Design and optimisation of a breeder MSFR using U/Pu cycle

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Outline

- Context
    - Current situation
    - Reference MSFR
- Conception of MSFR-Cl
    - Fuel circuit design
    - Processing unit
- Deployment scenarios

Context

- Global warming ➔ need to shift from fossil to low-carbon energy sources
- Commercial nuclear reactors worldwide
  - Used to provide cheap, abundant and reliable electricity
  - U/Pu cycle (only available fissile element in ores being ^{235}U)
  - Non-breeder reactors, cheap uranium
  - Open cycle → long-lasting wastes
  - Some public trust issues (accidents, wastes) and heavy safety requirements
- Option: 4th generation including MSRs
  - MSFR selected as the reference concept in the Generation 4 International Forum

Reference MSFR

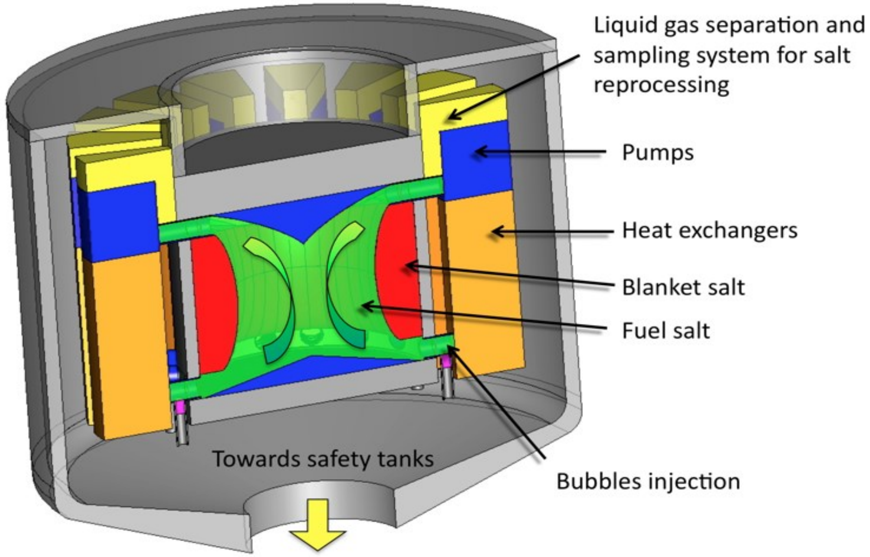
- Liquid circulating fuel acting also as the coolant
  - Intrinsic safety, gravitational draining available
  - Simplified fuel fabrication & possibility for fuel composition adjustments without stopping the reactor

- 3 GW_{th} breeder MSFR in $^{232}Th/^{233}U$ cycle
  - **LiF as solvent**, in which ThF_4 and UF_4 are dissolved
  - Very promising (excellent intrinsic safety and good performances)

- Why studying another one? The current situation
  - Industry developed around $^{238}U/^{239}Pu$ cycle
  - Large stockpile of ^{dep}U; TRUs available
  - Limited solubility of trivalent TRU in fluoride salts

➔ Interest of the Chloride MSFR

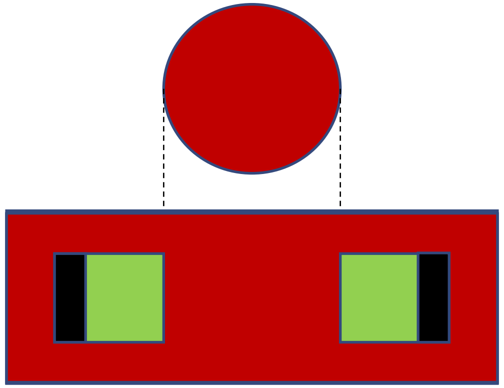
Fuel circuit of the reference MSFR (@CNRS)



MSFR-Cl conception

- Fuel
  - Fissile matter: TRUs from spent fuels (ex-UOx, ex-MOx)
  - Fertile matter: ^{dep}U (99.8% of ^{238}U)
  - Solvent: NaCl with 97% to 99% enrichment with ^{37}Cl

  ➔ $NaCl\text{-}^{dep}UCl_3\text{-}(TRUs)Cl_3$
  - Eutectical mix



Schematic of the fuel circuit

- Operation constraints
  - Fuel = coolant: additional inventory in recirculation loops with heat exchangers
  - HX must be protected from neutron flux: addition of neutronic protection
  - Avoid the removal of An from the core: $BR_{fuel} < 1$ and fertile blanket ➔ $BR_{tot} > 1$

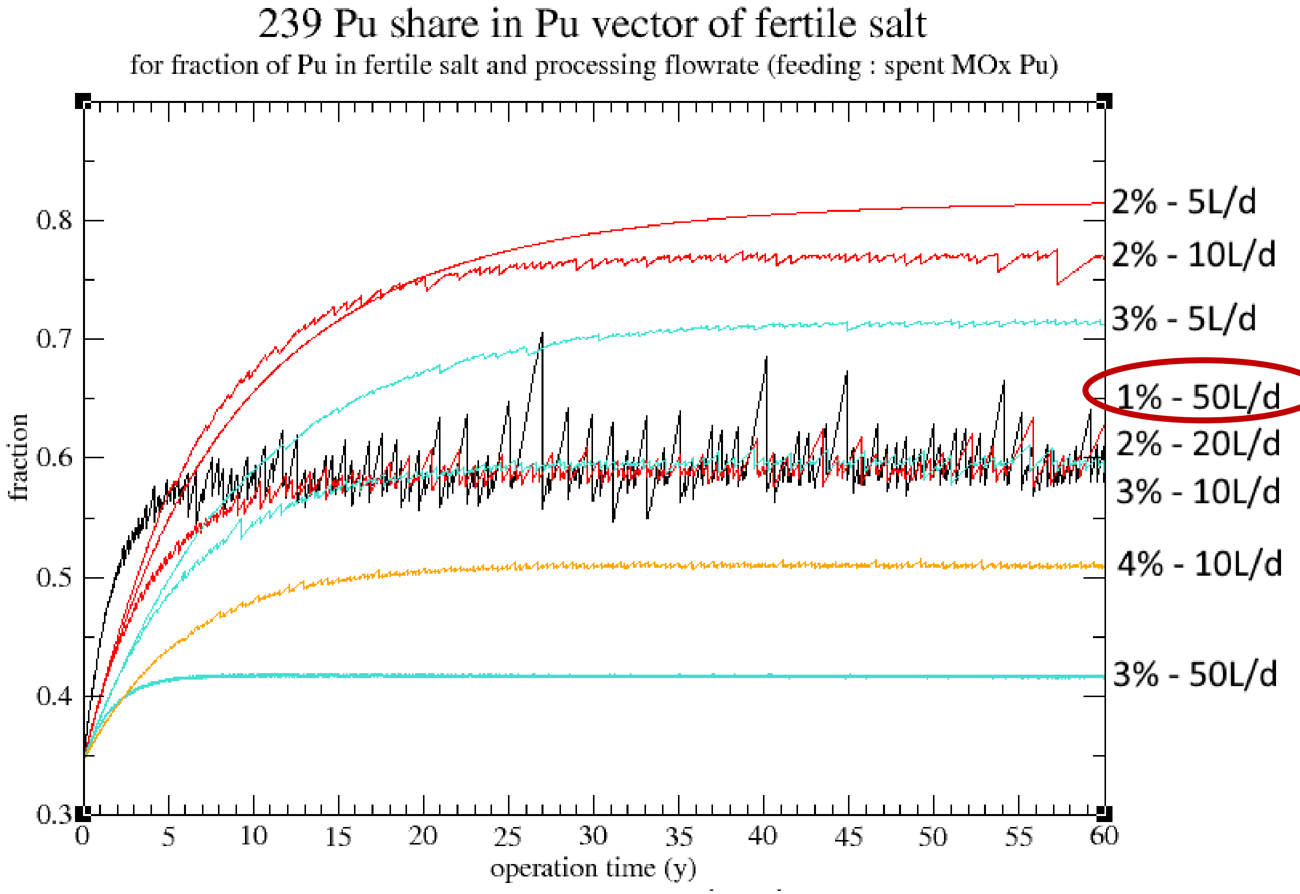
Fertile blanket

- Several challenges
  - Optimisation of the width for breeding: trade-off between low inventory and high BR
  - Resistance against proliferation: addition of low quality Pu

  ➔ NaCl-^{dep}UCl$_3$-$^{ex\text{-}MOx}$PuCl$_3$

- Consequences
  - Advantage: possibility to choose a given ^{239}Pu share by design

  ➔ Synergy with MOx-fuelled reactors
  - Inconvenient: the better the vector, the higher the increase in reactivity ➔ complex management



Current optimised configuration

	Reference MSFR	MSFR-Cl
Fuel salt volume	18 m^3	60 m^3
Fertile salt volume	(46cm w) 7.3 m^3	36.7 m^3 (96cm w)
Starting fissile inventory	5t (^{233}U) or 13t (TRUs)	15t (breeded Pu) to 22t (TRUs from spent MOx)
Total mass	74t (fuel salt) + 30t (fertile salt)	170t (fuel salt) + 103t (fertile salt)
Fuel treatment flowrate	40 L/d	100 L/d
Fertile treatment flowrate	40 L/d (An), 0.4 L/d (FPs)	50 L/d
Bubbling (removal period)	30 s	30 s

Smaller $\rho.c_p$

Neutron transparency

Static calculations: feedbacks

Feedback coefficients for initial composition of optimised configuration (MSFR-Cl)

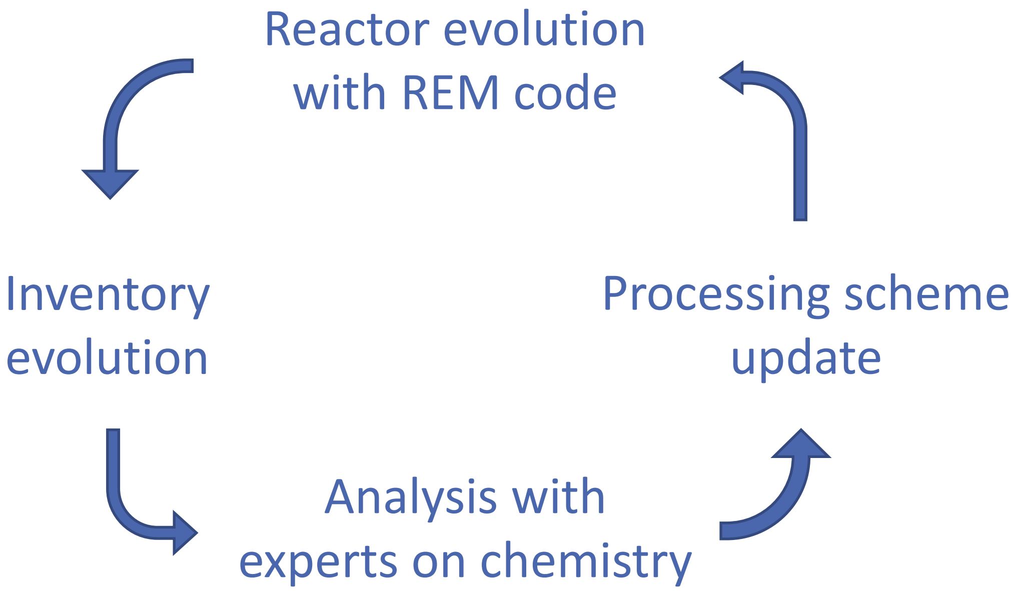
Fuel	Doppler coefficient (pcm/K)	Density coefficient (pcm/K)	total (pcm/K)
ex-MOx	- 0.4(2)	- 7.7(2)	- 8.1(3)
ex-UOx	- 0.7(2)	- 8.3(2)	- 9.0(3)
^{enr}U (e=16.4%)	- 0.6(2)	- 9.8(2)	- 10.4(3)
breeded Pu	- 0.7(2)	- 9.5(2)	- 10.2(3)

Feedback coefficients for initial composition of optimised configuration (reference MSFR)

Fuel	Doppler coefficient (pcm/K)	Density coefficient (pcm/K)	total (pcm/K)
^{233}U	-3.10 (8)	-3.12 (8)	-7.26 (8)

Done with ENDF-B7.1 and Serpent2

Salt processing

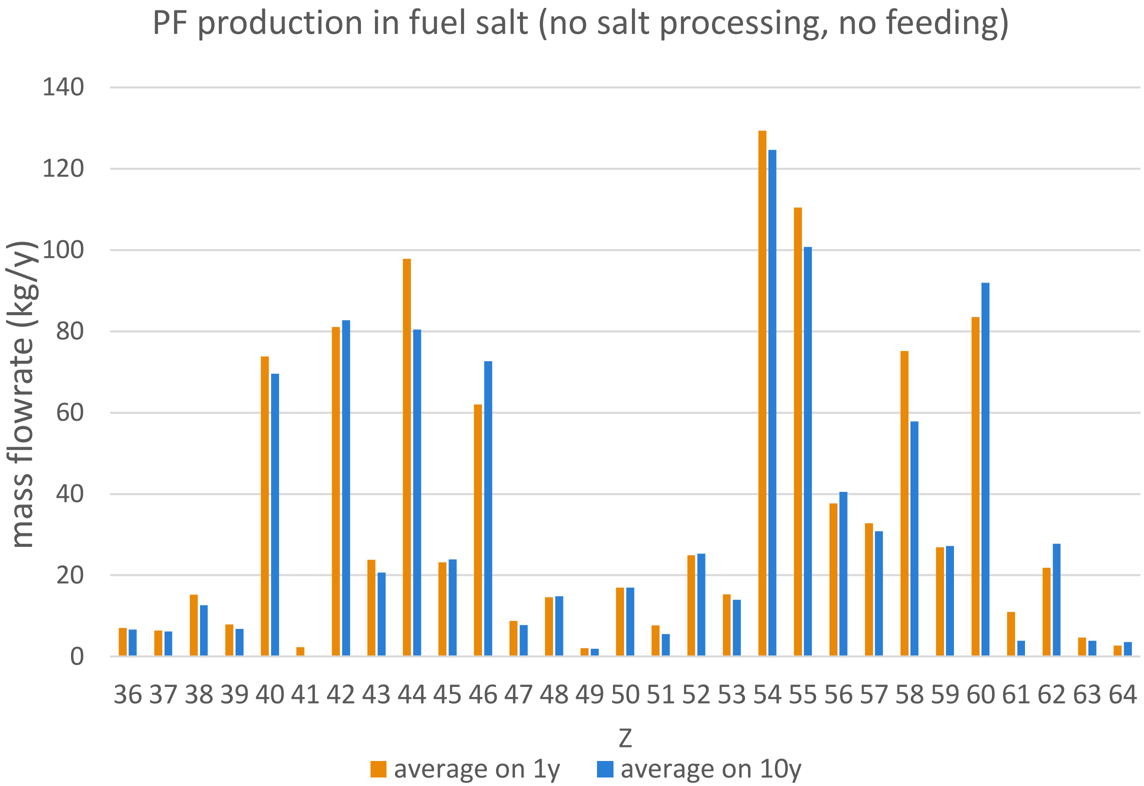


Reactor evolution with REM code

Processing scheme update

Analysis with experts on chemistry

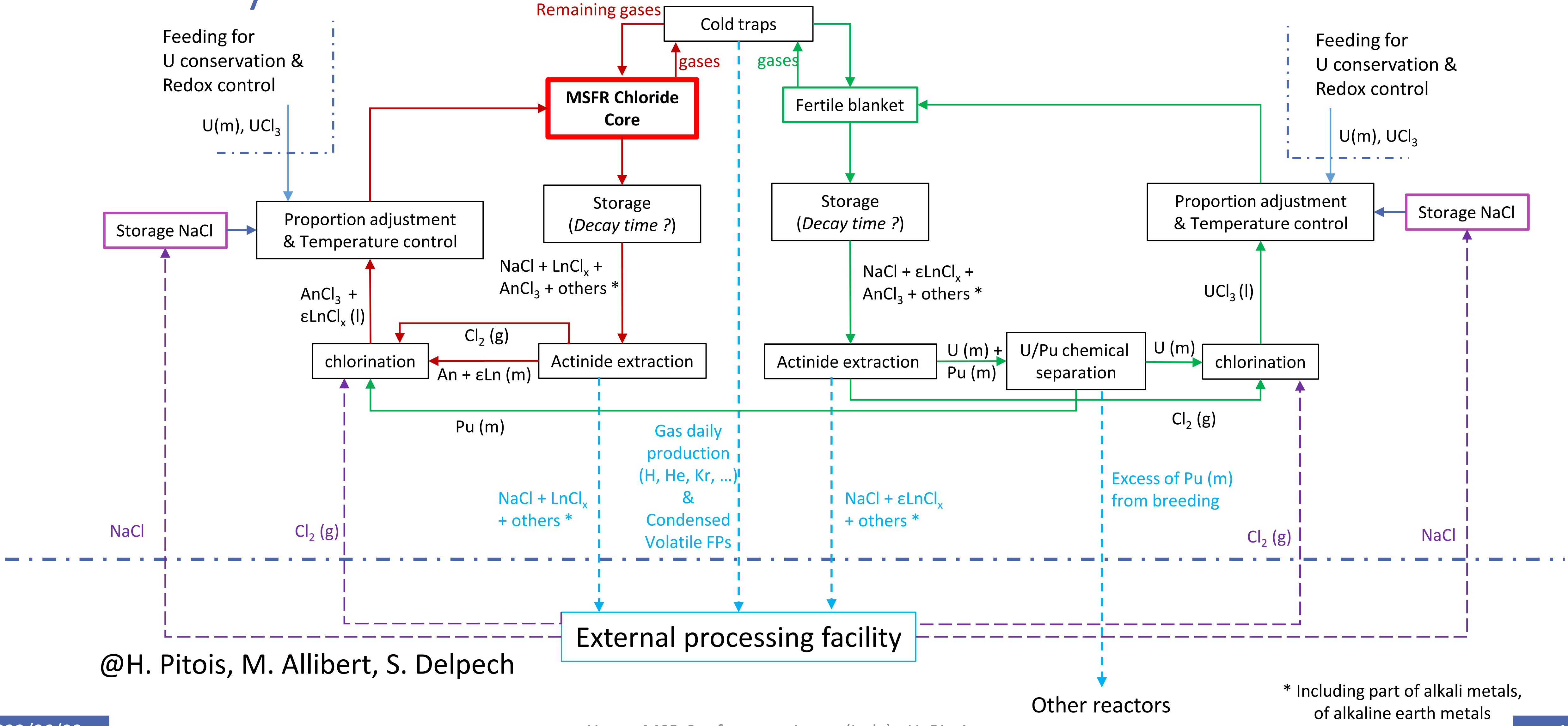
Inventory evolution



PF production in fuel salt (no salt processing, no feeding)

- 2 main options
  - Full on-site processing
  - Partial on-site processing with external facility

Principle diagram for on-site processing + external facility



Remaining gases

Cold traps

gases

gases

Feeding for
U conservation &
Redox control

U(m), UCl_3

MSFR Chloride Core

Fertile blanket

Feeding for
U conservation &
Redox control

U(m), UCl_3

Storage NaCl

Proportion adjustment
& Temperature control

Storage
(*Decay time ?*)

Storage
(*Decay time ?*)

Proportion adjustment
& Temperature control

Storage NaCl

$AnCl_3$ +
$\varepsilon LnCl_x$ (l)

$NaCl + LnCl_x +$
$AnCl_3$ + others *

$NaCl + \varepsilon LnCl_x +$
$AnCl_3$ + others *

UCl_3 (l)

Cl_2 (g)

chlorination

Actinide extraction

An + εLn (m)

Actinide extraction

U (m) +
Pu (m)

U/Pu chemical separation

U (m)

chlorination

Pu (m)

Cl_2 (g)

Gas daily
production
(H, He, Kr, …)
&
Condensed
Volatile FPs

$NaCl + LnCl_x$
+ others *

$NaCl + \varepsilon LnCl_x$
+ others *

Excess of Pu (m)
from breeding

NaCl

Cl_2 (g)

Cl_2 (g)

NaCl

External processing facility

@H. Pitois, M. Allibert, S. Delpech

Other reactors

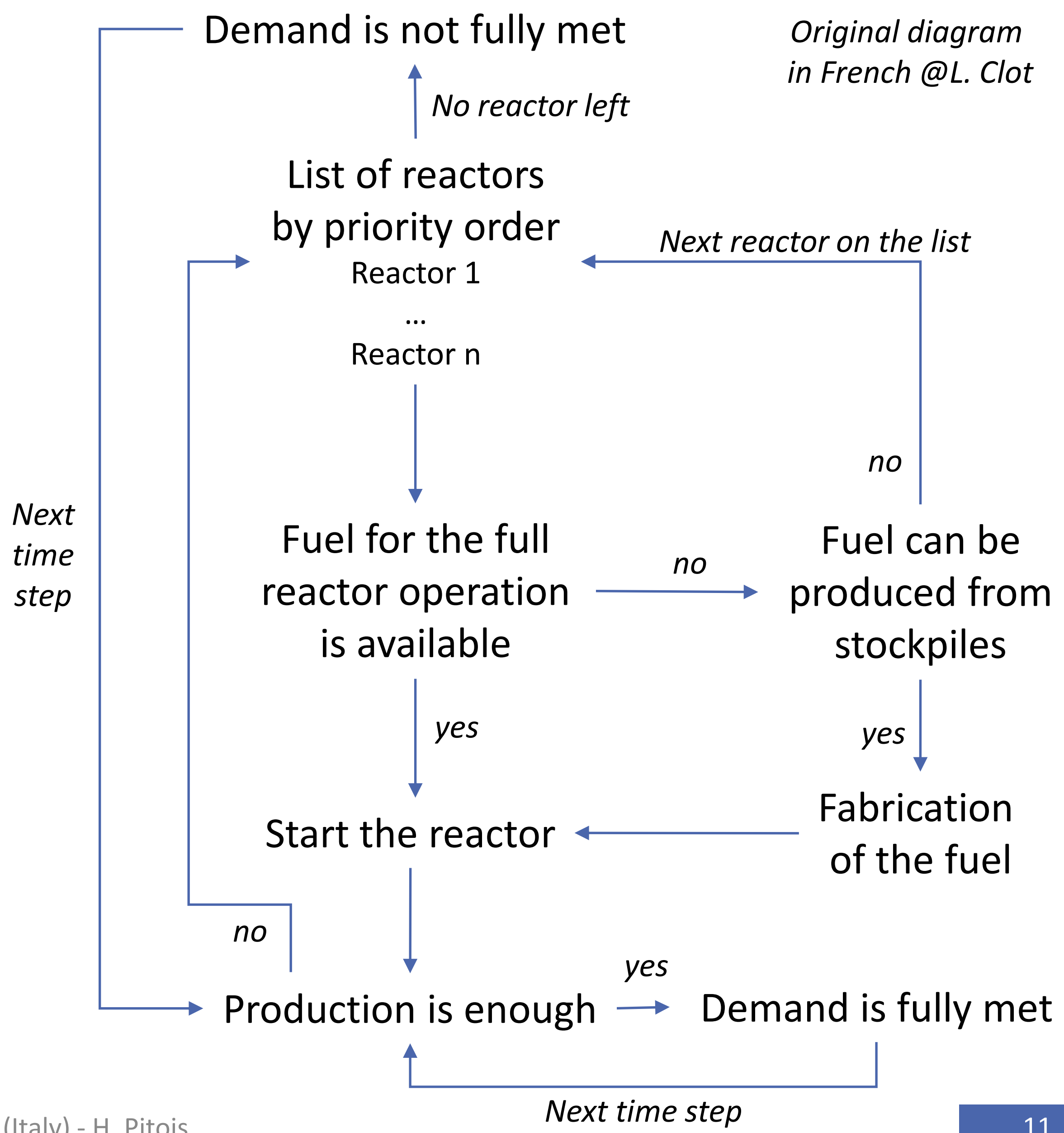
* Including part of alkali metals,
of alkaline earth metals

Deployment scenarios

- Purposes
  - Give orders of magnitude for the mass evolutions of interest
  - Measure the impact of insertion of the MSFR-Cl on a reactor fleet in comparison to a full water-reactor fleet
  - Minimise spent fuel stockpiles
- First tests performed on French fleet

LPSC scenario code algorithm

Original diagram in French @L. Clot



Demand is not fully met

No reactor left

List of reactors by priority order

Reactor 1

…

Reactor n

Next reactor on the list

no

Fuel for the full reactor operation is available

no

Fuel can be produced from stockpiles

yes

yes

Fabrication of the fuel

Start the reactor

Next time step

no

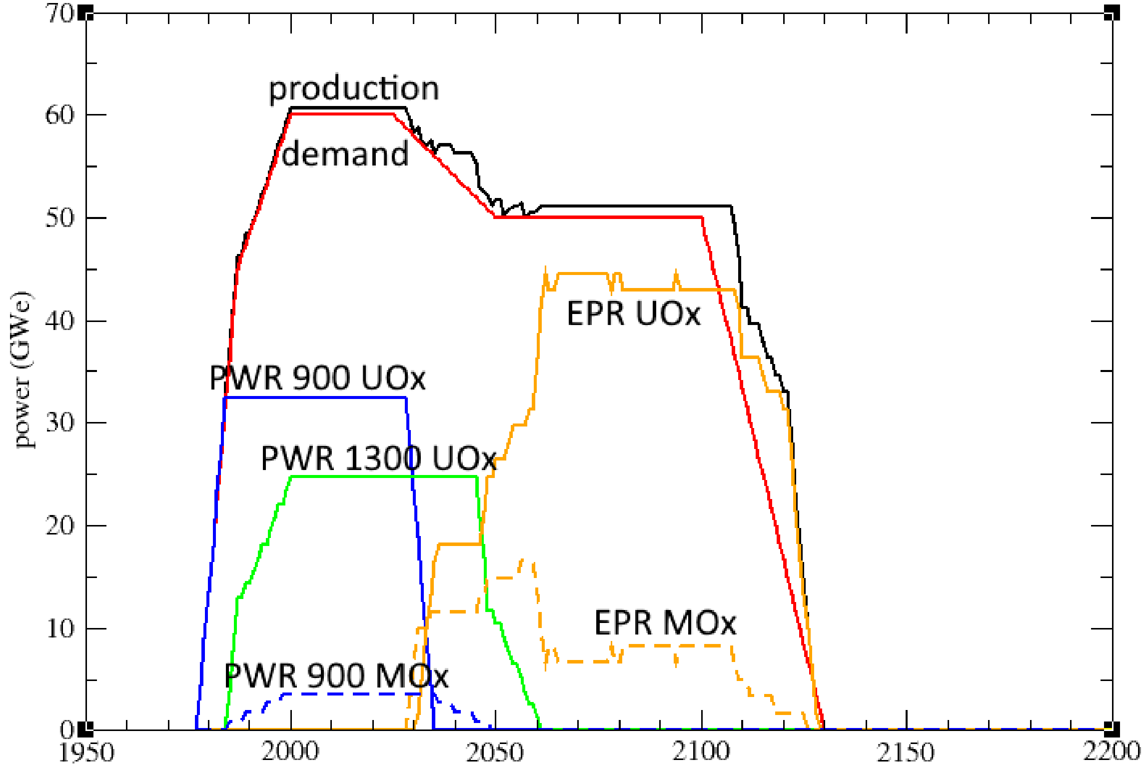
Production is enough

yes

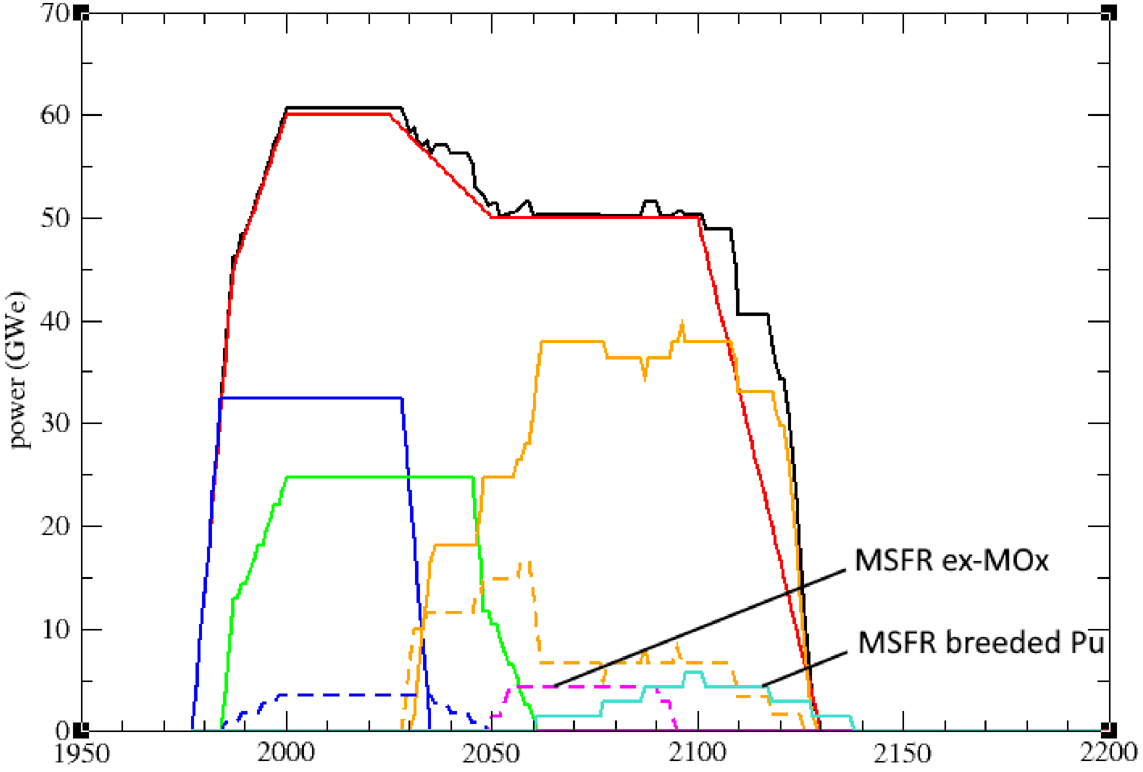
Demand is fully met

Next time step

Evolution of the fleet (French fleet, preliminary results)



Reference



With MSFRs-Cl

- 2025: start of EPRs (fuel order: MOx fuel, UOx fuel)
- 2050: start of MSFRs-Cl (fuel order: spent MOx fuel TRUs, spent UOx fuel TRUs, breeded Pu)

Evolution of stockpiles

Scenario	^{nat}U consummed	TRUs ex-UOx final mass	TRUs ex-MOx final mass	Other TRUs final mass	Total TRUs final mass
Reference	844 10^3t	234t	238t	0	471t
With MSFRs-Cl	797 10^3t	215t	22t	244t	481t
Difference	- 47 10^3t	- 19t	-216t	244t	10t

- Reduction of ^{nat}U consumption
- Small deployment of MSFRs-Cl due to running out of spent MOx fuel TRUs
  - Ongoing tests to improve the deployment using alternative proliferation resistance strategy & difference fuel order

- Future work on worldwide scenarios with constraints on U availability

Take home messages

- LiF used in reference MSFR cannot accomodate large amount of trivalent TRUs → use of NaCl
- Different solvents and different fuels
  - New geometry
    - (NaCl < LiF as coolant and more transparent to neutrons ➔ larger total volume of salt)
  - Different feedback coefficients
    - Larger density feedback but much smaller Doppler
  - New salt treatment unit
  - New strategy for proliferation resistance & possibility to refine degraded Pu for MOx reproduction
- Small benefit for France-only scenario with abundant and cheap ${}^{nat}U$
  - Future work for worldwide scenarios with constraints on U & fissile matter availability

Thank you for your attention

Tools

	Thermal-hydraulics	Neutronics	Deployment
Main code used	SONGe (multi-criteria optimisation code, genetic algorithm)	REM (evolution under constraints)	ISF (reactor fleet deployment under constraints)
Equations solved	Thermal-hydraulic equations	Boltzmann equations Bateman equations	Mass conservation
Variables followed	Fraction of salt in/outside the center Power for pumps Salt velocity …	Initial inventory Inventory evolution Feedback coefficients	Natural uranium consumption Waste stockpile & radiotoxicity

Reactor	Power (MWe)	Load factor	Lifetime (y)	Mass input (t/y)	Mass output (t/y)	Starting time	Ending time
PWR 900 UOx	900	0.8	50	^{enr}U: 20	TRUs ex-UOx: 0.22 FPs: 0.68 ^{rep}U: 19.1	1977	1988
PWR 900 MOx	900	0.8	50	MOx: 20	TRUs ex-MOx: 0.22 FPs: 0.68 ^{rep}U: 19.1	1985	2000
PWR 1300 UOx	1300	0.8	60	^{enr}U: 28.89	TRUs ex-UOx: 0.32 FPs: 0.98 ^{rep}U: 27.59	1985	2020
EPR UOx	1650	0.8	30	^{enr}U: 36.67	TRUs ex-UOx: 0.40 FPs: 1.25 ^{rep}U: 35.02	2025	2099
EPR MOx	1650	0.8	30	^{enr}U: 36.67	TRUs ex-MOx: 0.40 FPs: 1.25 ^{rep}U: 35.02	2025	2099