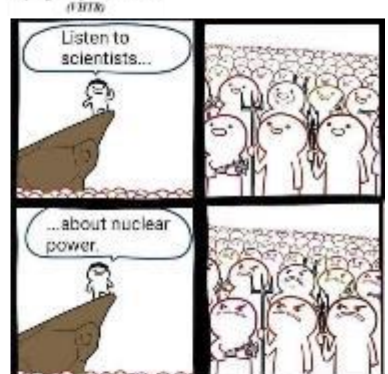
The perfect GenIV reactor is safe, cheap, resistant to proliferation, sustainable, flexible and compatible with the intermittency of renewable energies

→ everyone is trying to square the circle





Advanced GenIV reactors can improve the acceptability of nuclear energy



Two mature reactor type searching for rentability : SFR et HTR

One alternative to SFR with feasibility issues : LFR

Two reactor type searching for a new dynamics : GFR & SCWR

One promising reactor type with challenging feasibility issues : MSR

Lot of new AMR (Advanced Modular Reactor) are flowering

Amongst them, MSR systems are well represented

Also a growing interest in Micro-reactors, including maritime

Land Based Water Cooled Reactors			
CAREM	SMART	RUTA-70	DHR400
ACP100	UNITHERM	NuScale	RITM-200
CAP200	VK-300	mPOWER	NUWARD
IRIS	KARAT-45	W-SMR	BWRX-300
DMS	KARAT-100	SMR-160	HAPPY200
IMR	ELENA	UK-SMR	CANDU SMR

Micro Reactors	
IHTR	MMR-5
IMSBR	MMR-10
eVinci	AURORA
U-Battery	MoveluX

Fast Reactors		
4S	W-LFR	SSTAR LFR
BREST-OD-300	SEALER	URANUS
SVBR-100	LFR-AS-200	ARC100
EM^2	LFR-TL-X	

High Temperature Gas-cooled Reactors			
HTR-PM	MHR-100	XE-100	HTTR-30
DPP-200	PBMR-400	A-HTR 100	HTR-10
GT-MHR	HTMR-100	MMR	RDE
MHR-T	SC-HTGR	GTHTR300	StarCore

Marine Based Water Cooled Reactors	
ACPR50S	VBER-300
KLT-40S	ABV-6E
RITM-200M	SHELF

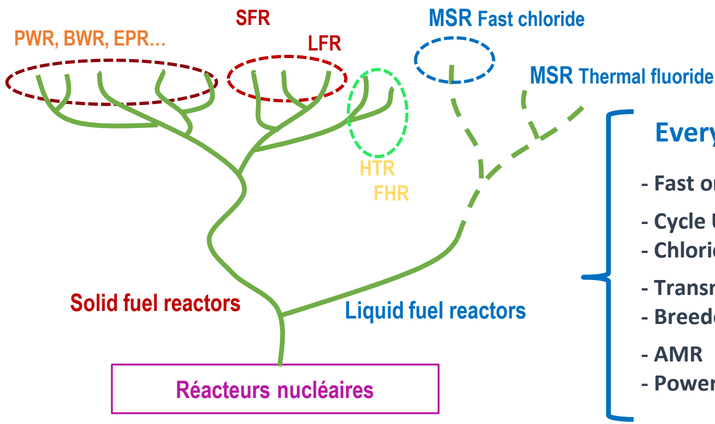
Molten Salt Reactor		
IMSR	SSR-WB	CA WB
CMSR	SSR-TS	KP-FHR
THORCON	LFTR REACTOR	MCSFR
FUJI ITMSF	MK1 PB-FHR	

Prototype or research reactors
AMR
Power > 400MWé

In bold, the more mature projects until ~ 2035

Moving panorama !

	Operation	Construction	Projects
SFR	BOR60 (RU), BN600 (RU), BN800 (RU), CEFR (CN), FBTR (IN), JOYO (JP)	CFR600 (CN), PFBR (IN), MBIR (RU)	**VTR (US),** ARC-100 (CA), **NATRIUM (US), BN1200 (RU),** CFR1000 (CN), ESFR-SMART (EU), JSFR (JP)
HTR	HTR-10 (CN), HTTR (JP)	HTR-PM (CN)	**X-Energy (US),** U Battery (UK), HTMR (UK) StarCore (CA), STL (SA), **USNC (US)**
LFR	-	BREST-OD300 (RU)	SVBR-100 (RU), **MYRRHA (BE), CLFR10 (CN), CLFR300 (CN)**, SSTAR (US), LFR300 (US/UK), ALFRED (EU), SEALER (SW), HYDROMINE (UK)
GFR	-	-	ALLEGRO (V4G4), EM2 (US)
MSR	-	-	**Terrapower MCFR (US), IMSR (CA)**, Seaborg (DN), THORCON (US), **Kairos KP-FHR (US),** Fuji (JP), MOLTEX(UK/US), MOSART (RU), **TMSR-LF (CN), TMSR-SF (CN)** CMSR (CN), SSR (UK), Elysium MCSFR (US)…
SCWR	-	-	CSR1000 (CN), Small-SCWr (CN), SCWR-300 (CA)



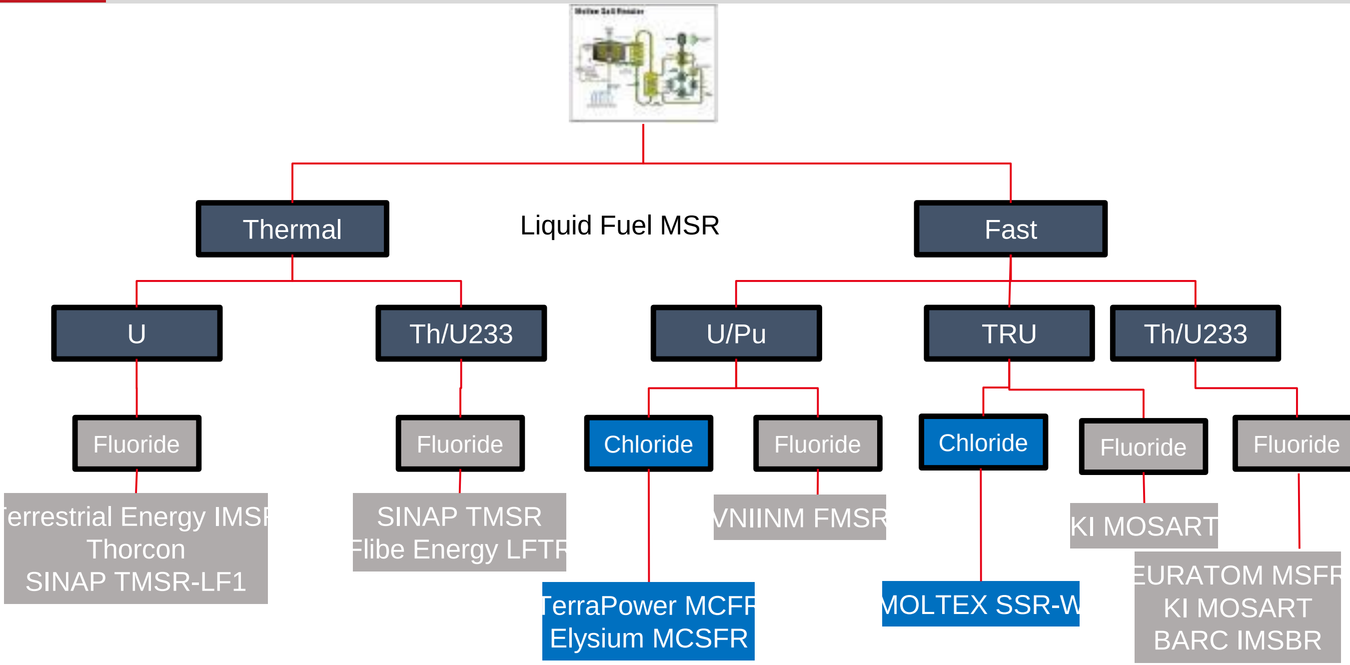
Every MSR is specific

- Fast or thermal
- Cycle U238/Pu or Th/U233
- Chloride or Fluoride
- Transmutation
- Breeder or burner
- AMR
- Power reactors

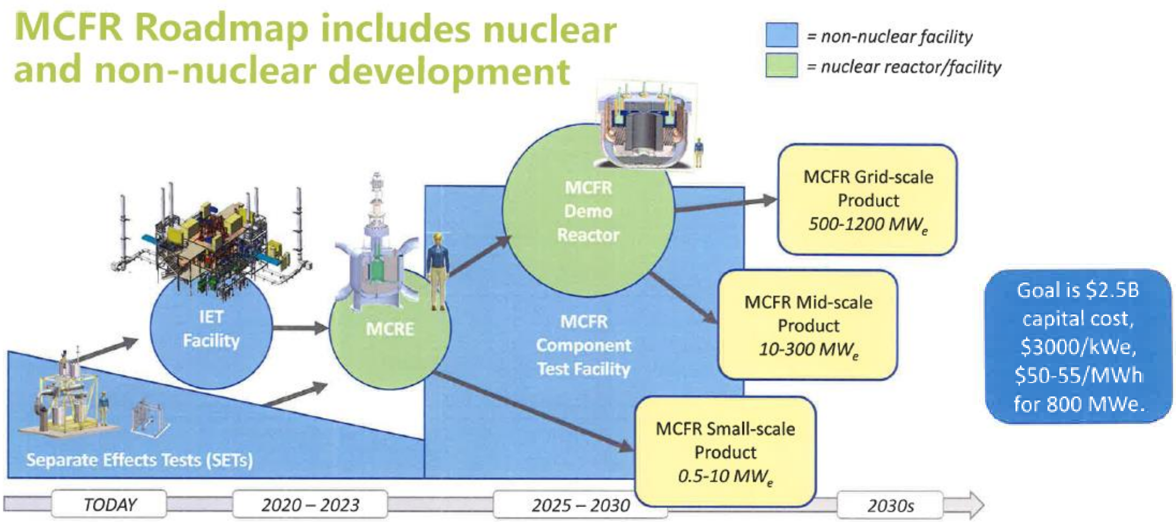
FHR (Fluoride High Temperature Reactors) use a solid fuel cooled by a molten salt >> closer to HTR issues than MSR

- *"popular concept" for investors, acceptability potential, disruptive concept, expected gains on investment costs vs unproven feasibility, material, chemical and corrosion problems*
- A lot of concepts, only a few startups have test loops and do certain technological developments (like Terrapower or Kairos).

MSR CLASSIFICATION



- Terrapower (Bill Gates) invests more and more on the MCFR, in parallel of their SFR development (NATRIUM)
- U/PU cycle, fast spectrum, chloride salt
- Small experimental reactor (MCRE) scheduled in 2025 at INL, 90M$ in 7 years from DOE (ARDP -Advanced Reactor Demonstration Program)
- Consortium Southern Energy / Terrapower / ORANO



China

Two prototypes in construction

FHR : TMSR-SF1 10MW

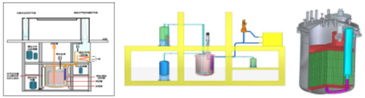
MSR : TMSR-LF1 2MW (fluoride, U-Th)

TMSR-LF1 will start in 2021

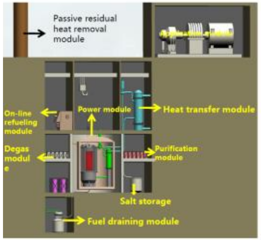
2MW TMSR-LF1

- Demonstrate concept of MSR with liquid fuel and pyroprocessing
- Demonstrate Th-U cycle and its features
- Platform for future reactors and Th-U cycle R&D

Power	2MW
Temperature	630 ℃ / 650 ℃
Type	Integrated design
Fuels	$LiF\text{-}BeF_2\text{-}UF_4\text{-}ThF_4$
Residual heat removal	Passive air natural circlation system



Development of an AMR of 168 MWé

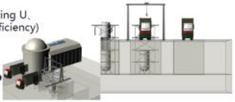


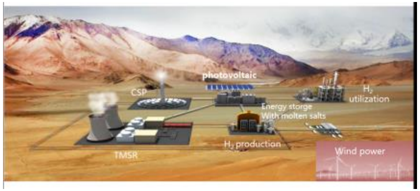
- **Key modules**: power、heat transfer、fueling draining、Passive residual heat removal、on-line refueling
- **Application modules**: generator、hydrogen production、Changed、etc. (Changed with goals)

Power	168MWe
Temperature	600 ℃ / 700 ℃
Efficiency	40%-50%
Th power	>=20%
Main vessel	5.2m×6.0m (D×H)
Safety	Passive residual heat removal system
Economics	Cheaper than coal

Modular construction and operation

- **Power module life: 8 y** (Material life)
- **Fuel salt dry-process time: 8 y** (extracting U、Th，removal fission products,improve fuel efficiency)
- **Other modules: changed easily**
- **On-line fueling without shut down**
- **Multi-building one by one (decrease co**

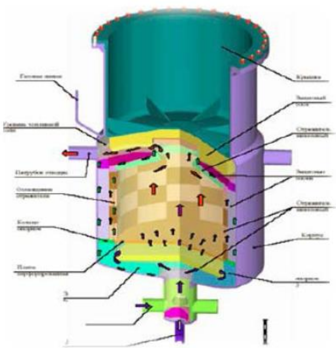


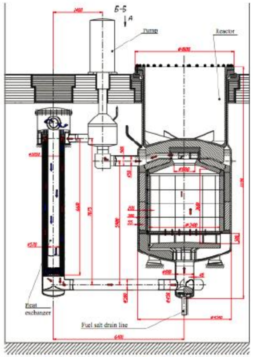


- **Kurchatov institue works on the** MOSART project (1000 MWe)
- Fast spectrum with fluoride salt for actinides conversion
- Material and components developpement, chemistry and processing R&D

MOSART by Kurchatov, Russia

2400 MWt /1000 MWe	Liquid fuel	Fast	Initial fuel: Pu and MA trifluorides from PWR spent fuel in LiF-BeF2 U233 to be provided by Th adjustment (single and double fluid concepts studied)





Announcement by Rosatom in December 2019 of the construction of an experimental molten salt reactor near Krasnoiarsk to incinerate minor actinides
~ 2030

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- **Assets and limits of the concept**
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Potential assets

Nuclear fuel cycle

- Multirecycling of Pu
- Minor actinides transmutation

Intrinsic safety

- Potentially no severe accident
- Strong negative neutronic feedback
- No pressure
- Salt solidification in case of leakage

Flexibility

- Load following capability

Feasibility issues

Salt chemistry

- Mastering solubility and precipitation issues
- Lack of data
- Uncertainties for operating the system

Materials

- Corrosion
- High temperature
- Structure irradiation (no clad as 1st barrier of containment)

Safety in operation

- Operation and maintenance processes
- Fission products management, radioprotection

Economy

Potential advantages:

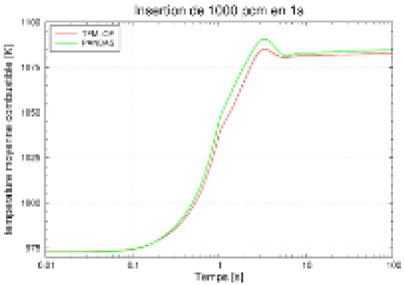
- High burnup ratio: no limitation due to irradiation damage on structure
- Simplified fuel cycle (no extraction of residual fissile material from spent fuel)
- Reactor simplicity:
  - Fuel tank without internal structures except irradiation and thermal protections of the walls
  - No mechanical devices for plant operation, except pumps
- No pressure in the circuit in normal operation and no chemical exothermic reactions with molten salts capable to generate pressure in the containment building
- High temperatures thus high thermodynamic efficiency and possibilities of heat production (or other high T°C applications)

Technical barriers to be overcome:

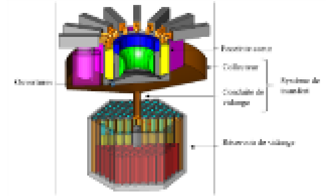
- Generally, low maturity level => development and qualification program to be defined
- Technology for reactor equipment
- Components and materials qualification (high T°C, irradiation, salt environment)
- Possible life duration limitation of reactor structures (irradiation damage, fission products deposition on the intermediate heat exchangers…)
- Management of salt composition and of the redox characteristics
- On-line processing scheme or processing in batch to be defined
- Definition of safety provisions to be further defined
- Needs and technology for in-service-inspection to be defined
- High melting point requiring heating systems

Potential advantages:

- With fast spectrum, negative feedback effect immediately occurs when the salt temperature varies: intrinsic safety advantages with regards to reactivity accidents
- No risk of fuel compaction and risk limitation for other reactivity insertion (the core contains the exact amount of fissile needed for criticality)
- Capability to remove the fuel (i.e., draining) from the critical zone
- Fission gases are continuously released from the core and stored in tanks not damaged by the core accidents
- No chemical reaction with air (no fire) and water (no hydrogen production)



Fuel salt T°C evolution after a 1000 pcm reactivity insertion in 1 second (from D. Gerardin PhD thesis)



MSFR fuel circuit with its emergency draining tank (as proposed by CNRS and studied in SAMOFAR)

Technical barriers to be overcome:

- No recent licensing experience
- Prevention of corrosion, including suitable surveillance measures
- Monitoring and in-service inspection measures
- More in depth identification of risks to be further led, encompassing all types of events, all initial states (notably start-up and shutdown), and all the plant (not only the reactor zone)
- Risk of precipitation and concentration of fissile matters (including, out of the reactor zone)
- Volatility of the salts to be studied both for operation (deposits…) and safety (releases…)
- Risks associated to fission products extracted from the fuel circuit
- Further study of the absence of severe chemical reactions between salt and other materials

Environmental impact

Potential advantages:

- Fast neutron spectrum and high burnup ratio drastically reduce the amount of minor actinides in the wastes, in particular with the ^{233}U/Th fuel cycle
- Capability to burn trans-uranium elements generated in the LWR
- Fast neutron spectrum increases the amount of natural resource: quite 100% of U and 100% of Th compared to 0.7% of ^{235}U
- Fluoride and fast neutron spectrum: no wastes difficult to manage such as ^{36}Cl and graphite

Technical barriers to be overcome:

- Decontamination and waste packaging
- Techniques to limit the production and release of tritium to be developed
- Radiological and non radiological (incl. fluorine gas) impact of off-site installations (salt manufacturing, extraction and conditioning of fissile and fertile matters, waste processing…) to be studied also

Proliferation resistance and physical protection

Potential advantages:

- Limitation of transportation of fissile materials, if not operated as a breeder (or as an actinide burner)
- With $^{233}U/Th$ fuel cycle misappropriation is difficult (high gamma emission)
- Limited need for salt handling in fast spectrum

Technical barriers to be overcome:

- Proliferation resistance and physical protection issues to be further examined, with adequate safeguards methods, in particular considering the location of radioactive matters in different parts of the installation

Flexibility and adaptation to the electrical grid needs

Potential advantages :

- The immediate negative feedback effect due to salt dilatation leads to very limited temperature variation even in case of large power variation need
- Control rods for adjusting the generated power could be unnecessary
- Adapted to electrical grid with a significant share of intermittent production sources (renewable)
- High temperatures thus high thermodynamic efficiency and possibilities of heat production (or others high T°C applications)

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SALT SELECTION

Salt choice depends on reactor type, processing and safety requirements

- Melting temperature, volatility, density…
- Corrosion
- Stability domain
- Neutronics
- Actinides and FP solubility
- Behaviour under irradiation
- Interaction with air/water
- Toxicity
- (re)processibility
- Availability/cost

Safety issues!!!

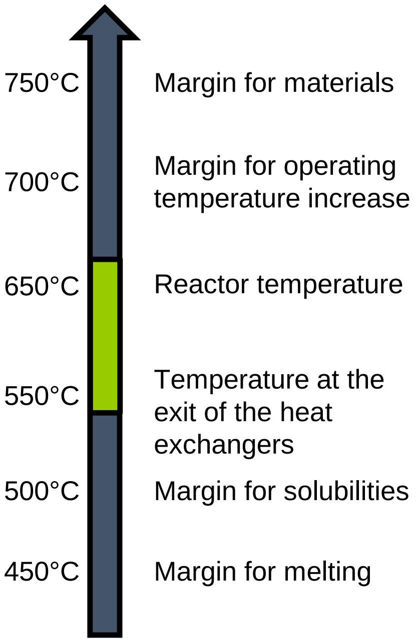

Table 2. Solubilities of PuF_3 and UF_4 in the FLiNaK salt system   Melting 454°C, (727K)

Temperature, K	Individual solubility [4, 5], mol %		Joint solubility, mol %	
	PuF_3	UF_4	PuF_3	UF_4
550°C 823	6.1 ± 0.6	15.3 ± 0.8	1.16 ± 0.14	1.75 ± 0.26
600°C 873	11.1 ± 1.1	24.6 ± 1.2	2.9 ± 0.3	3.5 ± 0.5
650°C 923	21.3 ± 2.1	34.8 ± 1.7	13.2 ± 1.6	11.0 ± 1.6
700°C 973	32.8 ± 3.3	44.7 ± 2.2	19.1 ± 2.3	17.3 ± 2.6
750°C 1023	No data	No data	21.0 ± 2.5	19.0 ± 2.8
800°C 1073	No data	No data	22.5 ± 2.7	20.0 ± 3.0

SALT SELECTION

- **Salt selection depends on the reactor objectives : U/Pu cycle vs U/Th cycle, fast vs thermal, large reactor vs SMR…**

- **Fluorides salts often used for thermal spectrum and/or thorium**

→ Valuable feedback from the ORNL's MSRE

- **Chlorides salts as an interesting alternative for fast spectrum**

- Hardening neutronic spectrum >> **better conversion of actinides**
- More suited for multirecycling of Pu (lower solubility of Pu in fluoride salts)
- 37Cl enrichment necessary but feasible

For example in the french context (closed fuel cycle, Pu multirecycling, transmutation) we focus on chlorides fast MSR for actinides conversion (reducing ultimate wastes)

Investigation of NaCl-$PuCl_3$ type of salts (+ UCl_3, $AmCl_3$, $MgCl_2$, $CaCl_2$…)

Gen4 isogenerator

Transmutation

Chemistry reasons

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Closed fuel cycle is the reference strategy

U&Pu recycling in existing PWR, already deployed

Multiple recycling in PWR is considered, R&D program

R&D on Fast Reactors is still ongoing at CEA

- → **Significant results and knowledge acquired from ASTRID SFR program**
- → **Increase the maturity and performances of SFR : safety, economy, fuel cycle**
- → **Opportunity to re-open R&D paths : SMR SFR and alternative technologies like MSR**
- → **Feasibility of actinides conversion in MSR**

⇒ New R&D program on FR and related closed fuel cycle

Basic research and numerical simulation	Technological developments	Sketches and survey

R&D on Severe Accidents and materials/lifetime justification

NEW INNOVATIVE DESIGNS INCLUDING MSR

Objectives of innovative sketch project

Maintain advanced reactors expertise

- Design sketchs : global vision of design, sfaety, performance, economics
- GIF participation and international collaboration

Innovation dynamics

- SMR and advanced reactors are attractive concepts for young generation
- transversal « sketch team » within CEA

Improve competitiveness of SFR

- « safety vs cost dilemma »
- Evaluation of interests, opportunities and limits of SMR-SFR

2 SFR sketch

Other fast reactors evaluation

- Theoretical assets of fast MSR : safety, fuel cycle, flexibility
- Big challenges : chemistry, corrosion, materials

1 MSR sketch

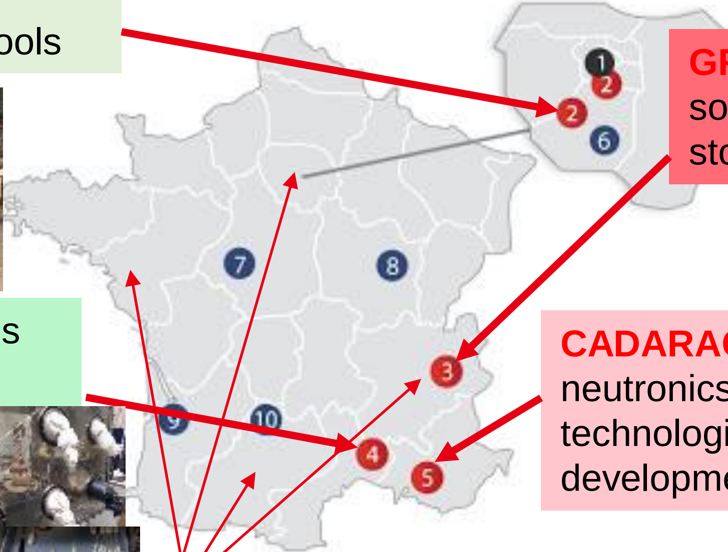
→ ***Fast MSR, U/Pu cycle chloride salt***

WHAT IS A SKETCH ?

- PRE-DESIGN
- WITH EVALUATIONS : SAFETY, PERFROMANCES, COSTS
- FOR LONG-TERM OPTION

SACLAY : corrosion, materials, simulation tools

MESCAL facility

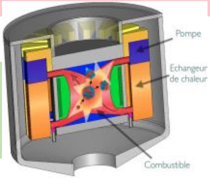


GRENOBLE : solar salts, thermal storage salts

MARCOULE : actinides chemistry, fuel cycle, ATALANTE hot lab

CADARACHE : neutronics, reactor design, technological developments

CNRS expertise : MSFR design, simulation tools, thermochemistry



- PHD AND POST-DOC OPPORTUNITIES

Open to increase international collaboration :

- **Gen4 International Forum**
- **SAMOSAFER and future European projects**
- **JRC on fuel salt data acquisition**

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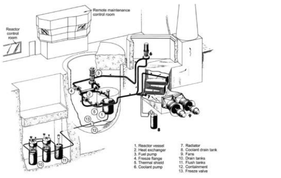
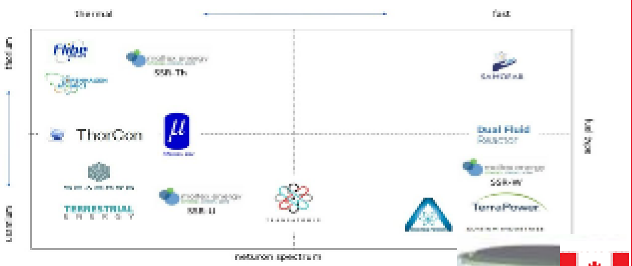
USA experience
ARE (1954) and MSRE (1965-1970)
Thermal spectrum, Flibe, uranium, 7MWth

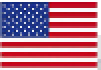




Renewed interest in MSR since 10 years : assets for resolving safety & waste issues, innovation attractive for investors, dozens of new concepts

Startups, mainly north-american





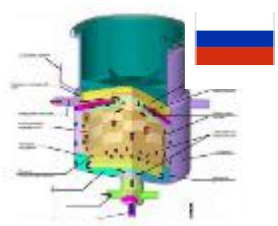
300M$ / 7y from DOE for a test reactor (Hermes- ORNL- 50MWth)

90M$ / 7y form DOE for an integral experiment (MCRE - INL)

IMSR – Terrestrial Energy

National programs

TMSR 2MWth – Fluroride – thermal – U/Th
Starting 2021

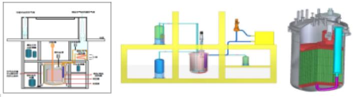


MOSART – ROSATOM/Kurchatov

2MW TMSR-LF1

- Demonstrate concept of MSR with liquid fuel and pyroprocessing
- Demonstrate Th-U cycle and its features
- Platform for future reactors and Th-U cycle R&D

Power	2MW
Temperature	630 ℃ / 650 ℃
Type	Integrated design
Fuels	LiF-BeF$_2$-UF$_4$-ThF$_4$
Residual heat removal	Passive air natural circlation system




R&D NEEDS ON MSR FEASIBILITY

Salt chemistry

- Salt purification, role of oxygen, precipitation issues
- Corrosion experiments
- Material screening (including additive fabrication)
- Experimental data acquisition on salts properties (including the real salt with actinides and FP)

Reactor design and operation

- Neutronics design
- From primary circuit to the power conversion system
- Design of components and instrumentation
- How to operate and maintain the reactor ? What are the wastes ? Do we have proliferation issues ? Radioprotection ?

Simulation tools

- Isotopic & physical & chemical evolution code
- Neutronic/thermalhydraulic coupling
- Mass transfers, Fission product speciation, off-gas system…

MSR can be a « game-changer » for nuclear energy acceptability

At the same time…

Careful with false promises !
The simple, safe and cheap reactor is often a paper reactor

Simplicity is the ultimate sophistication
Léonard de Vinci

What is simple is false. What is complicated is useless.
Paul Valéry

THANK YOU FOR YOUR ATTENTION

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