Technological Innovations to Change Radioactive Waste into Resources

-The Key to Sustainable Nuclear Energy Utilization-

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Three Pillars of R&D in JAEA

- **Synergy** of Nuclear ×Renewable
- Make nuclear power itself **Sustainable**
- Diversification of nuclear energy utilization （**Ubiquitous**）

Technology to Change Radioactive Waste into Resources

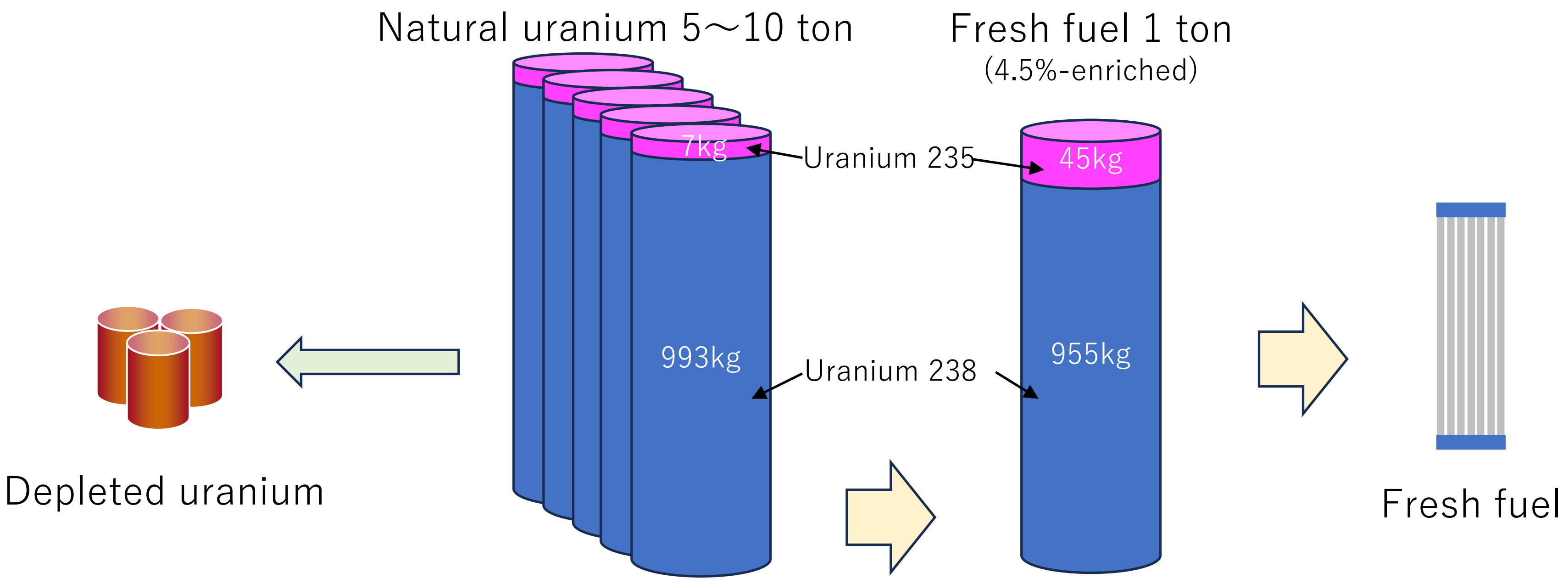
1. Storage battery use of depleted uranium
   (**Synergy**, **Ubiquitous**)

2. Utilization of elements in spent fuel
   (**Sustainable**)

3. Power generation by heat and radiation
   (**Ubiquitous**)

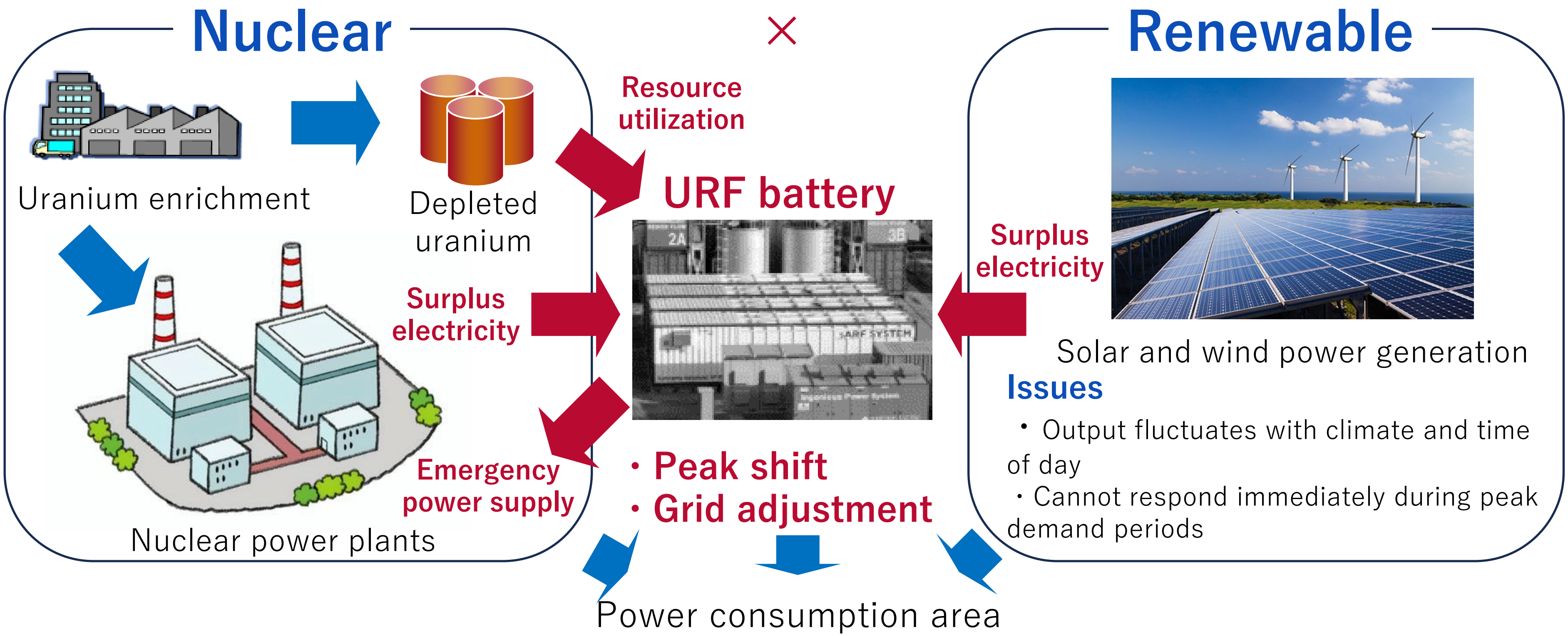
16,000 tons

Background: Storage battery use of depleted uranium



- Fresh fuel for nuclear power plant is enriched uranium.
- Depleted uranium is stored for future use in fast reactors.
- **About 16,000 tons** of depleted uranium are stored in Japan (as of 2021)

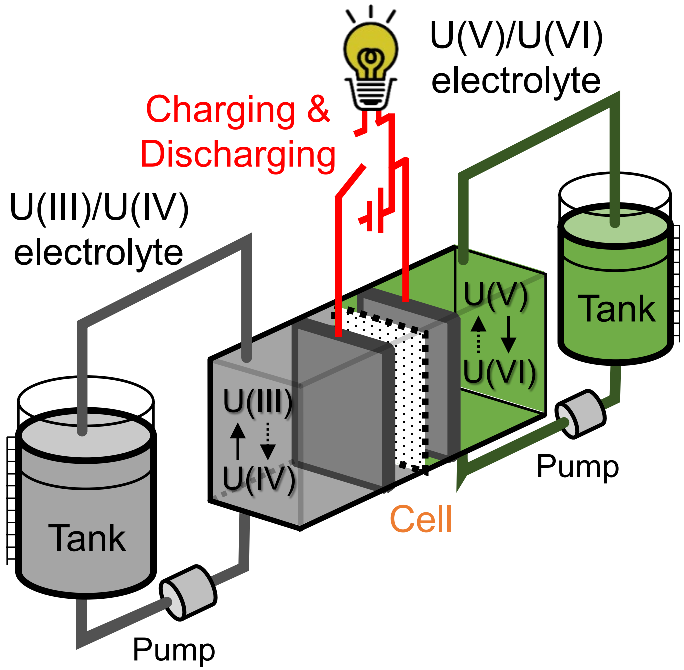
Purpose



- Develop uranium-based redox flow battery (URF battery) to convert depleted uranium into resource.
- Store surplus electricity from renewable energy and nuclear power generation to contribute peak shift and grid stabilization.

“Sumitomo Electric Industries Redox Flow Battery 202103"
Sumitomo Electric Industries Technical Document

URF battery



- Storage battery that charges and discharges by promoting the redox reaction of ions through pump circulation.
- Focusing on the oxidation/reduction reaction of uranium (using the oxidation states of trivalent (U^{3+}), tetravalent (U^{4+}), pentavalent (UO_2^{+}), and hexavalent (UO_2^{2+}))

Large capacity： 30,000 kWh※ (for 3,000 house/day) in one URF with 650 tons of uranium. (16000 tons equals 740,000 kWh)

Low running cost： Almost no performance degradation to charging and discharging.

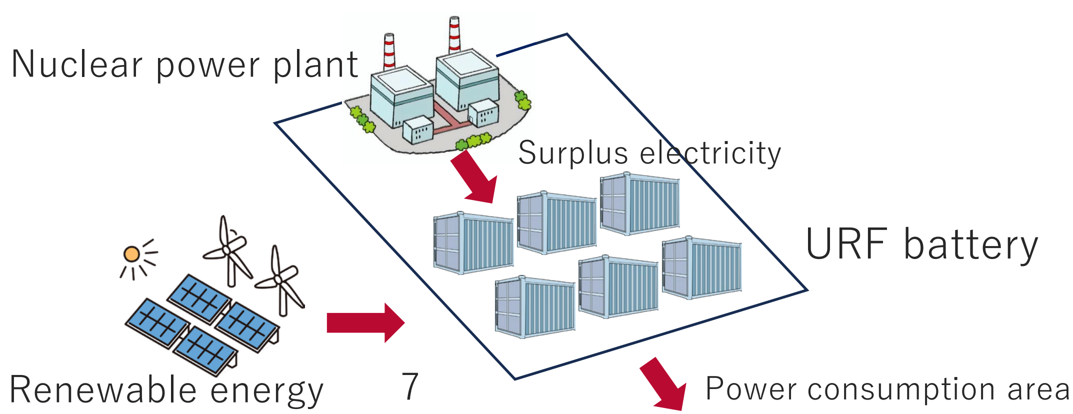
Domestic： 100% of the battery source is uranium that can be procured in Japan.

Effective use：”Storage” of depleted uranium into “Electricity storage”.

※EMV 0.5V, 80% efficiency

Advantages/Disadvantages of using Uranium

- **Advantages**
  - RF batteries in practical use are composed of vanadium.
    - Vanadium is completely dependent on foreign countries.
  - The use of depleted uranium enables **domestic production.**
  - **More efficient** than vanadium.
    (Charging loss：Vanadium=20%, Uranium=3%)
- **Disadvantages**
  - Uranium valence becomes unstable due to contamination with water
  → Can be stabilized by electrolyte preparation
  - Handling of uranium as nuclear fuel material
  → Installation on nuclear power plant sites



Current Status and Future Prospects

- Since the report on the organic solvent-based uranium battery in 2007 [*1], the only reports on the URF battery are published from Japan (JAEA and Tokyo Institute of Tech.) [*2, 3].
- Constructed a small-scale battery using uranium as active material and confirmed its operation

→ If proof-of-principle is achieved, it will be **the first achievement in the world**.

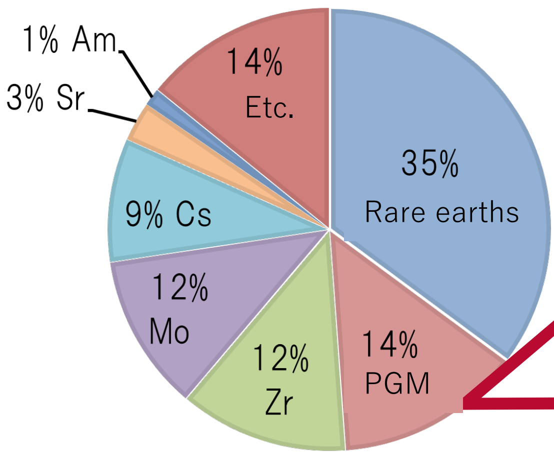
Target	2023/R5	2024/R6	2025/R7	2026/R8	2027/R9	2028/R10	～2035
Development of URF battery	**Proof-of-principle of URF battery**	Design of URF battery		**5Wh-class energy storage (100g scale of uranium)**		**5kWh-class energy storage (100kg scale of uranium)**	**Achievement of MWh-class energy storage (ton scale of uranium)**

Bold-underline indicates WORLD-FIRST

*1: T. Yamamura et al., J. Phys. Chem. C, 2007, 111, 50, 18812–18820.
*2: K. Ouchi et al., Chem. Lett., 2021, 50, 1169–1172.
*3: K. Takao, Dalton Transactions, 2023, 52, 9866.

30 billion yen

Background: Utilization of elements in spent fuel



Percentage of metallic elements in spent fuel (excluding U and Pu)

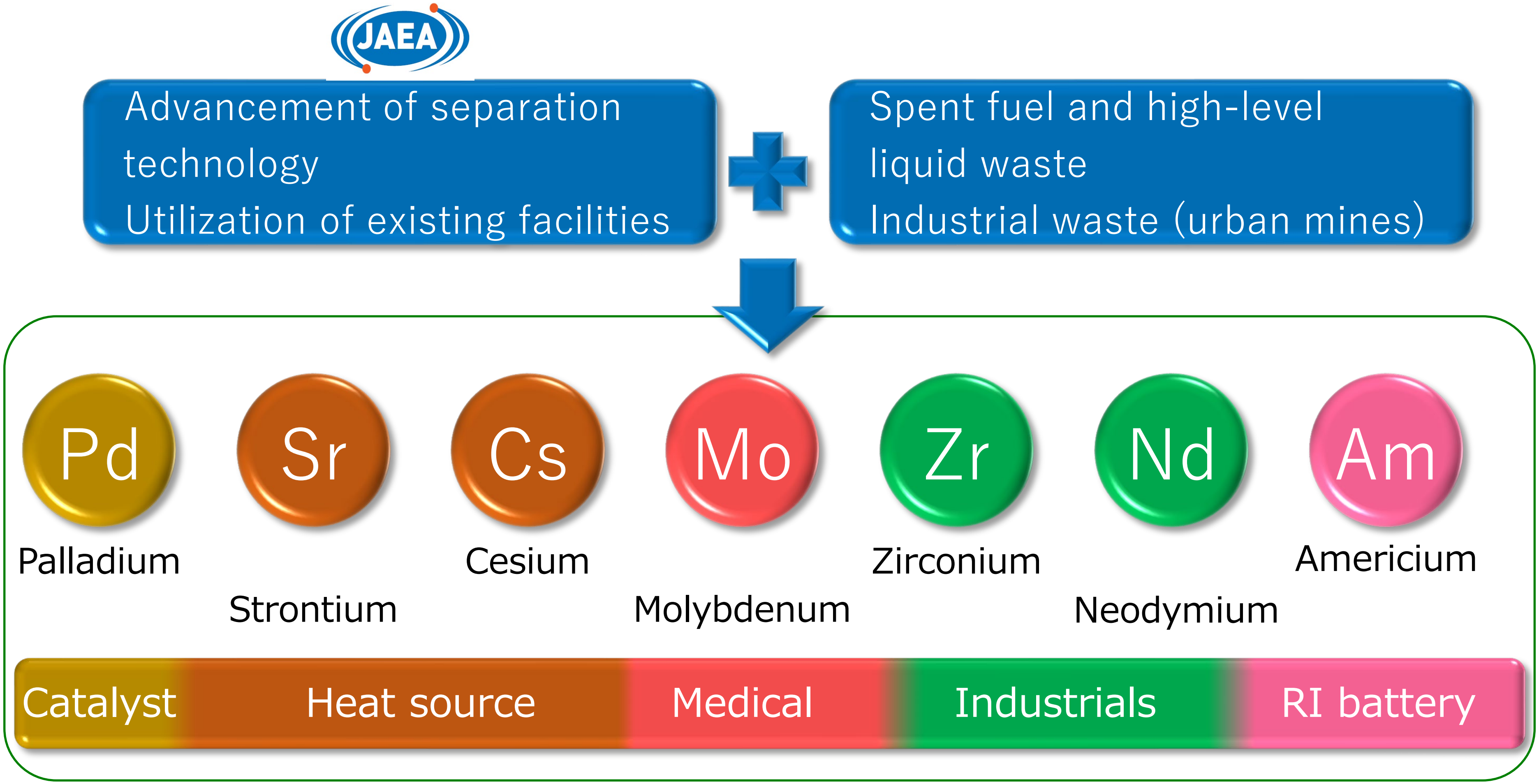
	Application	Amount*1	Supply ratio*2	Price*3
Ru	Catalysts	2.4 t/y	15%	4.6 bln. yen
Rh	Coat、catalysts	0.5 t/y	7%	20.1 bln. yen
Pd	Catalysts, dental material	0.8 t/y*4	2%	5.1 bln. yen

Platinum Group Metals (PGM) contains a value of **about 30 billion yen/y.**

- Spent fuel is **a valuable resource** containing elements such as rare earths and PGM
- Developing supply sources leads **to ensure resource security**

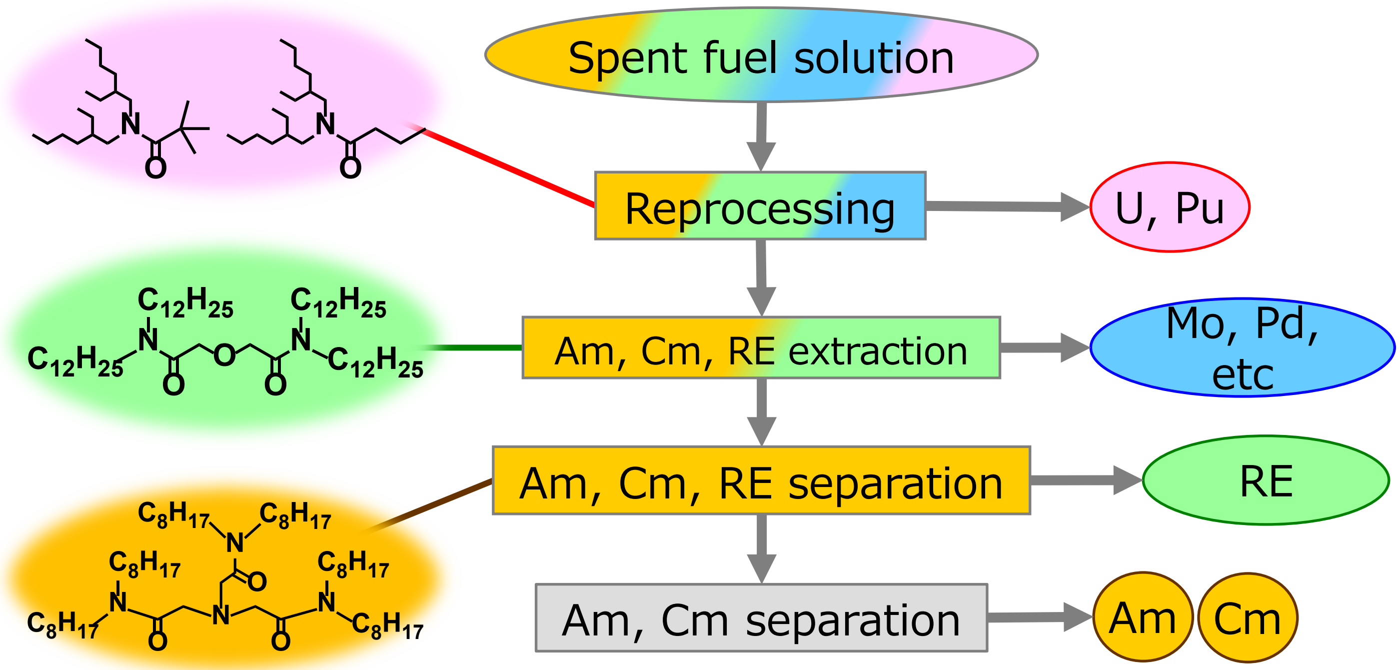
*1: 800 tons of spent fuel processed per year
*2: Percentage of annual domestic demand
*3: Calculated at the unit price as of April 28, 2023
*4: Even-odd separation of isotopes (ImPACT Fujita program result) will be performed, and only even-numbered nuclei are assumed to be used.

Purpose

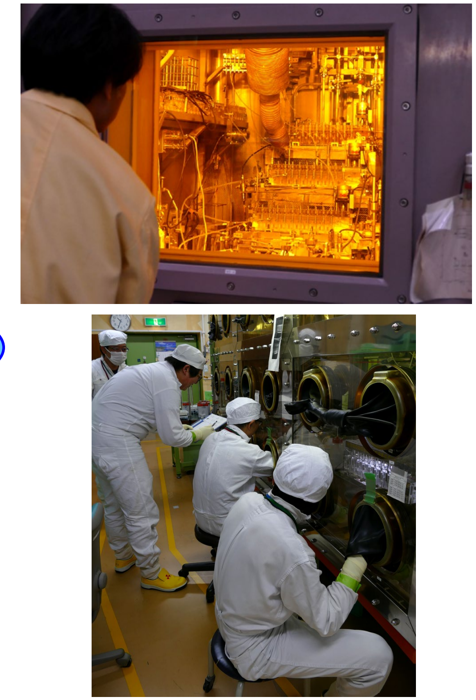


- **Development of practical separation and utilization technologies for useful elements**

Separation by solvent extraction



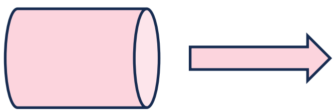
Schematic flow of SELECT process



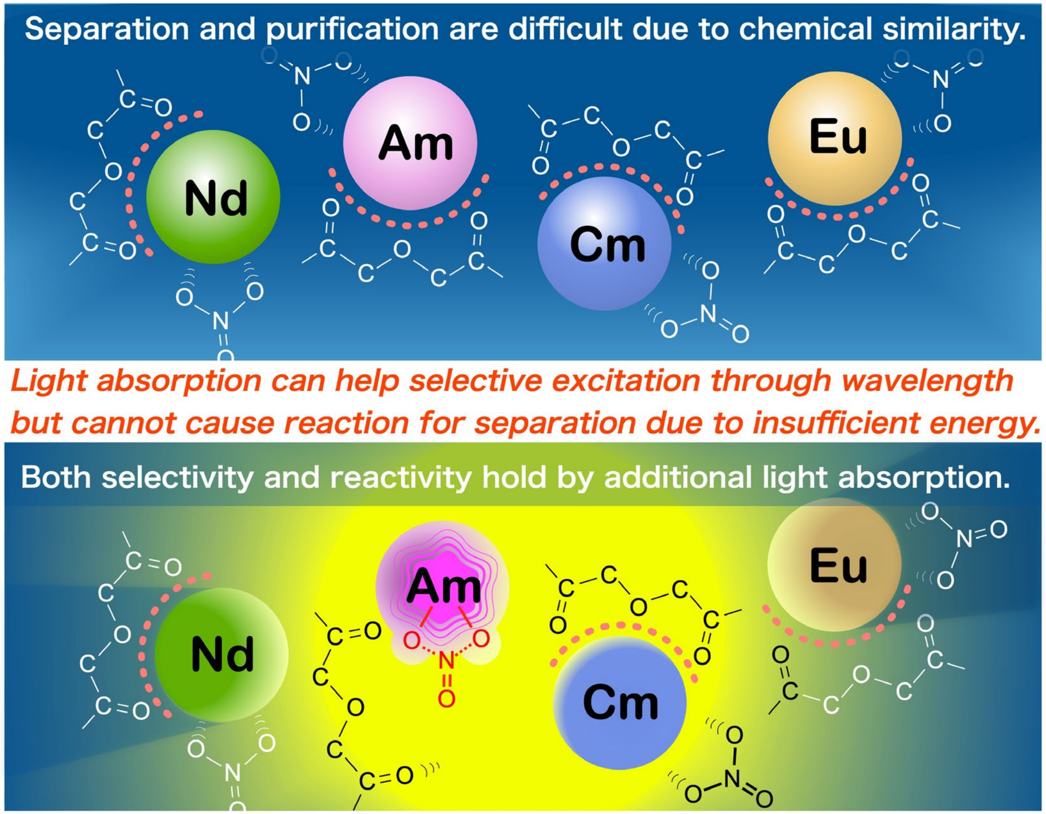
Testing at NUCEF, JAEA

- Further development is underway **to improve the solvent extraction process (SELECT process)** developed by JAEA.
- This technology is effective in reducing the volume and hazardous level of radioactive waste by combining with nuclear transmutation.

Laser-assisted separation



Laser at a specific wavelength for Am(III) absorption



- Laser-induced photochemical reaction enables a new separation scheme.
- Simplification of processes and reduction of secondary waste are expected because of the high selectivity.

・S. Matsuda, et al., Science Advances, 8, 20 (2022).
・Press release 2022/5/20, https://www.jaea.go.jp/02/press2022/p22052003/

Current Status and Future Prospects

- Although research has been conducted to separate useful elements from spent fuel, it is still in the basic research stage and has not yet reached the stage of practical application.
  - In the ImPACT program※, Pd 95% recovery was confirmed by wet electrolysis.
- Advancement of the separation process by solvent extraction (SELECT process) and development of the laser-assisted separation method.
- **Application of technologies to urban mines.**

Target	2023/R5	2024/R6	2025/R7	2026/R8	2027/R9	2028/R10	～2035
Enables separation of various useful elements from high-level liquid waste		Separate small amounts of Am for RI batteries		**Target achieved with a few dozen grams of dissolution solution of spent fuel**		**Target achieved with a few hundred grams of actual waste**	**Target achieved with a few kilo-grams of actual waste**

Bold-underline indicates WORLD-FIRST

※ImPACT Fujita program, 2014-2018

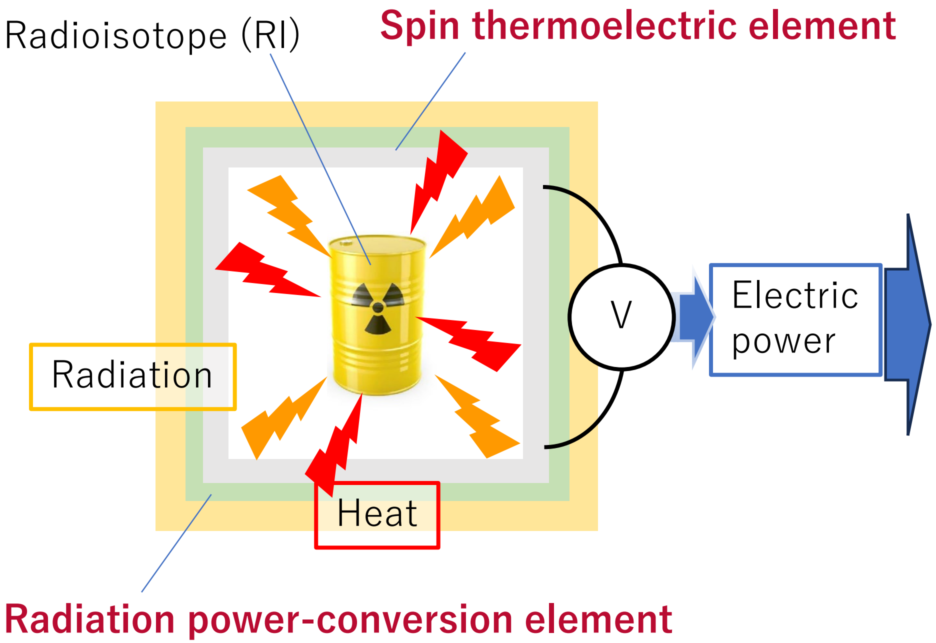
4.8 kg

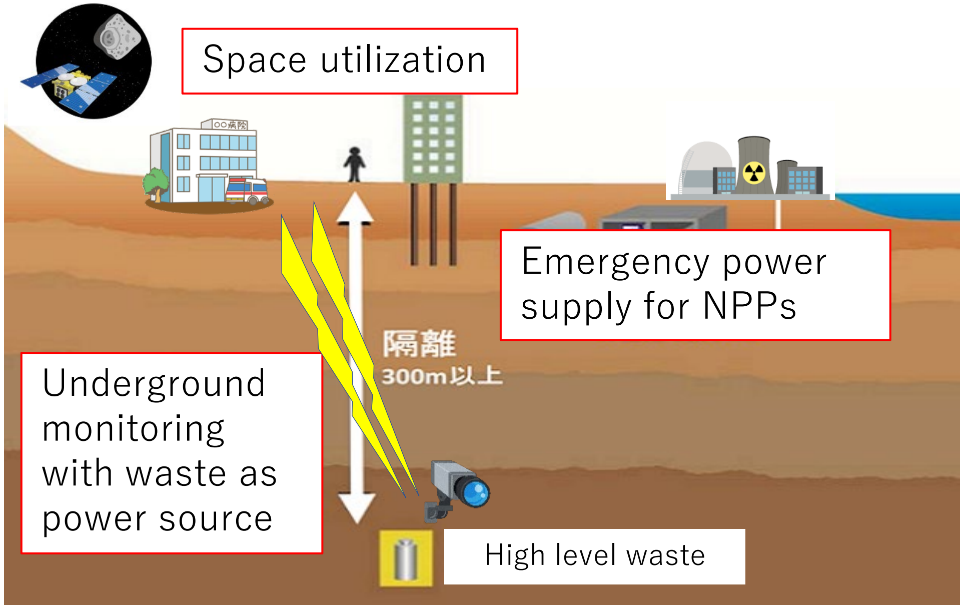
Background: Power generation by heat and radiation

- Heat source of NASA Mars exploration rover：$^{238}PuO_2$ **4.8kg** (110We)
  - Thermoelectric devices are sensitive to radiation.
  - ^{238}Pu has high heat generation but low radiation.
- Radiation tolerant thermoelectric element could expand the options for isotopes as heat sources.

https://inl.gov/mars-2020/
https://www.ornl.gov/news/ornl-produced-plutonium-238-help-power-perseverance-mars

Purpose





- Realization of semi-permanent, maintenance-free power supplies in harsh environments that are not easily accessible by humans.

Spintronics

Hybrid technology of **electric** and **magnetics**

Spin (Origin of magnetism)

⇨ Spin current ←**Magnetic current**

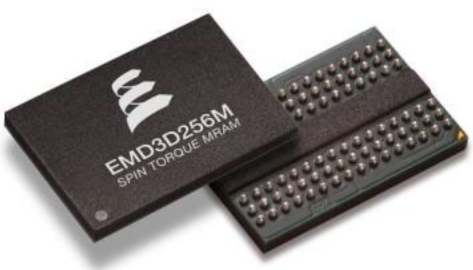
Active in the micro world!

Charge (Origin of electricity)

⇨ Current ←A major player in electronics

Cause of heat generation!

Electron



Magnetic random access memory

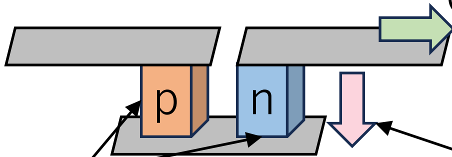
By Everspin (US)

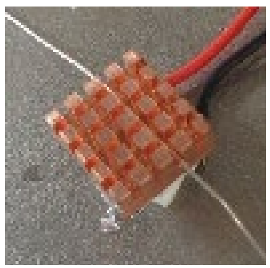
Innovations in memory element tech.

Energy saving + **Radiation resistance**

Spin thermoelectric element

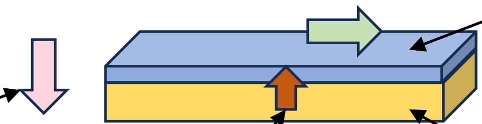
Conventional thermoelectric element





- Used in many fields
- Power is proportional to the number of elements
- Semiconductor elements are connected in series, and performance may deteriorate due to partial damage

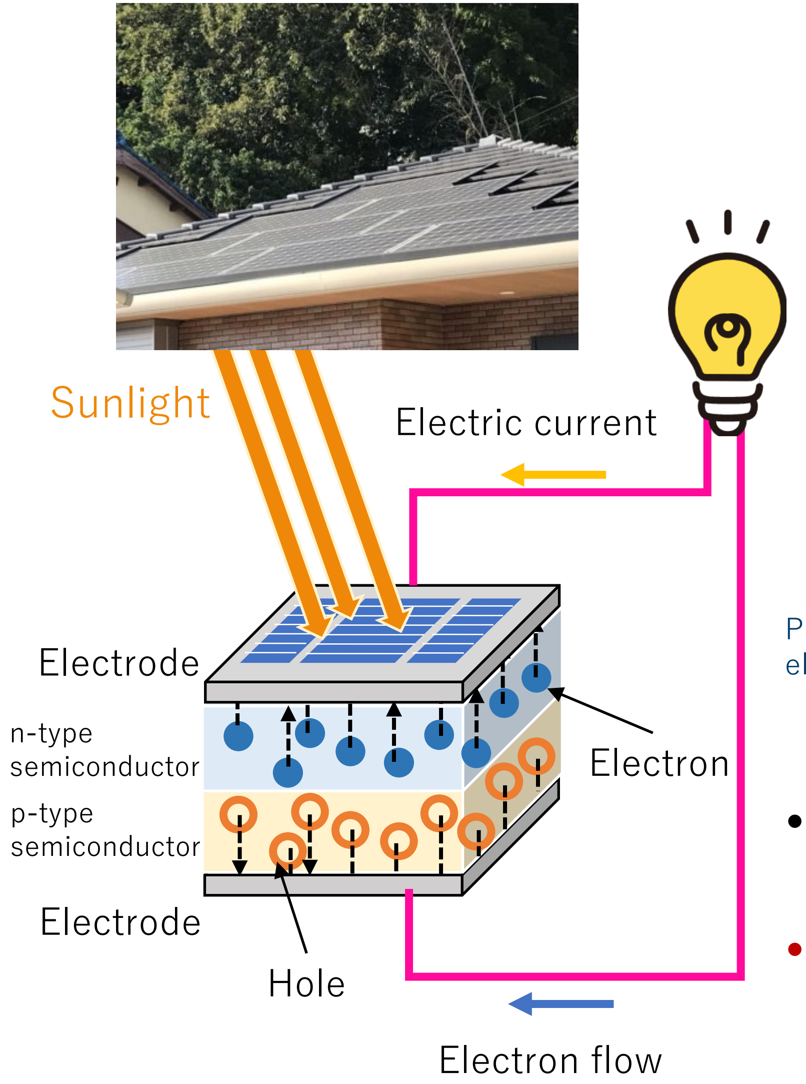
Spin thermoelectric element

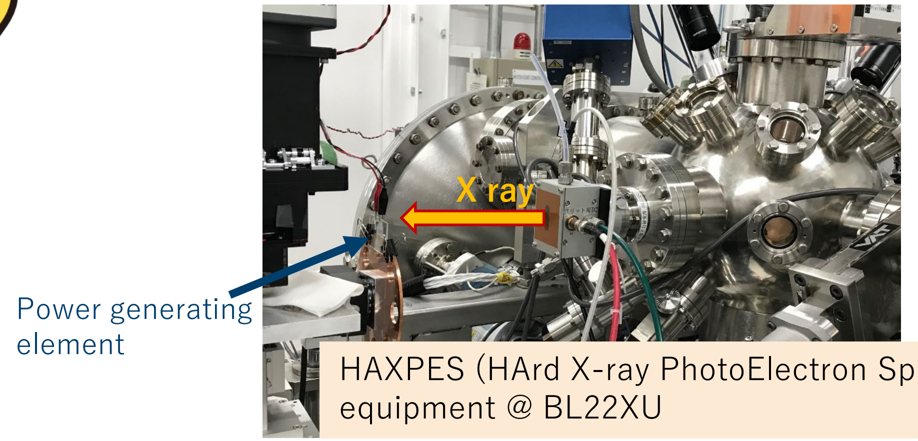


- New technology based on spintronics
- Power is proportional to the width of the thin film
- **High radiation resistance** because it is composed of metal and magnetic material.

- The integrity of the element has been confirmed by irradiating it with 1 MGy of gamma rays

Power generation by radiation





HAXPES (HArd X-ray PhotoElectron Spectroscopy) equipment @ BL22XU

- Power generation from gamma rays instead of sunlight
- Performed the principle demonstration of Ni/SiC using synchrotron x-rays instead of gamma rays

Current Status and Future Prospects

- Proof of principle for both technologies has been confirmed.
  - Spin thermoelectricity (4W/m^2 at 10°C difference),
  - Radiation power generation (1W/m^2 by 30 keV-6.6x10^{13} [photon/cm^2/s])
- It is required to improve power generation efficiency and to demonstrate test using radioactive waste.

Target	2023/R5	2024/R6	2025/R7	2026/R8	2027/R9	2028/R10	～2035
Development of high efficient ・Spin thermoelectric devices ・Radiation power generation devices	Demonstration of power generation using RI, etc.		**Demonstration of power generation using radioactive waste and spent fuel**		**Completion of prototype combined with RI batteries**	**Achieved W-class power generation**	**Achieved kW-class power generation**

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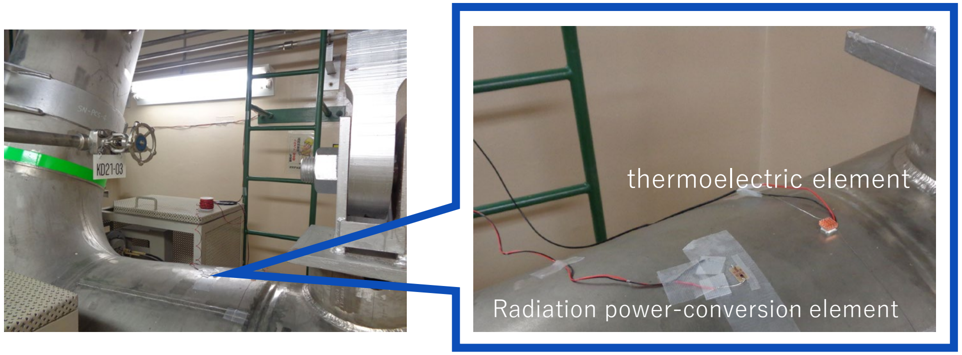
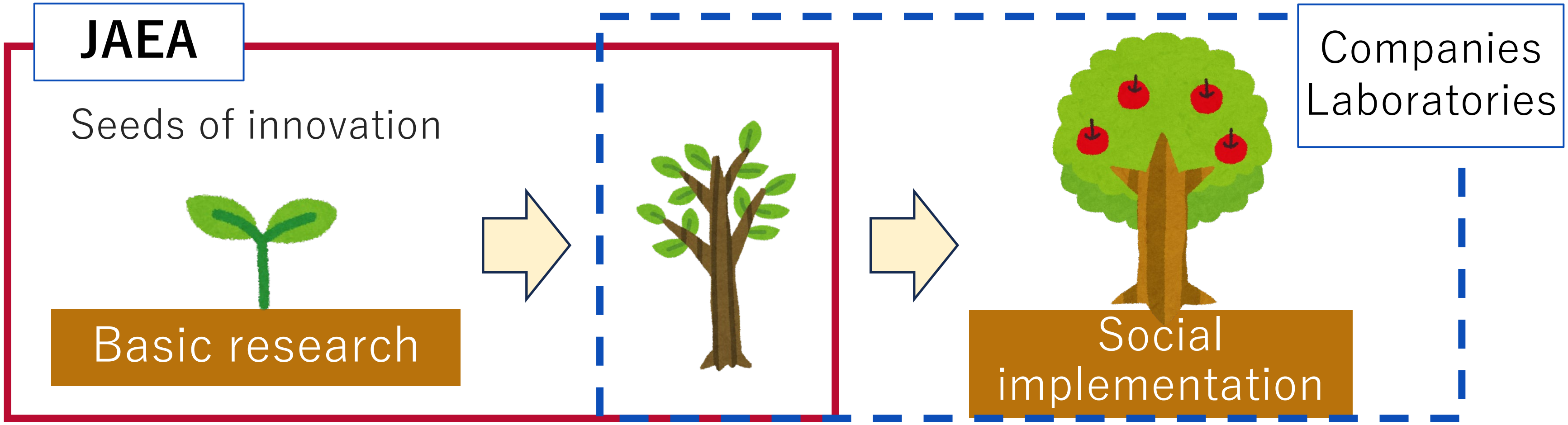


Thermal and radiation power generation test in JRR-3 primary cooling system piping

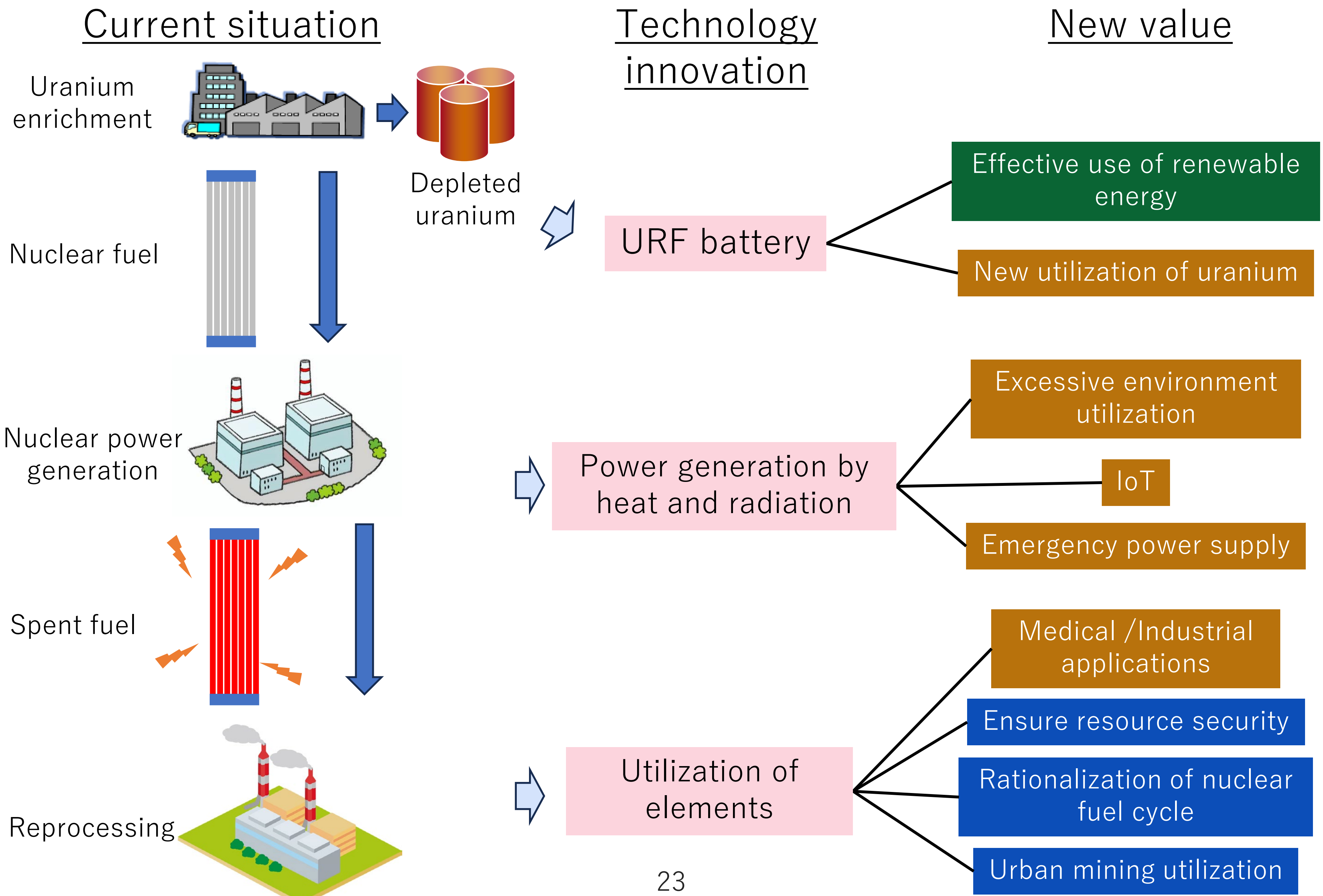
Summary

- We promote research on the following technologies for converting radioactive waste into resources
  - **Storage battery use of depleted uranium (Synergy)**
  - **Utilization of elements in spent fuel (Sustainable)**
  - **Power generation by heat and radiation (Ubiquitous)**



From insourcing to outsourcing

Targeted image



Appendix

Type of storage battery

Type	Lead	Nickel metal hydride	Lithium-ion	NAS	Redox flow
Capacity	～MW-class	～MW-class	～1MW	**MW-class or higher**	**MW-class or higher**
Monitoring	△	△	△	△	◎
Safety	○	○	△	△	◎
Resource	○	△	○	◎	△ (in case of vanadium)
Heating during operation	-	-	-	Required (≧300°C)	-
Lifetime (number of cycles)	17 years (3150)	5-7 years (2000)	6-10 years (3500)	15 years (4500)	Required evaluation **(no limit)**

https://www.cas.go.jp/jp/seisaku/npu/policy04/pdf/20120705/sanko_shiryo1.pdf