



International Workshop on the Chemistry of Fuel Cycles for Molten Salt Reactor Technologies,
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MOSART FUEL CYCLE CHEMISTRY FEATURES

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In MSR devices solid fuel elements are replaced by liquids

- Today wide variety of MSRs, in which a flowing molten salt mixture based on fluorides or chlorides contains fissile / fertile material serving as fuel and coolant, have begun development around the world. Proposed neutron spectra range from thermal to fast and also include time varying spectra. Almost every known form of fissile / fertile material or fuel cycle is under consideration.
- The MSR has many advantages compared to other reactor types, like the capability of operation with different fuel compositions without core modification, on-line or at-line fuel salt processing with multiple actinides recycling, no need for fuel manufacturing, and a high level of sustainability because MSR can be run as a TRU transmuter from UNF or as a breeder in the uranium or thorium fuel cycles. World-wide, all of these operation modes for the MSR are investigated.
- Molten salt fluorides as fuel and coolants offer interesting reactor features such as compatibility with container material, very good transport properties, strong irradiation resistance, high thermal stability and boiling points as well as operation at low pressure. This constitutes a significant safety and economic advantages.



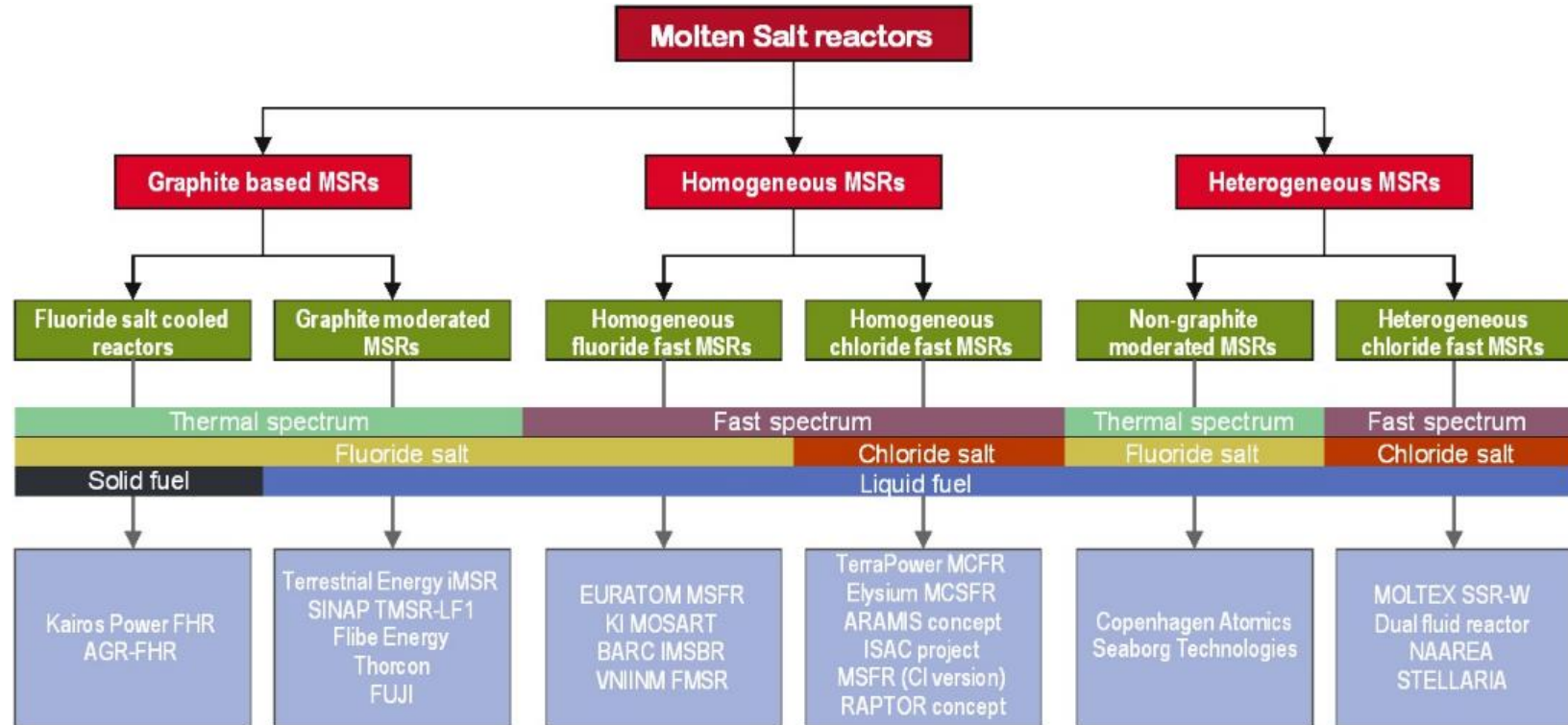
Liquid fuel MSR makes the following possible:

- minimize the initial reactivity excess, which in solid-fuel reactors is compensated by control rods;
- reduce the amount of fission products and decay heat in the fuel salt;
- maintain low pressure in the fuel by removing gaseous FP's from it.

The radiation safety of MSR is determined by reliable sealing of the actinides and fission products within the reactor circuit and by an effective system for fuel processing.

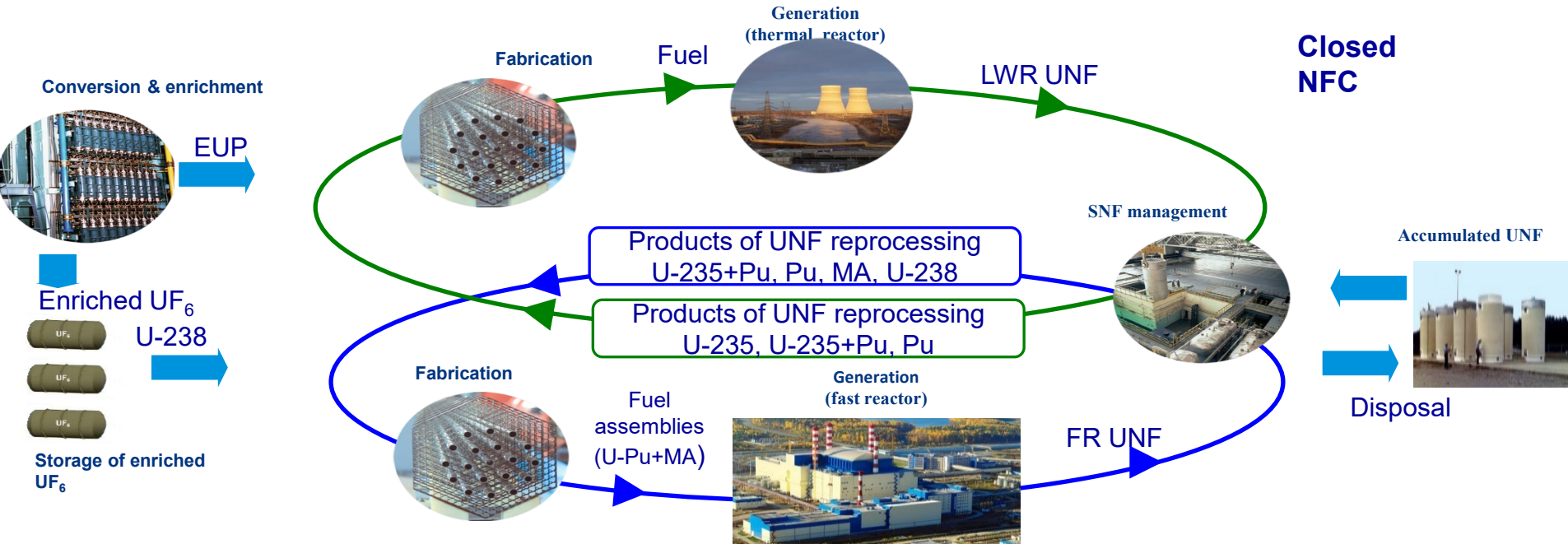
Also playing an important role is the capacity of the fuel salt mixture to retain many dangerous radionuclides in a wide range of the physical parameters, which are characteristic for emergency modes and disruption of normal operation.

MSR Systems





RF: Two Component Nuclear Power System

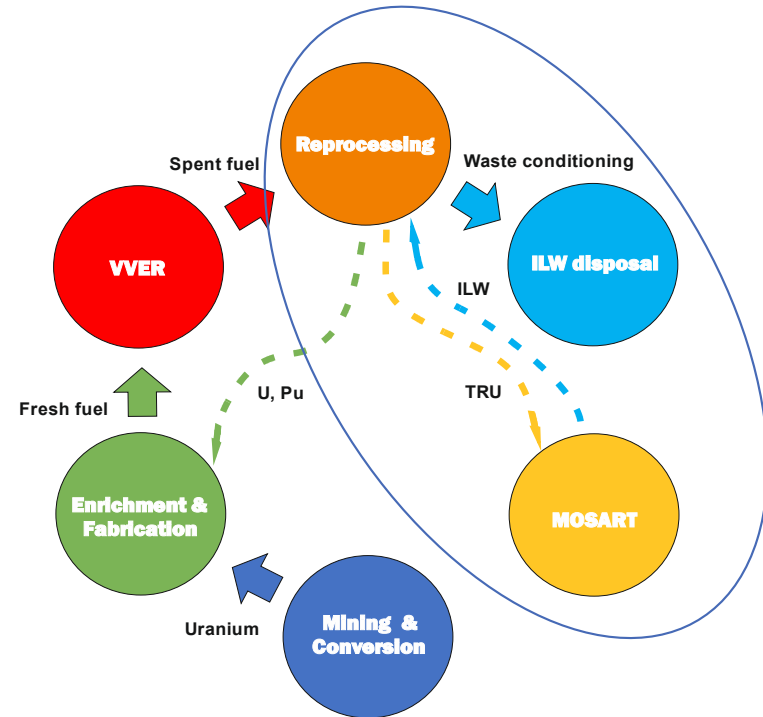


Use of dedicated burner for TRU, remaining after the main part of uranium and plutonium recycling to solid fuel thermal and fast reactors, may reduce the volume and radiotoxicity of HLW. The principle attraction of the MSR technology in this application is the use of fuel material flexibility (easy of “short cooled” fuel preparation, processing and multiple recycling) for gaining additional profits as compared with solid fuel materials.



It is assumed that the closed fuel cycle will be organized as follows: the bulk of the removed U and Pu return to thermal and fast solid fuel reactors, and the remaining TRU's are transferred for utilization in the MOSART system

In order to avoid nuclear matter diversion, the MOSART is integrated (1) at the front end with UNF aqueous reprocessing plant and (2) at the back end with the fuel salt clean up pyro facility, all located at the MCC site.



- During 50 yrs of operation 2,4 GWt MOSART can utilize more than 12t of MA. Last TRU loading will be transferred to the next MOSART unit to be constructed at the MCC site.
- The co-location of MOSART and UNF reprocessing plant, will provide the MCC site and the surrounding customers by electricity (about 8 TWe·hrs per year), facilitates the problems of nuclear materials transport and radwaste management. As with fluid fluoride-based fuel the entire fuel element fabrication process is excluded, providing for exceptional flexibility.
- The fuel can be blended into reactor straightly as needed at any time. Also, there is no need for long cool times and interim storage. This saves for MOSART significant part of the front-end efforts (including radiation doses) and cost.
- All fresh fuel fluorides containing significant quantities of fissile materials for initial loading and make-up, will be manufactured on-site at the MCC site by hydrofluorination process.



When choosing the fuel salt and container materials for the MOSART, the following criteria should be taken into account:

- fuel salt compatibility with structural materials at temperatures up to 750 °C;
- total concentration of actinide fluorides in the fuel salt, taking into account the soluble FP is less than the solubility at the minimum temperature in the fuel circuit;
- melting point of the fuel salt is below 550 - 600 °C;
- saturated vapor pressure at operating temperatures is less than 1 mm Hg;
- ability to control the redox potential of the fuel salt during operation; availability of effective methods for An recycling and purification of fuel salt from soluble FP's;
- actinides losses to waste in recycling below 0.1%;
- the MA recycling time is much less compared the soluble FP's removal time.

The fuel salt selected for the MOSART is molten $\text{LiF-BeF}_2\text{-AnF}_n$ mixture. Among the main factors to chose this mixture are: (1) experience of successful operation of the MSRE in the US ORNL with a fuel based on the LiF-BeF_2 mixture including PuF_3 additions; (2) database on the main physical and chemical properties for molten LiF-BeF_2 salt mixtures; (3) methods for fuel $\text{LiF-BeF}_2\text{-AnF}_n$ salt mixture clean up melt developed on laboratory scale.



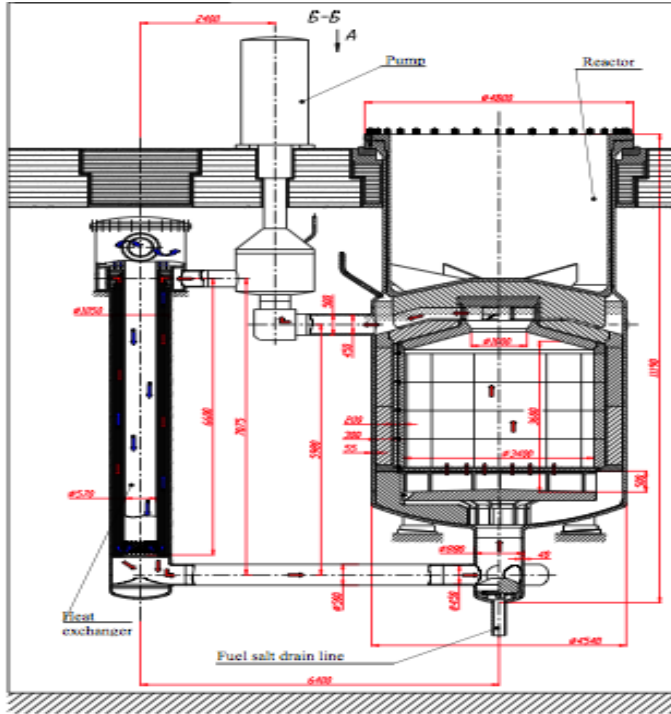
The MOSART advantages are the ability to vary widely the MA content in fuel salt without losing the inherent safety and the absence the fuel fabrication and re-fabrication in multiple actinides recycling.

As result there are significant proliferation resistance and safeguards implications related to the fuel make-up and chemical processing in MOSART plant: (1) there will be continuous variation of isotopic concentrations in the fuel salt from both actinides transmutation and chemical processing; (2) refueling scheme include the ability to continuously feed the core with different fissile material; (3) plate-out of noble metals in the primary circuit could complicate inventory tracking.

Fuel Li,Be,An/F salt mixture represents a unique combination of high-temperature and high-radiation environments that will be challenging for diversion as well as measurement techniques and instrumentation: (a) temperature in the reactor or fuel processing plant will always be kept in liquid state within 650 - 750°C; and (b) fuel salt will be highly radioactive even outside the primary circuit.



Li,Be,An/F MOSART option with homogeneous core fueled by TRU fluorides is under consideration:



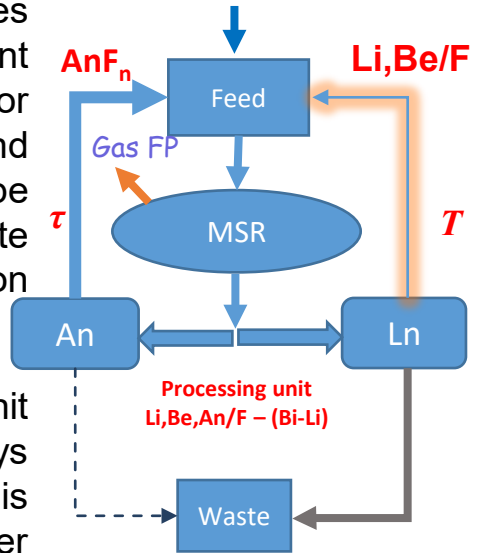
- Max temperature of the fuel salt in the primary circuit made of special Ni-Mo alloy is mainly limited by Te IGC depending on salt Redox potential
- Min temperature of fuel salt is determining not only its melting point, but also the solubility for AnF_3 in the solvent for this temperature



To achieve fuel maintenance, (1) the fuel must be delivered to and into the reactor in a proper state of purity and homogeneity, (2) the fuel must be sufficiently protected from extraneous impurities, and (3) sound procedures must exist for provision of the required redox potential in the system.

All fresh fuel fluorides containing significant Pu quantities + MA for initial loading and make-up, will be manufactured onsite by hydrofluorination process.

In pyroprocessing unit MA would always accompany Pu, this operation would never produce a “clean” material that would be attractive for diversion.



$T \gg \tau$
 T – soluble FP removal time, 300 days
 τ – An recycling time, 30 days

Methods for FP removal and An's recycling include:

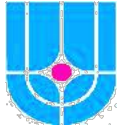
- continuous removal of Xe and Kr by the He sparging;
- addition of TRUs to replace that lost by burnup;
- recycling of all actinides,
- removal of soluble FPs (principally rare earths);
- removal of a portion of the insoluble noble FPs.

The Li,Be,An/F MOSART development does not make sense without the creation of the reactor fuel cycle, therefore, it implies the simultaneous and mandatory development of the flowsheet and technology for the chemical fuel salt processing based on reductive extraction into liquid bismuth containing dissolved lithium as a reducing agent.



MSR designs under considerations, in which a flowing molten salt mixture based on fluorides contains fissile material serving as fuel and coolant, represent a reactor plant integrated with a pyro processing unit

- Existing IAEA PR&PP approaches are mainly applicable to the U-Pu, but not to minor actinides based fuel cycles, and to item counting for solid fuel reactors, as well as to bulk material accountancy for the front and back end of the nuclear fuel cycle.
- These techniques and associated instrumentation for bulk accountancy have been developed predominantly for enrichment, fuel fabrication, and aqueous reprocessing. However, none of these bulk accountancy measures can be directly applied to high temperature MSR designs, in general, and for MOSART in particular, without evaluation and potential modification.
- Almost no work has been done to determine how will the fissile material content in the fuel salt mixture be determined, when it is in the primary circuit, in drain tanks, or in processing unit. Note, that after each recycling fuel is getting less attractive for fissile material diversion.



Main provisions concerning the fuel cycle chemistry for MOSART are:

- (1) fuel salt processing in batch (or continuous) mode in order to quickly return An's free of soluble FP's to the core within 1 month;
- (2) the removal for soluble FP's (rare earths, including Sm and Eu) - about 1 yr;
- (3) main fuel cycle operations are based on the molten salt and liquid metal system with relatively low concentrations of actinides;
- (4) operations with isolating of particular pure actinide fractions are excluded.

Main uncertainties in MOSART fuel cycle are associated with the need to:

- specify the criteria for fuel salt processing (the degree of fuel salt purification from certain FP groups, actinide losses to waste);
- determine the fissile material loading into particular pyrochemical processing unit from safety point of view;
- study in details the procedure of fuel salt removal for processing with simultaneous addition in the reactor circuit of purified fuel salt in the same amount.



The diagram illustrates the development timeline of the Molten Salt Reactor (MSR) technology, categorized by facility type and time period.

Facility Types:

- Nuclear facility:** Represented by green shapes.
- Laboratory facility:** Represented by blue shapes.

Development Phases and Milestones:

- 2021:**
 - Separate Effects Tests & Materials Scoping:** Laboratory facility.
 - Integrated Effects Test & Materials testing:** Laboratory facility.
- 2024:**
 - Physics experiment Li, Be, Pu/F 100kW:** Nuclear facility.
- 2025 - 2030:**
 - Demo MOSART:** Nuclear facility.
 - Test MSR 10 MWt:** Nuclear facility.
- 2030-e:**
 - Demo MOSART 100 MWe:** Nuclear facility.
 - Full scale MOSART 2400 MWe:** Nuclear facility.

Additional Information:

- The **Molten Salt Component Test Facility** is a central hub for the development process.
- The **Test MSR 10 MWt** is a key milestone in the development of the full-scale reactor.
- The **Full scale MOSART 2400 MWe** is the final goal of the development program.



Summary

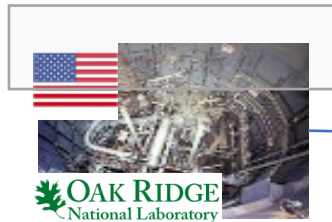
- ✓ MOSART offers alternative option for the long lived waste incineration: fuel cycle flexibility, simplified fuel processing, in-service inspection, no fuel transportation and refabrication, intrinsic safety features
- ✓ Along with the MOSART flow sheet development for the fuel salt processing associated with the MA, it is necessary to start first the detailed studies, and then the required experiments, including: (1) fuel salt clean up from samarium, europium, cesium, strontium and barium by sorption and (2) closure of the processing cycle for lithium-7.
- ✓ The strong international cooperation between the countries involved, has shown to be very effective in tackling the most prominent remaining R&D issues.



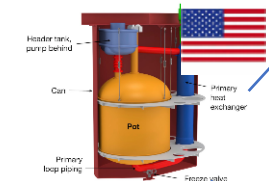
MSR in the World



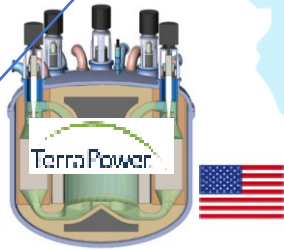
ARE (1954 Fluorides)



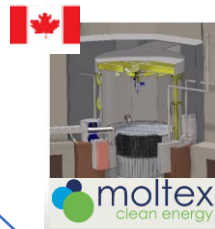
MSRE (1965-1970)
Fluorides
U/Th/Pu
~ 10 Mwth



Thorcon (2015-)
Fluorides



MCFR (2014-)
Chlorides MCRC 2025
(500 KWth)



MOLTEx
SSR
Chlorides
(2010-)

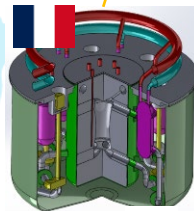


TERRESTRIAL
ENERGY



Abilene NEXT Fluorides ~2025

ARAMIS/ISAC
(2020-)
Chlorure



Fluorides
(2018-)
Terrestrial Energy
(2012 -)
IMSR
Fluorides

THORIZON (2014-)

Fluorides

SEABORG

FFluorides
(2014-)

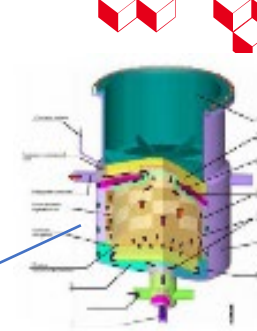


Fluorides

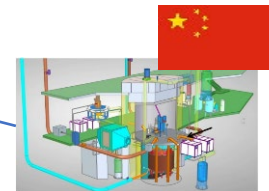
THORIZON (2014-)

SEABORG

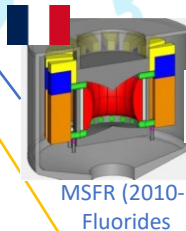
FFluorides
(2014-)



Kurchatov (2000-)
MOSART
Fluorides



TMSR – LF1 (2022-)
Fluorides
U/Th/Pu
~ 2 Mwth



MSFR (2010-)
Fluorides



Chlorides (2022-)



Chlorides (2021-)