



## IGD-TP 5th Exchange Forum

TWG3 - IEP IGD-TP/ SNETP

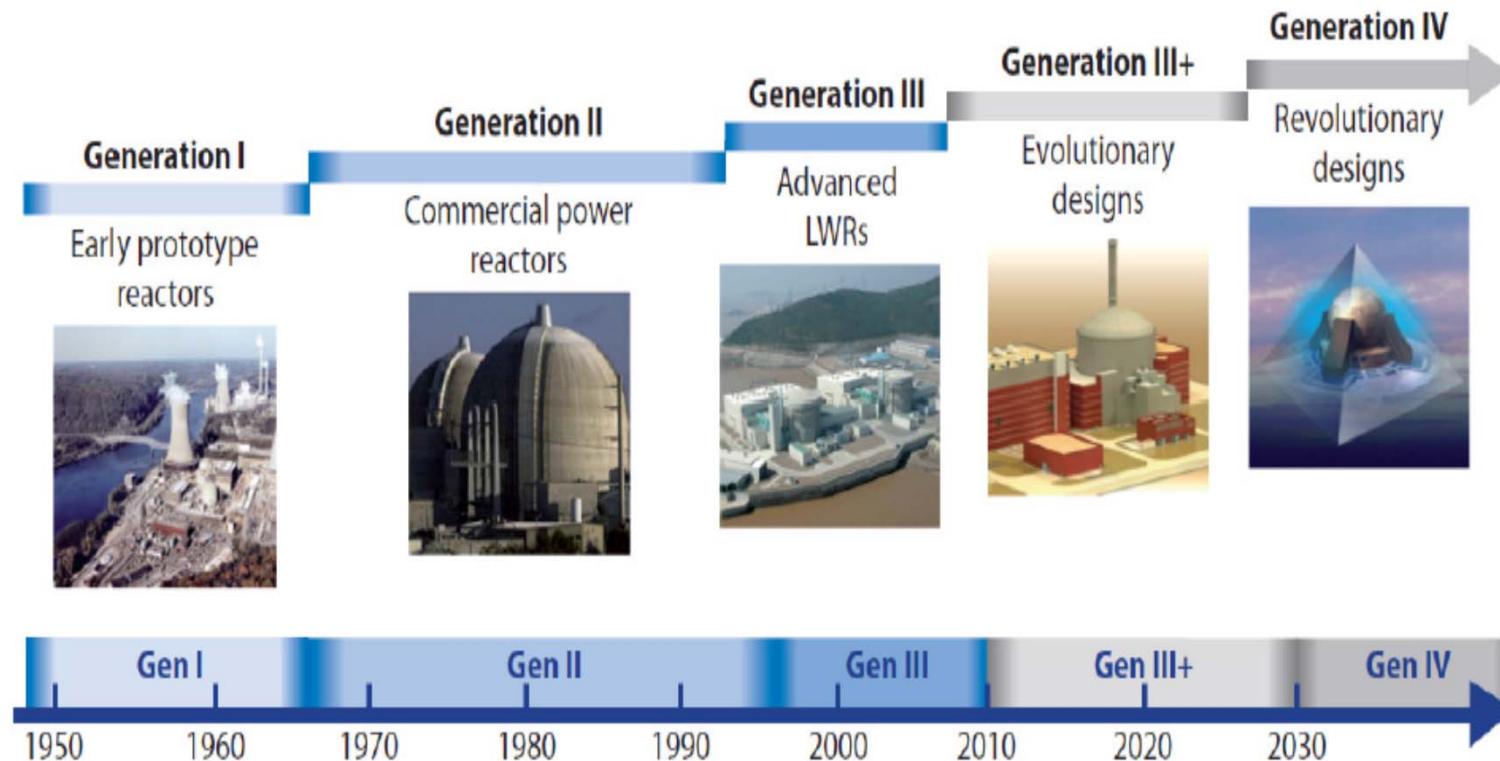
### SNETP- ESNII Generation IV reactors, related fuel cycle and disposal issues

M. Sepielli

SNETP Governing Board  
IGDTP-SNETP IEG

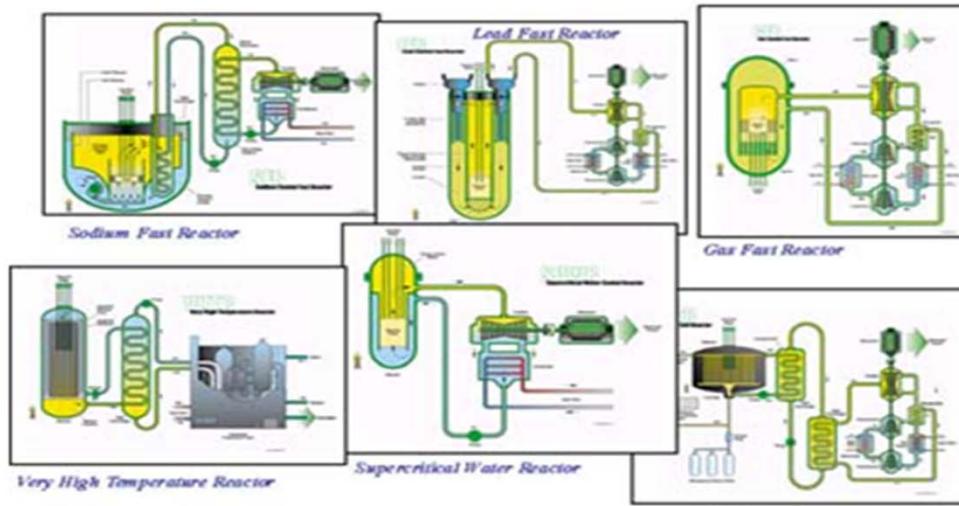
*Kalmar (Sweden), October 27-30, 2014*

**Figure ES.1: Generations of nuclear power: Time ranges correspond to the design and the first deployments of different generations of reactors**



- Optimum use of natural resources
- Nuclear waste minimization
- Minimum impact on the environment
- Safety / Economics / Non proliferation

## Gen IV System Concepts

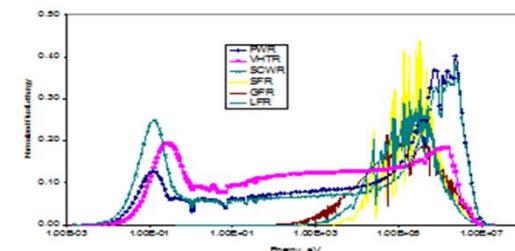


GEN IV Reactor Concepts

Reactor concept	GFR	LFR	MSR	SFR	SCWR	VHTR
Coolant	Helium	Pb or Pb-Bi	Molten salt	Sodium	Supercritical water	Helium
Spectrum ( $F_{\text{fast}}$ , $T_{\text{thermal}}$ )	$F$	$F$	$T$	$F$	$T/F$	$T$
Thermal efficiency (%)	48		44-50	42	44	50
Thermal power (MW)	~2400	125-3600	~2000	1500-4000	~3800	400-600
Power density (MW/m <sup>3</sup> )	50 - 100	10 - 150	22	200-300	100	6 - 10
Pressure (bar)	70	1	1	1	250	
Temperature core inlet/outlet (°C)	490 / 850	400 / 550	565 / 700	400 / 550	280 / 510	640 / 1000
Fuel	Carbide or nitride	Nitride, Oxide (or metallic)	Molten salt (fluorides)	Oxide, carbide, or metallic	Oxide (UO <sub>2</sub> , MOX)	Oxide or oxi-carbide
Fuel burnup (at%)	5-10	10-15		15-20	5	> 10
Fuel cycle	Closed	Closed	Closed	Closed	Closed	Open



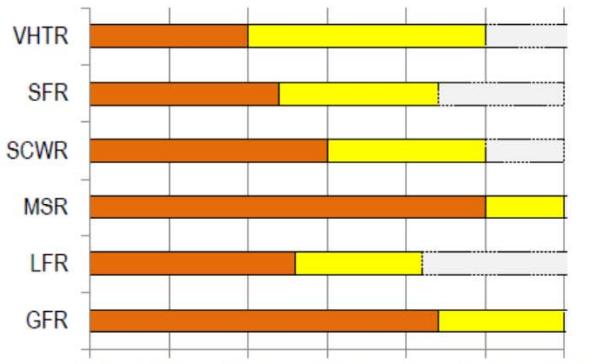
Neutron spectrum of GEN IV reactor concepts



ENEN\_Seminar, U of Pa, Nov. 2007



GIF roadmap 2013



■ Viability ■ Performance □ Demonstration

# Fuel System Options in GEN IV Fast Reactors

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**Table 1** Priority table. Items indicated in red are priority for the different fuel types.

	UPuO <sub>x</sub>	UPuC	UPuN
<b>GFR</b> <u>100W/cm</u> Tclad 800°C <u>Tfuel 1100°C</u> <u>Pu: 15-20%</u>	Priority : 3 SiC+liner <b>0 - 2 - 5 % Am</b> >95% dth	Priority : 1 SiC+liner <b>0 - 2 - 5 % Am</b> <b>80-85%dth vs open/closed porosity</b> 5% < M2C3 < 15%	Priority : 2 SiC+liner <b>0 - 2 - 5 % Am</b> 80-85%dth N/M: 1.0 and > 1.0
<b>LFR</b> <u>~400W/cm</u> <u>Tclad ~500°C</u> Tfuel °C <u>T91</u>	Priority : 1 <b>0 - 2 - 5 % Am</b> >95% dth <b>O/M 1,96 – 1,98 – 2,00</b>		Priority : 2 T91 316 Ti <b>0 - 2 - 5 % Am</b> 80-85%dth
<b>SFR</b> <u>500W/cm</u> Tclad 620°C <u>Tfuel 2400°C (O)</u> and 1400°C (C) <u>Pu: 15-20%</u>	Priority : 1 ODS - 15/15 <b>0 - 2 - 5 % Am</b> >95% dth <b>O/M 1,90 – 1,95 – 1,98</b>	Priority : 2 ODS - 15/15 <b>0 - 2 - 5 % Am</b> 80-85%dth	Priority : 3 ODS - 15/15 <b>0 - 2 - 5 % Am</b> 80-85%dth

# GEN IV Fuel Characteristics

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Reactor concept	GFR	SFR	LFR
Power density (MWth/m <sup>3</sup> of fuel element)	200	700	
Linear power (W/cm)	C/N : 100	O: 500 C : 500-800 M: 500	<i>idem</i>
Burn up (at%) And dose	5-10 40-80 dpaSiC	15-20 200 dpa	10-15 175 dpa
Pin geometry: <ul style="list-style-type: none"><li>- Φ pellet</li><li>- Φ int. clad</li><li>- Φ ext.clad</li></ul>	4.32 4.95 6.55	9.5 (2mm Φ hole) 9.73 10.73	<i>idem</i>
Temperature clad in/out at PPN (°C) Max. temp.	850/800 1000	537/500 620	
Fuel	Carbide or nitride	Oxide, carbide, or metallic	Nitride (or metallic)
Fuel temp (°C)	C/N: 1100	O: 2400 C: 1400	<i>idem</i>

Melting temp. UPuO<sub>2</sub>: 2740° C, UPuN : 2720° C (dissoc. ~1800° C), UPuC : 2325° C.

# GEN IV Reactor Concepts

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Reactor concept	GFR	LFR	MSR	SFR	SCWR	VHTR
Coolant	Helium	Pb or Pb-Bi	Molten salt	Sodium	Supercritical water	Helium
Spectrum ( <i>F</i> fast, <i>T</i> thermal)	<i>F</i>	<i>F</i>	<i>T</i>	<i>F</i>	<i>T/F</i>	<i>T</i>
Thermal efficiency (%)	48		44-50	42	44	50
Thermal power (MW)	~2400	125-3600	~2000	1500-4000	~3800	400-600
Power density (MWth/m <sup>3</sup> )	50 - 100	10 - 150	22	200-300	100	6 - 10
Pressure (bar)	70	1	<i>I</i>	1	250	
Temperature core inlet/outlet (°C)	490 / 850	400/ 550	565 / 700	400 / 550	280 / 510	640 / 1000
Fuel	Carbide or nitride	Nitride, Oxide (or metallic)	Molten salt (fluorides)	Oxide, carbide, or metallic	Oxide (UO <sub>2</sub> , MOX)	Oxide or oxi-carbide
Fuel burnup (at%)	5-10	10-15		15-20	5	> 10
Fuel cycle	Closed	Closed	Closed	Closed	Closed	Open

# GEN IV Fuel & Structural Materials

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System	Fuel Materials					Structural Materials						
	Oxide	Metal	Nitride	Carbide	Fluoride (liquid)	Ferritic-martensitic Stainless Steel Alloys	Austenitic Stainless Steel Alloys	Oxide Dispersion Strengthened	Ni-based Alloys	Graphite	Refractory Alloys	Ceramics
GFR			S	P		P	P	P	P	P	P	P
MSR					P				P	P	S	S
SFR	P	P				P	P	P				
LFR		S	P			P	P	S			S	S
SCWR-Thermal	P					P	P	S	S			
SCWR-Fast	P	S				P	P	S	S			
VHTR	P					S			P	P	S	P

P: Primary Option  
S: Secondary Option

# GEN IV Fuel&Structural Materials

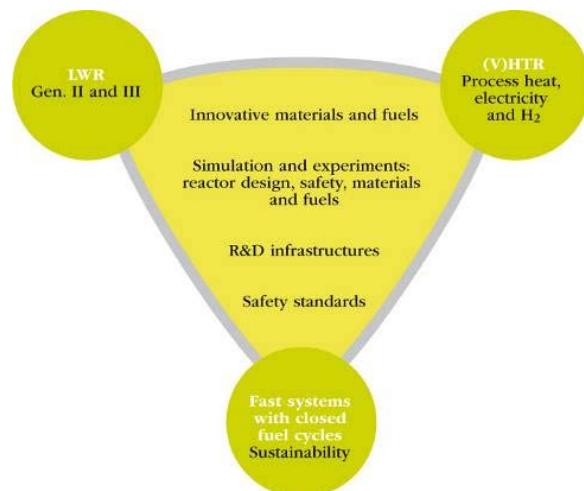
System	Spectrum, T <sub>outlet</sub>	Fuel	Cladding	Structural Materials	
				In-core	Out-of-core
GFR	Fast, 850°C	MC//SiC	Ceramic	Refractory metals and alloys, Ceramics, ODS Vessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20 Fe-12.5W-0.05C Ni-23Cr-18W-0.2 CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS
LFR	Fast, 550°C and Fast, 800°C	MN	High-Si F-M, Ceramics, or refractory alloys		High-Si austenitics, ceramics, or refractory alloys
MSR	Thermal, 700–800°C	Salt	Not Applicable	Ceramics, refractory metals, High-Mo Ni-base alloys (e.g., INOR-8), Graphite, Hastelloy N	High-Mo Ni-base alloys (e.g., INOR-8)
SFR (Metal)	Fast, 520°C	U-Pu-Zr	F-M (HT9 or ODS)	F-M ducts 316SS grid plate	Ferritics, austenitics
SFR (MOX)	Fast, 550°C	MOX	ODS	F-M ducts 316SS grid plate	Ferritics, austenitics
SCWR-Thermal	Thermal, 550°C	UO <sub>2</sub>	F-M(12Cr, 9Cr, etc.) (Fe-35Ni-25Cr-0.3Ti) Incoloy 800, ODS Inconel 690, 625, & 718	Same as cladding options	F-M
SCWR-Fast	Fast, 550°C	MOX, Dispersion	F-M (12Cr, 9Cr, etc.) (Fe-35Ni-25Cr-0.3Ti) Incoloy 800, ODS Inconel 690 & 625	Same as cladding options	F-M
VHTR	Thermal, 1000°C	TRISO UOC in Graphite Compacts; ZrC coating	ZrC coating and surrounding graphite	Graphites PyC, SiC, ZrC Vessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20Fe-12.5 W-0.05CNi-23Cr-18 W-0.2CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS

Abbreviations:

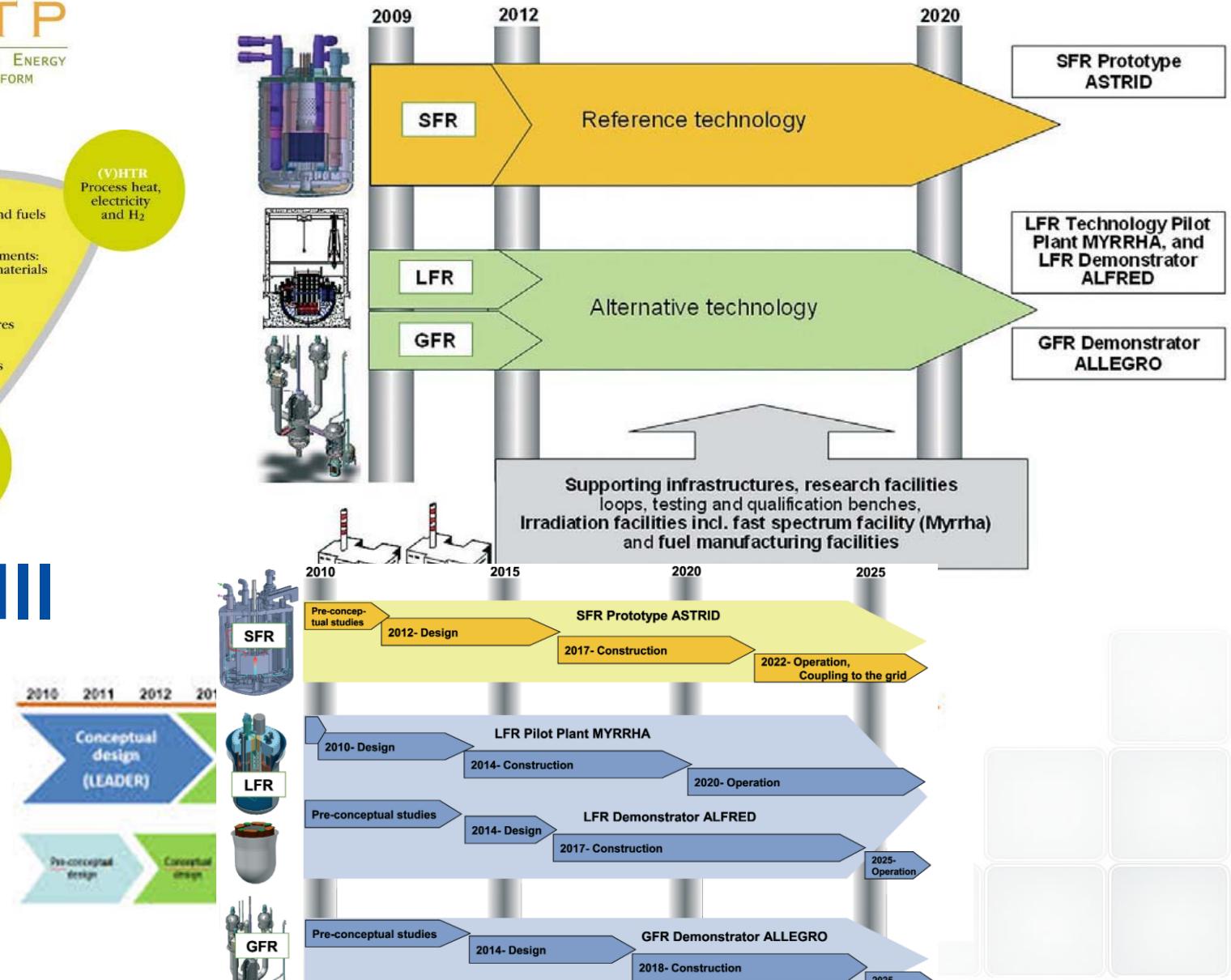
- F-M: Ferritic-martensitic stainless steels (typically 9 to 12 wt% Cr)
- ODS: Oxide dispersion-strengthened steels (typically ferritic-martensitic)
- MN: (U,Pu)
- NMC: (U,Pu)C
- MOX: (U,Pu)O<sub>2</sub>



# SNETP pillars and IV Generation Technologies

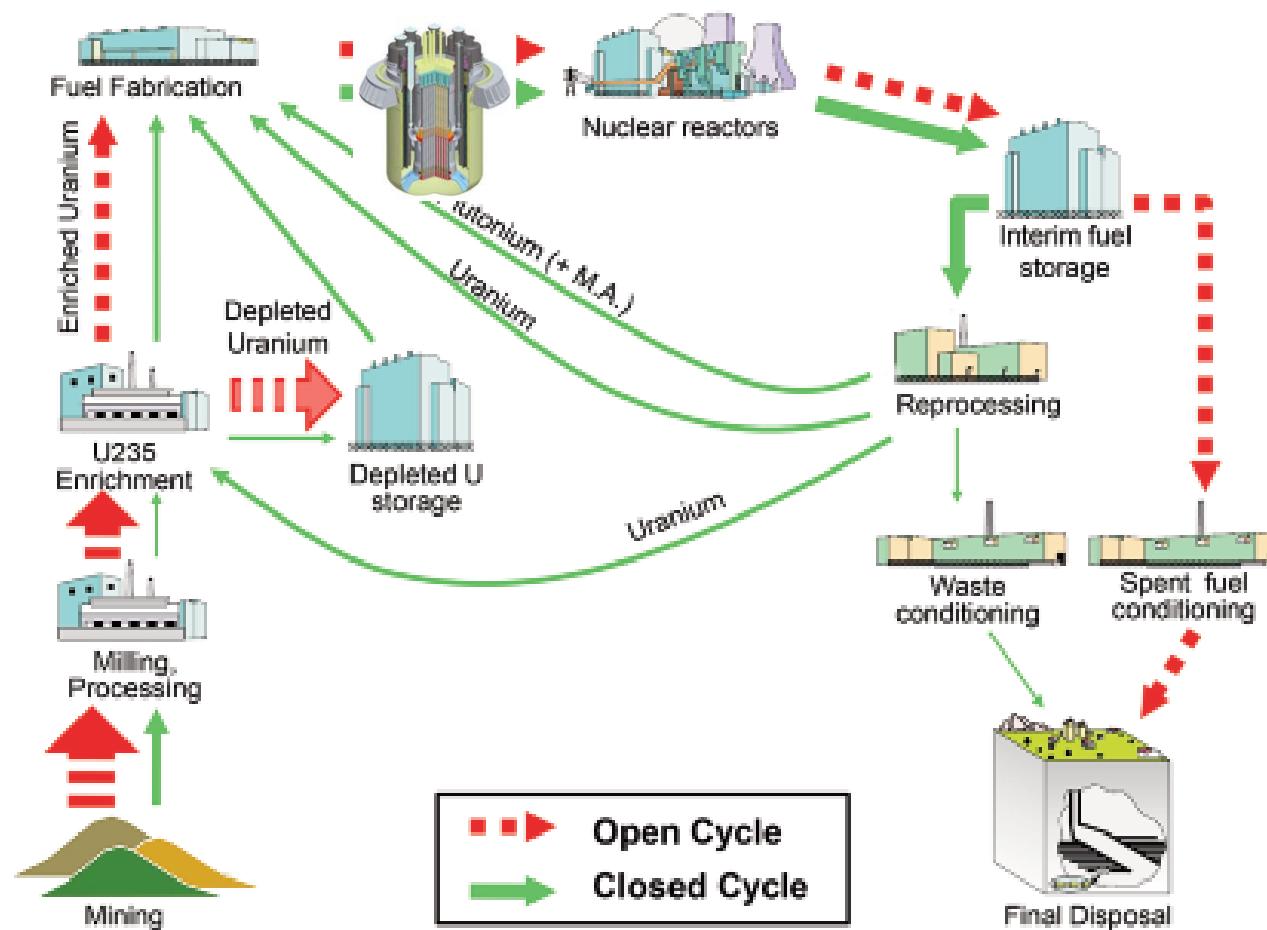
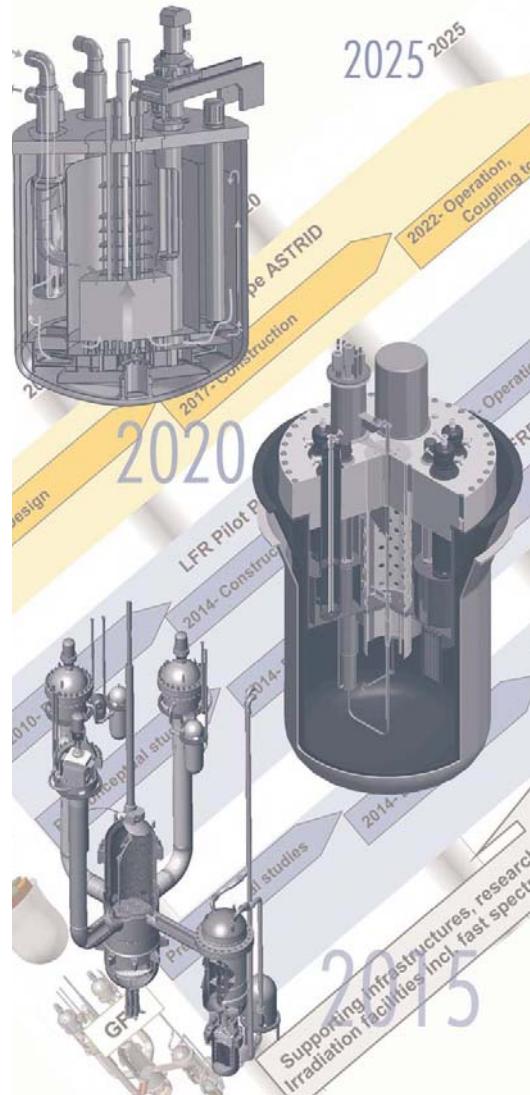


**ESNII**



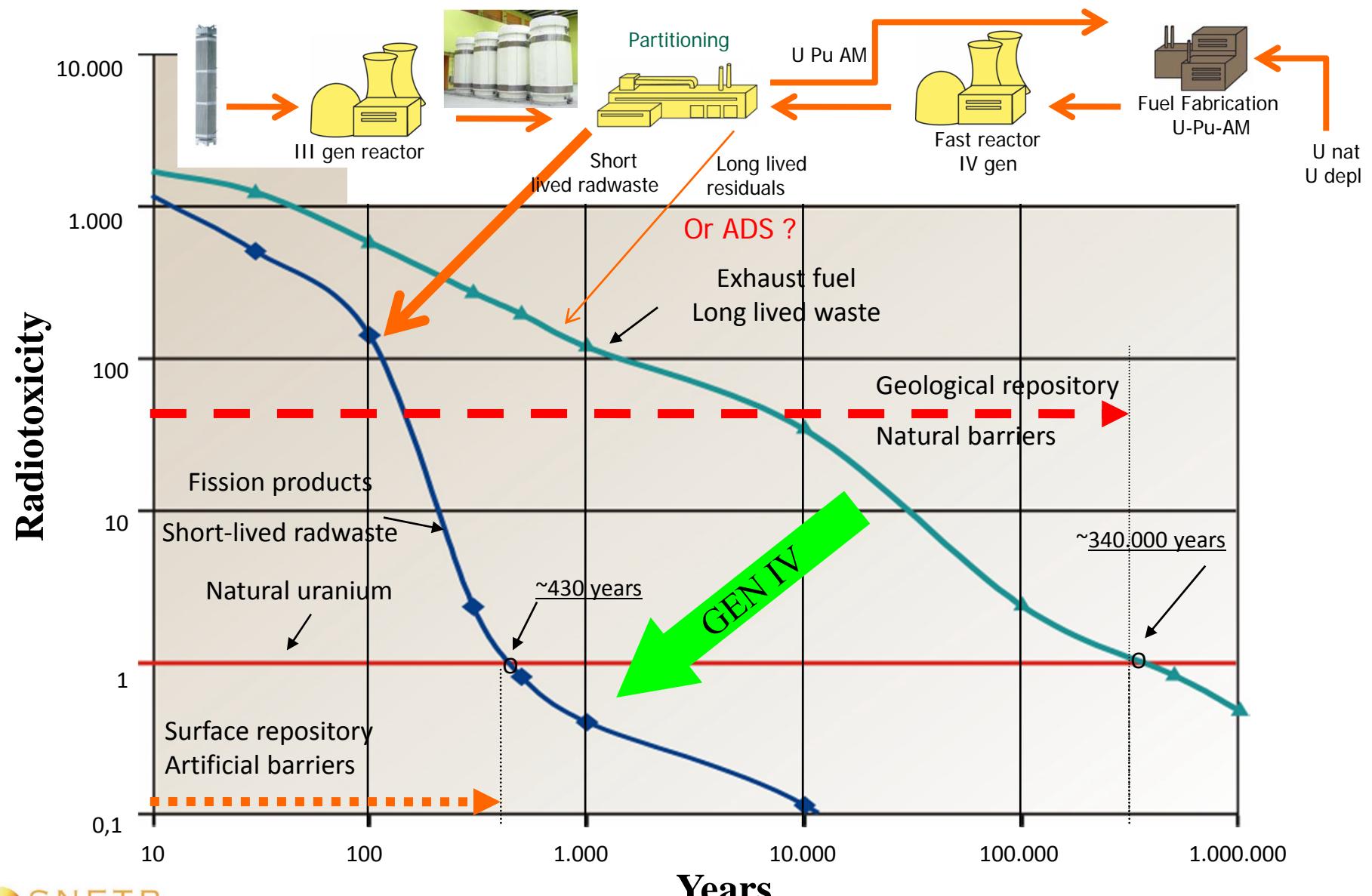
# Fast reactors and closed loop fuel cycle

## FROM SNE- TP

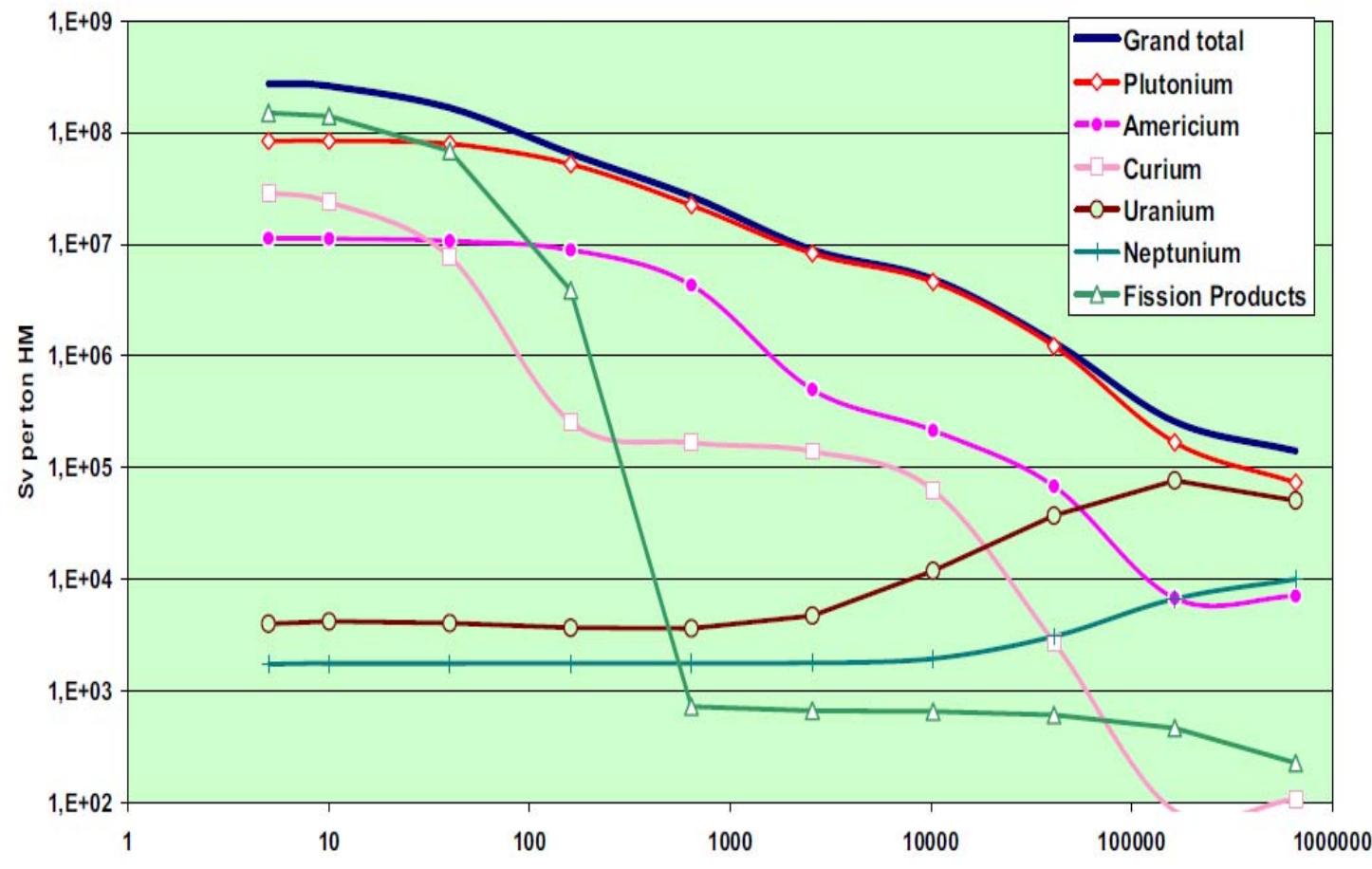


TO IGD-TP

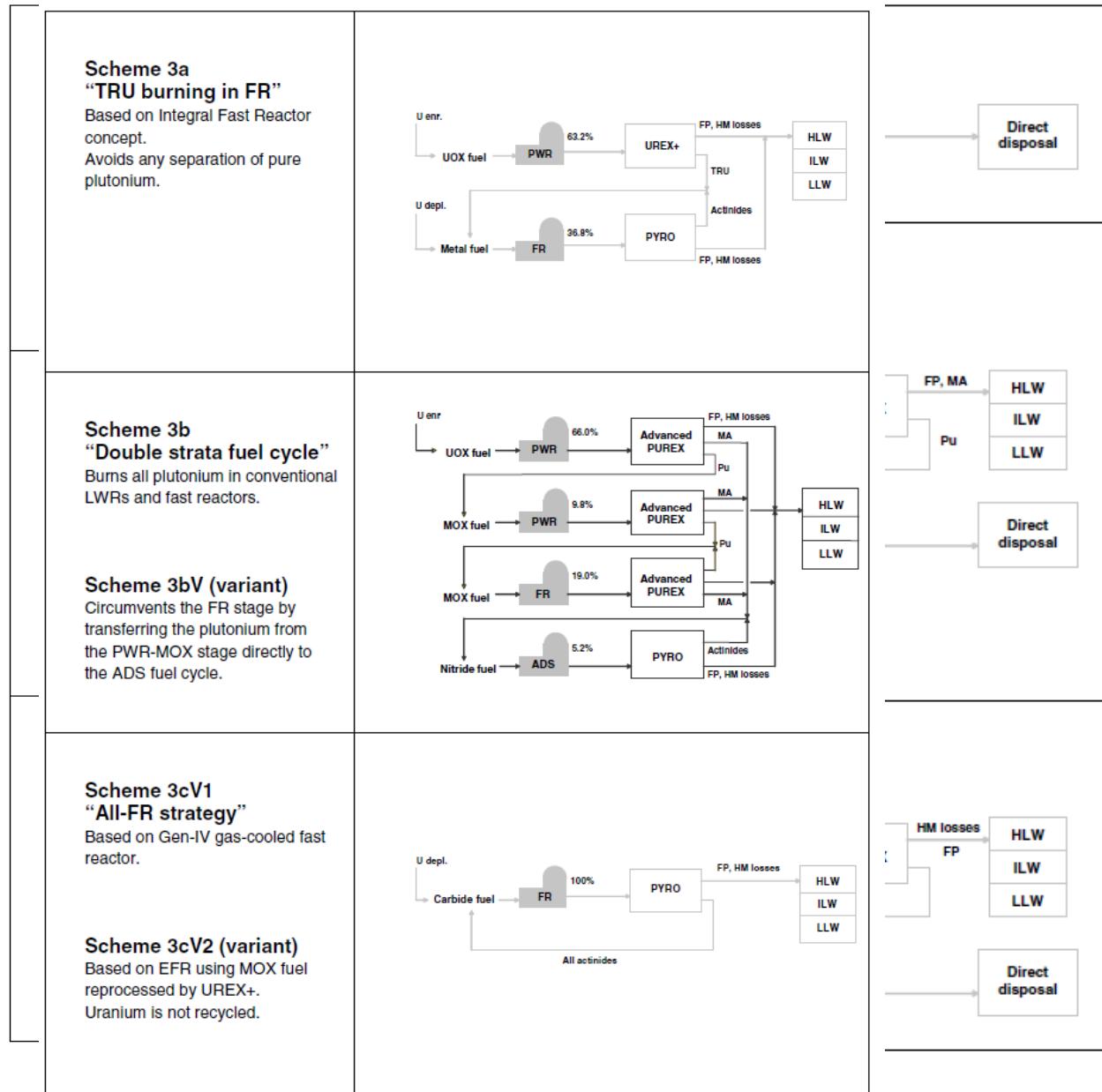
# Radiotoxicity drop with Gen IV



# Single component radiotoxicity decay

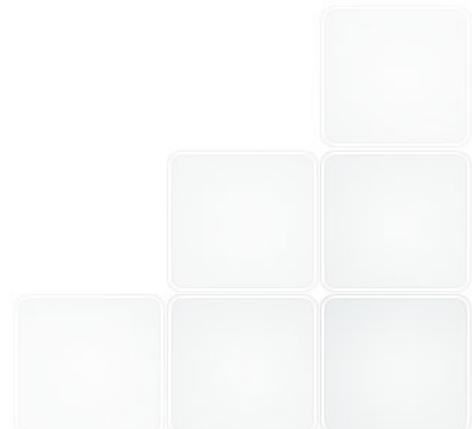


# Reprocessing schemes and resulting waste

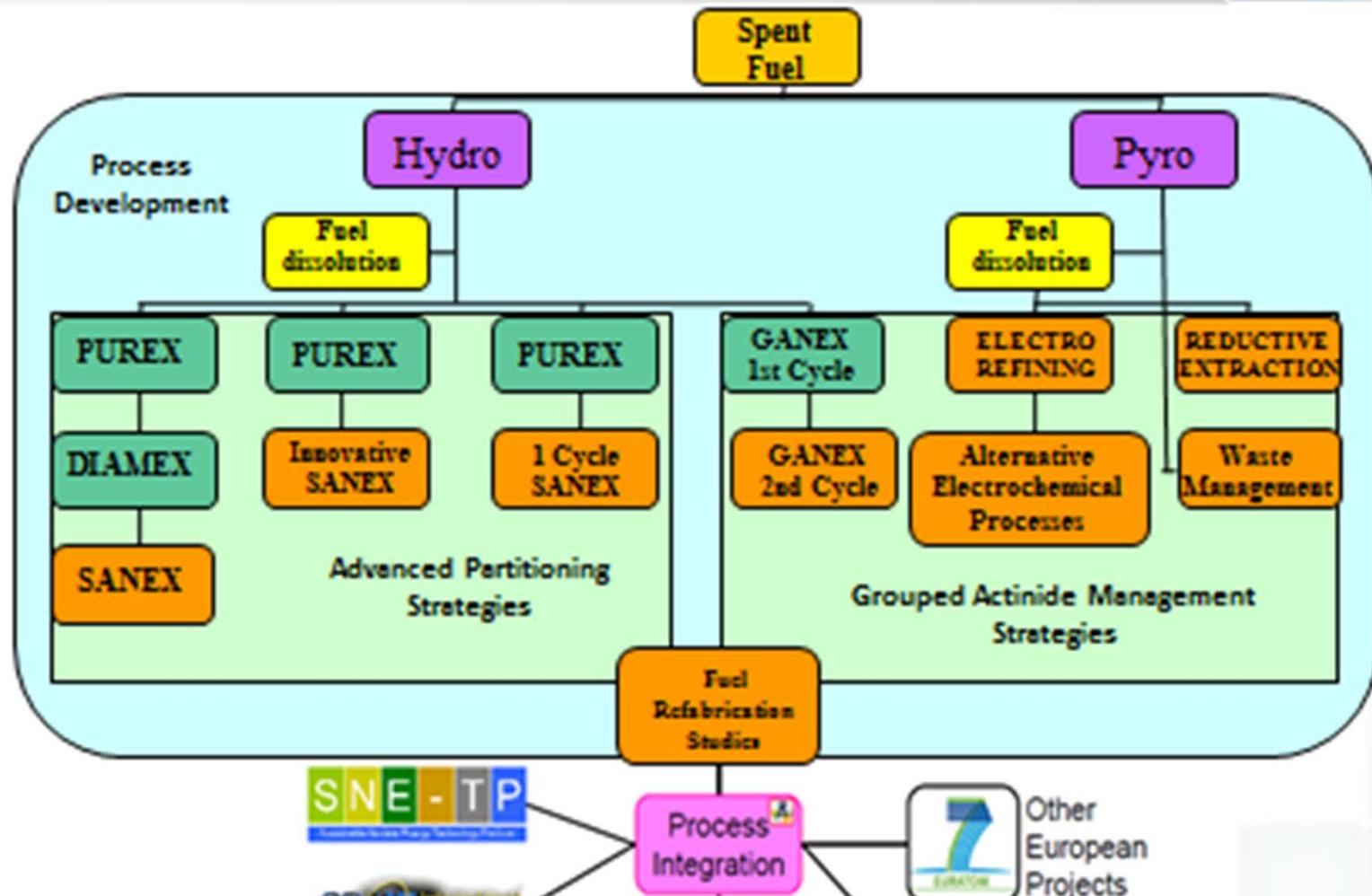


## The main reprocessing methods presently used:

- Co-extraction
- New extraction
- Uranium extraction (UREX)
- Electrochemical processing

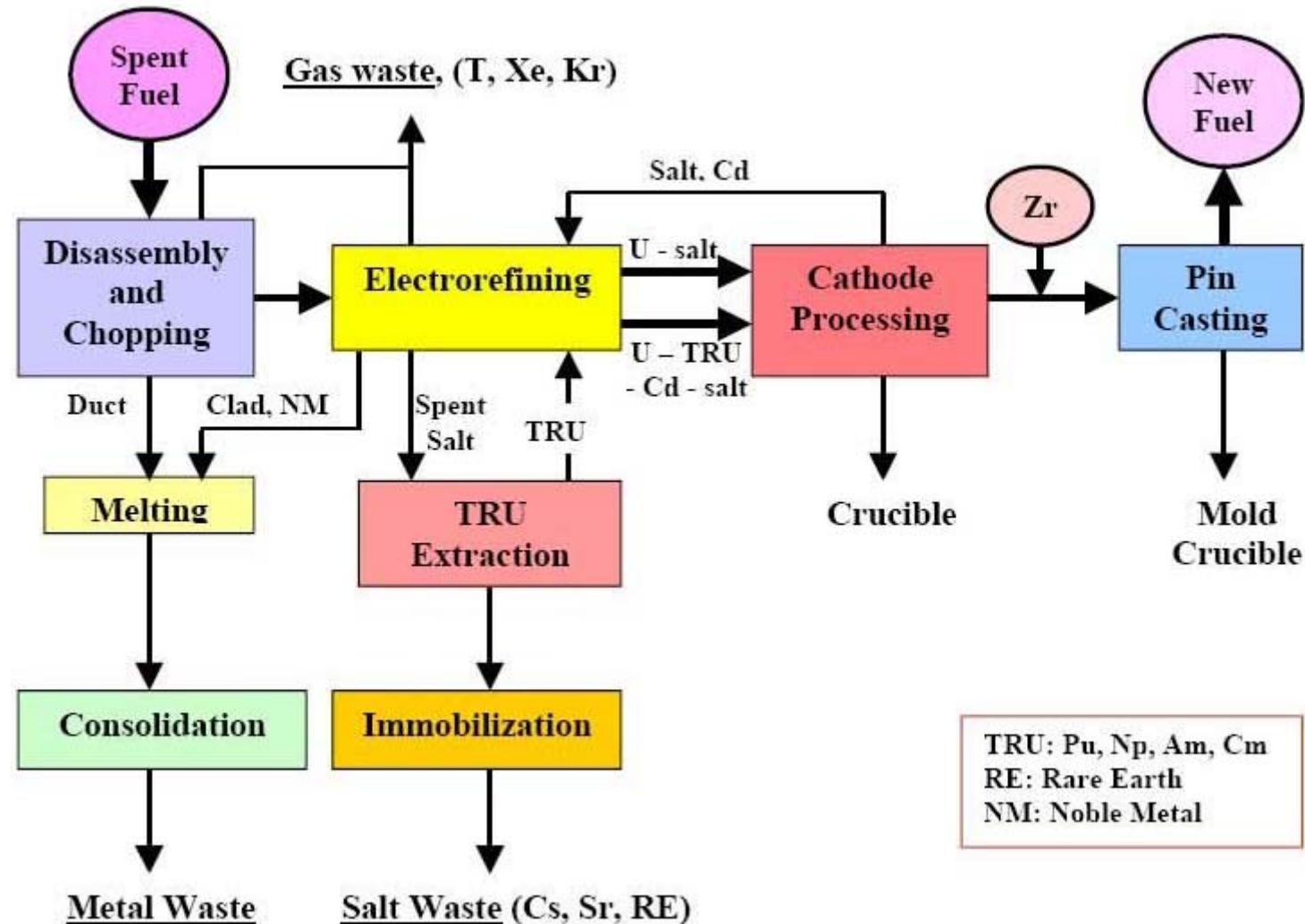


# Treatment of spent fuel

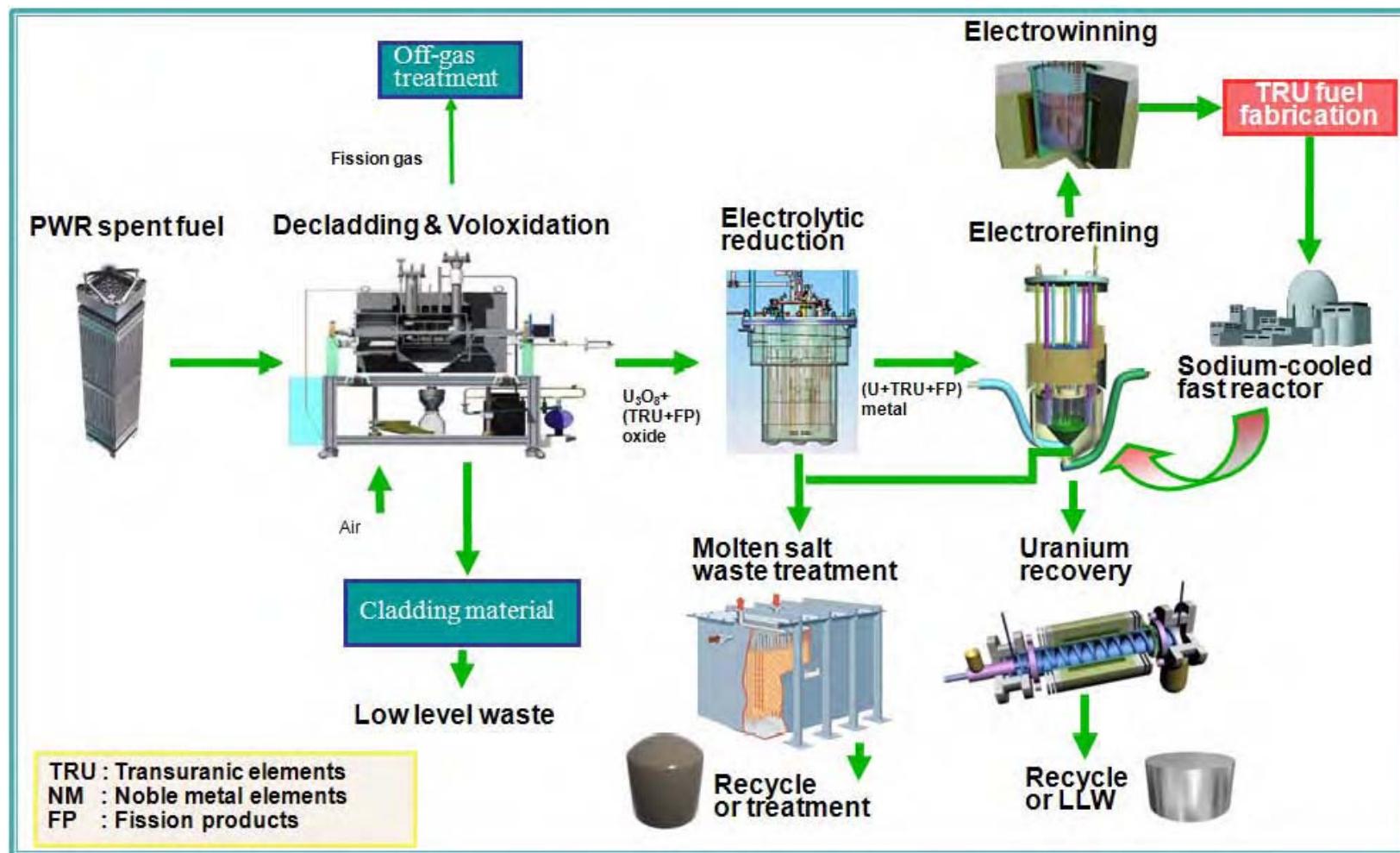


Assessment of reprocessing flowsheets for different fuel cycle scenarios  
with a view to their future demonstration at the pilot level

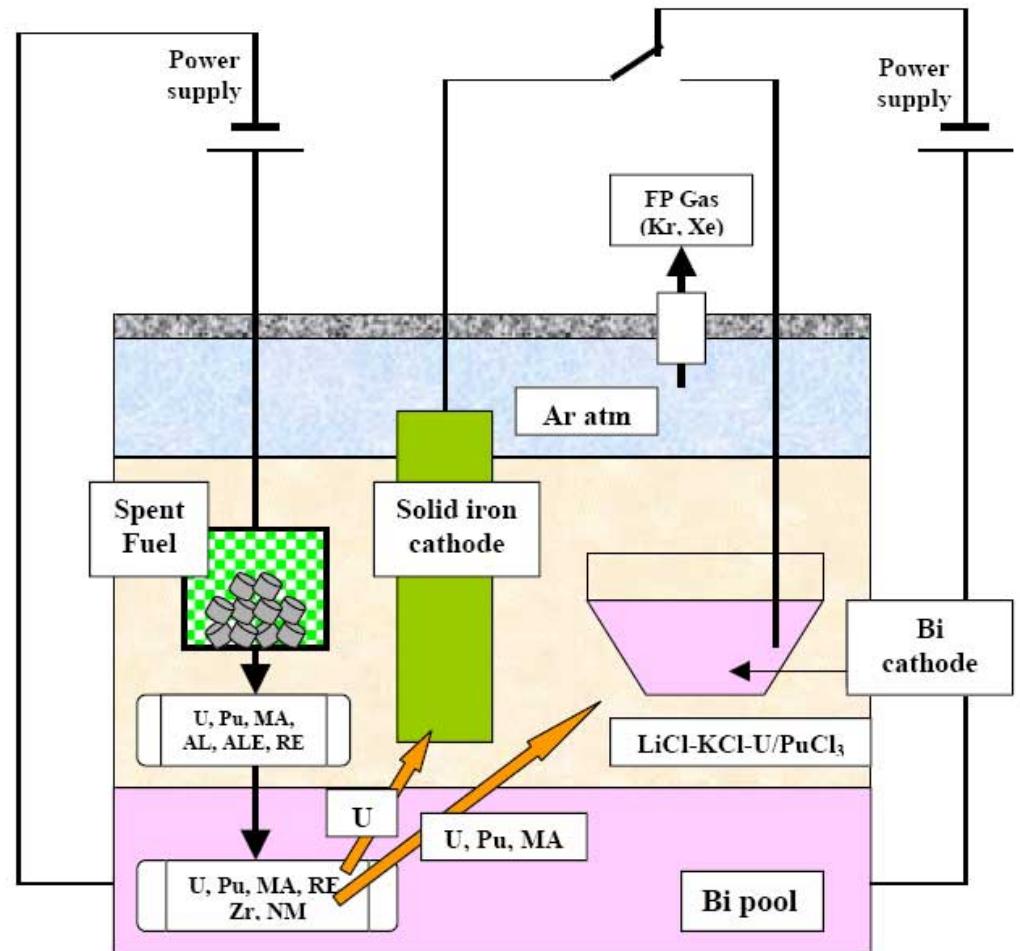
## Block diagram of the pyrochemical process for metal fuel



# Schematic illustration of the pyrochemical process for oxide fuel



## Electrorefining of metal fuel



MA: Minor Actinides

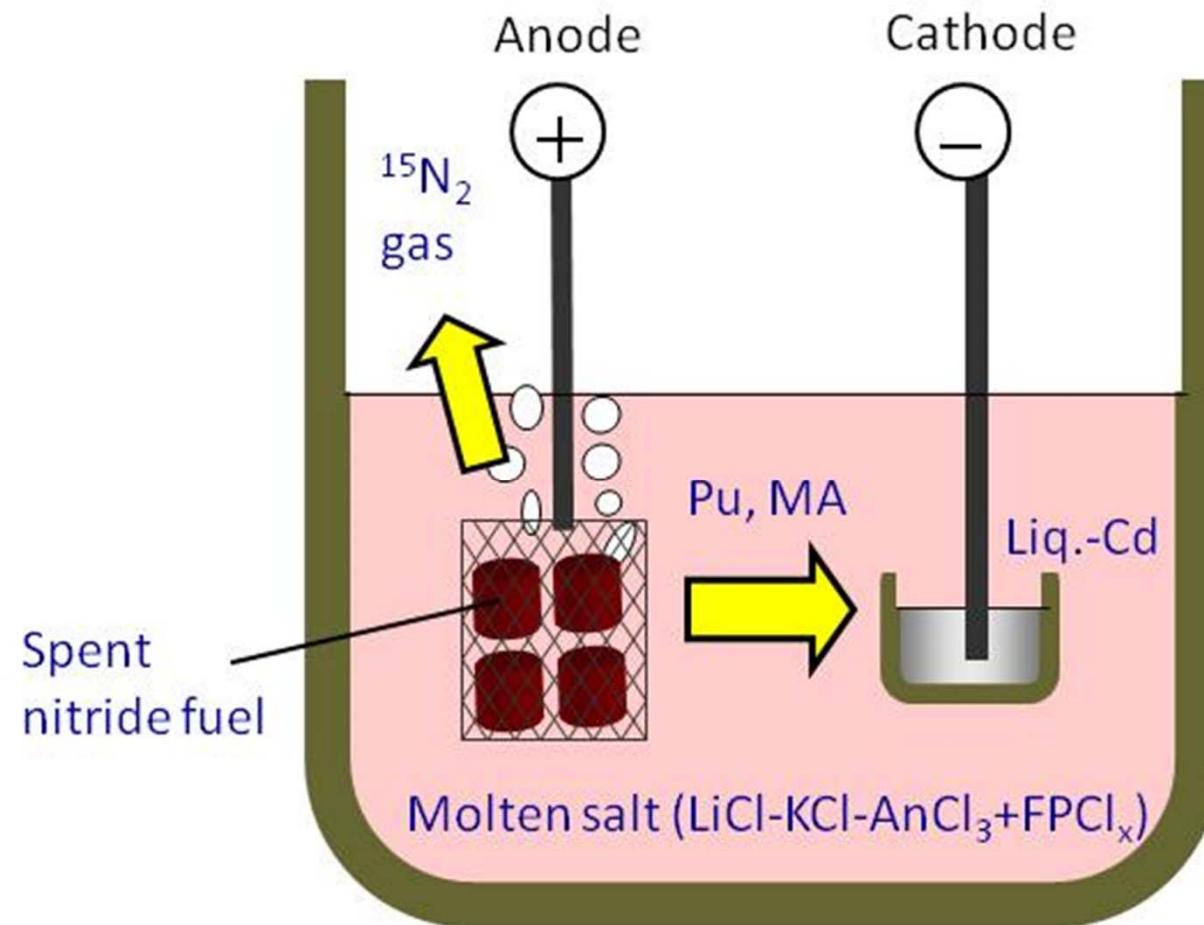
AM : Alkaline Metals

RE: Rare Earths

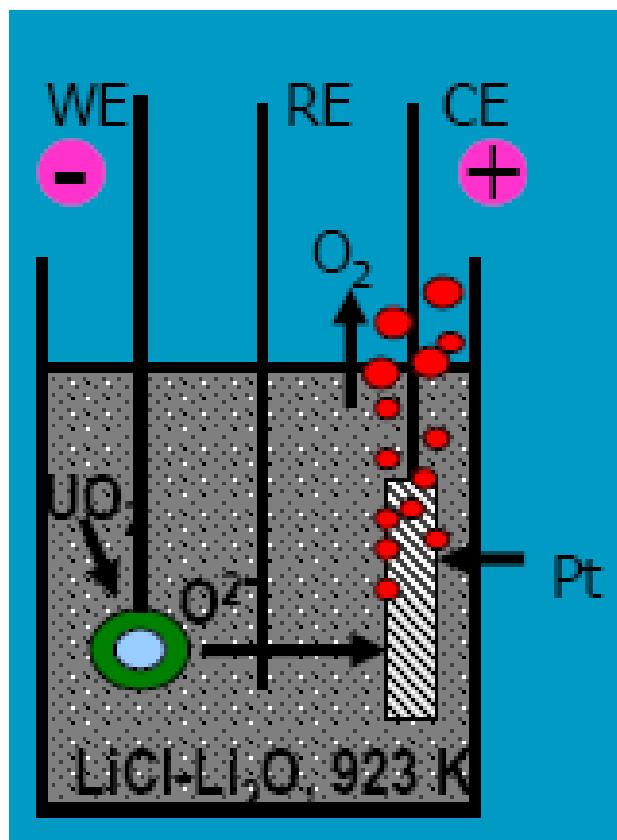
AEM: Alkaline Earth Metals

NM: Noble Metals

## Electrorefining of nitride fuel

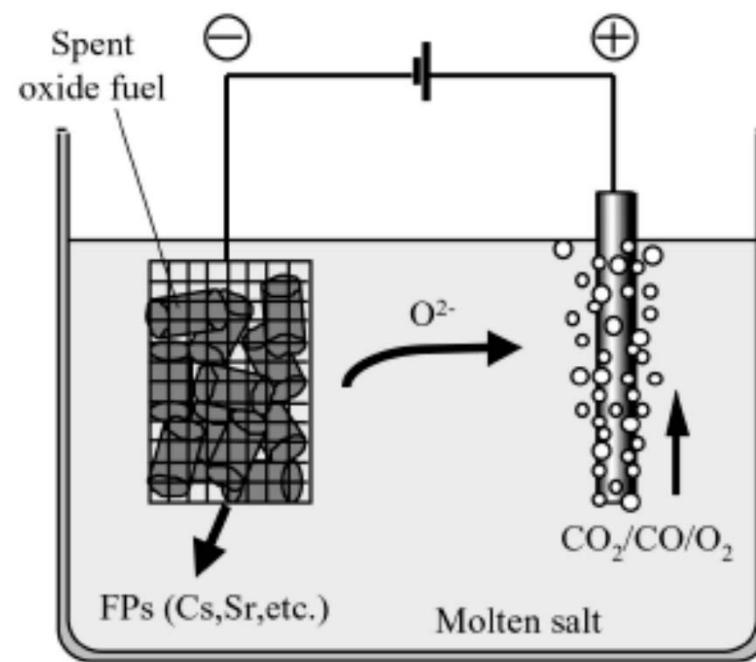


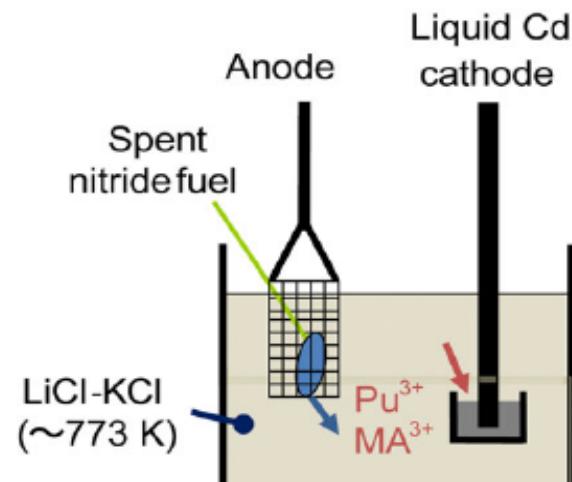
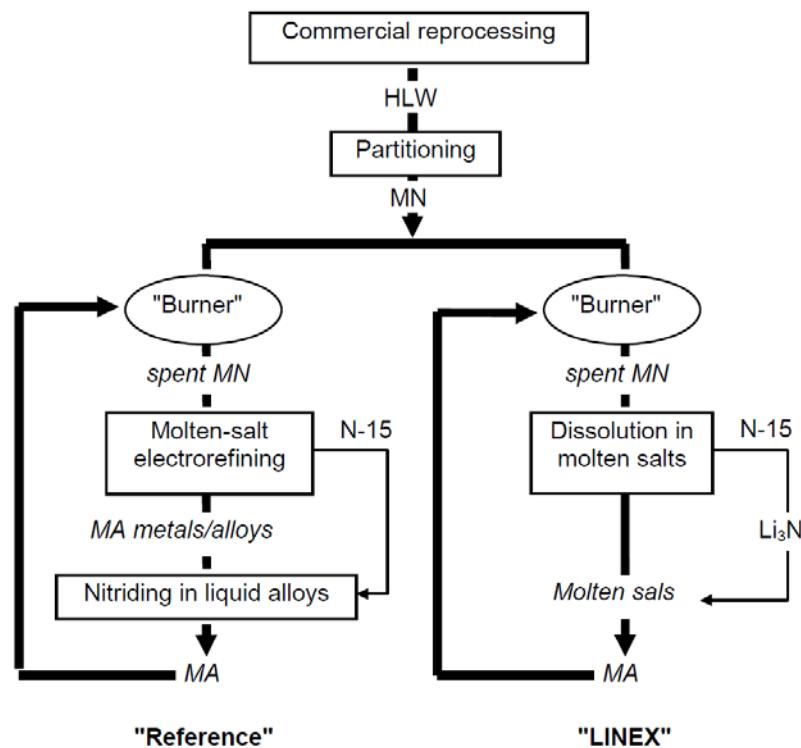
## Electroreduction of oxide fuel (USA, Japan, Korea) (anode made of platinum wire (left) or graphite (right))



Cathode :  
Actinide oxide is reduced to metal.

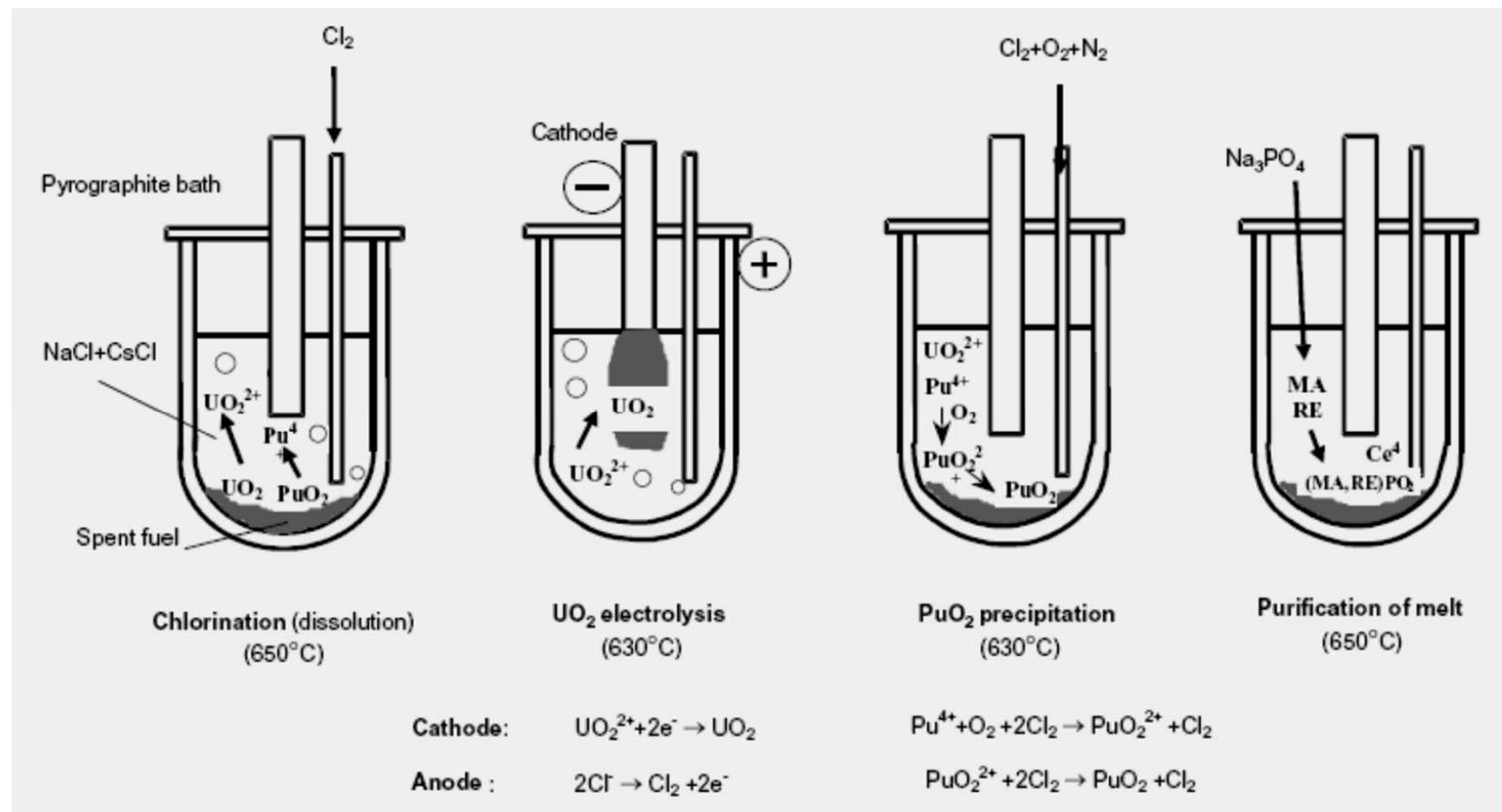
Anode :  
Oxygen or carbon oxide gas is evolved.





	Properties	UPO,	UPC	UPN	
	Density, g/cm <sup>3</sup>	11.0	13.6	14.3	
	HM Density, g/cm <sup>3</sup>	9.7	12.9	13.5	
	T <sub>melt</sub> , ° C	2775	2480	2780	
	Thermal conductivity, W/mK	2,9	19.6	19.8	
	PUREX compatible	Yes	No	yes	

## Electroreduction of oxide fuel (Russian method)



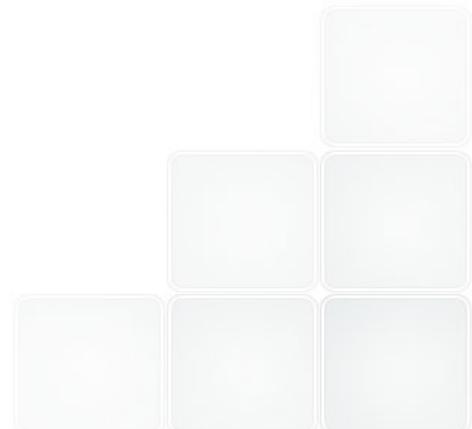
# Conditioning of chloride salt wastes from pyroprocesses with different matrices



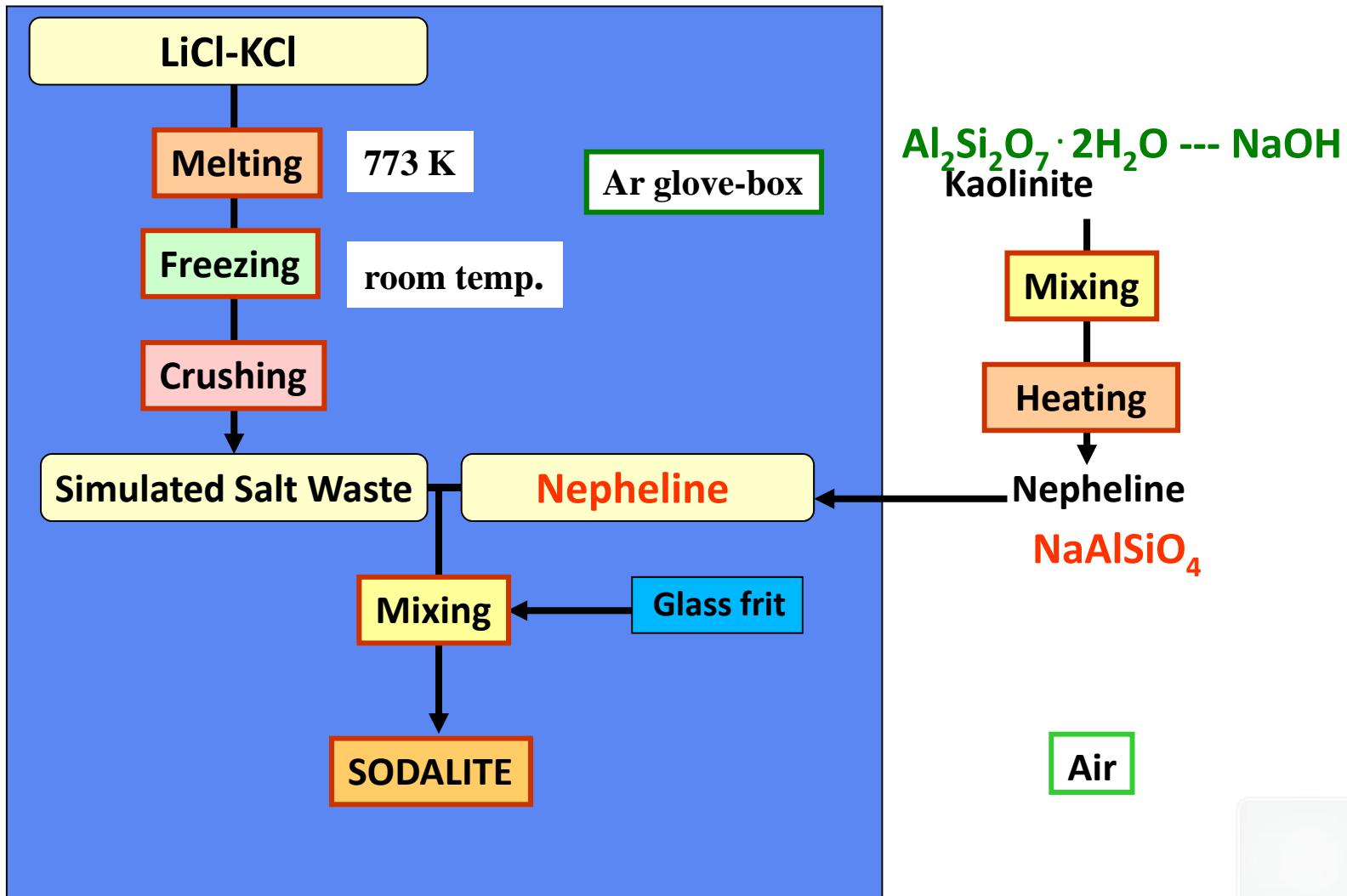
**SODALITE**

**SAP**

**MURATAITE-PYROCHLORE**

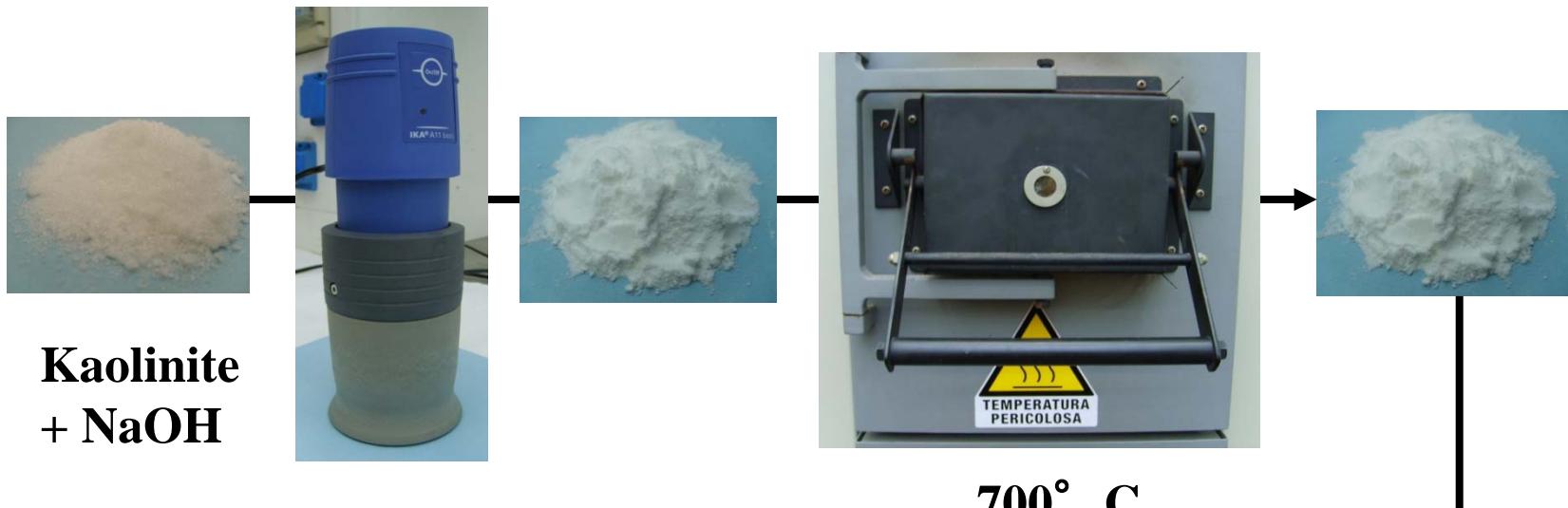


# SODALITE matrix

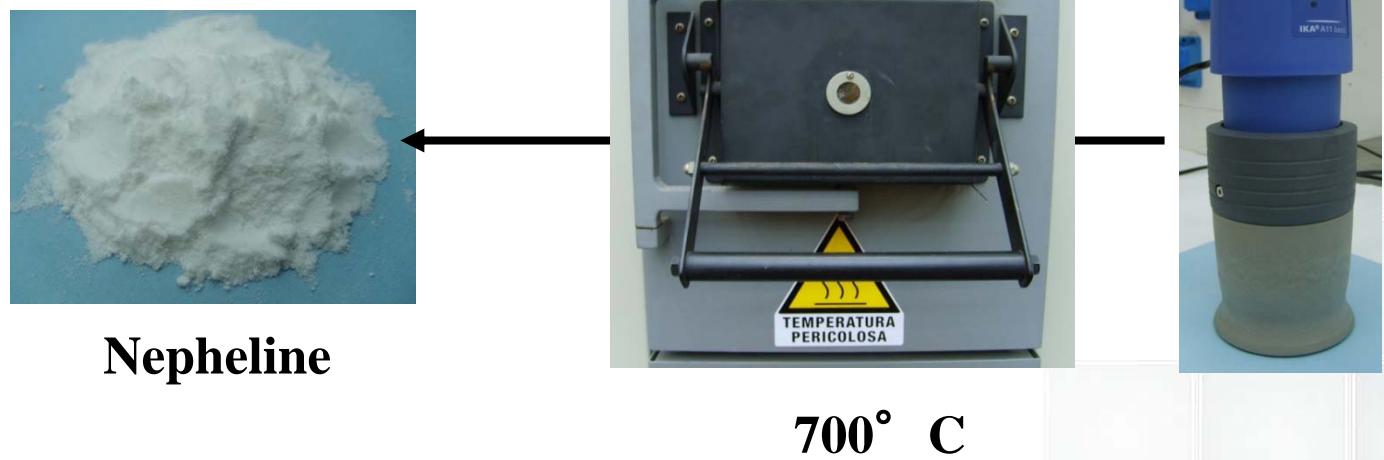


Outline of sodalite synthesis from kaolinite through nepheline

# SODALITE matrix



## Synthesis of nepheline



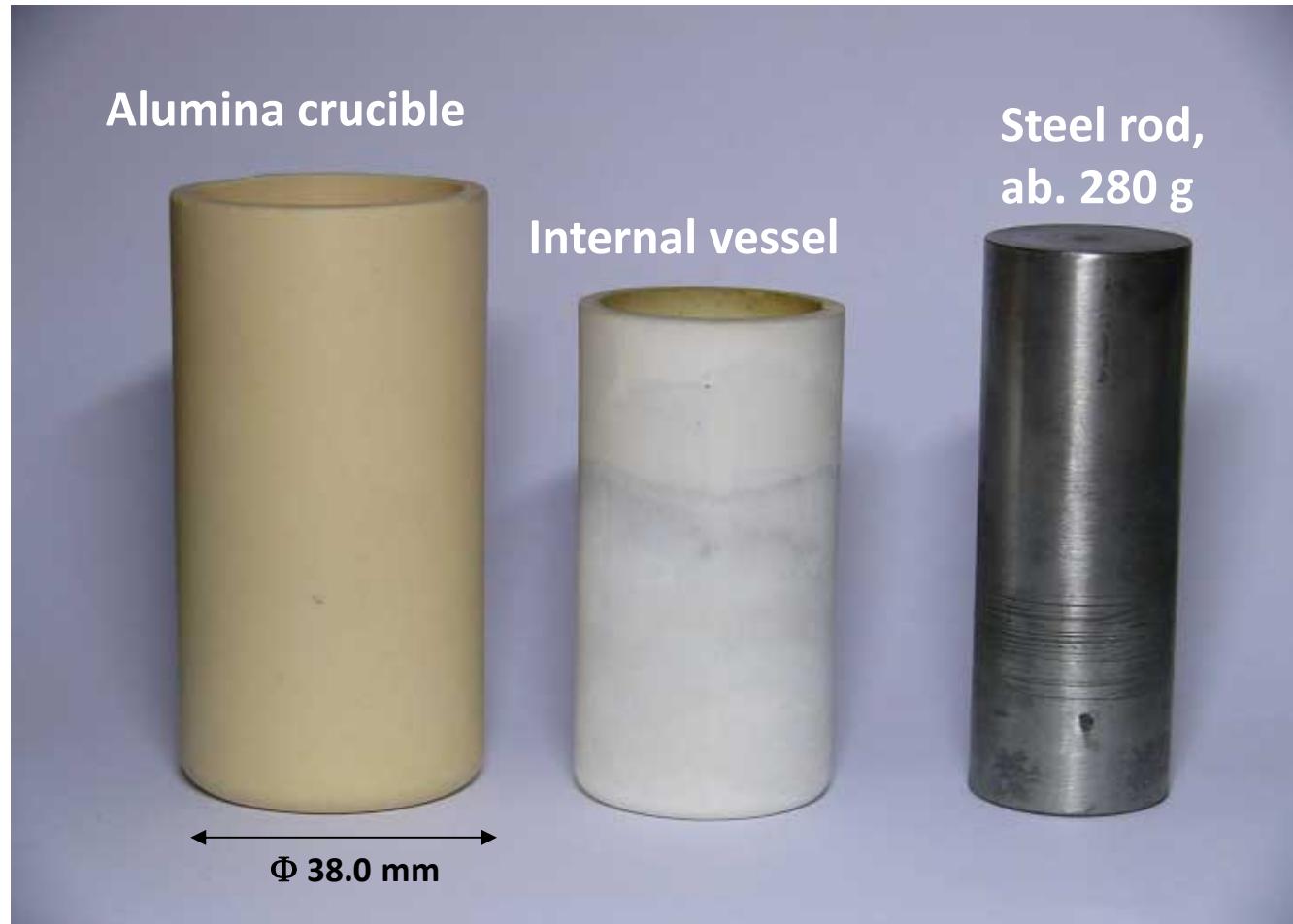
# SODALITE matrix



**Mixing and grinding of nepheline with LiCl-KCl**

# SODALITE matrix

Components used for labo. scale Pressureless Consolidation experiments



Mix of nepheline, salt waste and glass frit  
between alumina crucible and internal vessel

# SAP matrix



**Transparent hydrogels**



**Products obtained after  
each of the three main  
steps for preparation of  
SAP matrix**

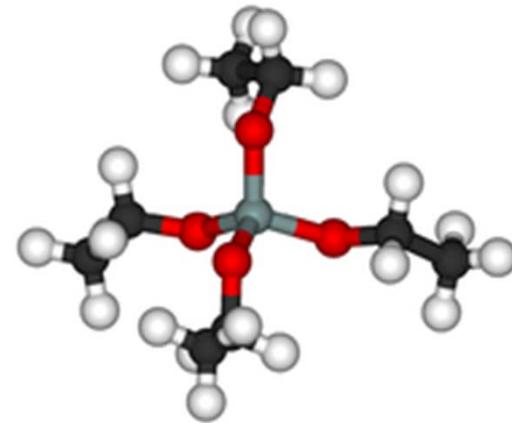
# SODALITE matrix



**Assembly of the components for thermal treatment  
at 925C for 7 hours**

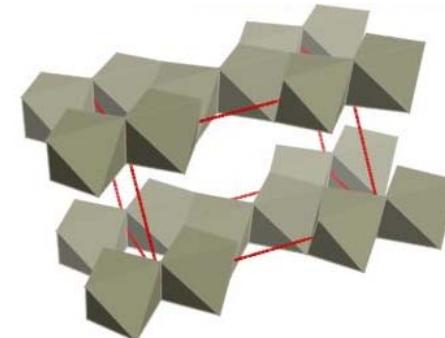


# SAP matrix

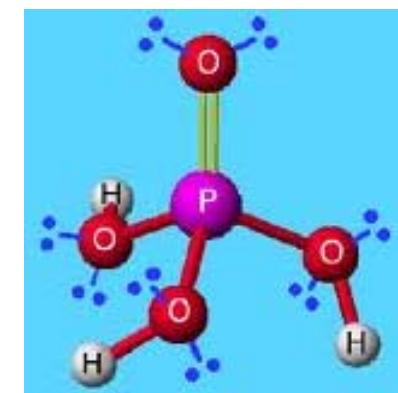


TEOS,  
Tetraethyl orthosilicate  
or tetraethoxysilane,  
 $\text{Si(OCH}_2\text{CH}_3)_4$

## Sources of Si – Al – P

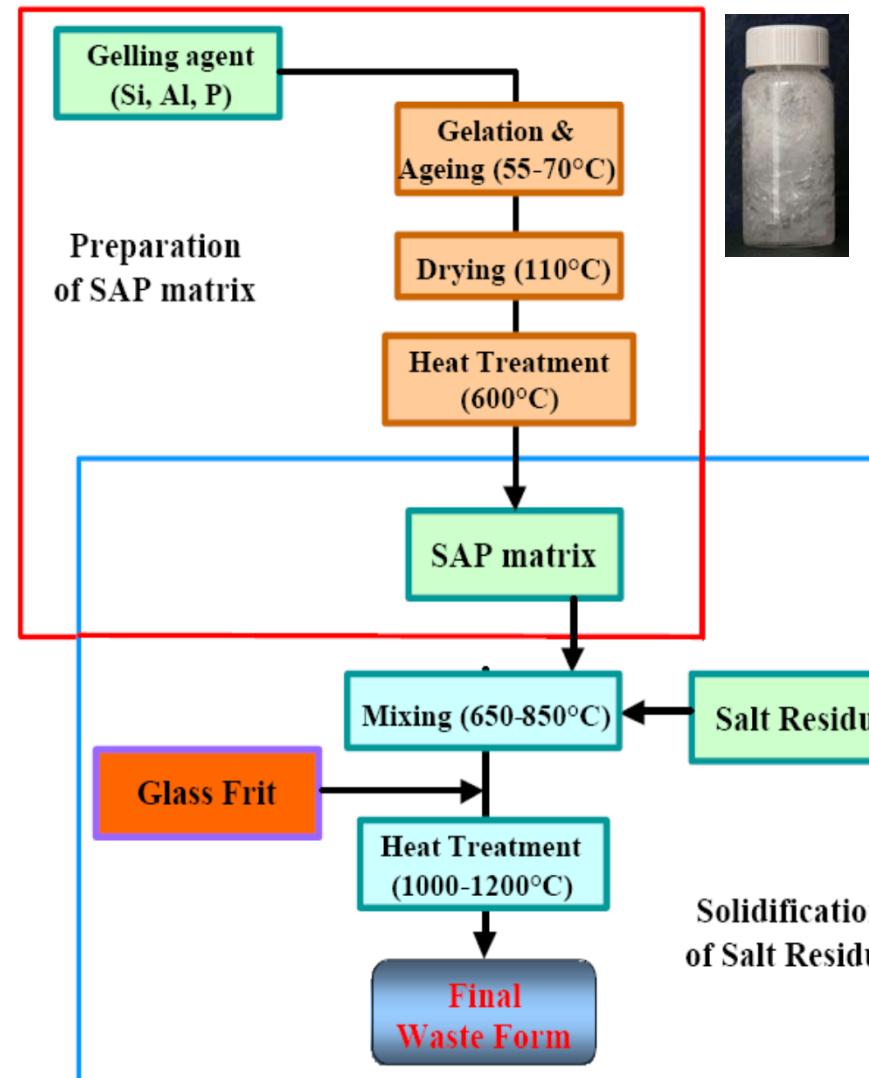


Aluminum (III) chloride,  
 $\text{AlCl}_3$



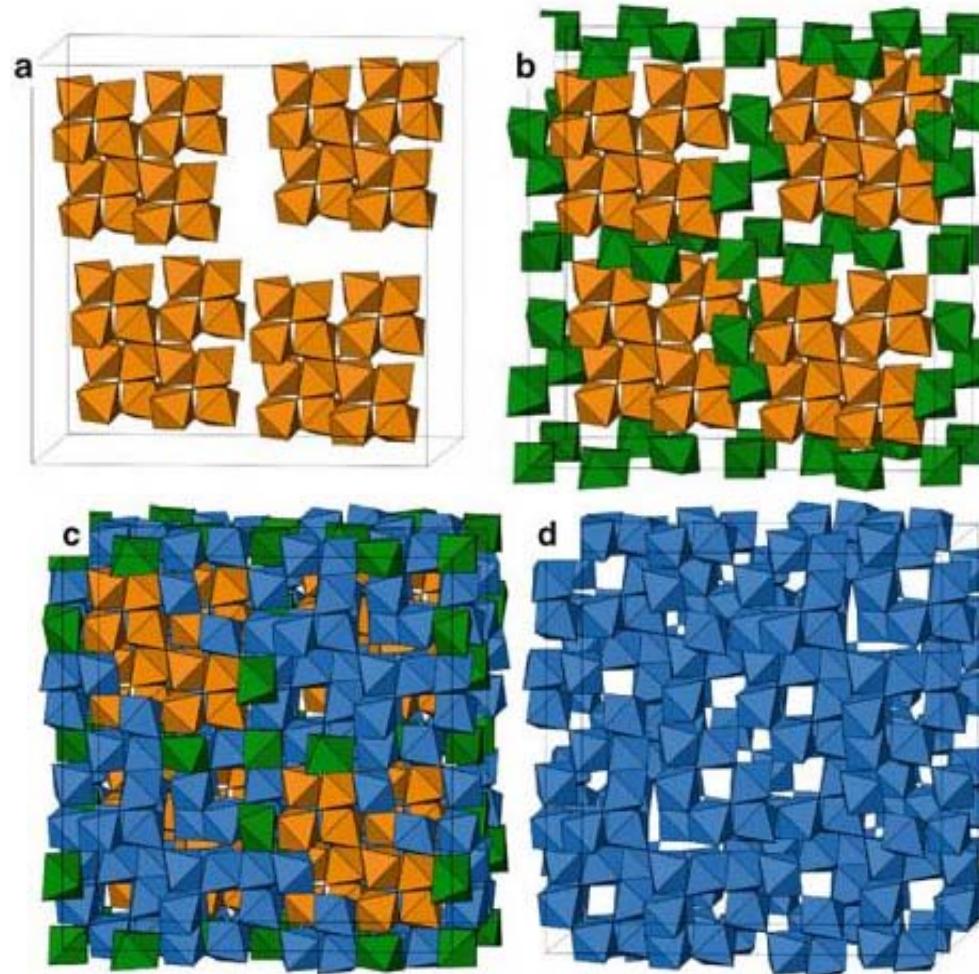
Phosphoric Acid,  
 $\text{H}_3\text{PO}_4$

# SAP matrix



Outline of SAP synthesis by a conventional sol-gel process

# MURATAITE matrix



Octahedral framework in the structure of Mu-5: arrangement of pyrochlore cluster<sup>a</sup> formed by corner sharing of  $Ti_1O_6$  and  $Ti_4O_6$  octahedra (a); linkage of pyrochlore clusters by  $Ti_3O_6$  octahedra (b); whole framework as combination of linked pyrochlore clusters and murataite-like framework formed by  $Ti_2O_6$  and  $Ti_5O_6$  octahedra ©; murataite-like framework (d)

# Evaluation of long-term behaviour of conditioned salt wastes



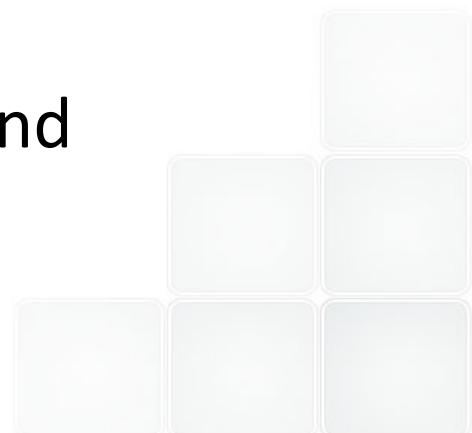
- Static leaching tests up to 150 days
- Assessment of the main parameters which influence fission products release (pH, temperature, contact time)
- Determination of the interactions between host matrix and individual fission elements



# Issues from SNETP - SRIA in fuel reprocessing



- Advanced reprocessing for MA separation, using hydro and pyro- metallurgical processes (UE Projects ACSEPT -> SACSESS)
- Conversion process from separation to re-fabrication
- Synthesys of new fuel and performance assessment in reprocessing
- Irradiation behaviour of MA-bearing MOX and carbide fuels, dedicated PIE programmes
- Industrial implementation of P&T&RF laboratories



# General SRIA issues from new waste to geological disposal

- Increasing fuel burn-up, most of TRU / MA
- Reducing FP as much as possible
- Reducing of Pu towards non proliferation
- Improve stability of chemical and physical form
- GD with more relaxed requirements in terms of volumes and masses, easy conditioning and storage, safety and economics
- Locating in depth

