Preliminary Design Assessment of the Molten Salt Fast Reactor

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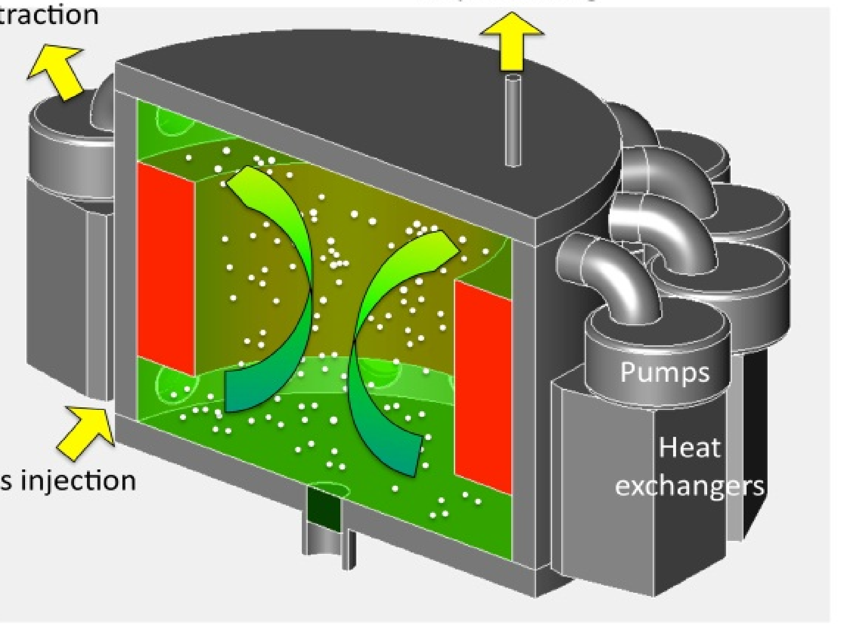
The concept of Molten Salt Fast Reactor (MSFR)

What is a MSFR ?

Molten Salt Reactor (molten salt = liquid fuel also used as coolant)

Based on the Thorium fuel cycle

With no solid (i.e. moderator) matter in the core ⇒ Fast neutron spectrum



Optimization Criteria:

Initial fissile matter (^{233}U, Pu, enriched U), salt composition, fissile inventory, reprocessing, waste management, deployment capacities, heat exchanges, structural materials, design..

⇩ Generation IV reactors: fuel reprocessing mandatory

Neutronic core of the MSFR associated to an on-site reprocessing unit (on-line in-core bubbling and batch chemical reprocessing during reactor operation)

Liquid fuelled-reactors: why "molten salt reactors"?

Advantages of a Liquid Fuel

- ✓ Homogeneity of the fuel (no loading plan)
- ✓ Heat is produced directly in the heat transfer fluid
- ✓ Possibility to reconfigure passively the geometry of the fuel:
  - One configuration optimize the electricity production managing the criticality
  - An other configuration allow a long term storage with a passive cooling system
- ✓ Possibility to reprocess the fuel without stopping the reactor:
  - Better management of the fission products that damage the neutronic and physicochemical properties
  - No reactivity reserve

Which constraints for a liquid fuel?

- Melting temperature not too high
- High boiling temperature
- Low vapor pressure
- Good thermal and hydraulic properties (fuel = coolant)
- Stability under irradiation
- Good solubility of fissile and fertile matters
- No production of radio-isotopes hardly manageable
- Solutions to reprocess/control the fuel salt

Best candidates = fluoride salt (LiF – 99.995% of ^{7}Li) or chloride ($NaCl$ – 99% in ^{37}Cl) salt

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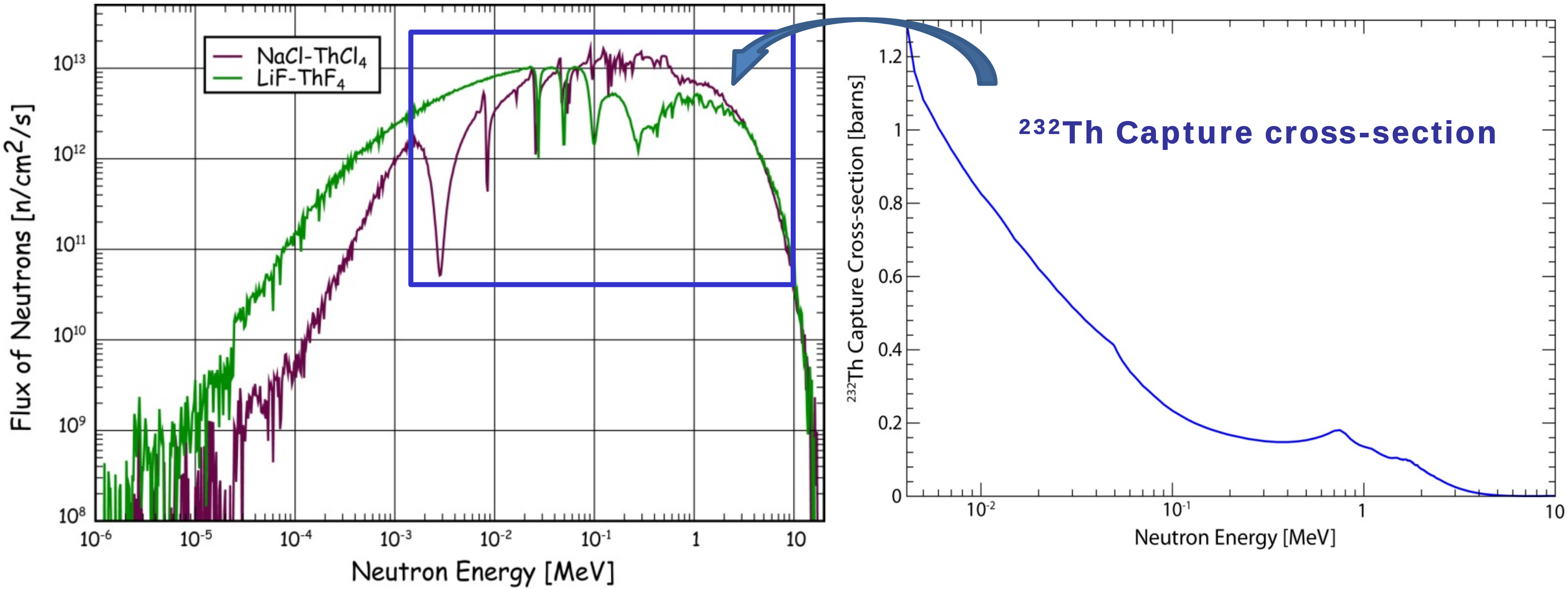
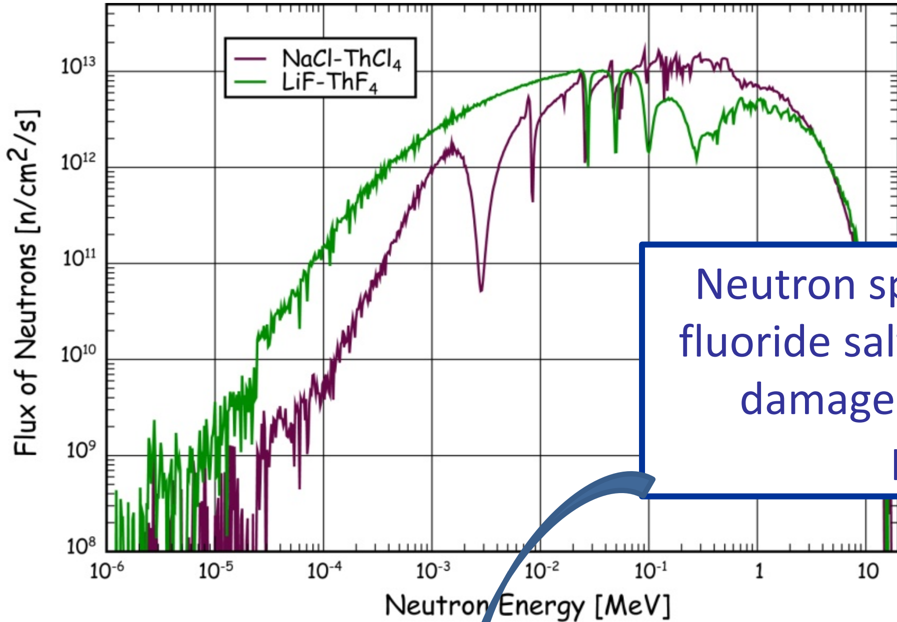
Molten Salt Reactors

MSFR: choice of the liquid fluid

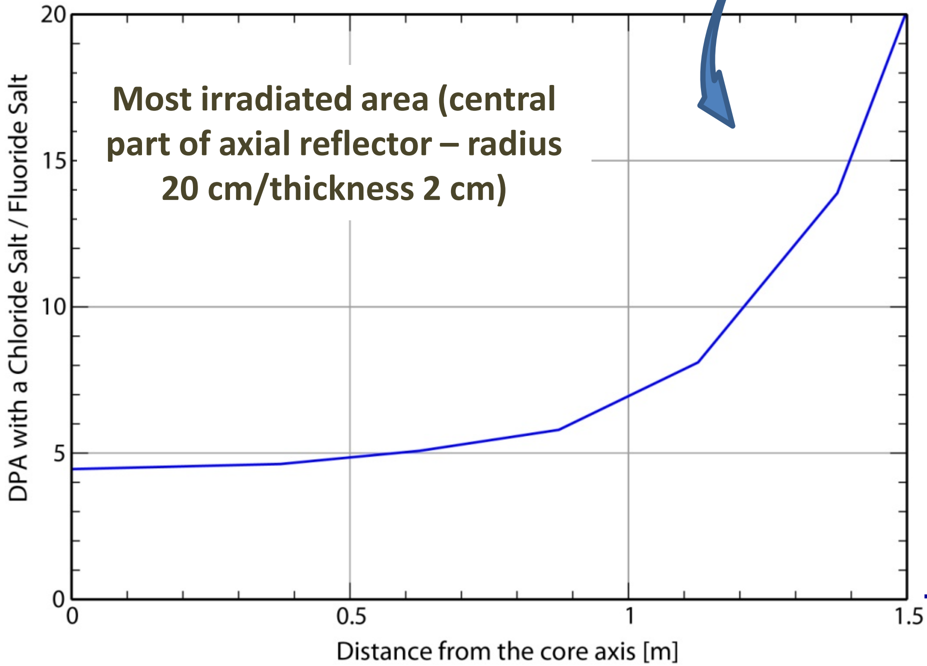


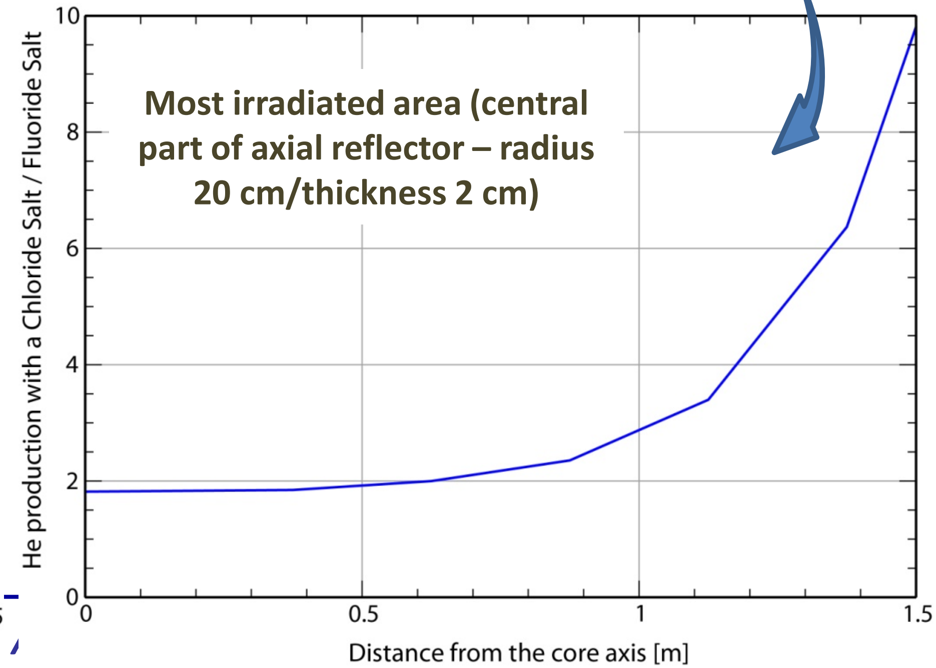
Parameter	Fluoride Salt	Chloride Salt
Thorium capture cross-section in core (barn)	0.61	0.315
Thorium amount in core (kg)	42 340	47 160
Thorium capture rate in core (mole/day)	11.03	8.48
Thorium capture cross-section in blanket (barn)	0.91	0.48
Thorium amount in the blanket (kg)	25 930	36 400
Thorium capture rate in the blanket (mole/day)	1.37	2.86
^{233}U initial inventory (kg)	5720	6867
Neutrons per fission ν in core	2.50	2.51
^{233}U capture cross-section in core (barn)	0.495	0.273
^{233}U fission cross-section in core (barn)	4.17	2.76
Capture/fission ratio α (spectrum-dependent)	0.119	0.099
Total breeding ratio	1.126	1.040

MSFR: choice of the liquid fluid



Neutron spectrum less fast with fluoride salt = reduced irradiation damages (both DPA and He production)





The concept of Molten Salt Fast Reactor

Design of the reference MSFR

- Initial Salt: 77.5%LiF – 2.5% $^{233}UF_3$ - ThF_4
- ^{233}U initial inventory per $GW_{él}$: 3260 kg
- ^{233}U production (breeder reactor): 95 kg/year
- Feedback Coefficient: -5 pcm/K

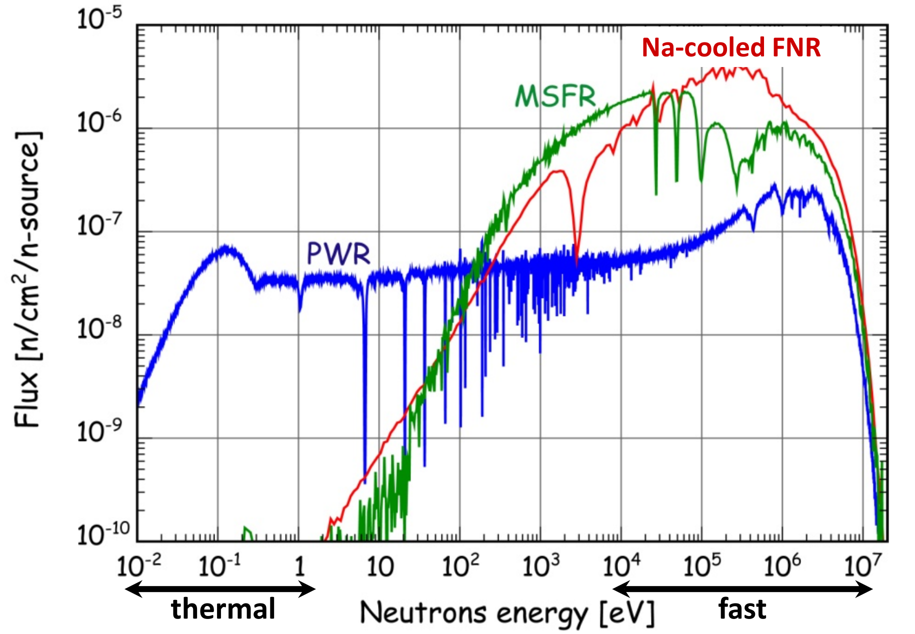
- Fuel Salt Temperature: 750 °C
- Produced power: 3 GW_{th} (~1.5 GW_{el})

- Core Internal Diameter = Core Height = 2.3 m

- Fuel Salt Volume: 18 m^3
  - 1/2 in the active zone (core + plenums)
  - 1/2 in the external circuit (heat exchangers, pipes, pumps)

- Thickness of Fertile Blanket: 50 cm
- Volume of Fertile Blanket: 7.7 m^3
- Initial Fertile Salt: 77.5%LiF - 22.5%ThF_4

- Core reprocessing: 10 to 40 l of fuel salt cleaned per day (on-site batch reprocessing for lanthanides extraction) + on-line He bubbling in the core



Breeder reactor (fed with Th)

Excellent level of deterministic safety (all negative safety coefficients)

The concept of Molten Salt Fast Reactor

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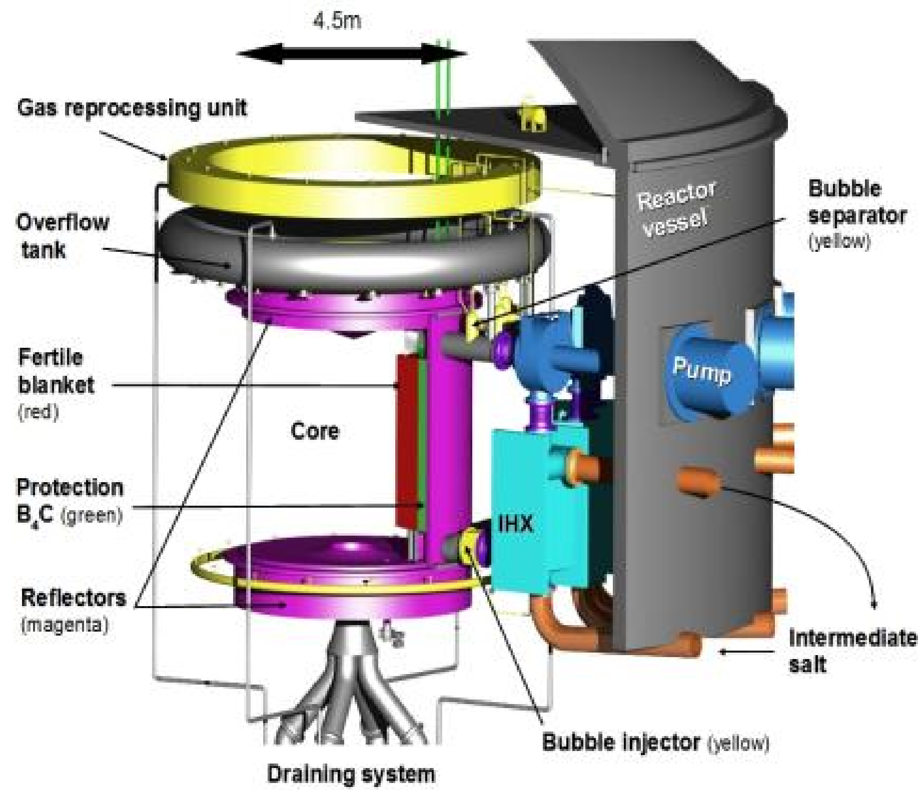
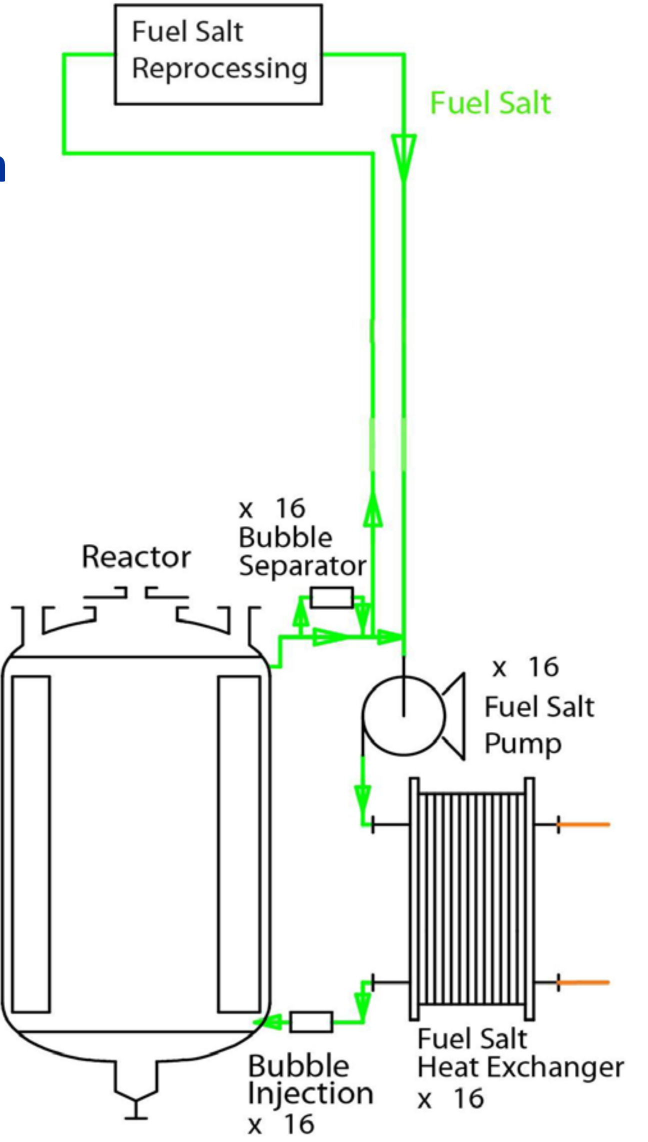
MSFR concept selected for further studies by the GIF “MSR Steering Committee” – Choice approved by the Policy Group (since 2008)



MSFR: conceptual design of the salt heat exchangers

"Fuel Salt Loop" = Includes all the systems **in contact** with the fuel salt during **normal operation**



Core:

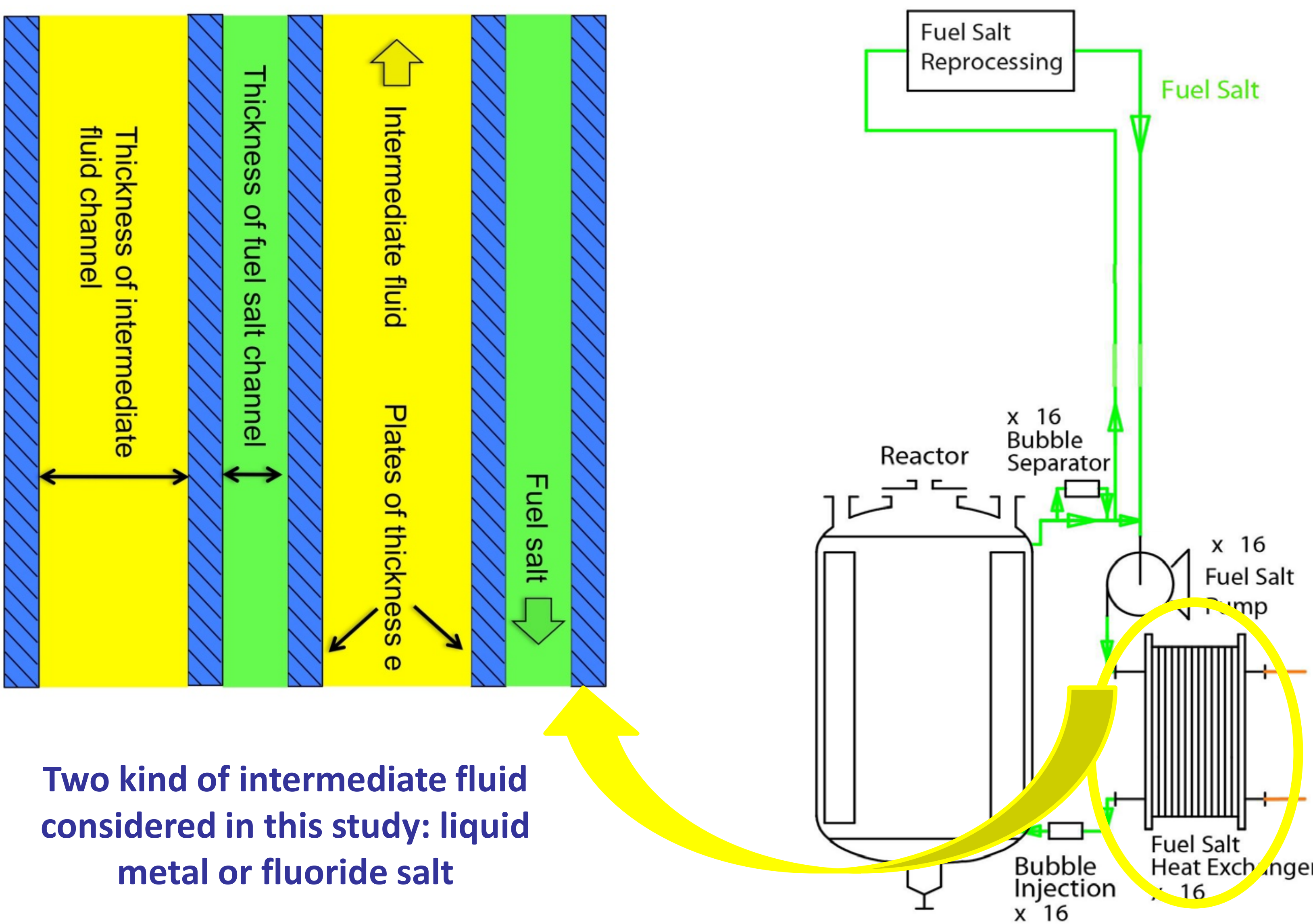
No inside structure

Outside structure: Upper and lower Reflectors, Fertile Blanket Wall

+ 16 external modules:

- Pipes (cold and hot region)
- Bubble Separator
- Pump
- Heat Exchanger
- Bubble Injection

MSFR: conceptual design of the salt heat exchangers



Two kind of intermediate fluid considered in this study: liquid metal or fluoride salt

MSFR: conceptual design of the salt heat exchangers

Constrained Parameter	Limiting value (P_{0i})	Acceptable deviation (σ_i)
Minimum thickness of the fuel salt channel	2.5 mm	0.05 mm
Minimum thickness of the plate	1.75 mm	0.035 mm
Maximum speed of the fuel salt	3.5 m/s	0.07 m/s
Maximum speed of the intermediate fluid (liquid lead)	1.75 m/s	0.035 m/s
Maximum speed of the intermediate fluid (salt)	5.5 m/s	0.11 m/s
Maximum temperature of the materials	700 °C	1 °C
Minimum margin to solidification of the fuel salt	50 °C	1 °C
Minimum margin to solidification of the intermediate fluid	40 °C	1 °C

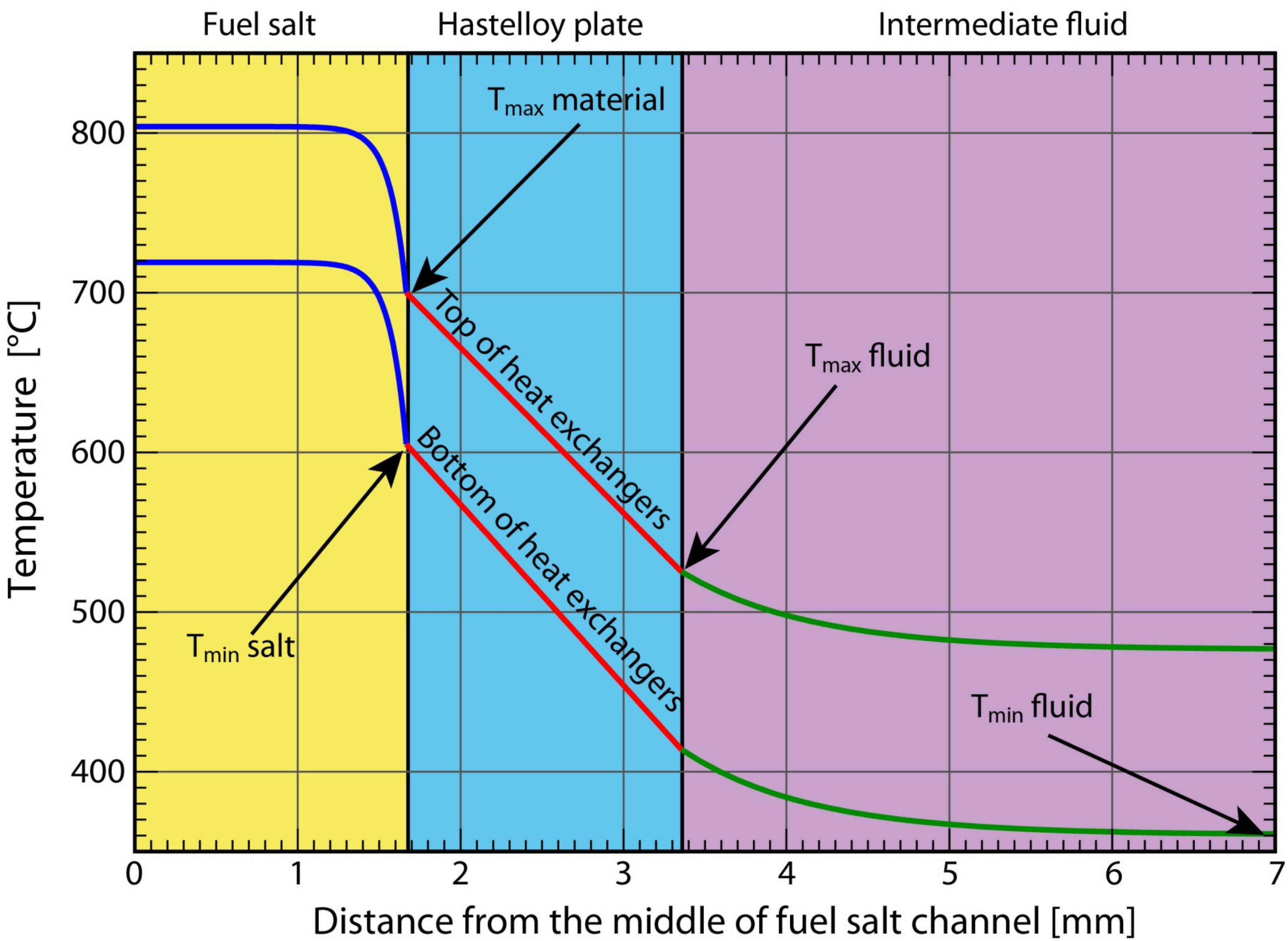
Each set of values of the variable parameters evaluated with the quality function:

$$\prod_i exp\left(\frac{P_i - P_{0i}}{\sigma_i}\right)$$

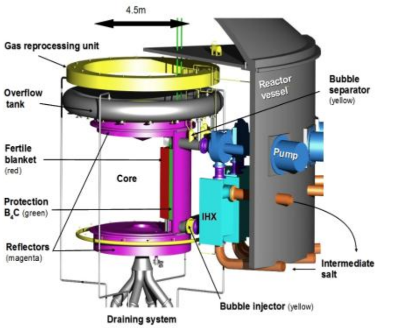
Variables of the study:

- ✓ the diameter of the pipes
- ✓ the thickness of the plates
- ✓ the gap between the plates on the intermediate fluid side (or "thickness of the intermediate fluid channel")
- ✓ the fuel salt temperature at core entrance
- ✓ the fuel salt temperature increase within the core
- ✓ the temperature increase of the intermediate fluid in the heat exchangers
- ✓ the mean temperature difference between the two fluids within the heat exchangers

MSFR: conceptual design of the salt heat exchangers



European 'EVOL' (Evaluation and Viability Of Liquid fuel fast reactor systems) Project (7th PCRD) - *EURATOM/ROSATOM cooperation*



EVOL objective: to propose a design of MSFR by 2013 given the best system configuration issued from physical, chemical and material studies

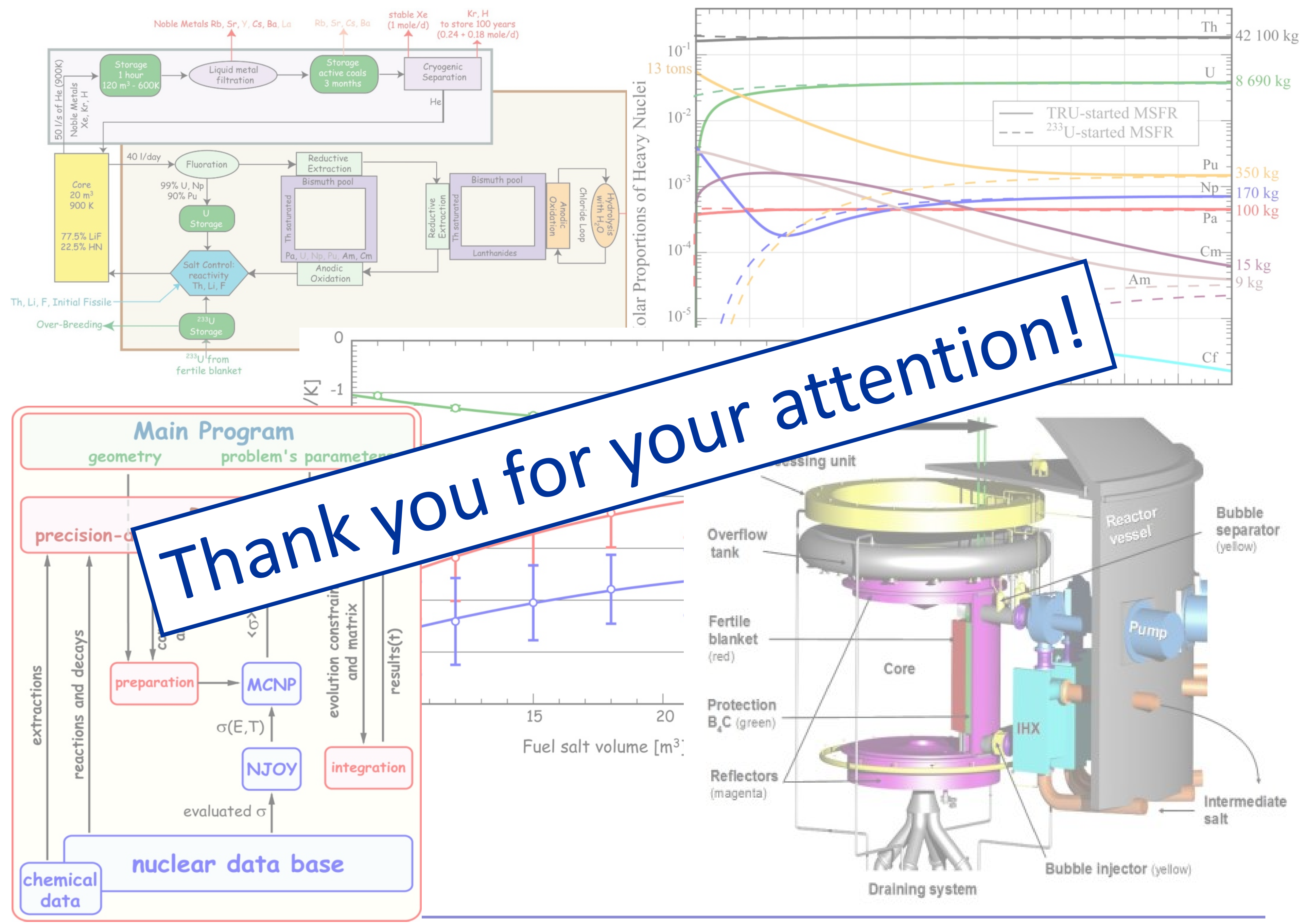
- **Recommendations for the design of the core and fuel heat exchangers**
- **Definition of a safety approach dedicated to liquid-fuel reactors - Transposition of the defence in depth principle - Development of dedicated tools for transient simulations of molten salt reactors**
- **Determination of the salt composition - Determination of Pu solubility in LiF-ThF4 - Control of salt potential by introducing Th metal**
- **Evaluation of the reprocessing efficiency (based on experimental data) – FFFER project**
- **Recommendations for the composition of structural materials around the core**

WP2: Design and Safety
WP3: Fuel Salt Chemistry and Reprocessing
WP4: Structural Materials

European participants to EVOL: France (CNRS: Coordinator, Aubert&Duval, INOPRO, Grenoble INP), EU (JRC – Institute for TransU Elements), Netherlands (Delft University of Technology), Germany (KIT-G, FZD), Italy (Politecnico di Torino), United Kingdom (Oxford University), Czech Republic (Energovyzkum Ltd), Hungary (Budapest University of Technology) + 2 observers (Politecnico di Milano, Italy and Paul Scherrer Institute, Switzerland)

+ Coupled to the ROSATOM project MARS (Minor Actinides Recycling in Molten Salt)

See http://lpsc.in2p3.fr/gpr/gpr/publis-rsfE.htm for more details on the MSFR



Thank you for your attention!

MSFR: choice of the liquid fluid

Element produced	Problem	Fluoride Salt	Chloride Salt
^{36}Cl produced via $^{35}Cl(n,\gamma)^{36}Cl$ and $^{37}Cl(n,2n)^{36}Cl$	Radioactivity - $T_{1/2}$ = 301000y		10 moles / y (373 g/year)
^{3}H produced via $^{6}Li(n,\alpha)$ t and $^{6}Li(n,t)$ α	Radioactivity - $T_{1/2}$ = 12 years	55 moles / y (166 g/y)	
Sulphur produced via $^{37}Cl(n,\alpha)^{34}P(\beta$-[12.34s]$)^{34}S$ and $^{35}Cl(n,\alpha)^{32}P(\beta$-[14.262 days]$)^{32}S$	Corrosion (located in the grain boundaries)		10 moles / year
Oxygen produced via $^{19}F(n,\alpha)^{16}O$	Corrosion (surface of metals)	88.6 moles/year	
Tellurium produced via fissions and extracted by the on-line bubbling	Corrosion (cf. Sulphur)	200 moles/year	200 moles/year

Combination of both neutronic and chemical considerations

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MSFR based on a molten LiF fuel salt

MSFR: conceptual design of the salt heat exchangers

Evaluated parameter	Pb	FLiNaK	$NaF\text{-}NaBF_4$
Diameter of the fuel salt pipes [mm]	301	283	303
Diameter of the intermediate fluid pipes [mm]	897	507	470
Thickness of the plates [mm]	1.61	1.51	1.65
Fuel salt temperature at core entrance [°C]	754	698	704
Fuel salt temperature increase in the core [°C]	89	106	98
Intermediate fluid temperature increase within the heat exchangers [°C]	99	41	66
Mean temperature difference between the two fluids in the heat exchangers [°C]	382	242	280
Intermediate fluid temperature at the heat exch. outlet [°C]	466	530	506
Thickness of the fuel salt channel [mm]	3.38	2.17	2.37
Thickness of the intermediate fluid channel [mm]	29.8	4.49	4.38
Fuel salt speed in the pipes [m/s]	3.92	3.97	3.73
Fuel salt speed in the heat exchangers [m/s]	3.85	2.36	2.91
Intermediate fluid speed in the pipes [m/s]	1.94	6.00	5.67
Intermediate fluid speed in the heat exchangers [m/s]	1.92	5.54	5.75
Maximum temperature of the intermediate fluid [°C]	523	622	595
Maximum temperature of the materials [°C]	701	701	699
Margin to the solidification of the fuel salt [°C]	43.7	54.7	46.7
Margin to the solidification of the intermediate fluid [°C]	39.6	34.5	56.2
Pressure loss of the fuel salt in the heat exchangers [bar]	2.56	2.03	2.56
Pressure loss of the fuel salt in the pipes [bar]	0.99	1.02	0.90
Pressure loss of the intermediate fluid in the heat exch. [bar]	0.09	2.09	1.66
Pressure loss of the intermediate fluid in the pipes [bar]	0.32	0.71	0.57