中国原子能科学研究院
中核集团 CNNC CHINA INSTITUTE OF ATOMIC ENERGY

IAEA TWG-NFCO, Apr. 16-18, 2024

The Strategy of Spent Fuel Management in China

Rushan LIN

China Institute of Atomic Energy

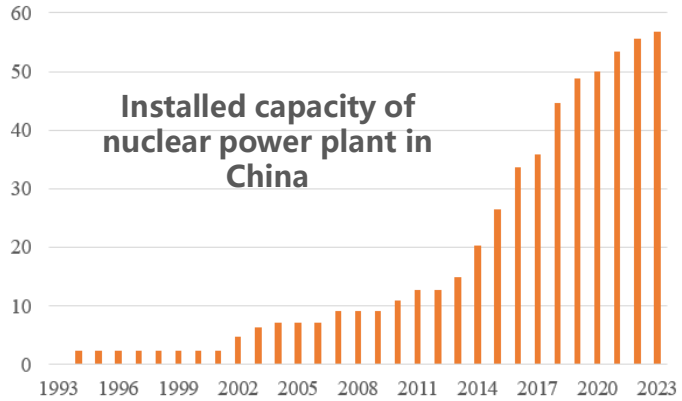
China National Nuclear Corporation

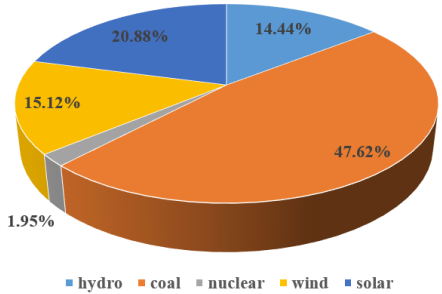
CONTENTS

01 Overview of nuclear energy prospect in China

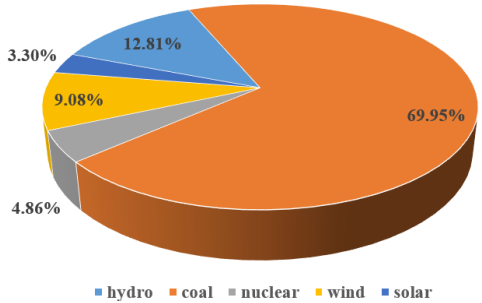
1.1 Energy production structure

- **Till December 2023, the nuclear power installed capacity of China arrived 56.78GW.**
- **The cumulative on-grid nuclear power was 406.709 billion kWh in 2023, increasing 4.05% from the same period in 2022.**
- **The utilization hours of installed nuclear power were 7661.08 hours, and the average unit capacity factor was 91.25%.**
- **Compared with coal power, nuclear power reduced the burning of standard coal by 123.395 million tons and reduced CO_2 emissions by 32.33 million tons, sulfur dioxide by 1.045 million tons, and nitrogen oxide by 913,100 tons.**



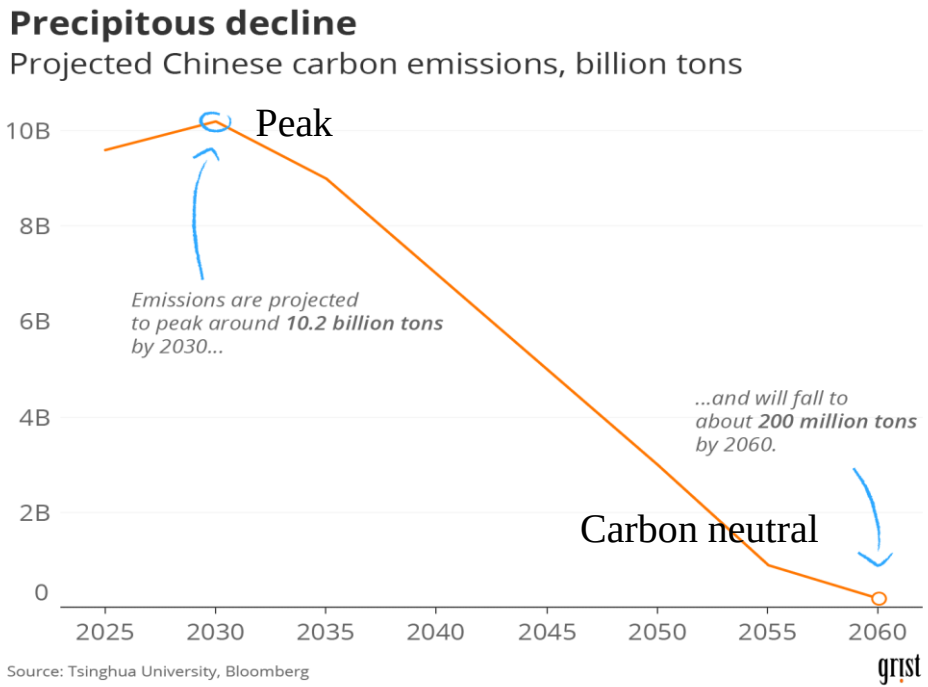


proportion of installed power capacity in 2023



proportion of China's electricity generation in 2023

1.2 China's commitment to carbon reduction



- China promised in Paris Climit conference，“Non-fossil Energy in China will account for about 20% of Primary Energy consumption”.It is expected that nuclear power will have more greater development by 2030.
- Chinese President Xi Jinping promised at the UN general conference in Sept 2020,"China will improve its country's independent contributions and adopt more powerful policies and measures to make carbon dioxide emissions peak by 2030 and become carbon neutral by 2060."
- **Nuclear energy is an important approach for China to carry out the international commitment of reducing carbon emission**

1.3 Status of Nuclear energy policy and Spent Fuel Management

➢ **Nuclear energy policy**

- **The nuclear energy must be developed safely and high efficiently.**
- **The strategy is to develop with three steps: thermal reactors, fast reactors, and fusion reactors.**
- **China has always adhered to the strategy of closed fuel cycle.**

➢ **Status of Spent Fuel Management**

- **Spent fuel storage facilities at some nuclear plants are close to full capacity.**
- **Due to there is no commercial reprocessing plant and the capacity of off-reactor storage pools in existing reprocessing facilities is insufficient, a series of measures have been taken for spent fuel wet storage over the years to increase storage capacity.**
- **Few dry storage facilities for spent fuel were eastablished.**
- **Plan to build commercial reprocessing plant.**

02 Selection of closed fuel cycle roadmap

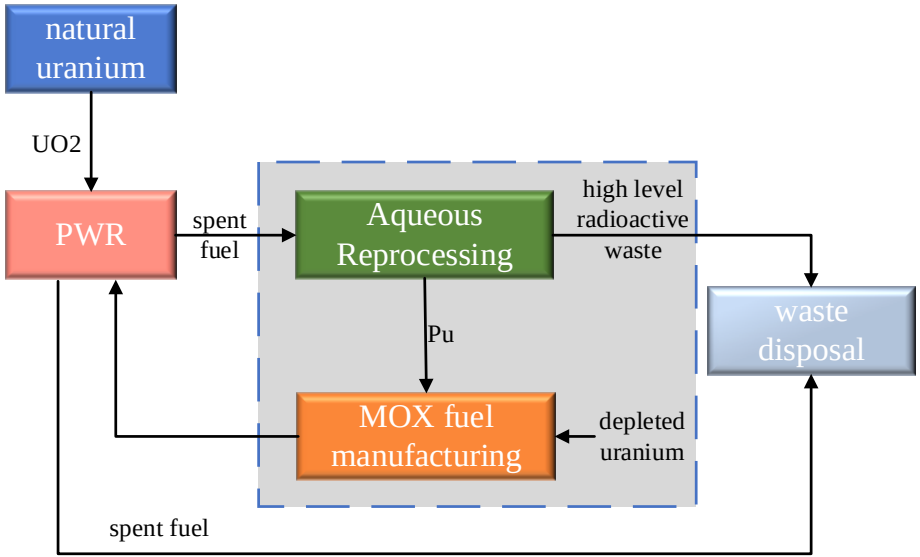
2 Selection of closed fuel cycle roadmap

Three development roadmaps for closed fuel cycles

- **Case1:** Only develop PWR. Spent fuel is processed by Aqueous Reprocessing.
- **Case2:** Develop PWR and MOX fuel FR. PWR spent fuel and FR MOX spent fuel are processed by Aqueous Reprocessing.
- **Case3:** Develop PWR , MOX fuel FR and CiFR (China integrated Fast Reactor nuclear energy system). The spent fuel of the PWR is processed by Aqueous Reprocessing, and the MOX spent fuel of the fast reactor enters the CiFR (spend fuel is processed by Dry Reprocessing).

2 Selection of closed fuel cycle roadmap

☐ Case1: Only develop PWR. Spent fuel is processed by Aqueous Reprocessing.



- **Description:**

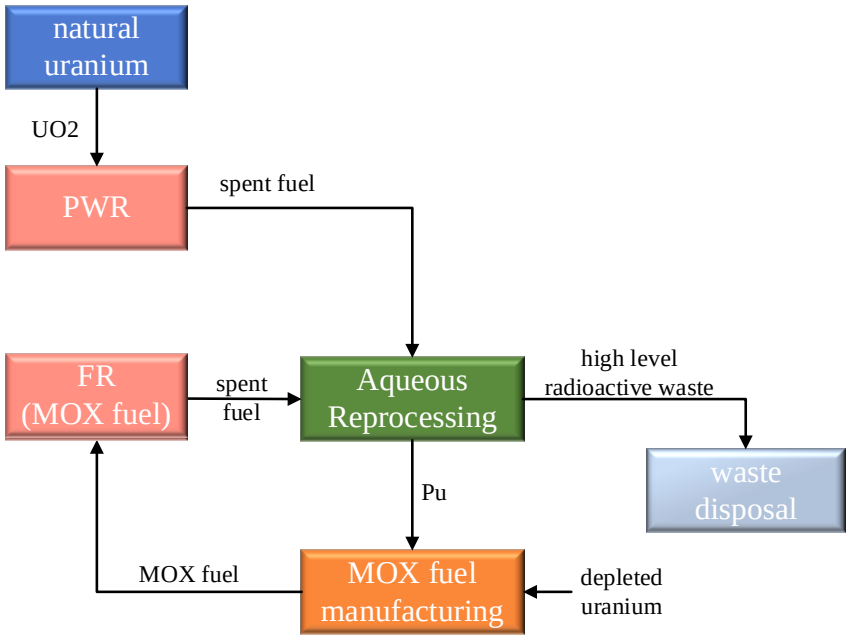
In the PWR MOX cycle, the spent fuel is processed by the Aqueous Reprocessing plant, and the Pu is recovered into MOX and returned to the PWR. Then the spent fuel is disposed of directly as waste.

- **Question:**

Without the development of fast reactors, due to the deterioration of plutonium quality, the number of cycles of recycled Pu in PWR is limited (1 to 2 times), the utilization rate of U resources is limited (only about 14% compared to One Through), and the long-life waste cannot be effectively transmuted.

2 Selection of closed fuel cycle roadmap

- **Case2: Develop PWR and MOX fuel FR. PWR spent fuel and FR MOX spent fuel are processed by Aqueous Reprocessing.**



- **Description:**

The spent fuel of PWR is processed by Aqueous Reprocessing plant, and Pu is recovered to make MOX fuel into MOX fast reactor. Fast reactor MOX spent fuel is treated using Aqueous Reprocessing.

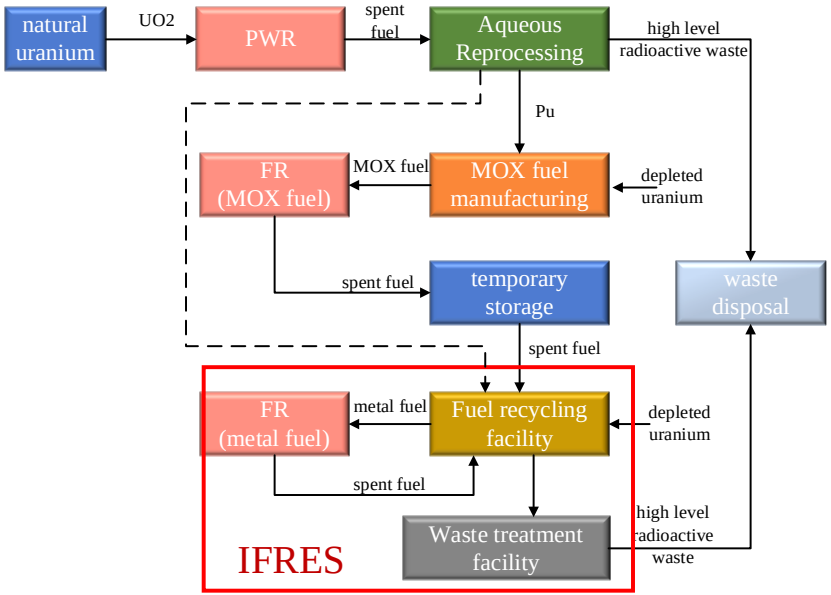
- **Question:**

Aqueous Reprocessing requires high spent fuel cooling time (more than 8 years), resulting in long circulation time outside the fuel reactor and low circulation efficiency;

The reprocessing technology of fast reactor MOX fuel cannot realize the recovery of minor actinide nuclides and cannot reduce the time of radioactive waste supervision.

2 Selection of closed fuel cycle roadmap

- **Case3: Develop PWR, MOX fuel FR and CiFR. The spent fuel of the PWR is processed by Aqueous Reprocessing, and the MOX spent fuel of the fast reactor enters into the CiFR.**



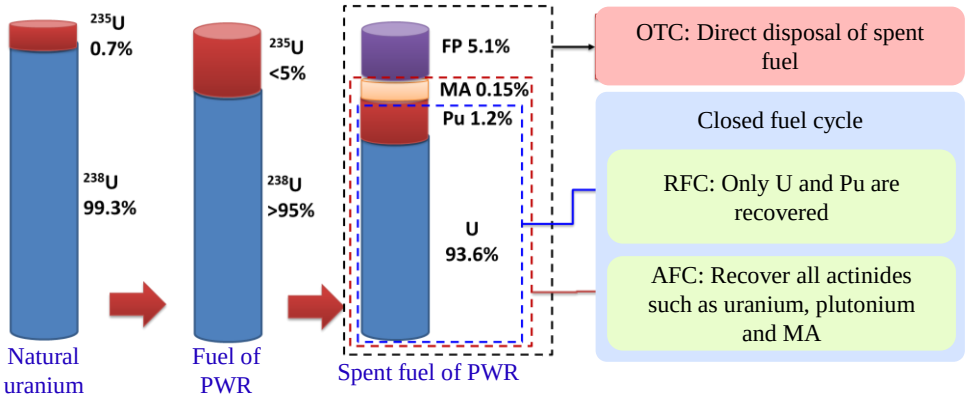
- **Description:**

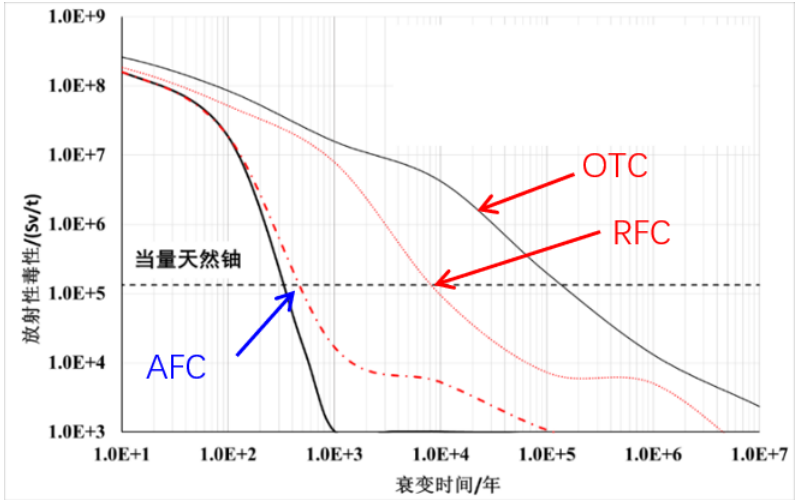
The spent fuel of PWR is processed by Aqueous Reprocessing plant, and Pu is recovered to make MOX fuel into MOX fast reactor. The spent MOX fuel is temporarily stored.

Then the spent MOX fuel enters the CiFR and processed by Pyro-Reprocessing, and the resulting product will be made into metal fuel and enters into the CiFR. The internal circulation of actinide elements is realized in the CiFR.

2 Selection of closed fuel cycle roadmap

- On the basis of U and Pu recovery, all actinide elements such as U, Pu and MA can be recovered and returned to fast reactors for reuse, which can maximize the utilization of U resources and minimize high-level radioactive waste, and comprehensively solve the fundamental problem of the sustainable development of fission nuclear energy.





2 Selection of closed fuel cycle roadmap

◘ Fast Reactor Development Strategy in China

Experimental reactor

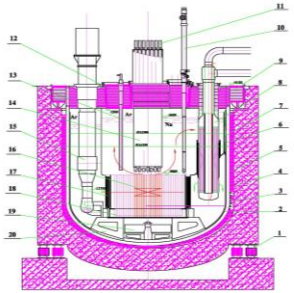
CEFR

2011

Demonstration reactor

CDFR600

2023



Commercial reactor

CiFR1200

~2035

2 Selection of closed fuel cycle roadmap

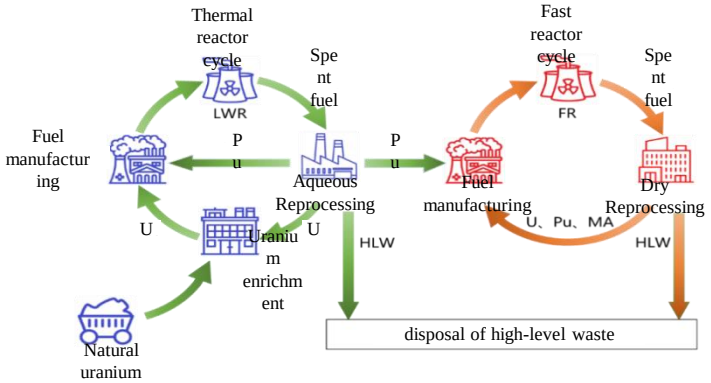
中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

◻ The concept of CiFR

China integrated Fast Reactor Nuclear Energy System is composed of several fast reactors and one fuel regeneration subsystem (Dry Reprocessing + fuel production line) and other supporting subsystems.

It is located at the same nuclear power plant site and forms a complete nuclear energy systems.

It can realize full utilization of uranium resources and minimize waste through rapid circulation and multiple cycles of core fuel in the plant.



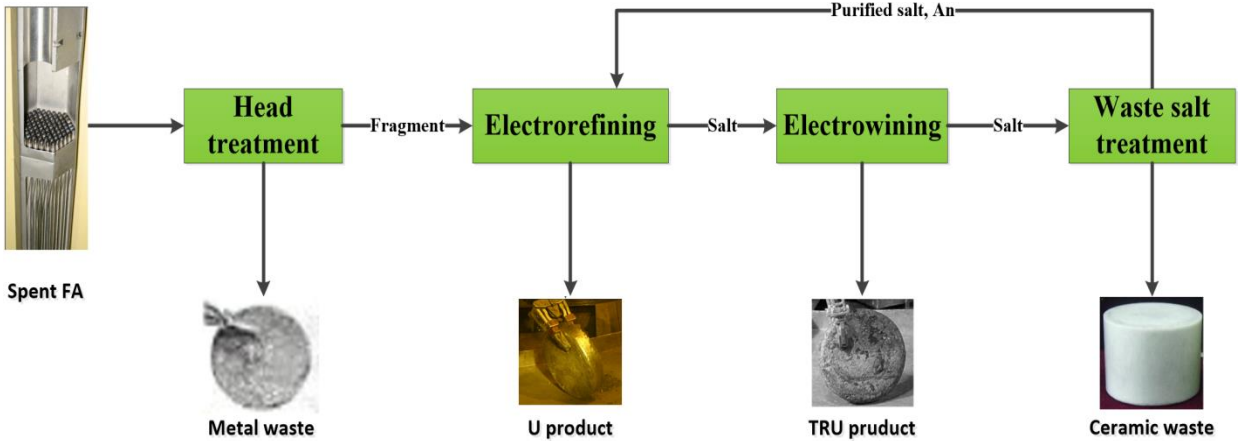
2 Selection of closed fuel cycle roadmap

□ Technical route of pyrorep. for FR SNF

The selection of metal fuel and dry processing technology creates conditions and engineering feasibility for the co-site layout of the reactor, fuel manufacturing plant, and spent fuel reprocessing line, that is, the integration of the fast reactor nuclear energy system.

Dry processing uses inorganic non-aqueous media, which has high radiation stability and does not require long-term cooling of spent fuel.

Dry processing results in U and TRU metal products, which are easy to be directly processed into metal fuels.



2 Selection of closed fuel cycle roadmap

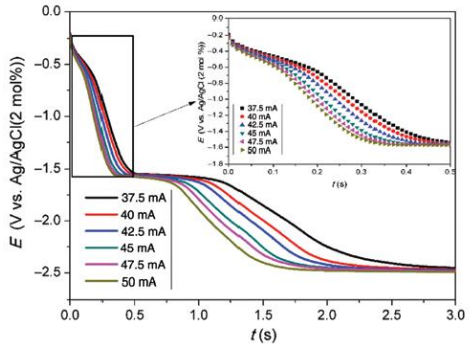
◘ Road map of pyrorep. of FR SNF

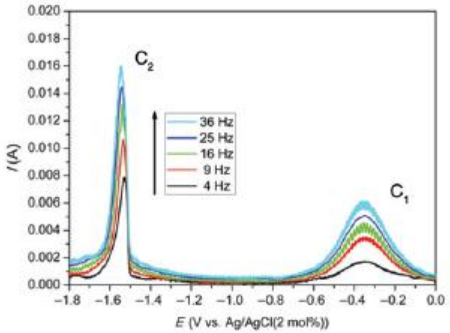
- ✓ **~2020, Basic knowledge of Pyrorep., TRL up to 3;**
- ✓ **~2025, Key technology research and technical route verification, TRL up to 5;**
- ✓ **~2030, Hot test and demonstration of engineering setup, TRL up to 6-7;**
- ✓ **~2035, Pilot demonstration of Pyrorep., TRL up to 8;**

03 Progress of pyroprocess and future plan

3.1 Progress of pyroprocess

☐ Electrochemistry of An in molten salt

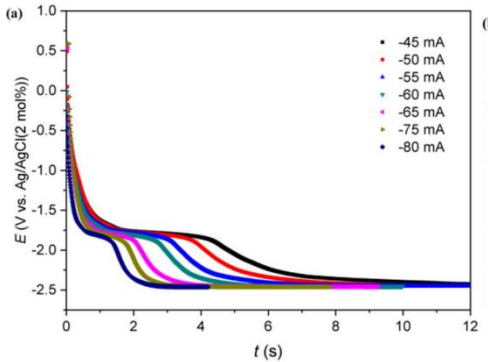


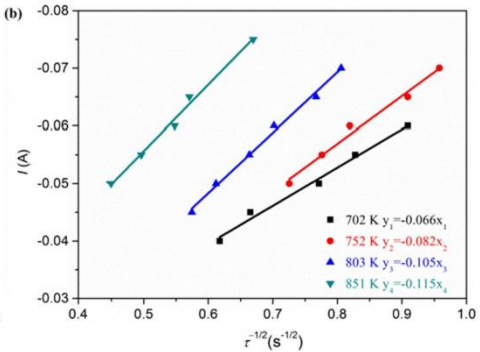


***Radiochim. Acta* 2019, 107(2):95–104**

Mechanism: $U^{4+} \rightarrow U^{3+} \rightarrow U$;

For U(III)/U(0), $E^{*0} = -3.050 + 7.34 * 10^{-5}T$





***J. Radioanal. Nucl. Chem.* 2024, 333:23–30**

Mechanism: $Pu^{3+} \rightarrow Pu$;

For Pu(III)/Pu(0), $E^{*0} = -3.194 + 6.4 * 10^{-4}T$

3.1 Progress of pyroprocess

☐ Separation process of An

- Separation of An(U, Pu) with FP.:

Uranium dendrites were obtained with high purity.

$SF_{U/Fe}$>500, $SF_{U/Ce}$>100

Uranium dendrite

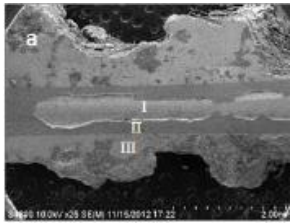
- Electroreduction of uranium oxide:

Uranium metal was obtained with yield above 99.5%.

- Separation of An(U,Th) via Aluminium cathode:

Only Al_3Th was obtained, while 3 uranium species were produced under potentiostatic, namely Al_2U, Al_3U, Al_4U.

Reduced U metal



An-Al alloy

3.1 Progress of pyroprocess

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

☐ Equipment development

Glove box for pyrorep. Studies was established:

- ✓ **Leakage: less than 10^{-5} vol%/h**
- ✓ **Fulfilled with Ar under ~ -300Pa**
- ✓ **Equipped with furnace and radiation shield.**

Batch scale equipment for pyrorep. studies were developed:

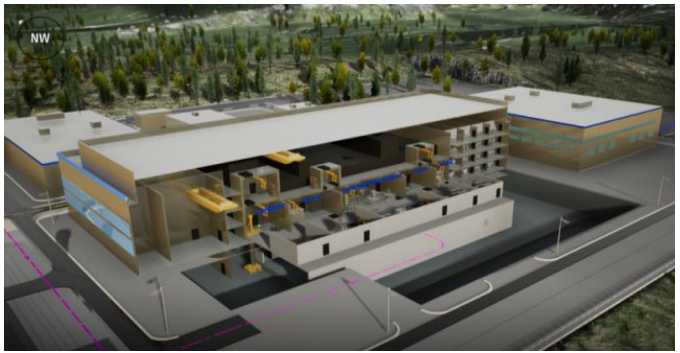
- ✓ **Electrorefining cell, electrowining cell, etc.**
- ✓ **10 kg HM, temperature up to 1000 K .**

3.1 Progress of pyroprocess

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

☐ Conceptual design of the PyroRep. demonstration facility

Conceptual design of PyroRep. demonstration facility was carried out, and main parameters were figured out.



Parameter	Value/Description
1) Reprocessing type	Pyroprocessing
2) Source item received	Spent metal fuels or MOX, without limitation of TRU content, burnup and cooling.
3) Capacity scale	20t/a，200d/a
4) Operating mode	Batch operation, molten salt transportation via pipe and pump.
5) Product form	U ingot, TRU ingot
6) Main sub-items	Spent fuel reception and temporary storage, U/TRU separation and purification, Molten salt treatment and recycle, Actinide product temporary storage, Waste treatment, Analysis and testing, Waste temporary storage, Auxiliary systems, etc.
7) Main product technical specification	U > 98%, $DF_{TRU、RE/U}$ >100 TRU>99.5%, $DF_{RE/TRU}$ >50
8) HAW form	Metal waste, Ceramic waste

3.2 Future plan

☐ Medium-long term plan

Feasibility analysis of flowsheet, basic research, technical route verification.

Hot test, demonstration of engineering setup

Pilot plant, demonstration of closed fuel cycle of FR

MOX/Metal → Metal

Commercial plant, industry application of PyroRep.

3.2 Future plan

☐ R&D Work in the Future

- **Key technologies to realize advanced features**

Technologies that require increased maturity include advanced closed fuel cycle, reactor core fit for full actinide cycle, fuel technology, and pyro processing technology.

- **Key technologies to realize economy**

In order to achieve commercialization, every stage of the fuel cycle should have a high economy

- **Key technologies to realize safety**

In order to be able to deploy, every stage of the fuel cycle should have a high level of security

3.2 Future plan

☐ Potential area for collaboration

- Pyroprocess equipment design
- Process monitoring and control of electrochemical Processes
- Partition of actinides from lanthanides
- Pretreatment and recycle of molten salts
- Integrated process study
- Corrosion behavior of structure materials in molten salts at high temperature
- …

04 Summary

4 Summary

- Nuclear energy is an important issue to realize the CO_2 neutral.
- At present, China's nuclear power development space is broad.
- To cope with the prospect of a large amount of spent fuel, China is sticking to the closed fuel cycle.
- Among the different closed fuel cycle roadmaps, China intends to adopt the all actinide cycle closed cycle route.
- A noval nuclear energy system of Integrated fast reactor (with inner fuel cycle) will be developed to build a binary nuclear energy system.
- Pyroprocessing via electrochemical process is the technical choice for the treatment of FR SNF.
- The spent fuel of fast reactor can be treated quickly by pyrorep., MA will be recovered with plutonium without pure plutonium steam.

Thank you for your attention!