Current Progress in Pyroprocess Technologies for TMSR in SINAP

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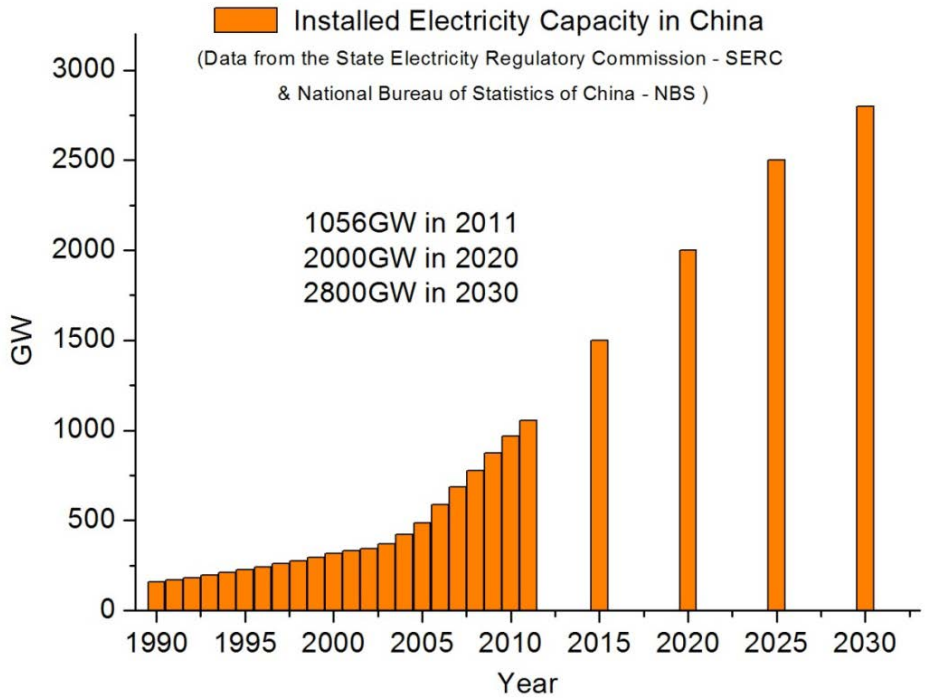
Summary

Outline

TMSR Project Overview

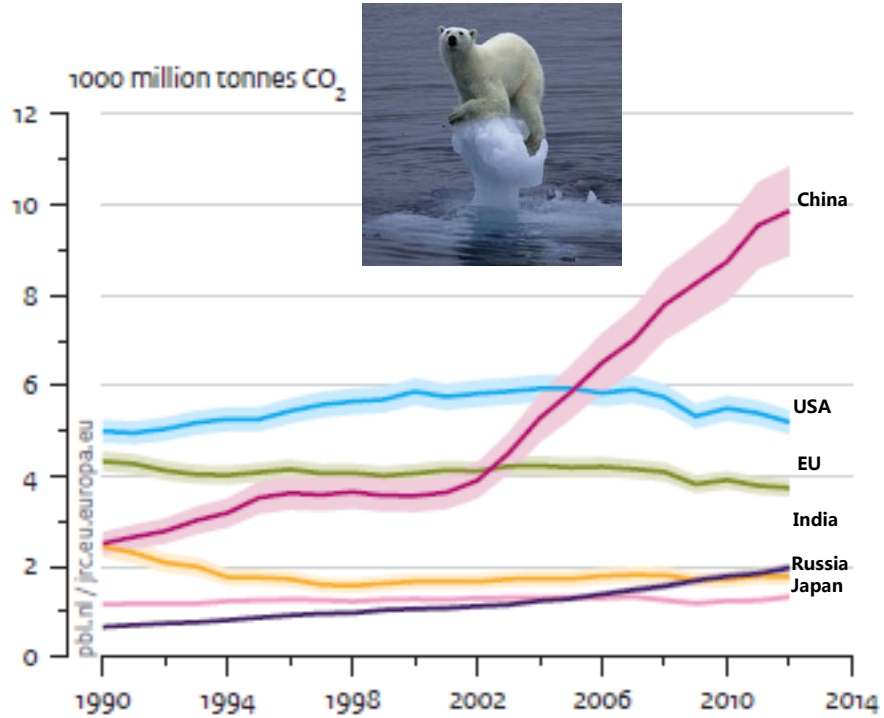
Energy Demand of China



Year	GW
1990	157
1995	226
2000	315
2005	486
2010	966
2015	1500
2020	2000
2025	2500
2030	2800

- China is the world‘s second-largest consumer of oil behind the United States
- China's electricity generation is dominated by fossil sources, particularly coal (70%)

Environmental Deterioration by Air Pollution



SOURCES：EDGAR 4.2 FT 2010 (JRC/PRBL, 2012); BP, 2013, NBS China, 2013; USGS, 2013l WSA, 2013; NOAA, 2012

Consumption of bio fuel produces large amount of CO_2 → greenhouse effect
Burning coal produces airborne particles → frequent haze in China

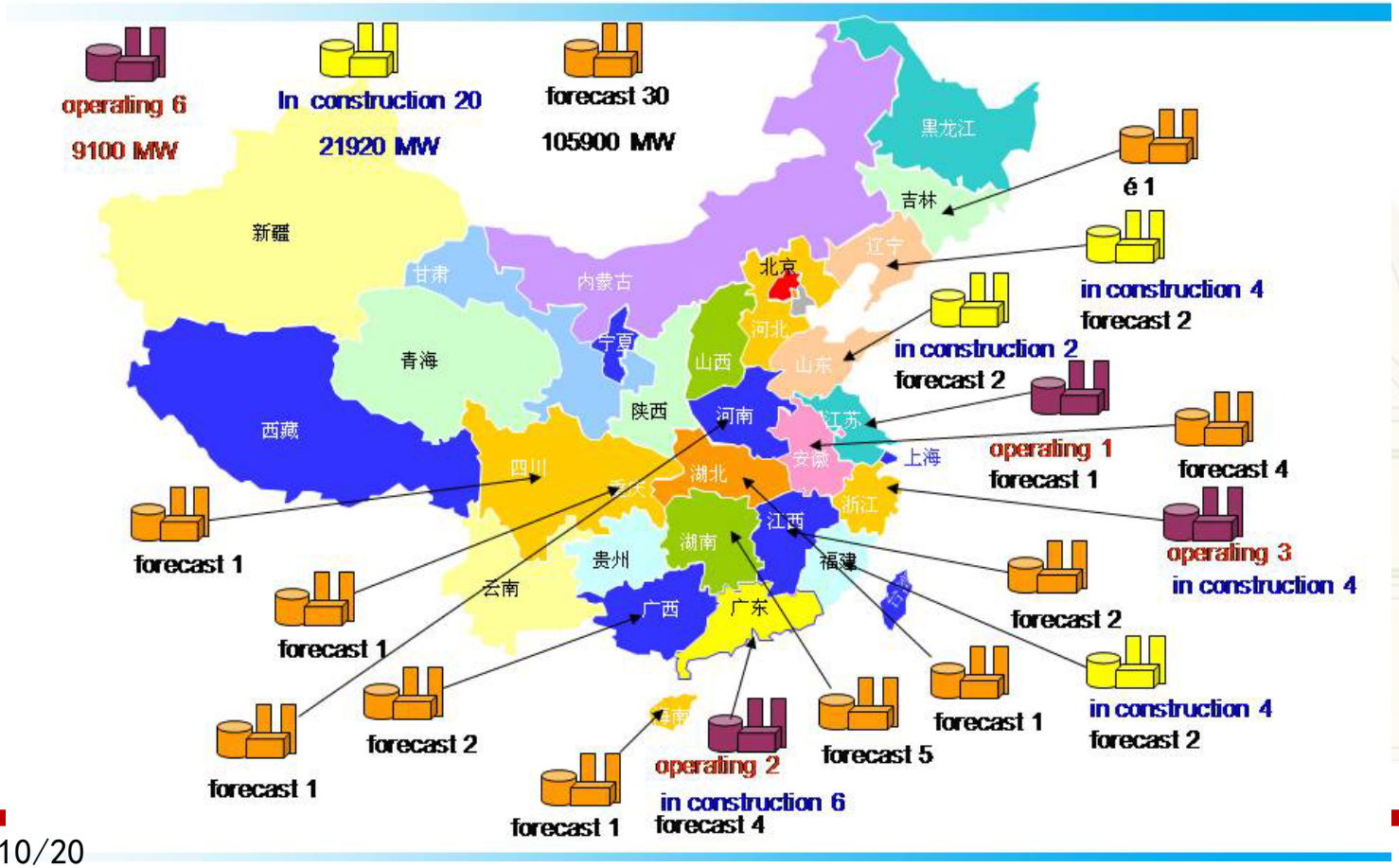
One of the best solution is NPPs

Nuclear Power Plants in China

- 17 reactors in operation
- 28 under construction
- More in plan including AP1000

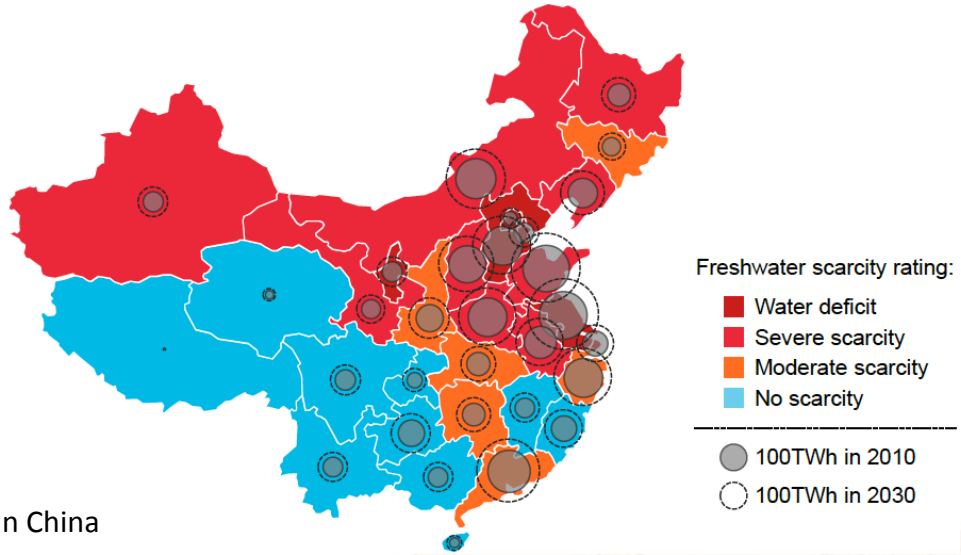
- 58 GW by 2020
- 100 GW by 2030
- 400 GW by 2050

  ~ 14% total electricity

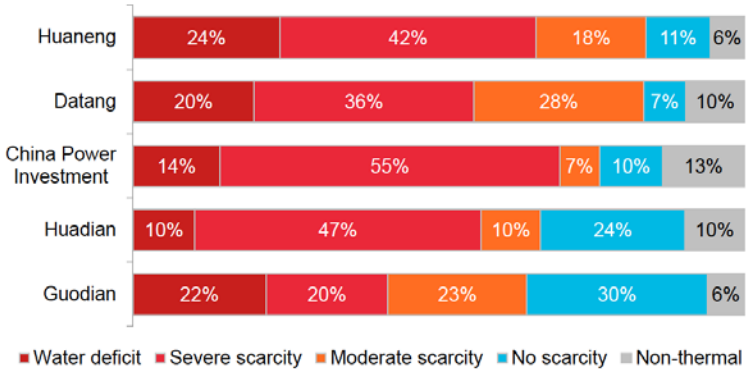


Freshwater scarcity Issue in China

Traditional NPP-- PWR requires a lot of water



Power generation vs. water scarcity by province in China



China Top Five's capacity in water scarce region

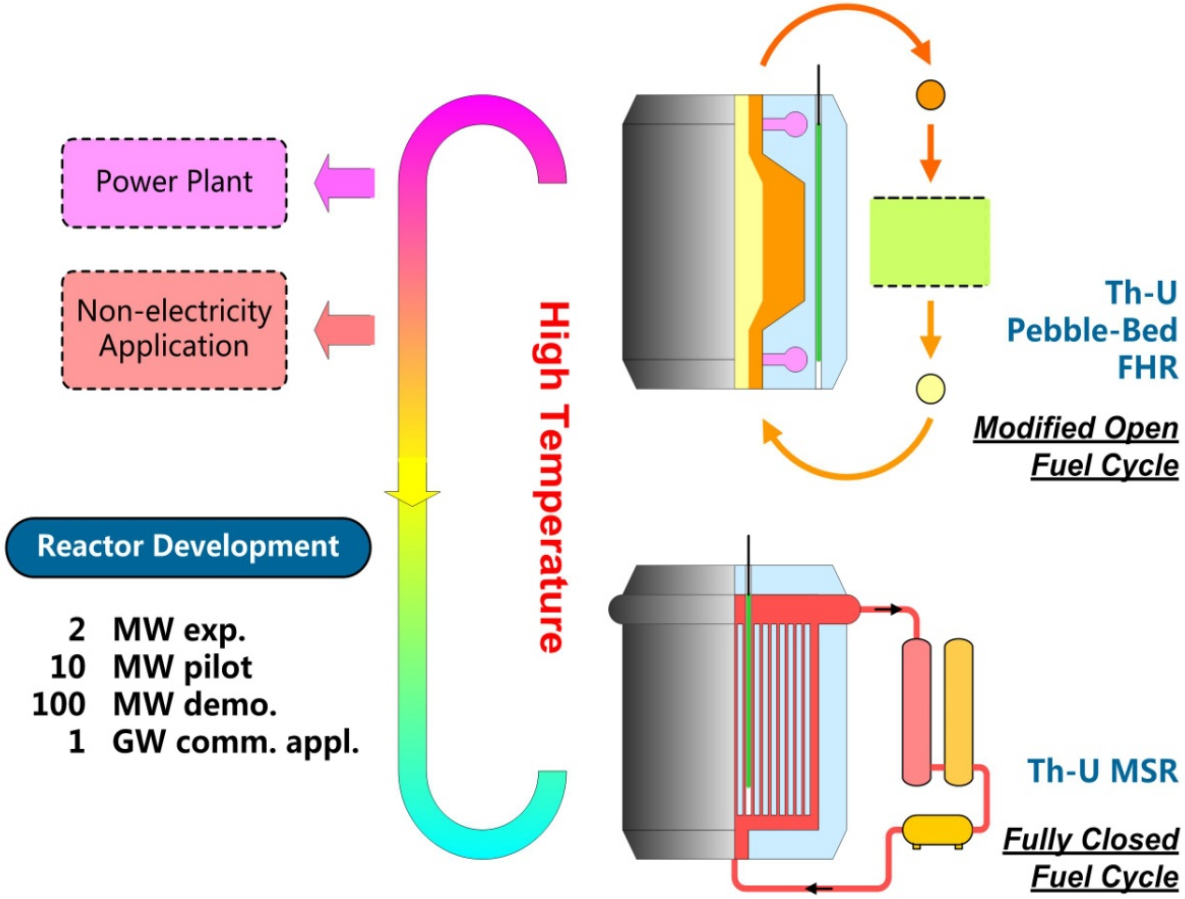
The best solution may be the FHR & MSR which use fluoride salts as coolant and with Air-cooling Brayton Cycle

TMSR Project in China

The goal of TMSR is to develop Thorium energy and non-electric application of nuclear energy based on TMSR (liquid fuel) and TMSR (solid fuel) during the coming 20-30 years

- **The Chinese Academy of Sciences (CAS) launched the Thorium Molten Salt Reactor (TMSR) research project in 2011**
- **CAS Center for Excellence in TMSR Energy System was found in 2014 at Shanghai Institute of Applied Physics (SINAP)**
- **Around 10 CAS institutes and 20 Universities participate**
- **Center has more than 400 professionals**
- **$350M was committed for 5 years; National Project is under way**

Scheme of TMSR Developing Strategy



Scheme of TMSR Developing Strategy

- Two reference reactor systems
  - TMSR-SF---solid pebble fuel
  - TMSR-LF---liquid fuel
- Three fuel cycle models
  - One through fuel cycle on TMSR-SF
  - Modified open fuel cycle TMSR-SF and TMSR-LF
  - Fully closed fuel cycle on TMSR-LF

TMSR Milestones

2015

- Start construction of
  - **TMSR-SF Simulator**
  - **10MW TMSR-SF test Reactor**
  - **2MW TMSR-LF test Reactor** & **Pyro-Process Facility**
- Full capability of non-radioactive laboratories in Jiading.

2017

- Commissioning of
  - TMSR-SF Simulator
  - 10 MW TMSR-SF (Reach full power)
  - 2MW TMSR-LF (Reach criticality)
- TMSR Nuclear Park (Phase I) in DaFeng.

2022

- Commissioning of 100 MW-class TMSR-SF and 10 MW-class TMSR-LF
- **Demonstration of pyroprocessing with TMSR-LF.**
- TMSR Nuclear Park (Phase II)

Outline

TMSR Fuel Processing Consideration

General Mission of TMSR fuel On-line Processing

- To keep the reactor in steady-state conditions by cleaning-up of the primary (fuel) circuit salt.
  - To clear away neutron poisons like Xe, Kr, lanthanides
  - To extract freshly constituted fissile material or its precursors
  - To secure refilling of fresh or reconstituted fuel into fuel circuit

Fuel salt	^{7}LiF、BeF_2
	Th、U
An	^{233}Pa、^{233}U、TRU
FPs	Kr、Xe、I
	Nb、Mo、Tc、Sc、Ru、Rh、Ag、Cd、In、Sn、Sb、Te、Zn、Ga、Ge、As、Se
	Y、La、Ce、Pr、Nd、Pm、Gd、Tb、Dy、Ho、Er、Sm、Eu
	Sr、Ba
	Rb、Cs
Impurities	Ni、Fe、Cr

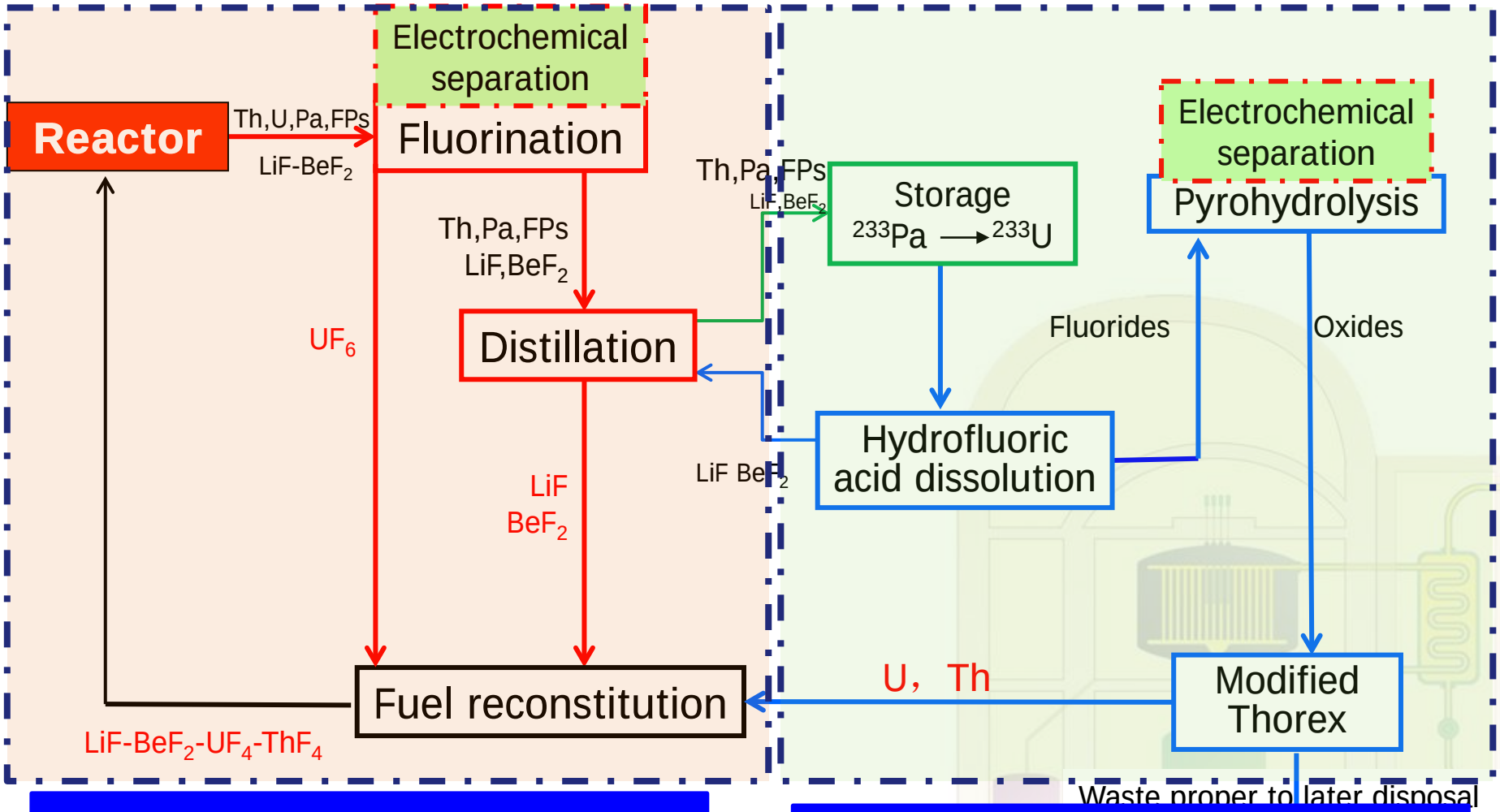
Principle for Designing TMSR Fuel Processing Flowsheet

- Separate valuable constituents from molten salt fuel and recycle
- On-line + off-line
  - separate and recycle U and carrier salt on-line
  - co-separating Th and ^{233}U (decay from ^{233}Pa) off-line and recycling at suitable time
- Develop methods which less affected by chemical components of irradiated fuel, and the products from process are reconstituted easily

Pyroprocess Technologies Priority to Develop

method	target	principle	advantage
Fluoride volatility	U	•Low boiling point of product $UF_4+F_2=UF_6(g)$ $UF_6+UF_4=UF_5$ $UF_5+H_2=UF_4$	•Matured technology •Rarely influenced by chemical components; •High recovery rate and purity •UF_6 can be recycled directly just after reduction in molten salt
Vacuum distillation	$^7LiF-BeF_2$	•Different volatilities between molten salt and FPs	•Simple principle •No chemical reaction •Recovered salt can be recycled directly
Electro-chemical separation	FPs or An	•Reduction deposition of metal on cathode $M^{n+}+ne^-=M$	•Safe

Flow sheet of TMSR Fuel Processing



On-line reprocessing and recycling

Off-line reprocessing

About Cs

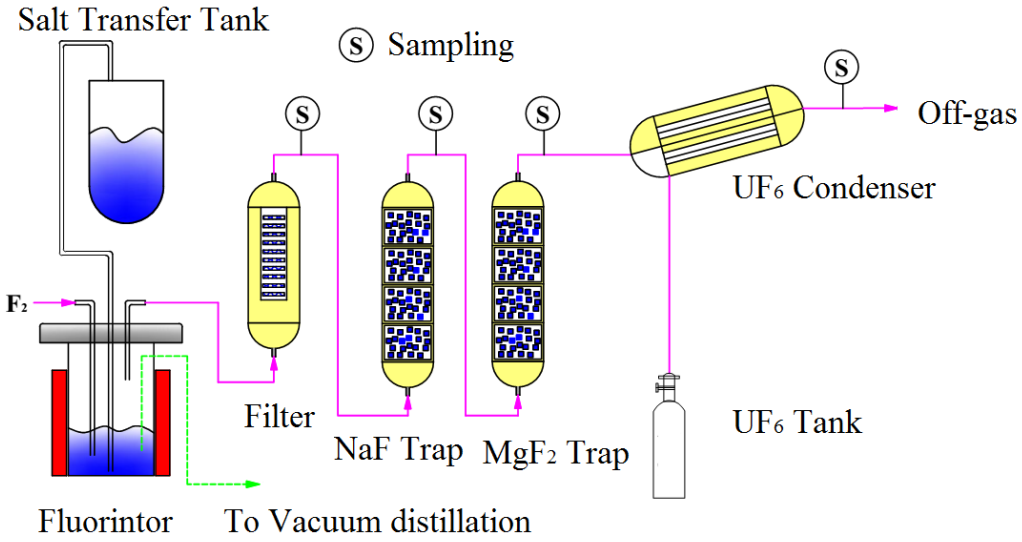
- Cs exists in fuel as CsF, has similiar chemical behavior with LiF, always accompanies with LiF in process.
  - Cs-133: a neutron poison, ranks as sixth most poisonous FP
  - Cs-137: heat-loaded FP
- Accumulation of Cs in reactor might influence the reactivity of the reactor
- How should we deal with it?

Outline

Research Progress

Progress in Fluoride volatility

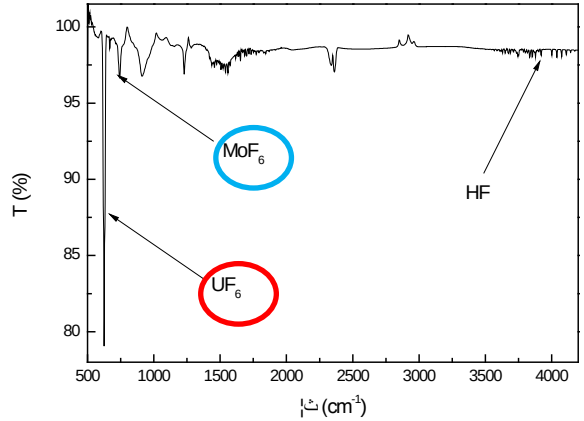
- Three key techniques are under developed
  - on-line infrared spectrum analysis for process monitoring
  - Sorption process for product purification
  - Gradient condensation to collect the volatile UF_6



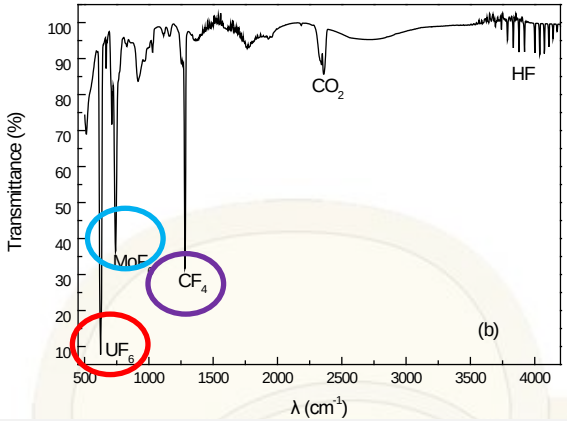
On-line Infrared Spectrum Analysis for Fluorination Process Monitoring

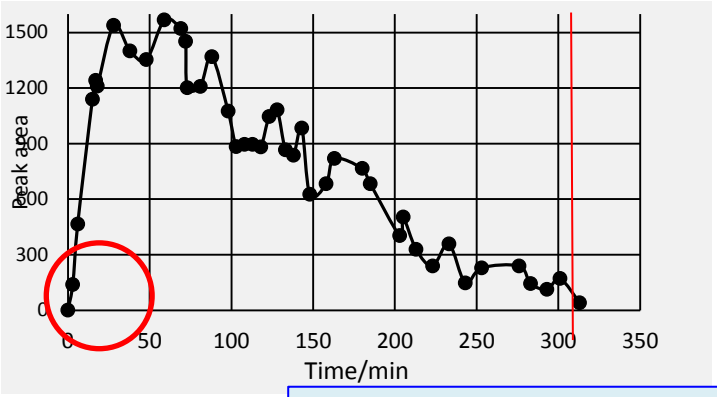
Gas-solid reaction between F_2 and UF_4 powder

Gas-liquid reaction between F_2 and UF_4 in KF-ZrF_4 eutectic salt

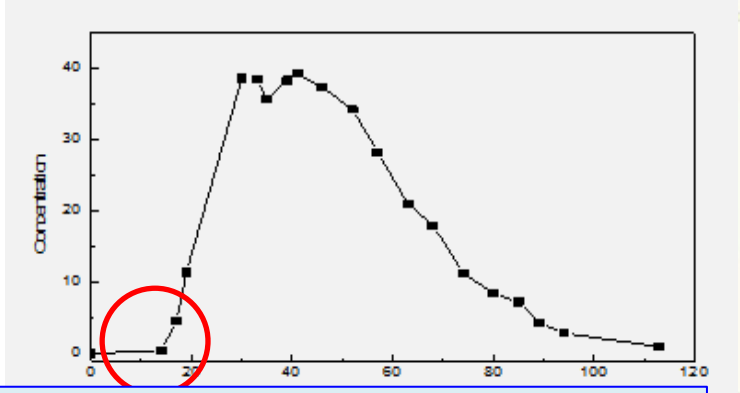


Infrared spectrum of gas product





Determination of process by infrared spectrum analysis



Infrared spectrum analyses can monitor fluorination process effectively
It can also reflect the corrosion of vessels

Corrosion Issue in Fluorination in Molten Fluoride salt

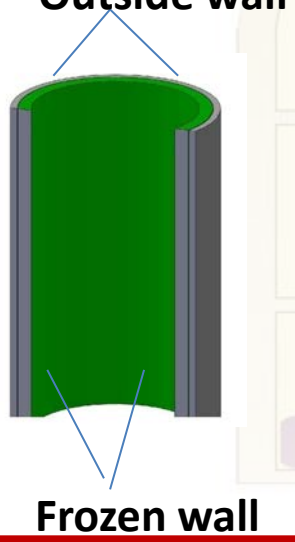
Result

✧ The Corrosion is serious.

Solution

✧ From a frozen-wall on the inner wall of vessel

✧ The components of the frozen-wall are same with the molten fluoride salt



Process in Low Prossure Distillation

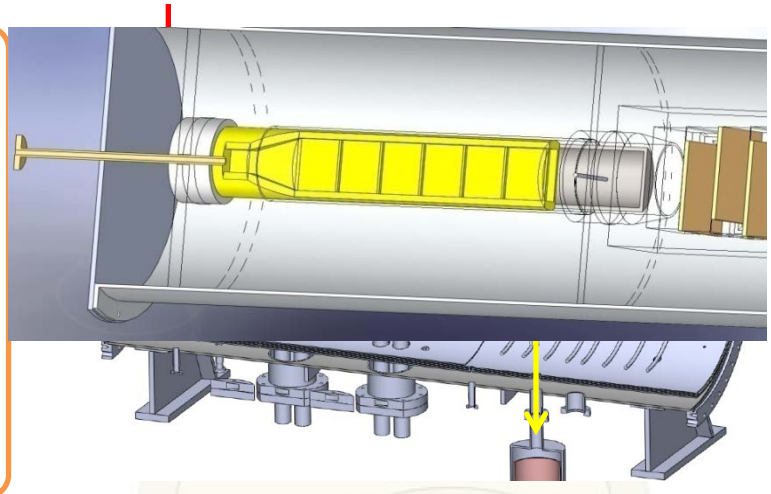
The development of horizontal distillation equipment

features

- Cascade evaporator surface to increase evaporation rates. Evaporator surface: 850 cm^2
- Labyrinth condenser to increase condensing area.
- Graphitic evaporator is heated **by induction coil**.
- Two distillation modes: Continuous and batch

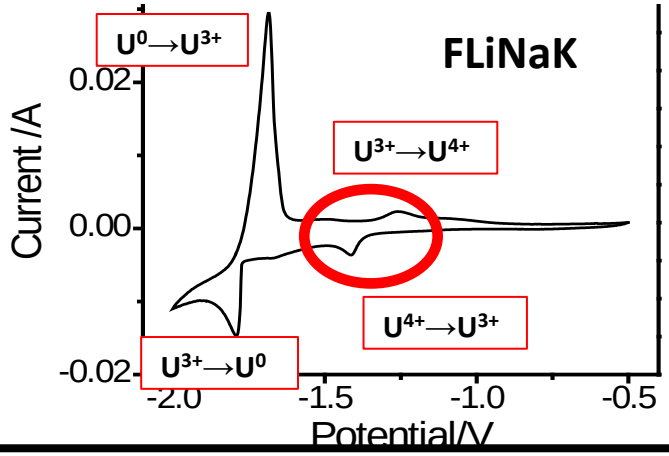
Preliminary results

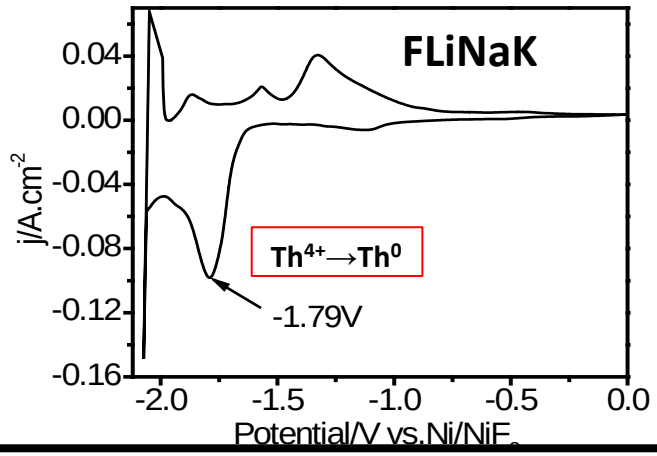
- Recovery ratio reaches **94%**.
- Distillation rate is 1 kg/h.



	Relative volatility (Respect to LiF)	DF
NdF_3	3.8×10^{-3}	2.6×10^{2}
SmF_3	3.5×10^{-5}	2.9×10^{4}
LaF_3	4.5×10^{-5}	2.3×10^{4}
EuF_3	2.9×10^{-3}	3.5×10^{2}
CeF_3	1.5×10^{-4}	6.9×10^{3}
GdF_3	7.1×10^{-4}	1.4×10^{3}

Electrochemical properties of interested elements in FLiNaK



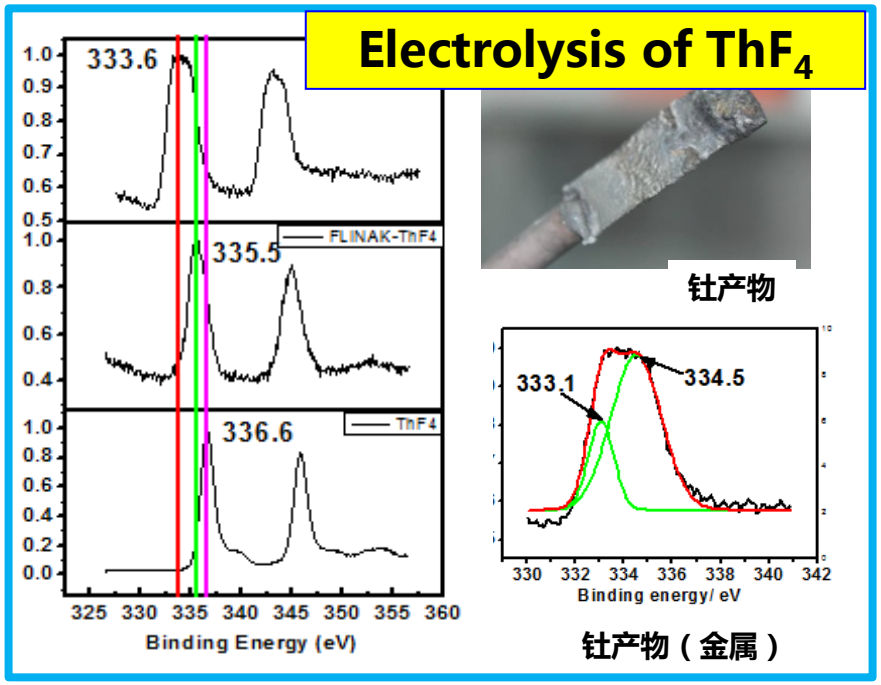


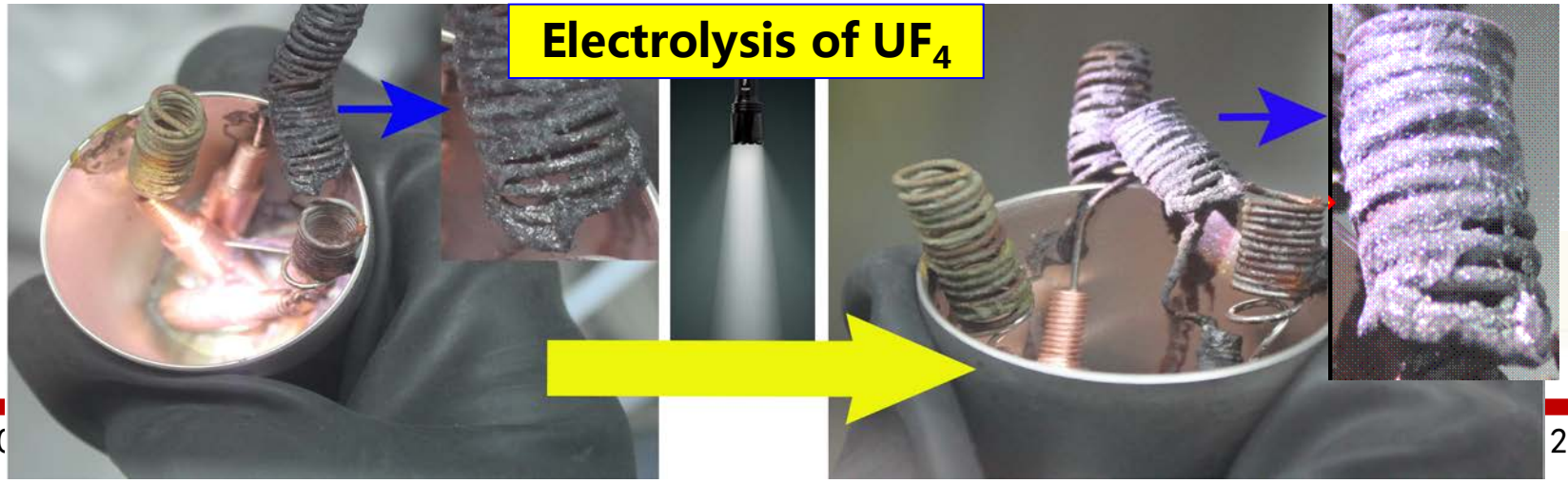
Reaction	E^0（V）vs. Ni/NiF_2	$D/cm^2.s^{-1}$	Separation
$Gd^{3+}+3e \rightarrow Gd^0$	-2.02/-1.68	3.2×10^{-4}	Y
$Y^{3+}+3e \rightarrow Y^0$	-1.96/-1.91	5.4×10^{-6}	Y
$Sm^{3+}+e \rightarrow Sm^{2+}$	-1.65/-1.53	7.4×10^{-6}	N
$Eu^{3+}+e \rightarrow Eu^{2+}$	-1.07/-0.89	1.3×10^{-5}	N
$Nd^{3+}+3e \rightarrow Nd^0$	-1.95/-1.88	1.1×10^{-5}	Y
$Zr^{4+}+4e \rightarrow Zr^0$	-1.86/-1.50	2.5×10^{-6}	Y
$Th^{4+}+4e \rightarrow Th^0$	-1.91/-1.66	8.4×10^{-7}	Y
$U^{4+}+e \rightarrow U^{3+}$ $U^{3+}+3e \rightarrow U^0$	-1.42/-1.24 -1.83/-1.69	1.3×10^{-6}	Y

Preliminary study of electro-separation in FLiNaK

Result

✧ Th and U can be electro-separation in FLiNaK





Outline

Summary

Summary

- The investigation of pyroprocessing of TMSR fuel including Fluoride volatility, vacuum distilation and electrochemical methods has been initiated with lab-scale in SINAP
- Pyroprocessing of irradiated nuclear fuel, as an integral part of TMSR nuclear system, presents various challenges.
- It is very important for us to learn from all countries which having successful experience. Effective scientific exchange and international collaboration will promote our work.

Thanks a lot for your kind attention !