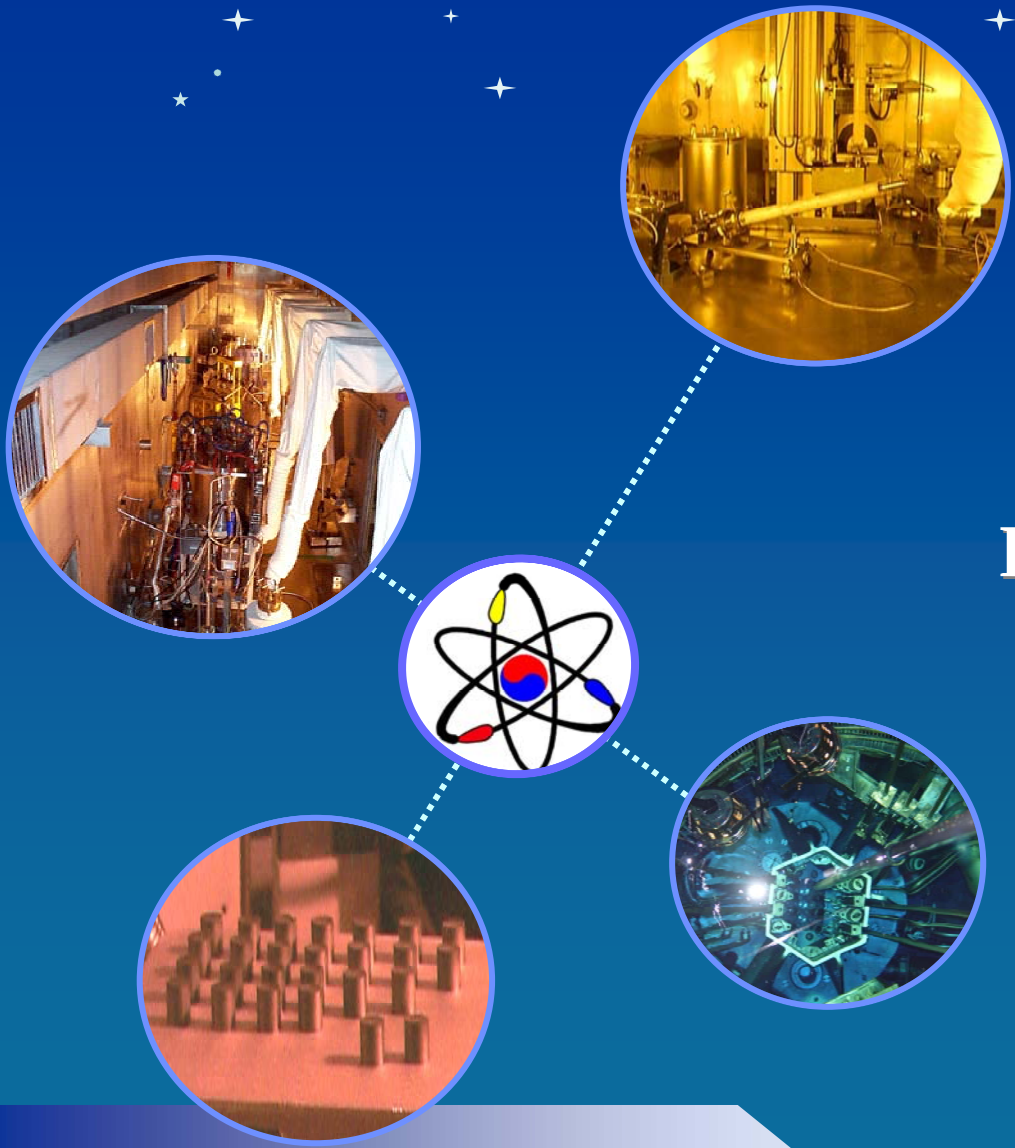

Current Status on Development of P & T in Korea

Eung Ho Kim

Korea Atomic Energy Research Institute

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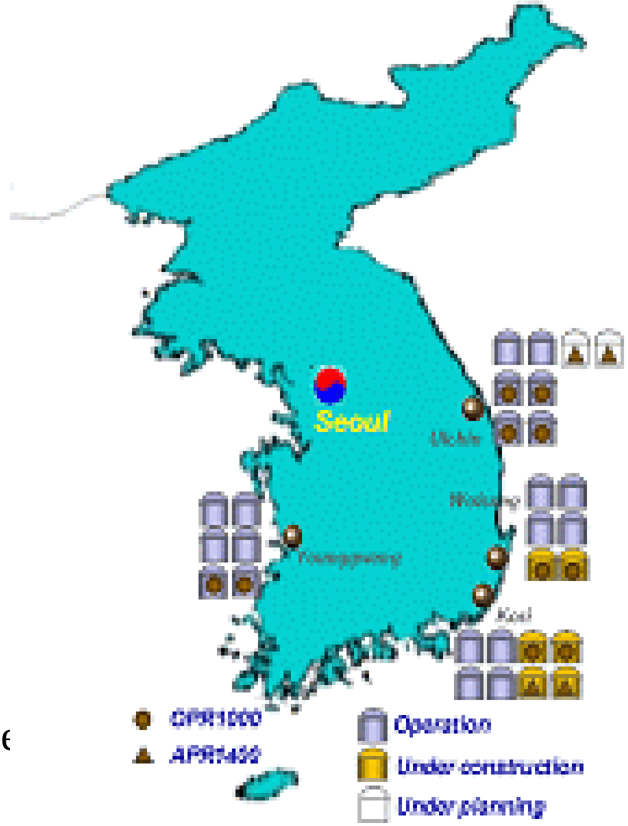
Backgrounds

❑ Energy Status in Korea

- Korea is importing about 97% of total energy
- Energy security becomes the most critical issue for the sustainable economic development

❑ Nuclear power generation and cumulated spent fuel

- PWR 16 units + CANDU 4 units
- 17.7 Gwe
- About 40% share
- 7,962 te (as of Dec. 2005), 19,324 te (by 2020)



❑ Korea has no fixed policy for spent fuel management

❑ Decision of AEC on Spent Fuel Management, Dec 2004

- Storage of spent fuels at nuclear power plant sites until 2016

-By expanding interim storage capacity

-By studying continuous R & D on spent fuel management technologie

“ Non-proliferation Nuclear Fuel Cycle”

❑ R & D studies on **promising fuel cycle technologies** are being carried out:

DUPIC, ACP and pyropartitioning for transmutation in either SFR or ADS

*DUPIC (**D**irect **U**se of **P**WR spent fuel **I**n **C**ANDU reactors),

ACP (**A**dvanced spent fuel **C**onditioning **P**rocess)

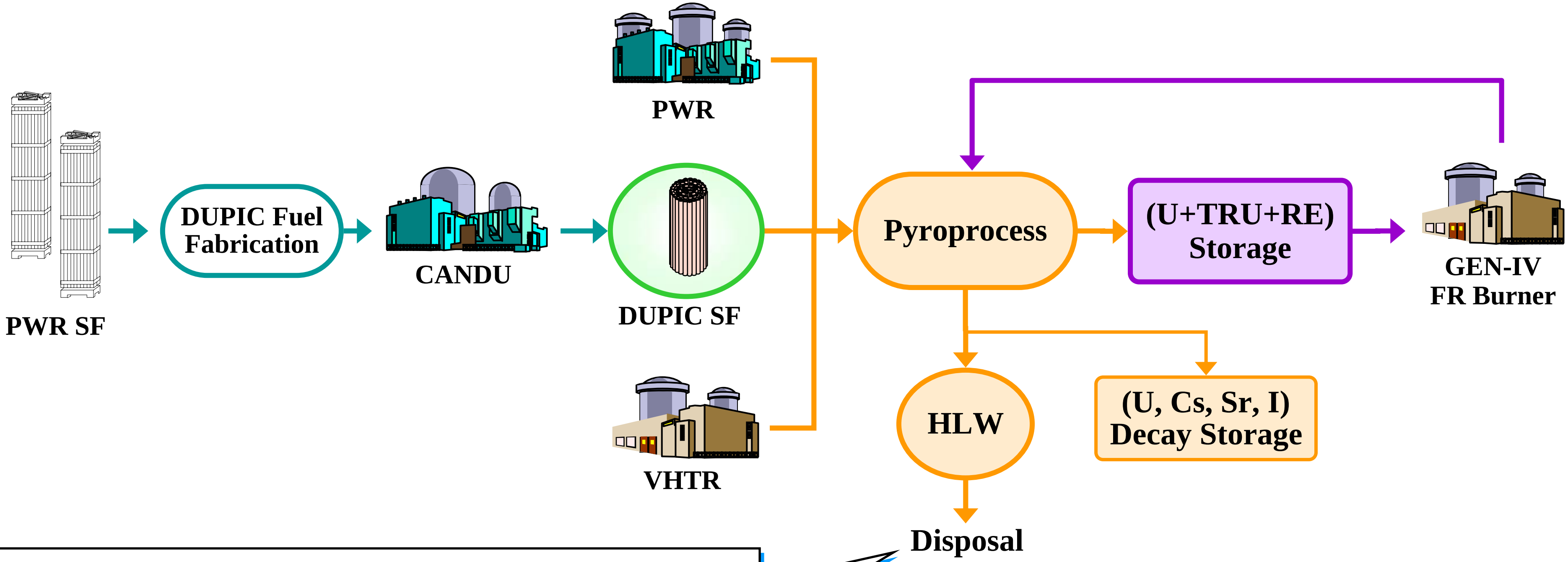
KIEP-21 … Korean Nuclear Fuel Cycle Concept (KAERI Proposal)

"K : Korean, I : Innovative, E : Environmentally friendly, P : Proliferation resistant, 21 : 21st C"

DUPIC Demonstration

Volume Reduction Demonstration

GEN-IV Closed Fuel Cycle Demonstration



PWR SF

DUPIC Fuel Fabrication

CANDU

PWR

DUPIC SF

VHTR

Pyroprocess

(U+TRU+RE) Storage

GEN-IV FR Burner

HLW

(U, Cs, Sr, I) Decay Storage

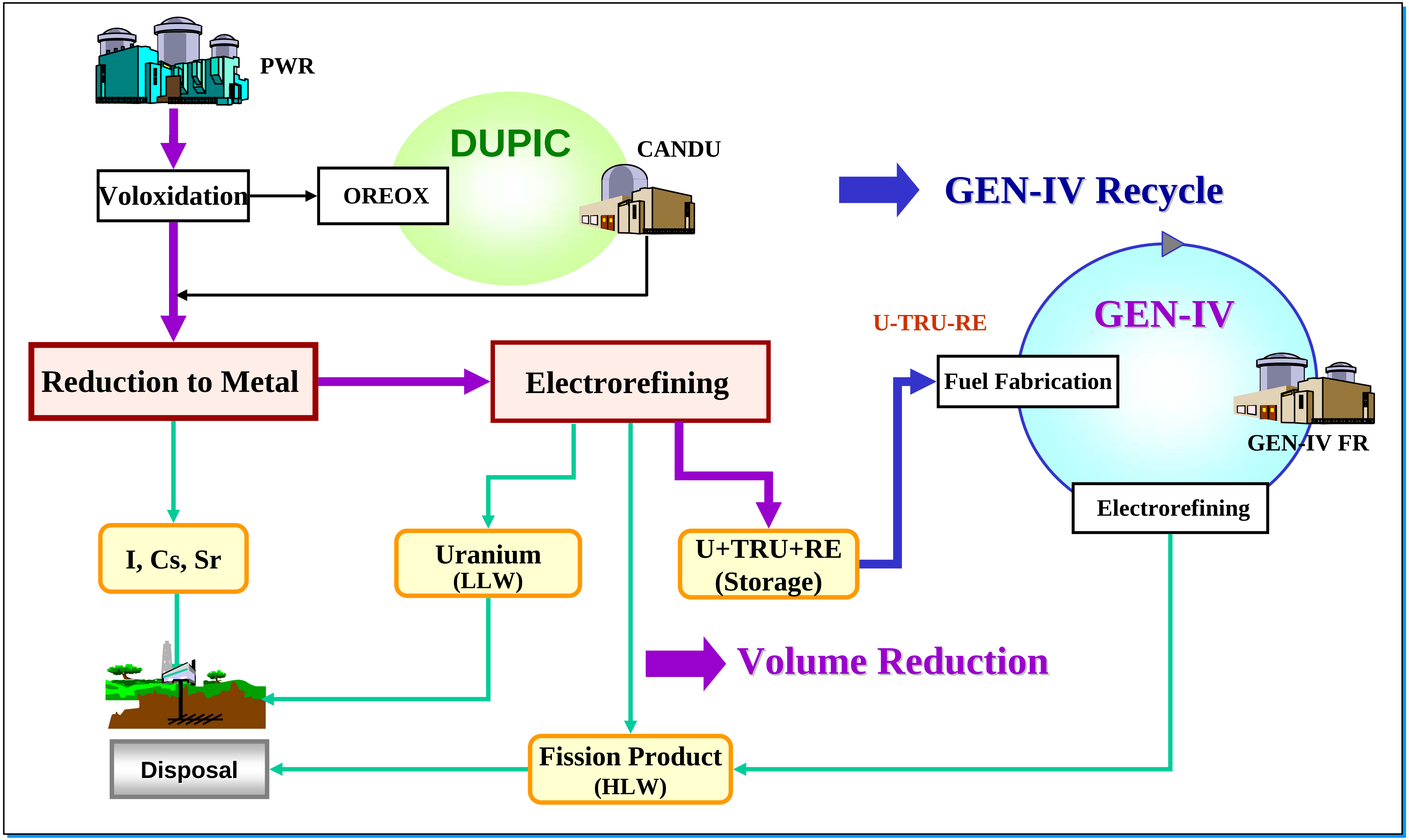
Disposal

Comparison with Direct Disposal of SF

- Reduction of repository space to 1/100
- Reduction of radiotoxicity to 1/100
- Enhancement of proliferation resistance by homogeneous transmutation of TRUs

Sustainability

Schematic Process Diagram of KIEP-21



PWR

Voloxidation

OREOX

DUPIC

CANDU

GEN-IV Recycle

U-TRU-RE

GEN-IV

Fuel Fabrication

GEN-IV FR

Electrorefining

Reduction to Metal

Electrorefining

I, Cs, Sr

Uranium
(LLW)

U+TRU+RE
(Storage)

Volume Reduction

Disposal

Fission Product
(HLW)

Timeline of Korean P & T Development

☐ **1991 : Launched DUPIC feasibility study (Korea-Canada-US joint program)**

☐ **1997 : Launched revised *10 Year Med- and Long-Term Nuclear R&D Program***

- **DUPIC/P&T/ACP**

☐ **2000 : Manufactured DUPIC fuel pellets and test pins using PWR spent fuel**

☐ **2001 : Started oxide electrolytic reduction and metal electrorefining studies**

☐ **2005 : Successfully demonstrated DUPIC pellet fabrication with high burnup fuel (65,000 MWd/tU)**

: Constructed ACP Demonstration Facility (ACPF, 20 kgHM/batch)

: Set-up 1 kgU/batch scale of uranium electrorefinning system

: Performed conceptual design of sub-critical reactor (HYPER) for transmutation

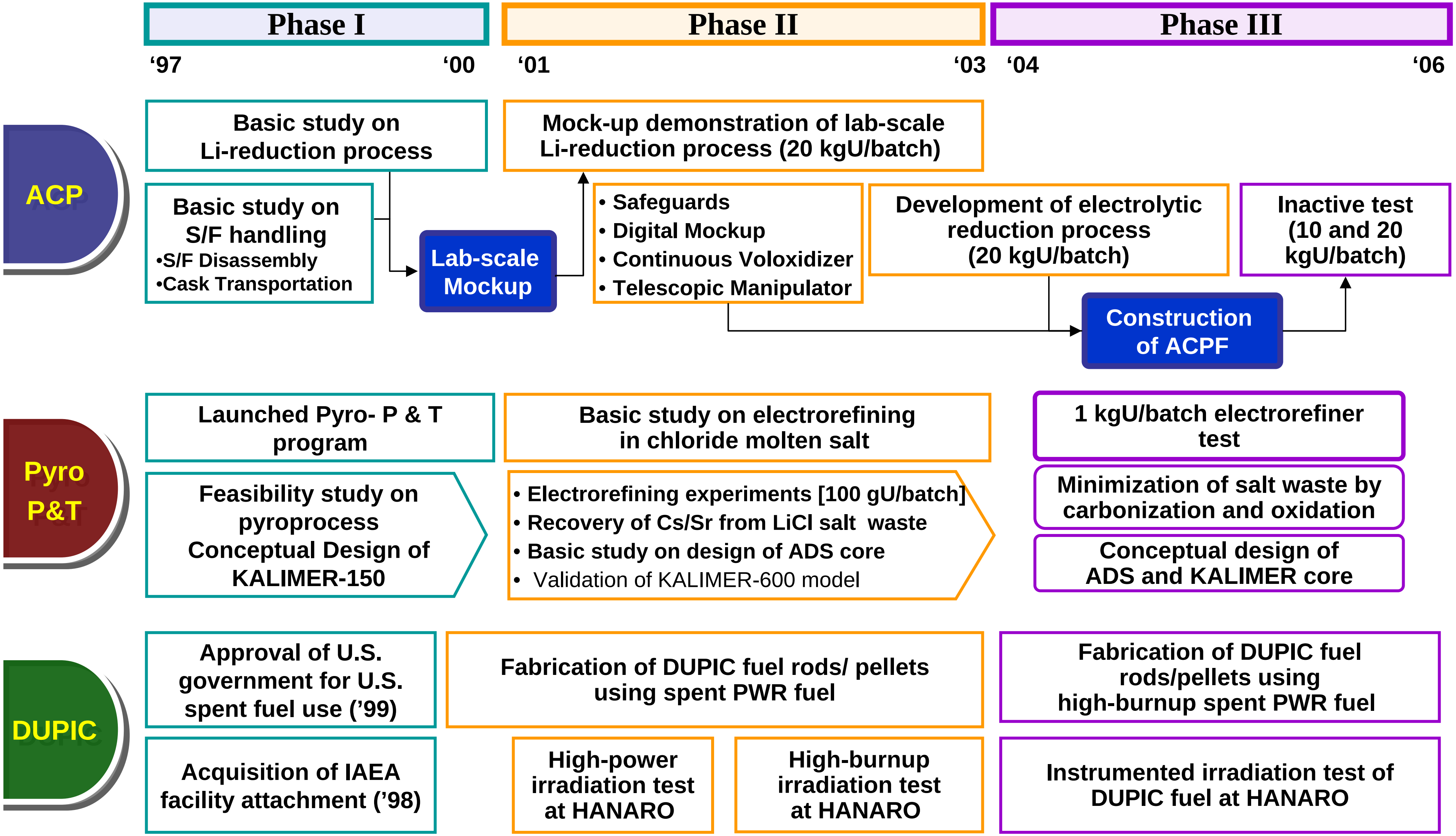
☐ **2006 : Agreed partnership in pyro and SFR under GNEP**

: Carrying out conceptual design of KALIMER-600 for transmutation

: Planning next 10 year Med-and Long Term Nuclear R & D Program

DUPIC/Pyroprocess/SFR(KALIMER-600)

Major Achievements in 1997~2006



Phase I ‘97 – ‘00

Phase II ‘01 – ‘03

Phase III ‘04 – ‘06

ACP

Phase I:
- Basic study on Li-reduction process
- Basic study on S/F handling
  - •S/F Disassembly
  - •Cask Transportation
- **Lab-scale Mockup**

Phase II:
- Mock-up demonstration of lab-scale Li-reduction process (20 kgU/batch)
- • Safeguards
- • Digital Mockup
- • Continuous Voloxidizer
- • Telescopic Manipulator
- Development of electrolytic reduction process (20 kgU/batch)

Phase III:
- **Construction of ACPF**
- Inactive test (10 and 20 kgU/batch)

Pyro P&T

Phase I:
- Launched Pyro- P & T program
- Feasibility study on pyroprocess
- Conceptual Design of KALIMER-150

Phase II:
- Basic study on electrorefining in chloride molten salt
- • Electrorefining experiments [100 gU/batch]
- • Recovery of Cs/Sr from LiCl salt waste
- • Basic study on design of ADS core
- • Validation of KALIMER-600 model

Phase III:
- 1 kgU/batch electrorefiner test
- Minimization of salt waste by carbonization and oxidation
- Conceptual design of ADS and KALIMER core

DUPIC

Phase I:
- Approval of U.S. government for U.S. spent fuel use (’99)
- Acquisition of IAEA facility attachment (’98)

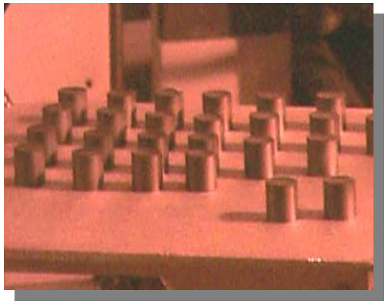
Phase II:
- Fabrication of DUPIC fuel rods/ pellets using spent PWR fuel
- High-power irradiation test at HANARO
- High-burnup irradiation test at HANARO

Phase III:
- Fabrication of DUPIC fuel rods/pellets using high-burnup spent PWR fuel
- Instrumented irradiation test of DUPIC fuel at HANARO

DUPIC Fuel Performance Evaluation

1998 - Installation of DFDF
1999 - Joint Determination (JD)
2000 - Fabrication of DUPIC Pellets and Rods
- High-Power Irradiation Test at HANARO
2002 - High-Burnup Irradiation Test
2004 - Instrumentation Irradiation Test at HANARO
2005 - DUPIC Fuel Fabrication Using High-Burnup Spent PWR Fuel

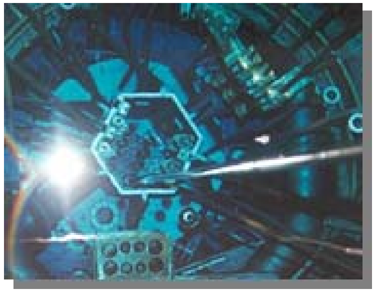
OREOX Powder



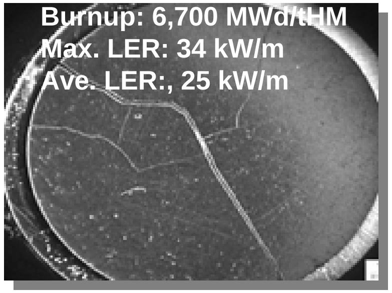
DUPIC Pellets

Remote Welding of Rod

Irradiation Rig



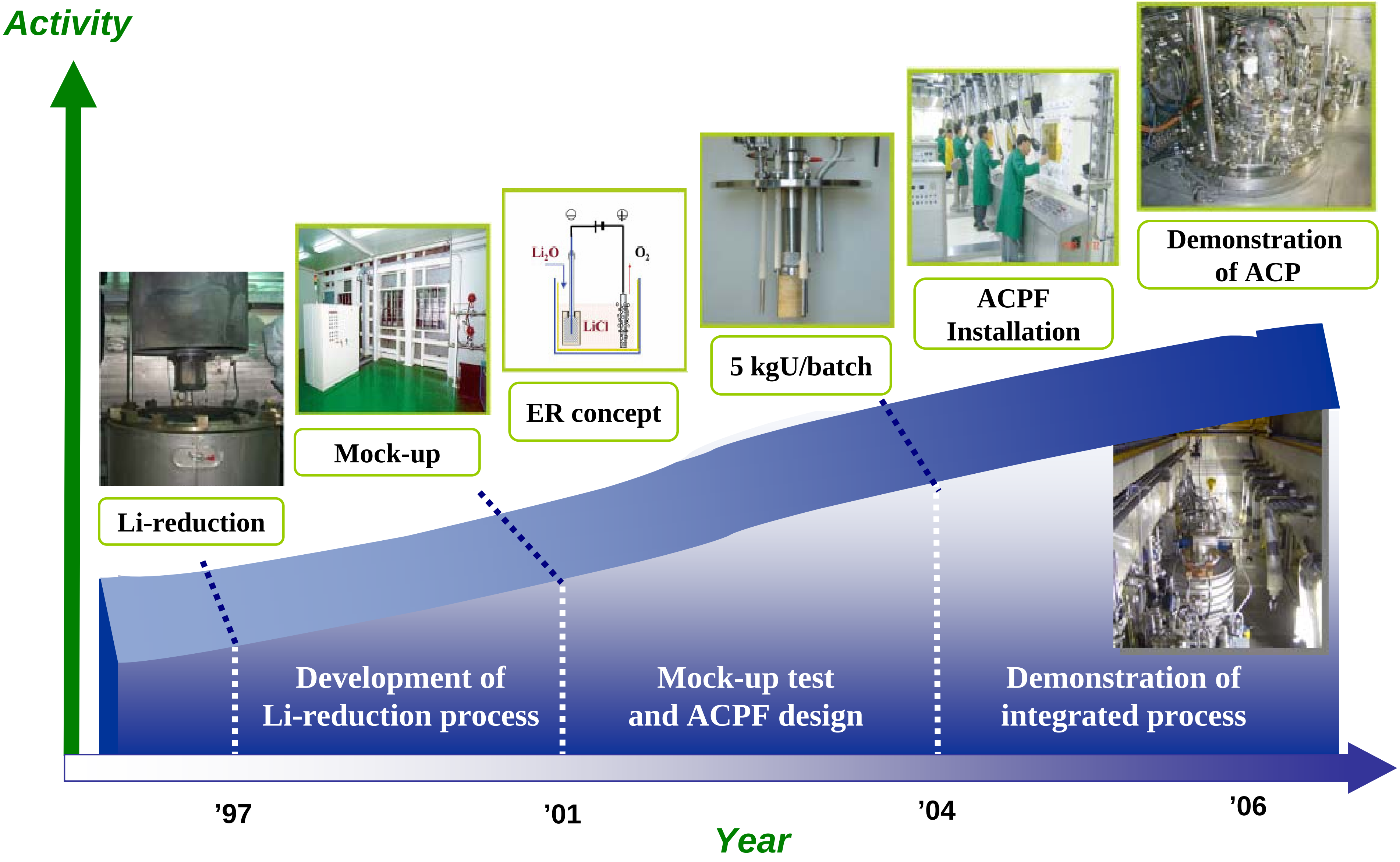
HANARO Irradiation



Post-Irradiation Exam.

DUPIC Fuel Development Facility (DFDF)

Milestones of ACP Development



Activity

Li-reduction

Mock-up

ER concept

5 kgU/batch

ACPF Installation

Demonstration of ACP

Development of Li-reduction process

Mock-up test and ACPF design

Demonstration of integrated process

’97

’01

’04

’06

Year

Lab-scale ACPF

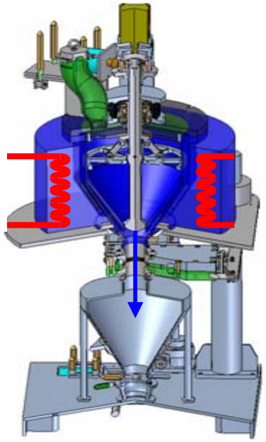
- **20 kgHM/batch Demonstration Process**
  - **Remote Operation and Maintenance**
  - **Interface Systems between Process Steps**
  - **Performance Evaluation of Process Systems**

Working Area

Inside Process Hot Cell

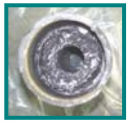
Main System of ACPF

Slitting Device



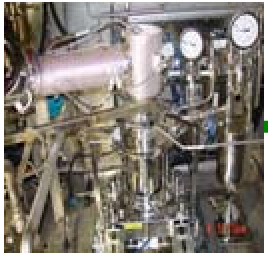
Voloxidizer

ER Reactor



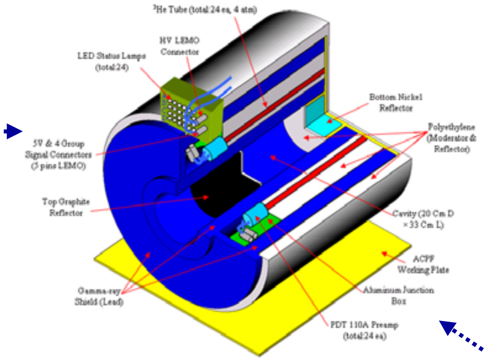
Smelter

U metal Ingot



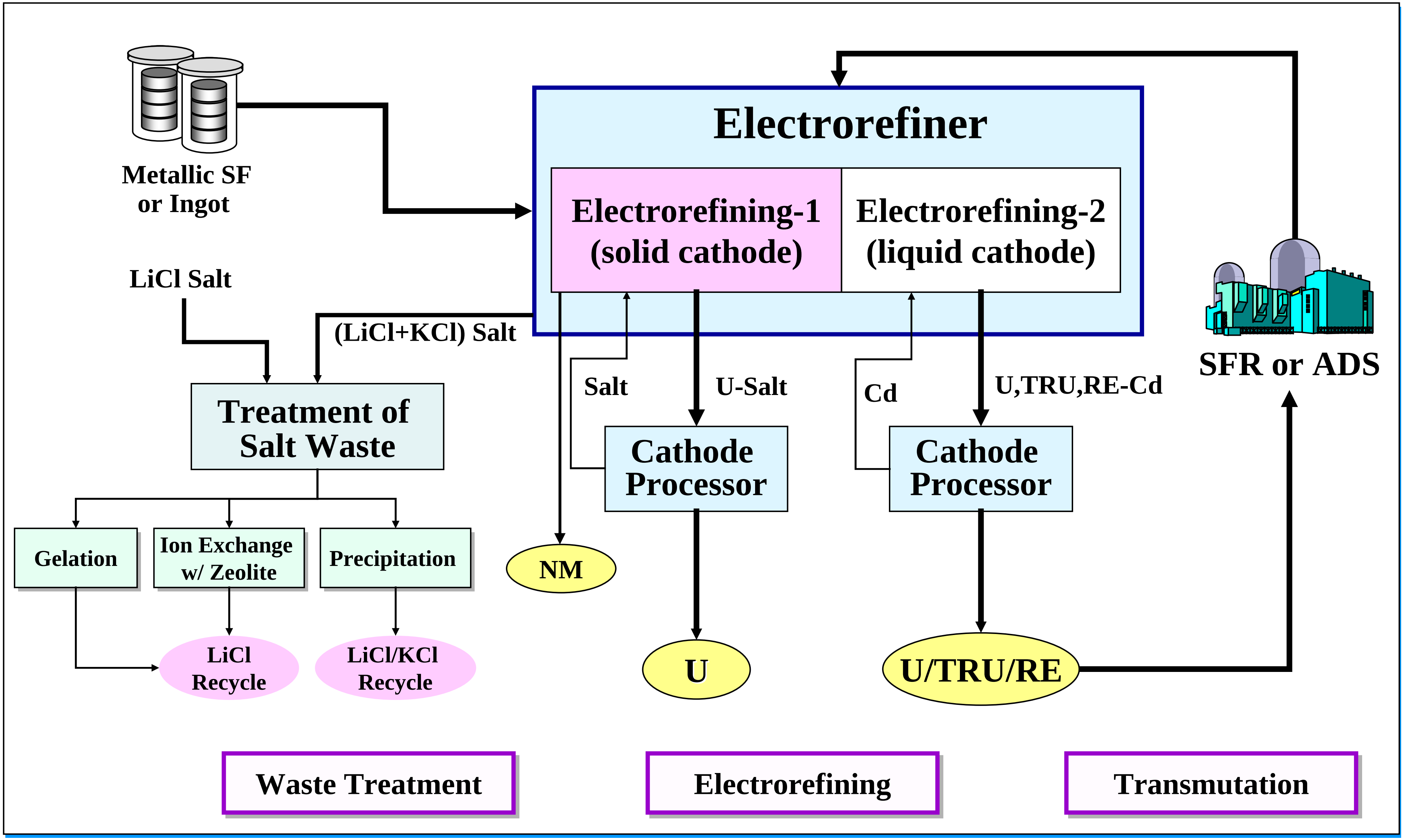
Waste Salt Conditioner

Salt Ingot



ACP Safeguards Neutron Counter

Pyro P&T


Metallic SF
or Ingot
LiCl Salt
(LiCl+KCl) Salt
Electrorefiner
Electrorefining-1
(solid cathode)
Electrorefining-2
(liquid cathode)
SFR or ADS
Salt
U-Salt
Cd
U,TRU,RE-Cd
Treatment of
Salt Waste
Cathode
Processor
Cathode
Processor
Gelation
Ion Exchange
w/ Zeolite
Precipitation
NM
LiCl
Recycle
LiCl/KCl
Recycle
U
U/TRU/RE
Waste Treatment
Electrorefining
Transmutation

Electrorefining

Mock-up for U Electrorefining Experiments

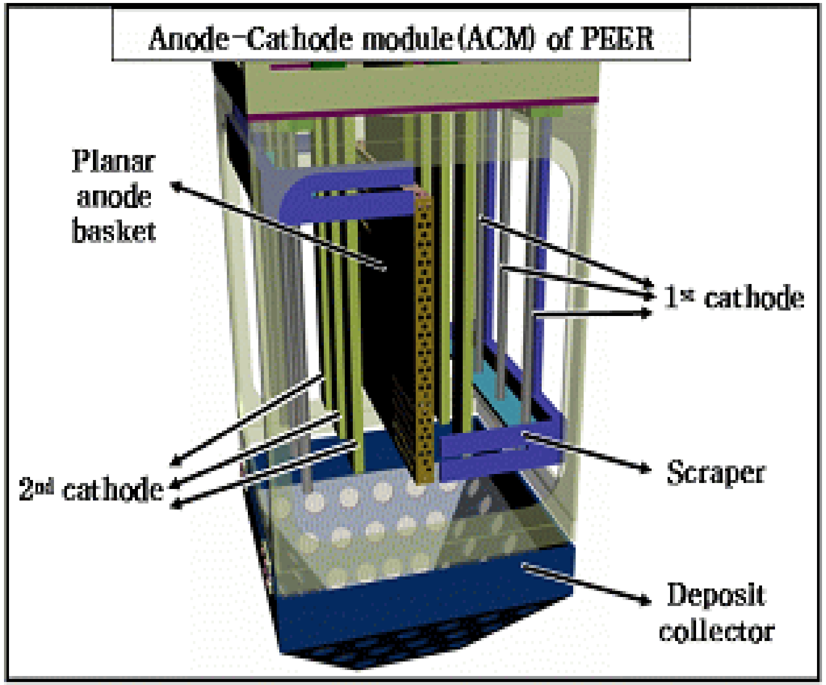
- 1 kgU/batch scale
- U electrorefiner & cathode processor

Electrorefiner

U-deposited Cathode

Cathode Processor

Example of Innovative Electrorefining Development

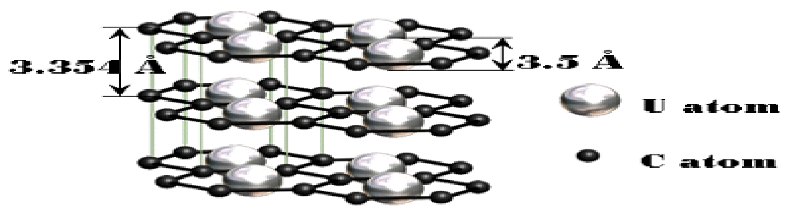

Anode-Cathode module (ACM) of PEER

Existing Cathode

- Necessity of scrapper to recover uranium dendrite during electrorefinning
- Occurrence of operation discontinue due to sticking between uranium dendrite and scrapper
- Impediment of high-throughput operation

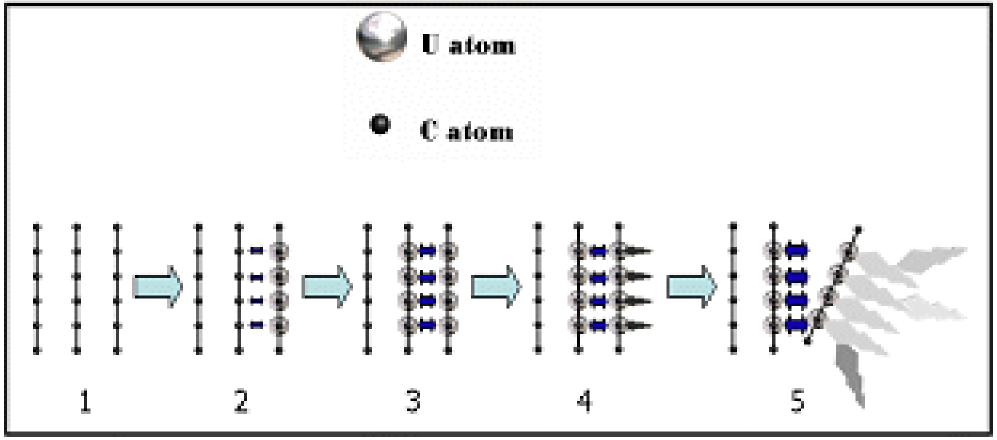
Graphite Cathode

- Keeping a relatively clean surface during electrorefinning without scrapping
- Spontaneously felling down uranium deposit into the collector



Formation of graphite intercalate

- The size of U atom is larger than the lattice distance of graphite
- The intercalation reaction cause lattice destruction of graphite



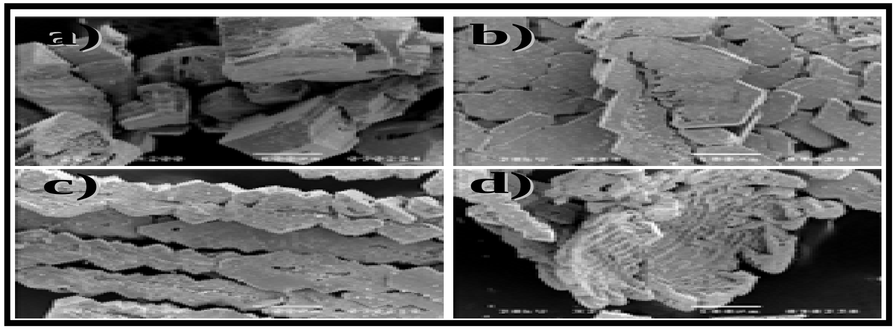
Experimental Results by Using Graphite Cathode

Graphite Cathode for High-throughput Electrorefining

- **Self-scrapping of the deposited uranium dendrite**
- **Improving current efficiency and continuity of an operation**

Graphite Cathode

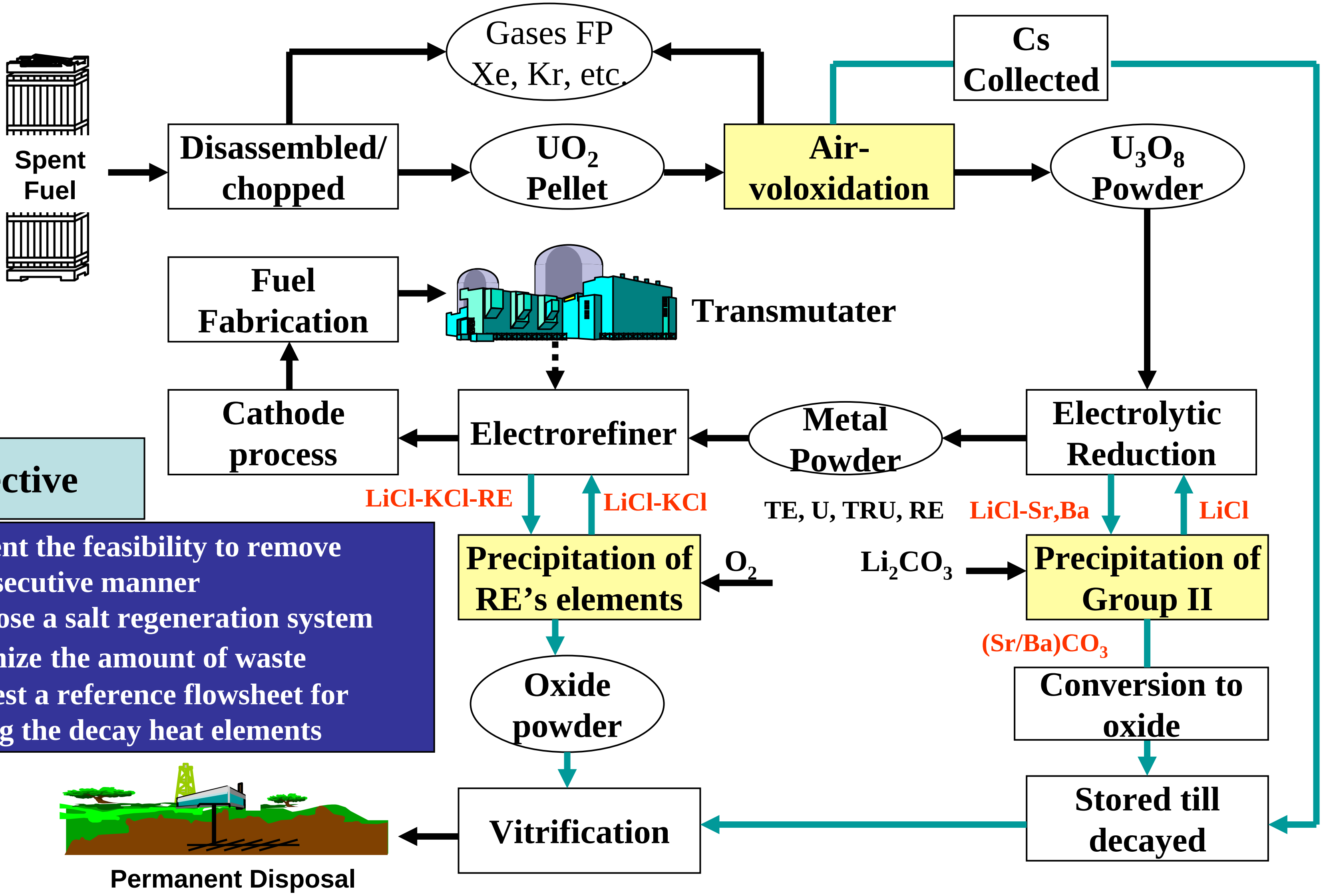
Self-scrapped Uranium Dendrites



a)100mA/cm^2 b)70mA/cm^2 c)140mA/cm^2 d) 177mA/cm^2

- The morphology of U deposit was not changed with current density
- The recovered deposit was metallic U, but little contamination(300ppm) of C was detected
- The effect of the minute C is not clear, but the carbon might be cleaned by using yttrium during casting($2UC+Y \rightarrow 2U+YC_2$, YC_2 will be floated on the U melt)

Strategy of Waste Salt Treatment



Objective

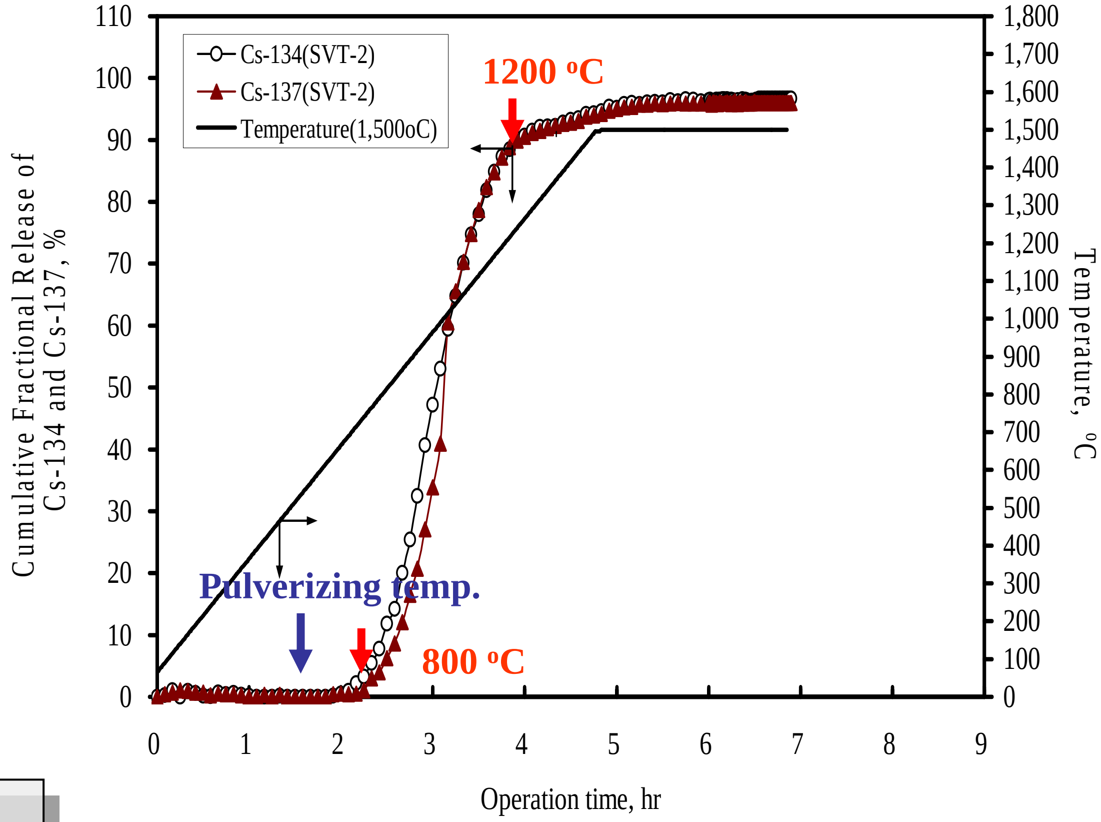
- To present the feasibility to remove in a consecutive manner
- To propose a salt regeneration system to minimize the amount of waste
- To suggest a reference flowsheet for removing the decay heat elements

Cumulative Release Fraction of Cs during Voloxidation

Release behavior of Cs

☐ Cs release
- Starting at about 800 °C
- Obtaining about 90 % release fraction at 1200 °C
- Removing higher than 95 % of Cs at 1500 °C

☐ No release of Cs at the pulverizing temperature of a sintered UO_2 pellet to U_3O_8 powder



Cumulative release fraction of Cs-134 and Cs-137

Further Study

☐ Effect of a characteristics of U_3O_8 powder heated to high temperature to remove Cs on oxide reduction at the electroreduction

Removal of Sr from Waste LiCl Salt by Precipitation

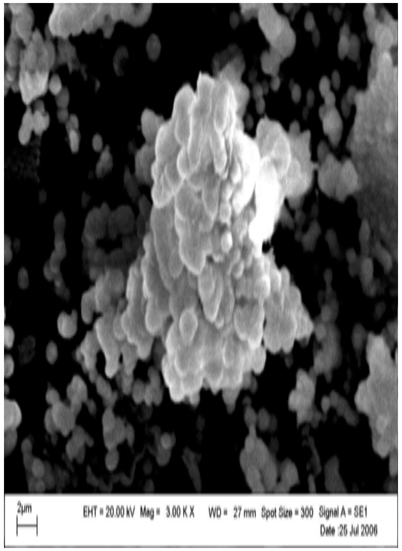
LiCl-$SrCl_2$ Salt

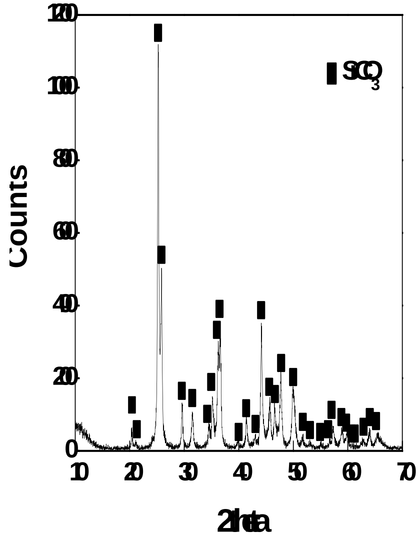
Li_2CO_3

Carbonate Precipitates
(small size precipitator)

- **Equipment**
  - -10 g of LiCl salt in capacity
  - -Stirring for mixing
  - -Alumina crucible
  - -Inert Atmosphere (N_2)

- **Operation Conditions**
  - -Temp. = 750 °C
  - -Using a fixed Sr content [Sr wt.%=2.38]
  - -Molar ratio of **[$Li_2CO_3/SrCl_2$= 1 ~ 5]**



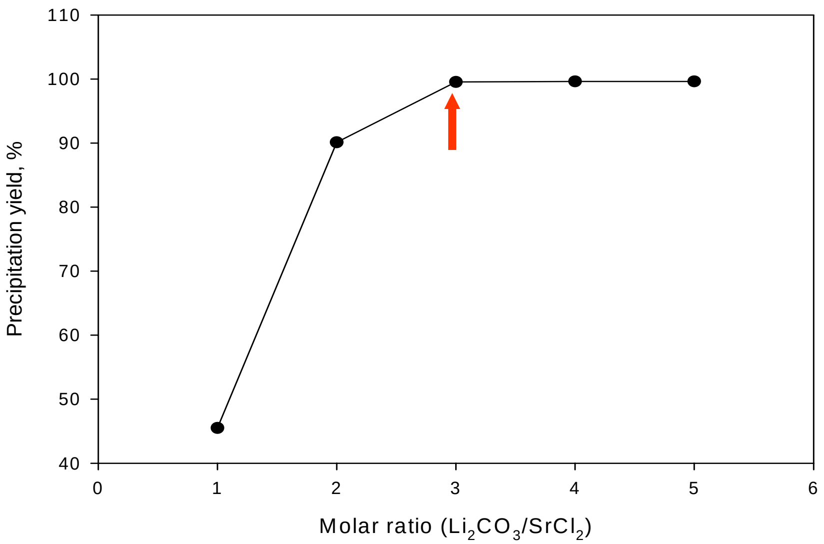


- **Recovery of precipitate**
  - -The salt dissolved in cold water, the resulting precipitate recovered, dried and analyzed

- **Analysis instruments : XRD, SEM, ICP**

- **Precipitation Mechanism**

$$SrCl_2 + Li_2CO_3 \rightarrow SrCO_3 + 2LiCl$$



Removal of Rare earth Elements from Waste LiCl-KCl Salt by Oxidation

- **Objective of this study**

  To remove rare earths as a precipitate by the reaction with oxygen gas

- **Equipment**

  -The oxygen bubbling through the salt containing rare earth in an alumina crucible

  -The loaded salt: 207 g (LiCl- 44.2wt.%)

- **Operating Conditions**

  -Contents of RE: 2.8 %-Y, 3.0%-Ce, 2.5%-Nd, 6.0%-Pr, 6.5%-La, 5.5%-Gd

  -Operation temperature: 723 – 1023 K

  -Oxygen flow rate: 1.5 ℓ/min

  -Measurement of RE contents in the salt by ICP

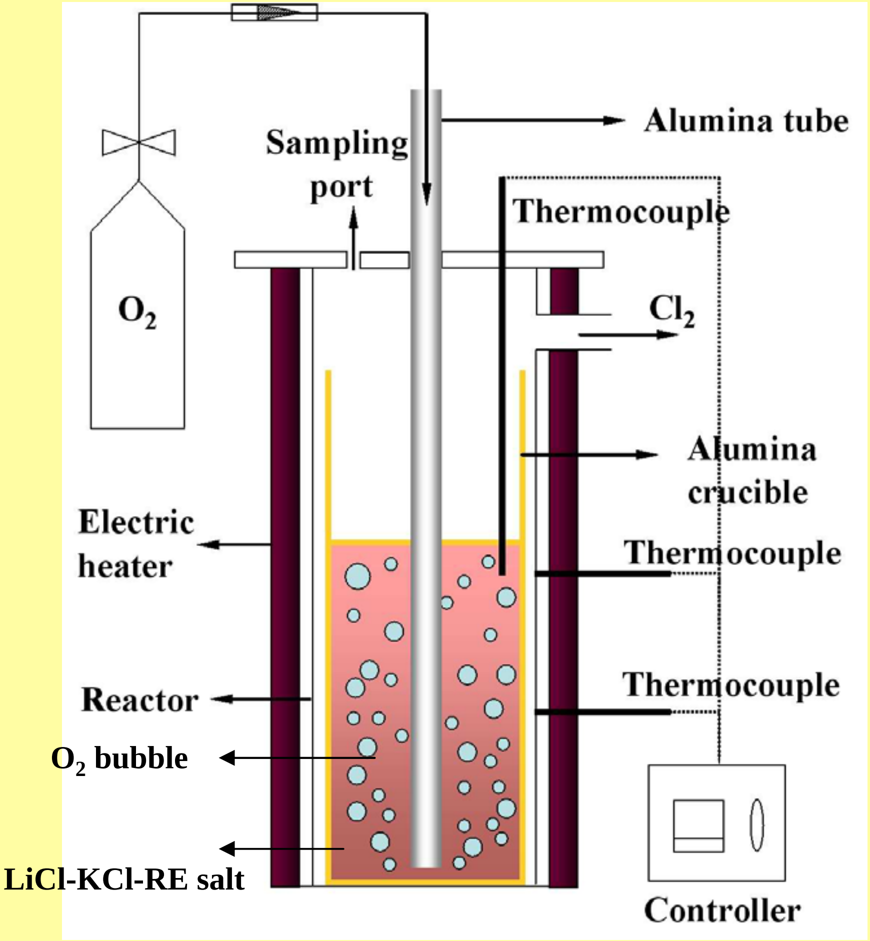
- **Experimental content**

  -Identified the produced precipitates by XRD

  -Established precipitation mechanisms

  -Calculated Precipitation-Conversion yields with an variance of temperature and time

  -Evaluated oxydation-precitation kinetics



- *Alumina crucible : 6cm I.D., 15cm H.*
- *Heater : surrounding ceramic heater*
- *Oxygen sparger : 7cm I.D.(1mm I.D. hole size ×10)*

Precipitation Yields of Rare Earth Elements

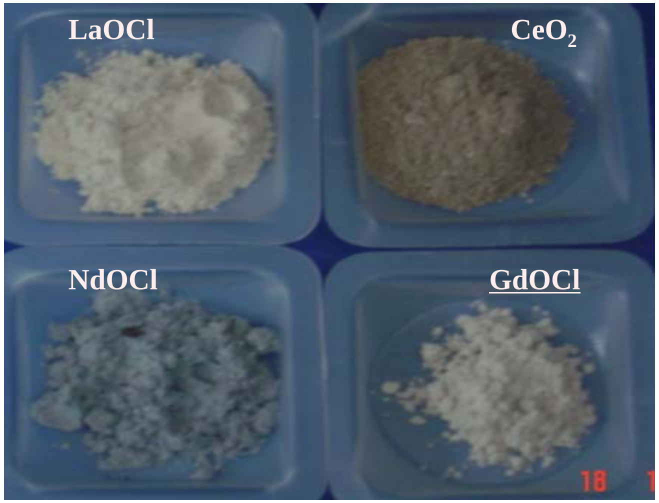
Precipitation yields of $RECl_3$
(O_2 flow rate: *1.5 ℓ/min, Time: 7 hours*)

$RECl_3$ \ T(K)	723	823	923	1023
YCl_3	**56.87**	**71.76**	**98.08**	**99.91**
$LaCl_3$	**33.26**	**63.44**	**86.42**	**94.39**
$CeCl_3$	**99.87**	**> 99.98**	**> 99.98**	**> 99.98**
$PrCl_3$	**55.08**	**87.84**	**99.94**	**> 99.98**
$NdCl_3$		**99.77**		**99.91**
$GdCl_3$		**95.68**		**> 99.89**

- **Precipitation yields of each element**

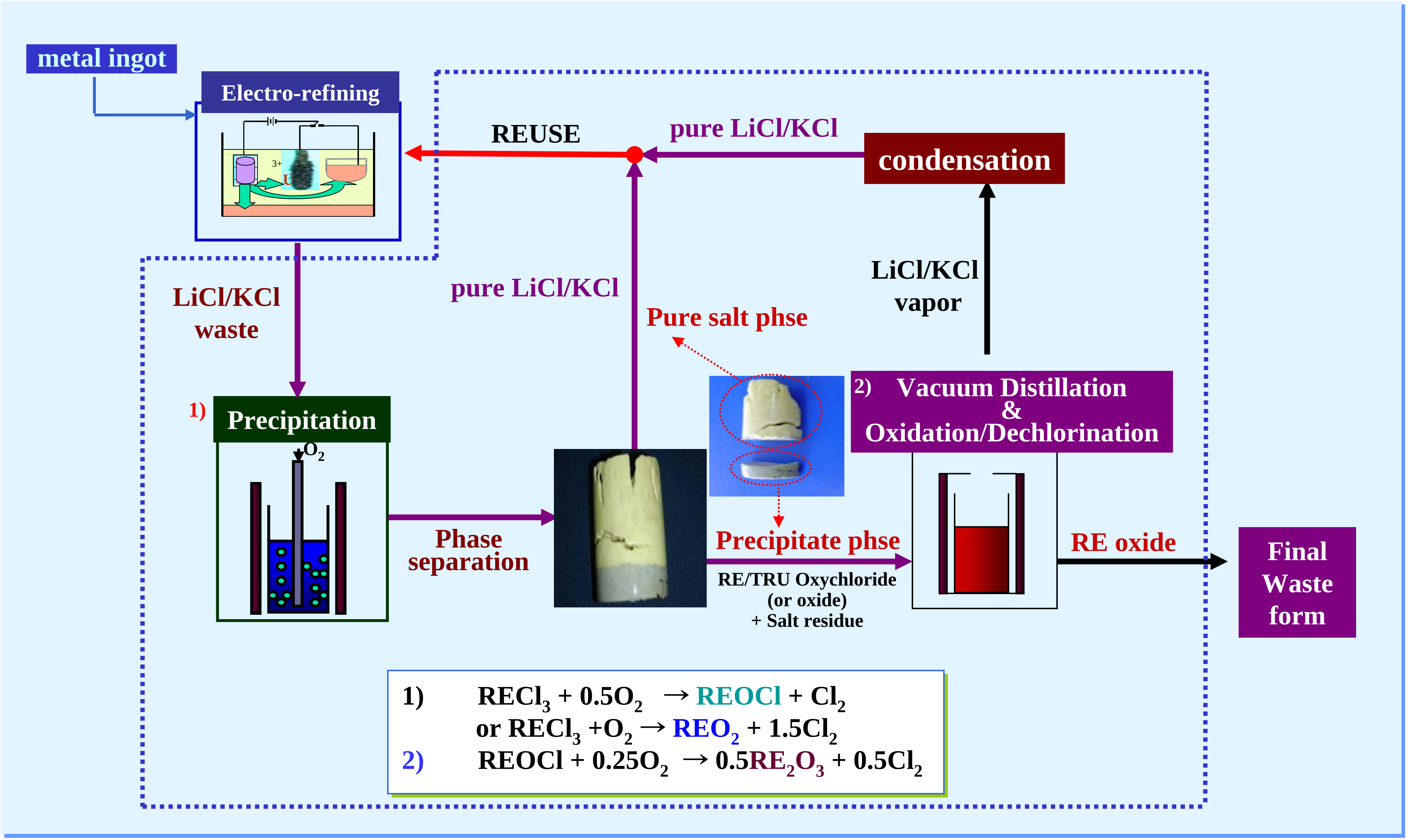
-All of rare earths: precipitation yield of higher than 99 %
-Ce: over 99 %, irrespective of temperature
-La recovered to less than 95 %, compared to others

phase separation



precipitates

Schematic Diagram for Waste Salt Recycle

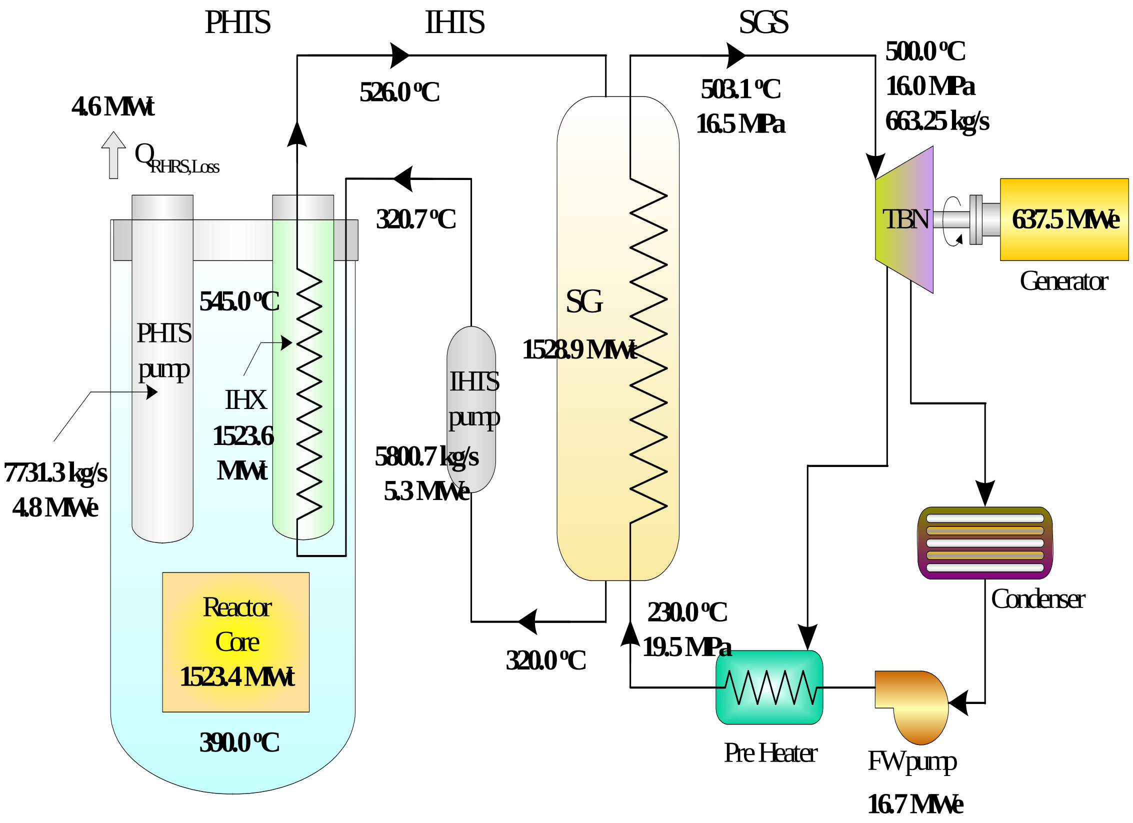


1) $RECl_3 + 0.5O_2 \rightarrow REOCl + Cl_2$

or $RECl_3 + O_2 \rightarrow REO_2 + 1.5Cl_2$

2) $REOCl + 0.25O_2 \rightarrow 0.5RE_2O_3 + 0.5Cl_2$

SFR-KALIMER-Development Plan



KALIMER-600 Steady State Heat Balance

Objective

-To develop energy generation as well as transmutation of long-lived nuclide

-To develop a advanced conceptual design of a SFR consistent with the GEN-IV SFR System Research Plan.

- **KALIMER-600**

  -Pool-type Sodium-cooled Fast Reactor

  -Fuel Type: **U-TRU-Zr metal fuel**

  -Reactor design life time: 60 years

- **NSSS of KALIMER-600**

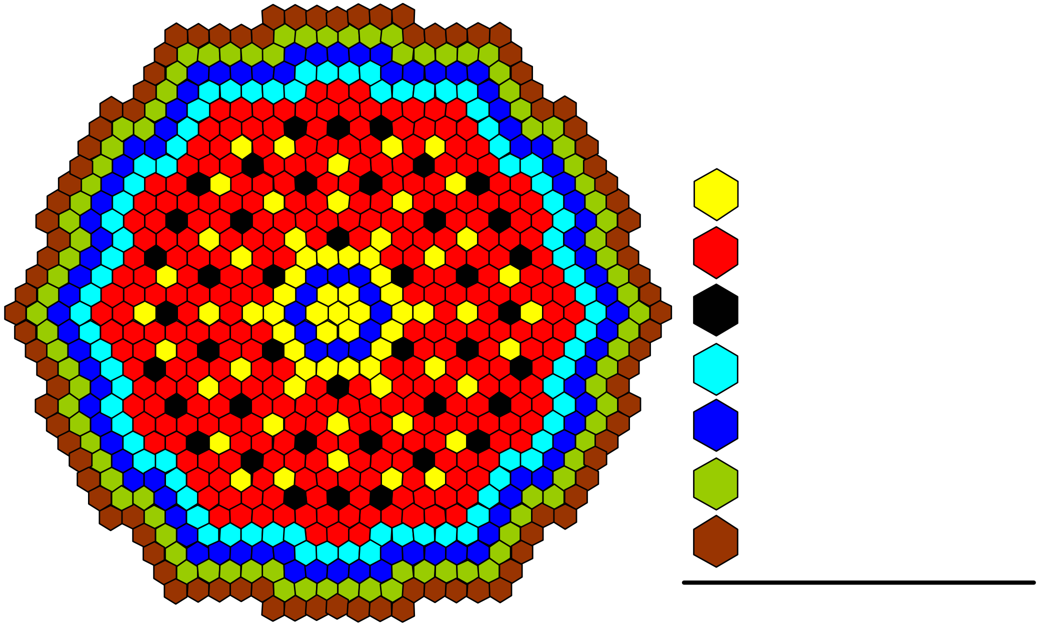
  -PHTS (Primary Heat Transport System)

  -IHTS(Intermidiate Heat Transport System)

  -SGS(Steam Generation System)

600MWe TRU Transmutation Core Design

- **Metal fuels with recycle of transuranics by pyroprocessing**
- **Enhanced proliferation resistance by removing blanket assemblies**
- **Core design studies for TRU transmutation**
- **Transmutation of TRUs produced by 2 LWRs of the same power and cycle length**



Thermal Output (MWth)	1,523
Active Core Height (cm)	90
Equivalent Active Core Diameter (cm)	483.8
Average Breeding Ratio	0.6562
Cycle length (EFPM)	11
Fuel Batches	6
Fuel Composition	U-TRU-10Zr
TRU in Heavy Metal (%)	34.2
Burnup Reactivity Swing (pcm)	3014
Average Core Power Density (W/cc)	223.8
Power Peaking Factor (BOEC/EOEC)	1.509/1.479
Average Discharge Burnup (MWD/kg)	121.7
Peak Fuel Discharge Burnup (MWD/kg)	181.7
Peak Fast Neutron Fluence (10^{23} n/cm^2)	3.83
Effective Delayed Neutron Fraction	0.00312
Sodium Void Worth (pcm)	821

Future Plan for KIEP-21

Phase IV

’07

’11

Phase V

’12

’16

Pyroprocess scale-up

Eng-scale mock-up demo.

Optimization of processes & equipment

Eng-scale demonstration

PYRO-PROCESS

- Process
  - Electrolytic reduction
  - High-throughput electrorefiner
  - LCC electrowinner
  - Head-end process
  - Salt waste recycle
- System Engineering
  - Safeguards technology
  - Remote technology
  - Waste handling
  - Evaluation of proliferation-resistance

Eng-scale mockup

- Process Optimization
  - Integrated cathode system
  - High-throughput electrorefining system
  - Continuous Salt/Cd distillation system
  - Head-end process
  - Cs/Sr recovery
- System Engineering
  - ESPF safeguards
  - Remotization
  - Process waste handling & storage
  - ESPF design & construction

Eng-scale pyroprocess facility (ESPF)

Modular

High throughput

Simple Design

Easy operational

Minimum waste

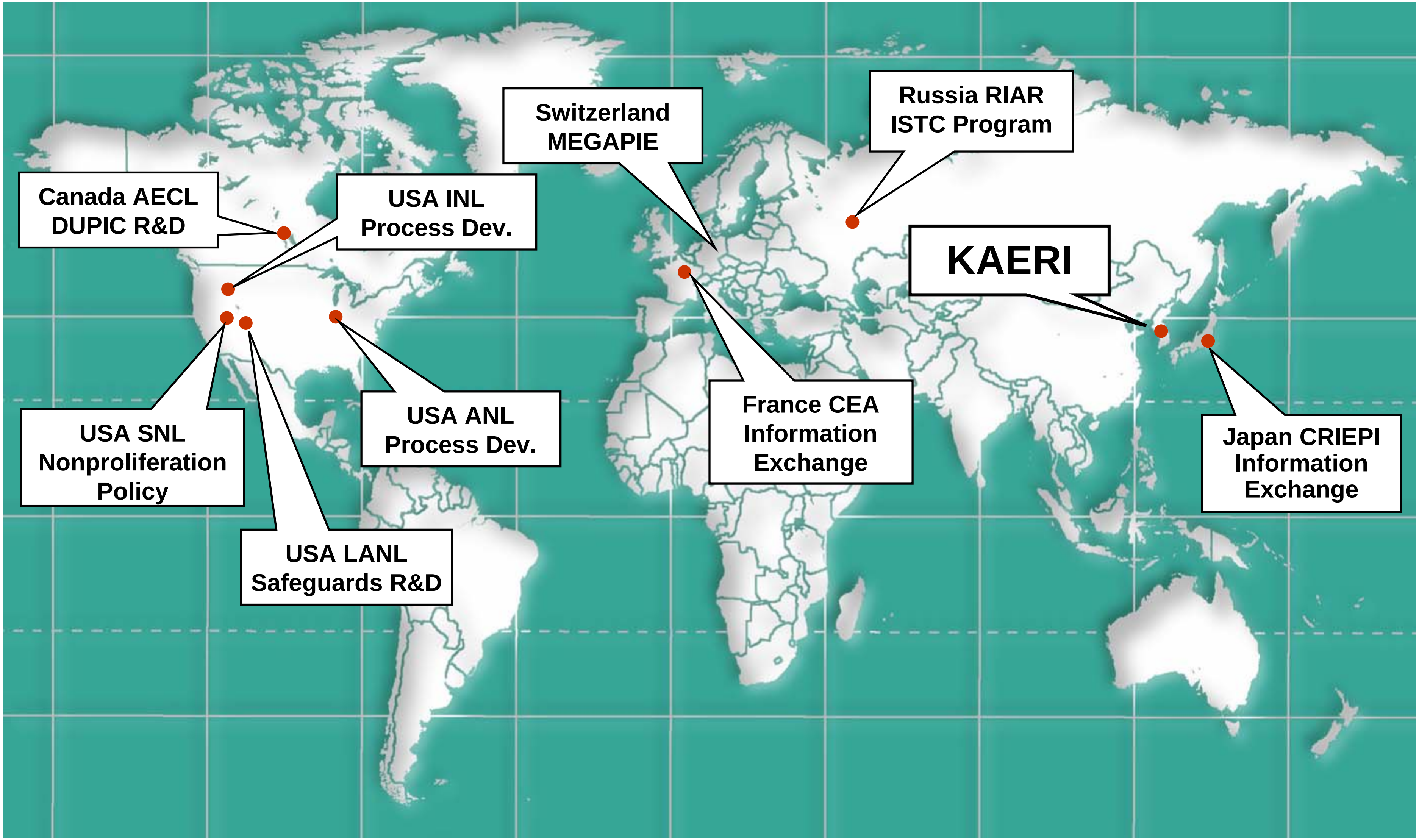
Safeguardable

SFR (KALIMER)

- Conceptual design of core and reactor system
- Advanced R & D: improvement of economics, safety and metal fuel
- Basic Key Technology Development: computational tools and sodium technology

Advanced SFR Conceptual Design

International Collaboration



Switzerland MEGAPIE

Russia RIAR ISTC Program

Canada AECL DUPIC R&D

USA INL Process Dev.

KAERI

USA SNL Nonproliferation Policy

USA ANL Process Dev.

France CEA Information Exchange

Japan CRIEPI Information Exchange

USA LANL Safeguards R&D

Conclusion

- Recently, Korea has been focusing on the development of a pyroprocess, by targeting a reduction of the volume, heat load and toxicity of the spent fuel and its application to the GEN-IV reactor systems through recycling and transmutation to close the fuel cycle
- The KIEP-21 based on pyroprocessing technology is expected to meet the challenges and will be harmonized with the GEN-IV reactor system development schedule
- This program will be continue through the long-term nuclear R & D plan of Korea by 2016
- International collaboration is essential and expected for the timely implementation of the pyroprocessing and transmutation technologies.