# Role of ADS and its development issues

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2021 Symposium on Nuclear Data

# Content

1. Role of ADS and Partitioning & Transmutation (P&T) technology in nuclear fuel cycle

2. Principle of ADS for MA transmutation

3. Nuclear data in ADS design

# 1. Role of ADS and Partitioning & Transmutation (P&T) technology in nuclear fuel cycle

# Nuclear fuel cycle in 2020

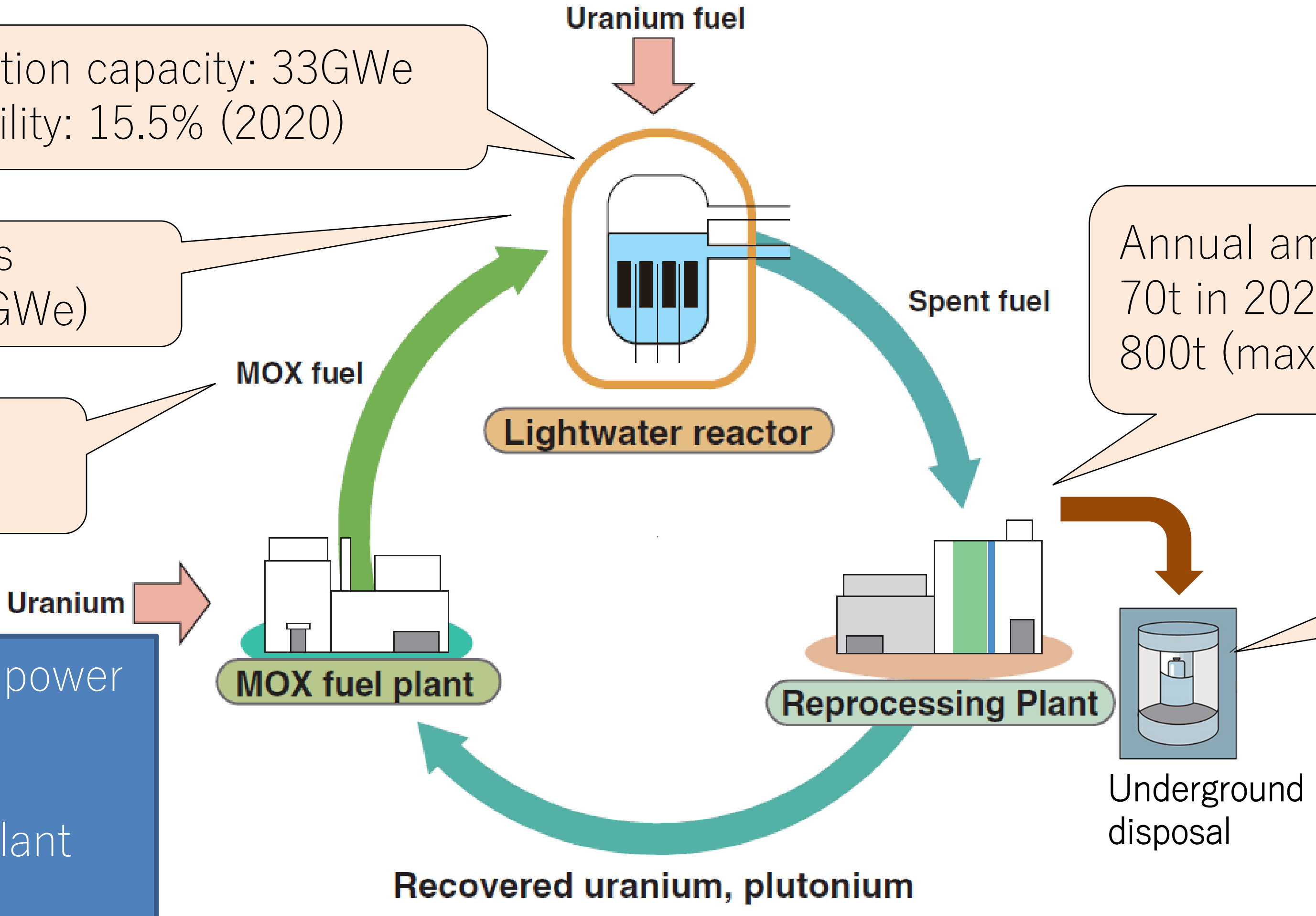
Generation capacity: 33GWe
Availability: 15.5% (2020)

MOX utilization in LWR is approved in 4 unit (3.81GWe)

LWR MOX fuel：
130t (max.)

Annual amount
70t in 2023
800t (max.)

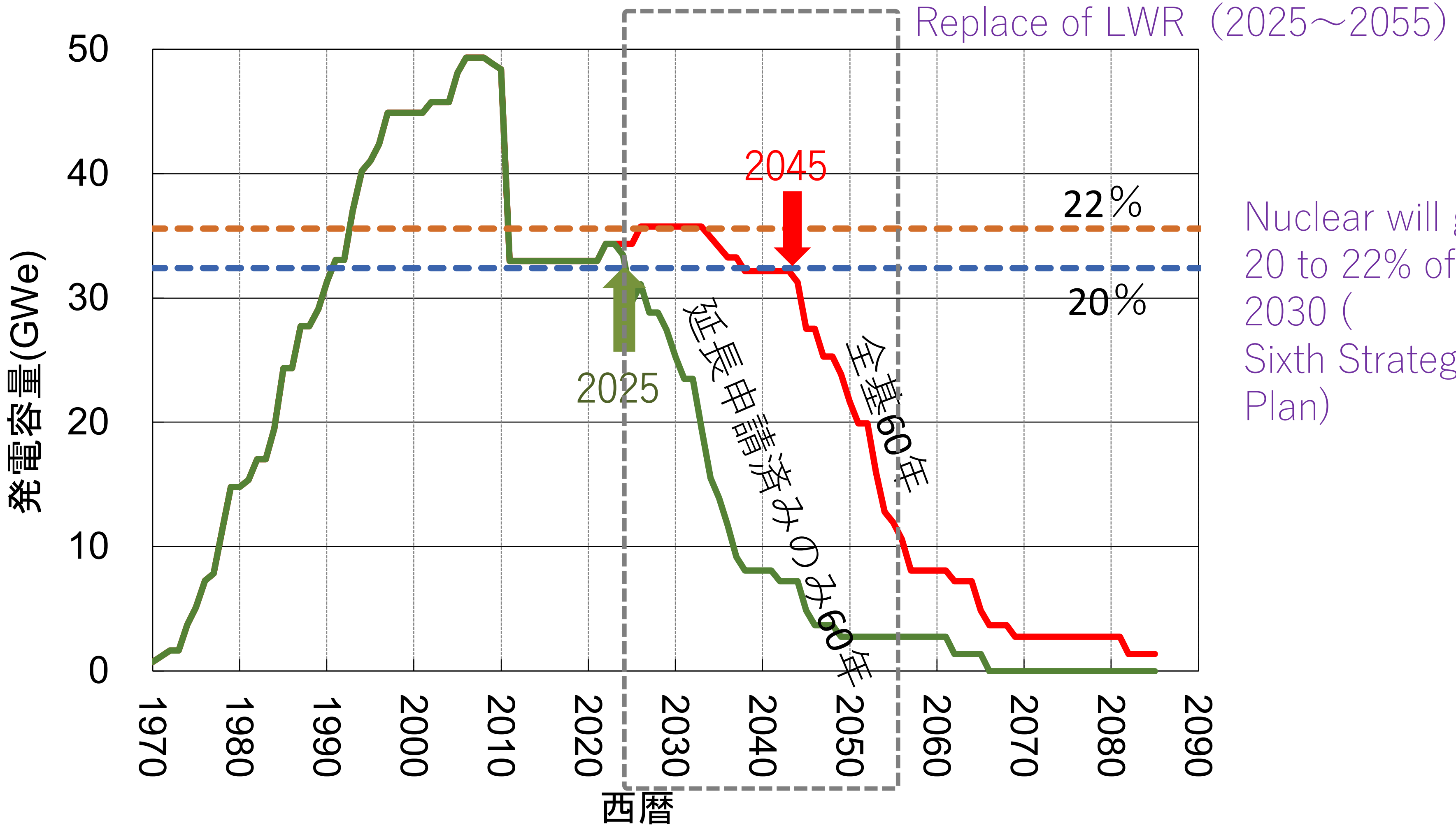
Literature survey started




- Gradual restart of nuclear power plants after meeting new regulatory standards.
- Rokkasho Reprocessing Plant will soon start operation !
- Literature survey on geological disposal of radioactive waste begins !

原子力・エネルギー図面集より編集

# Expected power generation capacity




Nuclear will generate 20 to 22% of total in 2030 ( Sixth Strategic Energy Plan)

To keep present scale, LWR must be replaced in from 2025 to 2045.

# Carbon neutral

"Aiming for a carbon-neutral, decarbonized society by 2050" (Prime Minister Kan, 2020/10/26)

Revised Global Warming Countermeasures Promotion Law (enacted on May 26, 2021)

- Basic principle of carbon neutrality by 2050
- Local use of renewable energy
- Information on corporate emissions

# 6th Strategic energy plan

The assumption of approximately 30-40% for nuclear power and thermal power with CO2 capture was used as a reference value for further discussion.

- As for the nuclear fuel cycle, ... we will proceed with efforts to establish it as soon as possible.
- Discussed Rokkasho plant, SF measures, final disposal, Pu balance, plutonium thermal SF reprocessing, etc.

Nuclear Energy Subcommittee (22nd meeting, March 22, 2021, Agency for Natural Resources and Energy)

# Toward 2050

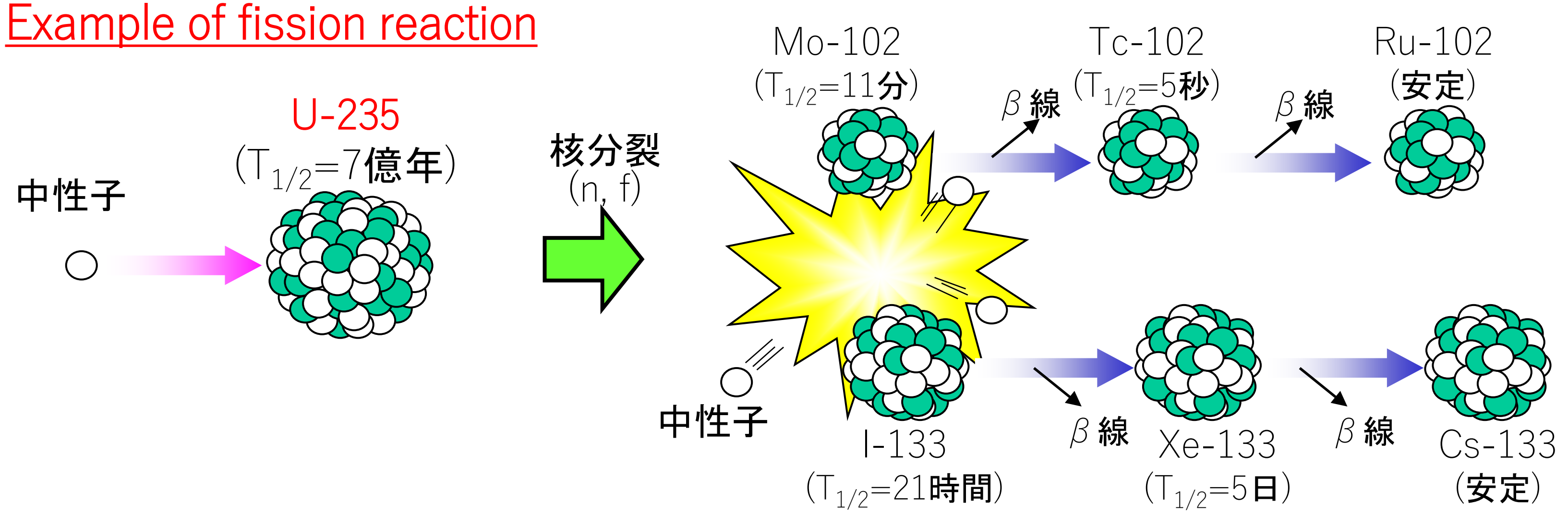
- Use only renewable energy?
- How much nuclear power will we use?
  - If we use them, reactor safety is an issue.
  - Even if we don't use them, spent fuel is an issue.
- What to do with the spent fuel?
  - Reprocess it and separate it to some extent.
  - Plutonium is both a resource and a waste. Use it as Plu-thermal.
  - Can't we separate the high-level waste more, which is the most radioactive?

➡ Partitioning and Transmutation technology

# Origen of radioactive isotopes:  1. Fission reaction

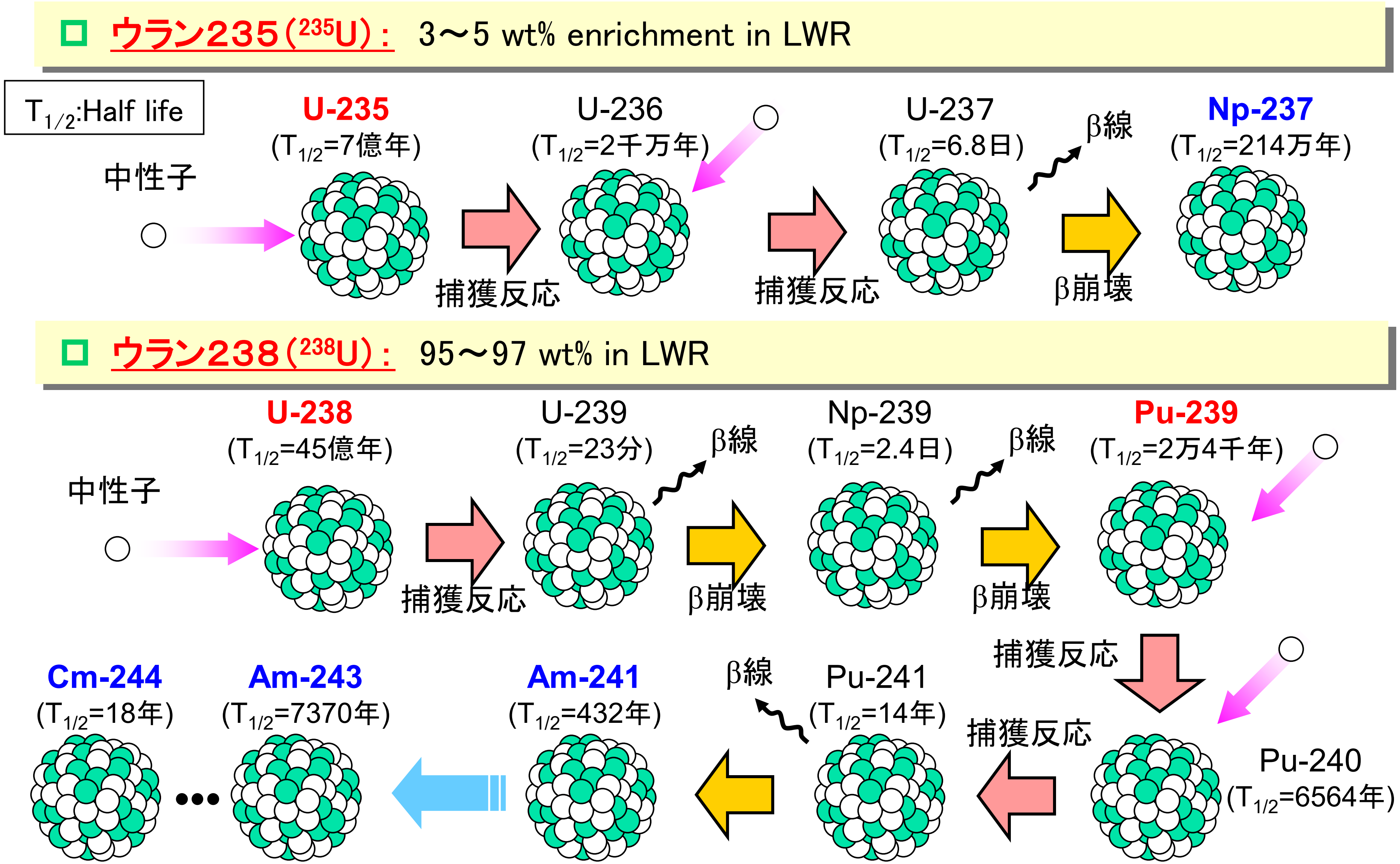
- ✓ Mainly, fission reaction of uranium 235 ($^{235}U$) and a neutron
- ✓ A uranium atom is converted to two Fission Product (FP)
- ✓ Energy of ~200 MeV and 2~3 neutrons are released. Neutrons engage next fission.

Example of fission reaction

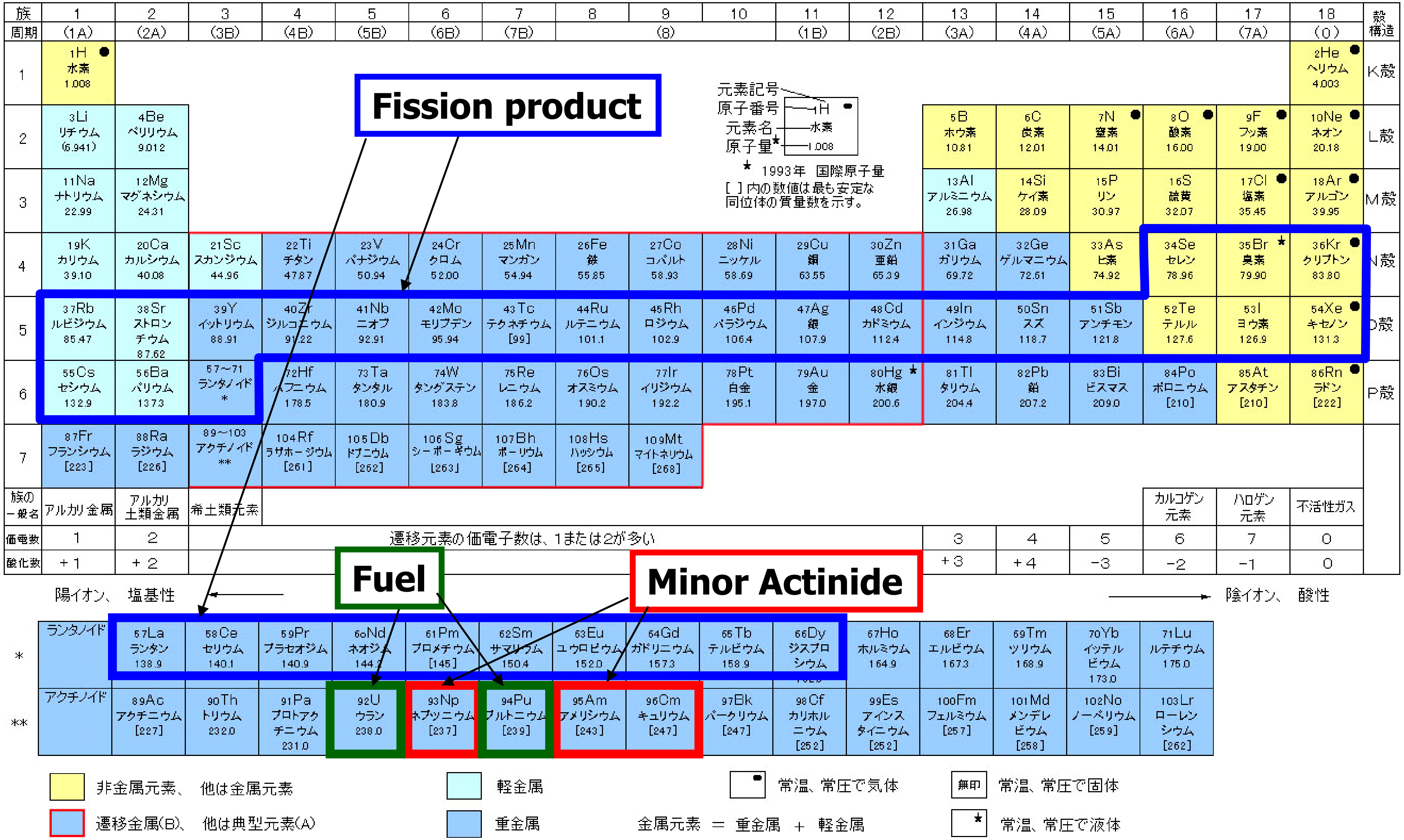


# Origen of radioactive isotopes: 2. Capture reaction

✓ Uranium captures neutron and converted to Pu and minor actinide (Np, Am, Cm)



# Where is FP and MA in Nuclear Chart ?



# List of Long-lived FP and MA

Actinides; Trans-uranic elements (TRU); Minor actinides (MA)

| Nuclide | Half-life (Year) | Dose coefficient (μSv/kBq) | Amount (/tHM) |
|---|---|---|---|
| U-235 | 0.7B | 47 | 10kg |
| U-238 | 4.5B | 45 | 930kg |
| Pu-238 | 87.7 | 230 | 0.3kg |
| Pu-239 | 24.11M | 250 | 6kg |
| Pu-240 | 65,61M | 250 | 3kg |
| Pu-241 | 14.29 | 4.8 | 1kg |
| Np-237 | 2.144M | 110 | 0.6kg |
| Am-241 | 432.6 | 200 | 0.4kg |
| Am-243 | 7.370K | 200 | 0.2kg |
| Cm-244 | 18.11 | 120 | 60g |

Fission products (FP); Long-lived fission products (LLFP); Short, Very high

| Nuclide | Half-life | Dose coefficient (μSv/kBq) | Amount (/tHM) |
|---|---|---|---|
| Se-79 | 0.295M | 2.9 | 6g |
| Zr-93 | 1.61M | 1.1 | 1kg |
| Tc-99 | 0.211M | 0.64 | 1kg |
| Pd-107 | 6.5M | 0.037 | 0.3kg |
| Sn-126 | 0.23M | 4.7 | 30g |
| I-129 | 15.7M | 110 | 0.2kg |
| Cs-135 | 2.3M | 2.0 | 0.5kg |
| Sr-90 | 28.79 | 28 | 0.6kg |
| Cs-137 | 30.08 | 13 | 1.5kg |

Dose coefficient= dose(Sv)/radioactivity(Bq).
An indicator of the dose by ingestion

# Under ground disposal

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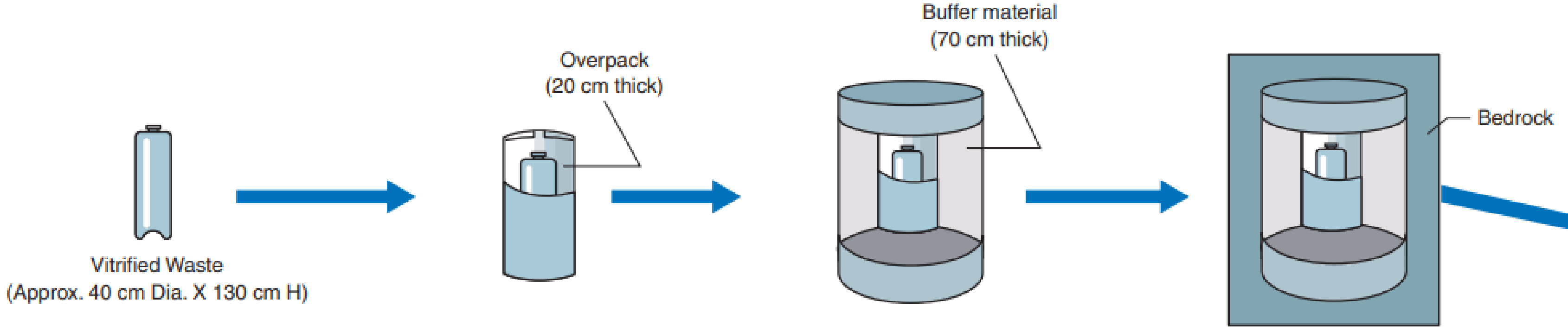
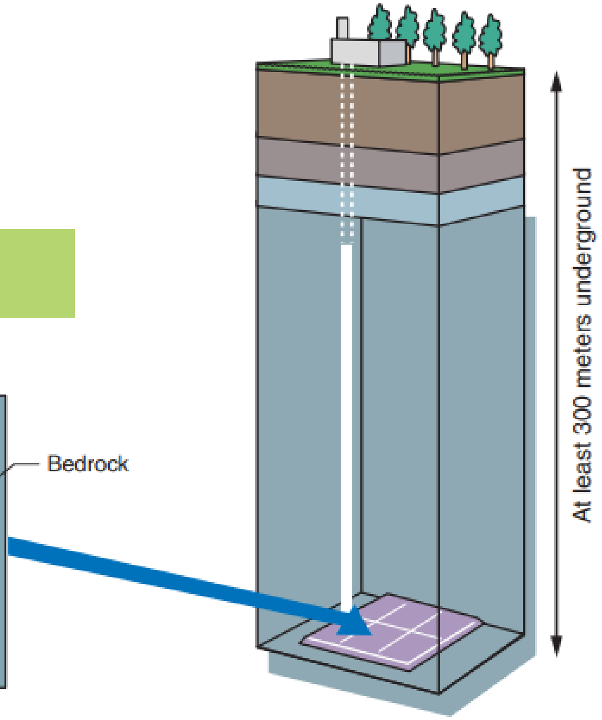



## Vitrified waste

**Radioactive waste is sealed in glass to prevent leakage into groundwater.**

The radioactive material is encased in a solid mass of glass.

## Overpack
(steel container)

**Vitrified waste is enclosed to prevent exposure to groundwater.**

Overpacking prevents the vitrified waste from any contact with ground-water for a period until the radioactiv-ity of the waste has decreased a certain degree.

## Buffer material
(compacted clay)

**Delays any seepage of radioactive material to groundwater.**

The buffer material is made of a clay called bentonite, a property of which is low permeability, which restricts the movement of water and the radio-active material.

## Bedrock

**Delays any seepage of radioactive material.**

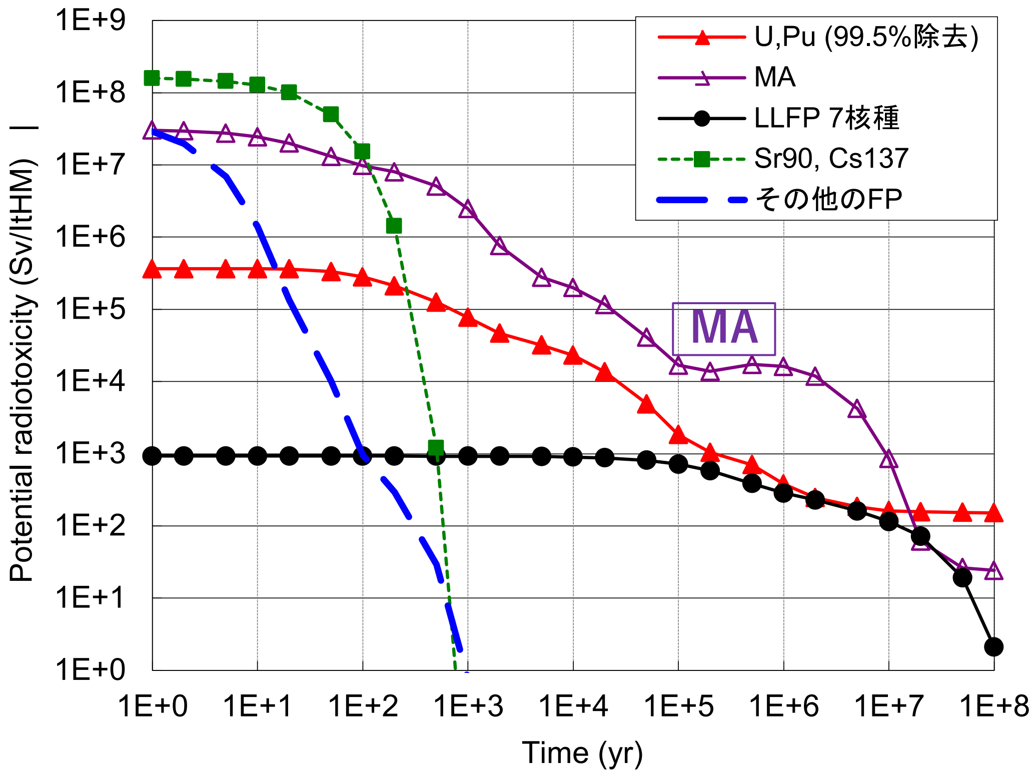
Groundwater moves extremely slowly through bedrock deep underground, so the radioactive material seeps into the bedrock and is absorbed, slowing the movement even more.

## Geological Disposal Facility

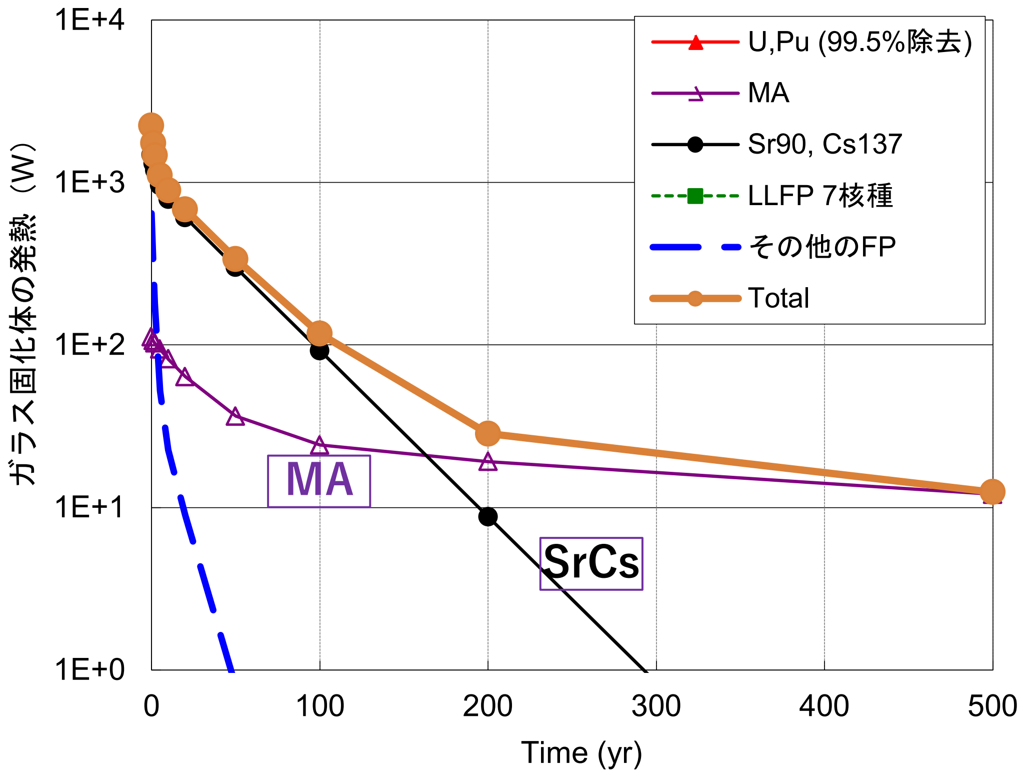
When waste is stored at more than 300m underground, even if the radioactive material were to melt, it would take a very long time to reach our living environment, and by that time the radiation would be so slight compared to the radiation we receive in our daily lives, that it would have no impact on human health.

**Engineered Barriers** + **Natural Barriers** = **Multi-Barrier System**

# Source term in repository

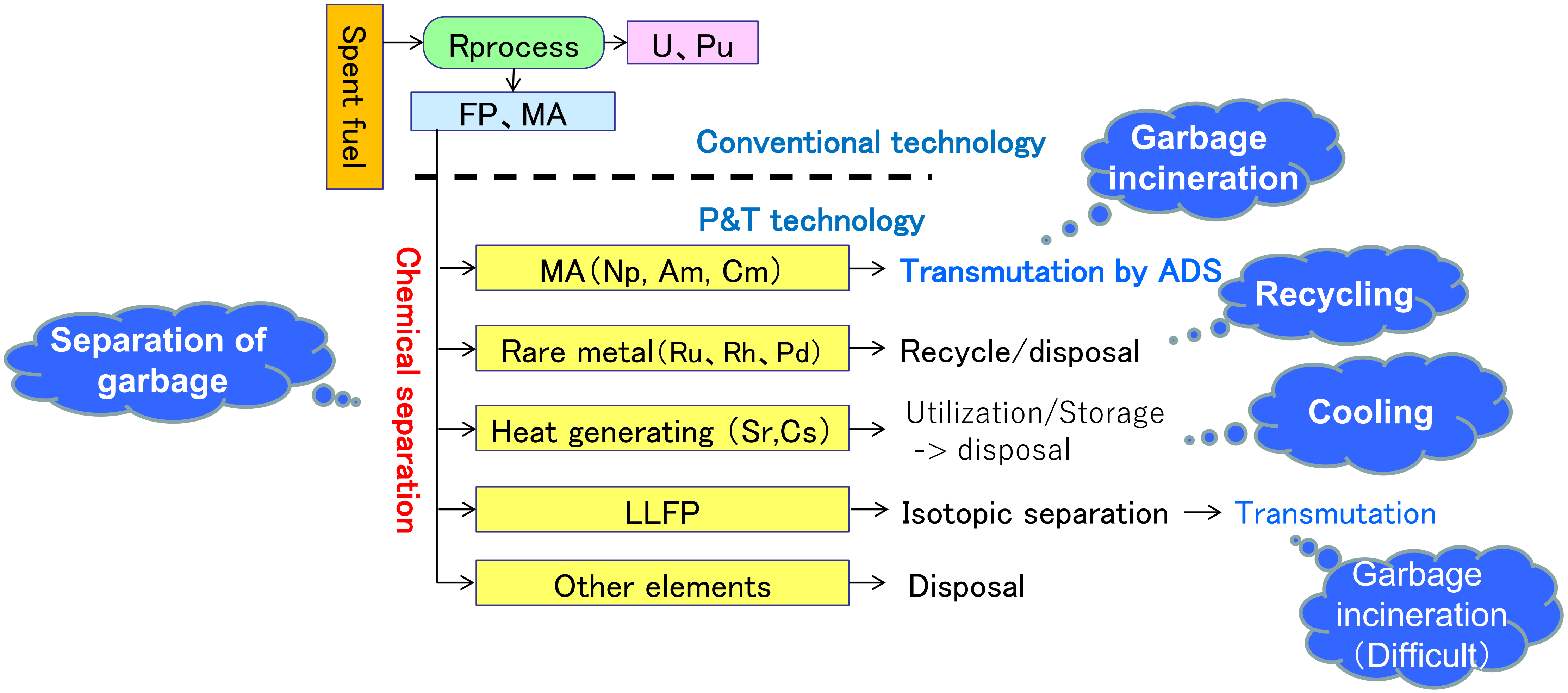



Radioactivity (dose) in glass

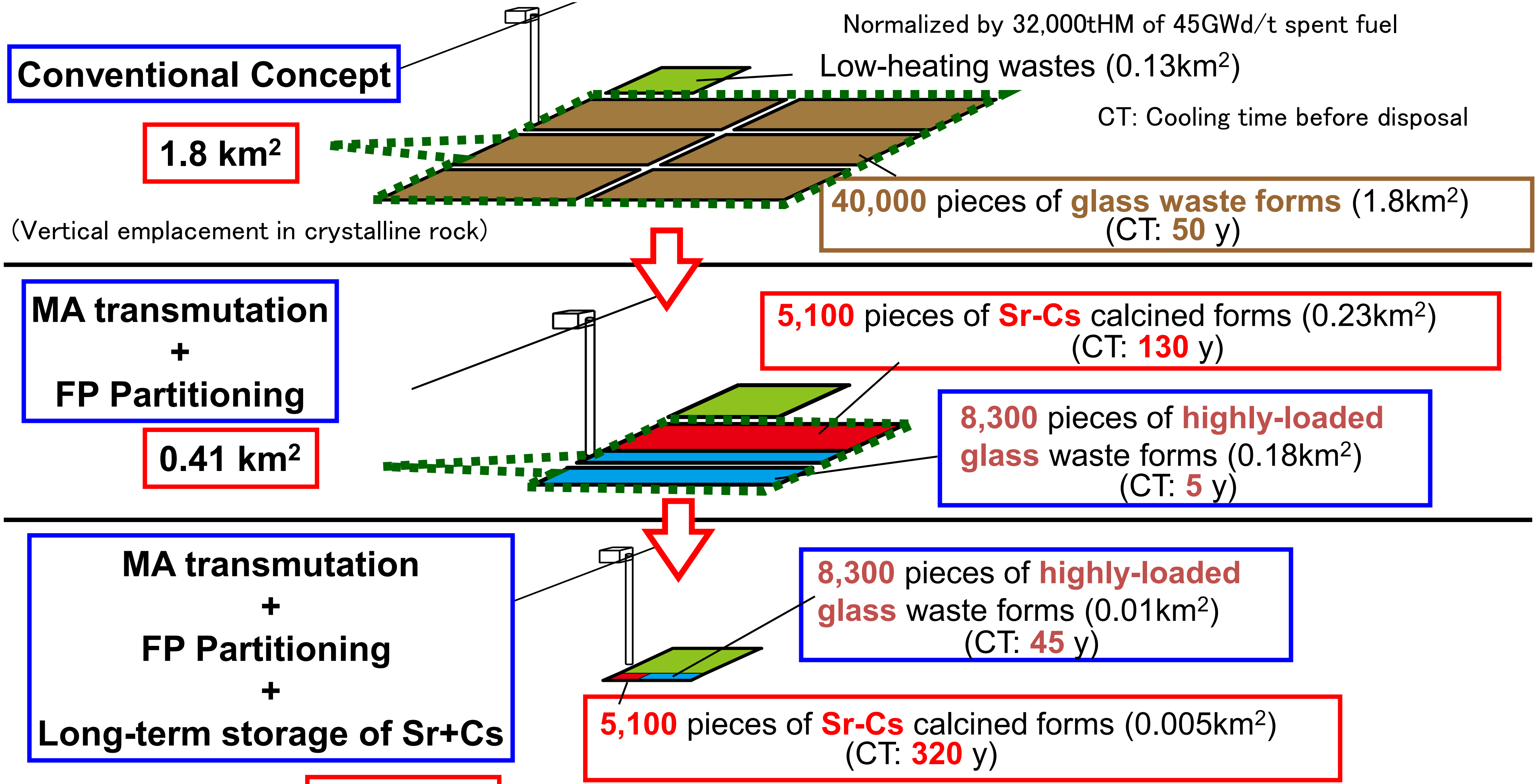



Heat generation in glass

# Change source term by P&T



# Impact on repository scale by P&T




Ref. : K. Nishihara, et al., "Impact of Partitioning and Transmutation on LWR High-level Waste Disposal", J. Nucl. Sci. Technol., 45(1), 84-97 (2008).

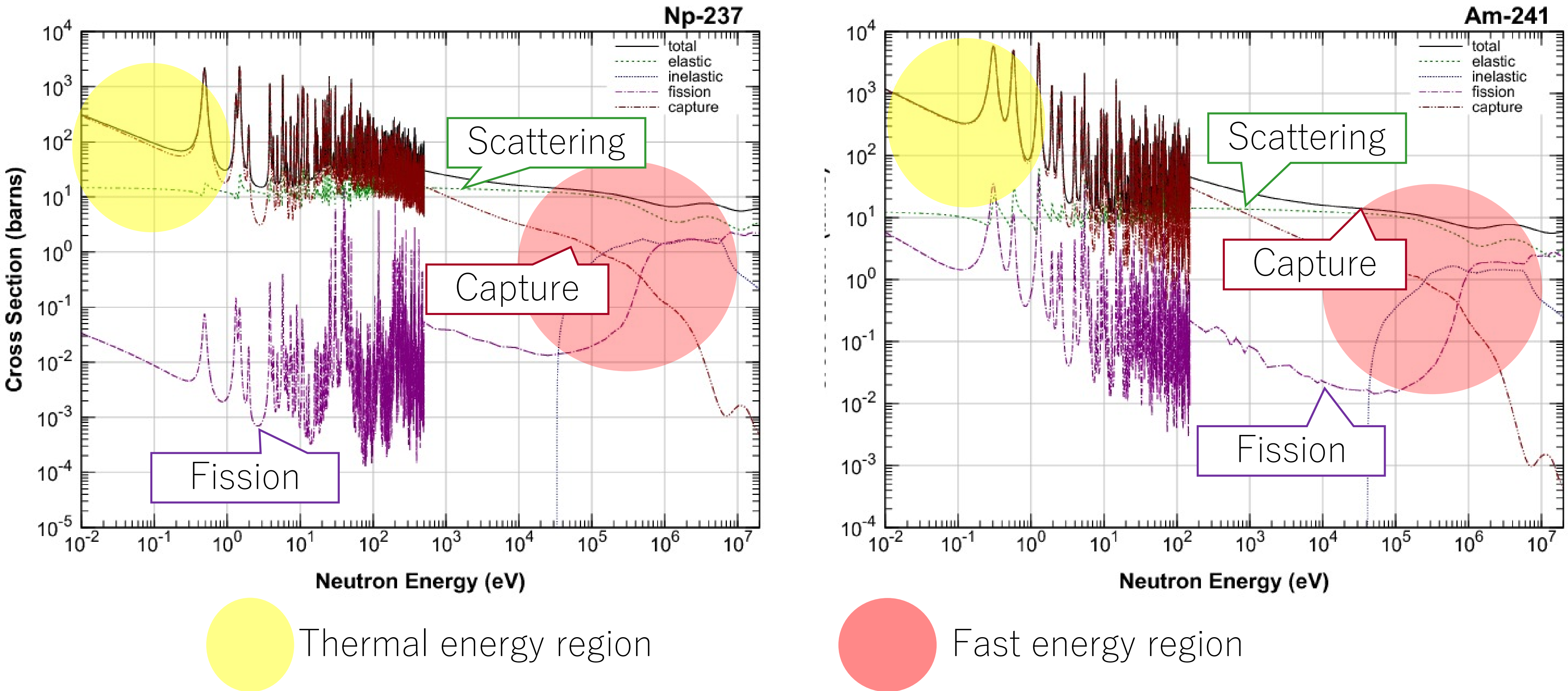
# 2. Principle of ADS for MA transmutation

# Nuclear Reaction Cross Section of MA

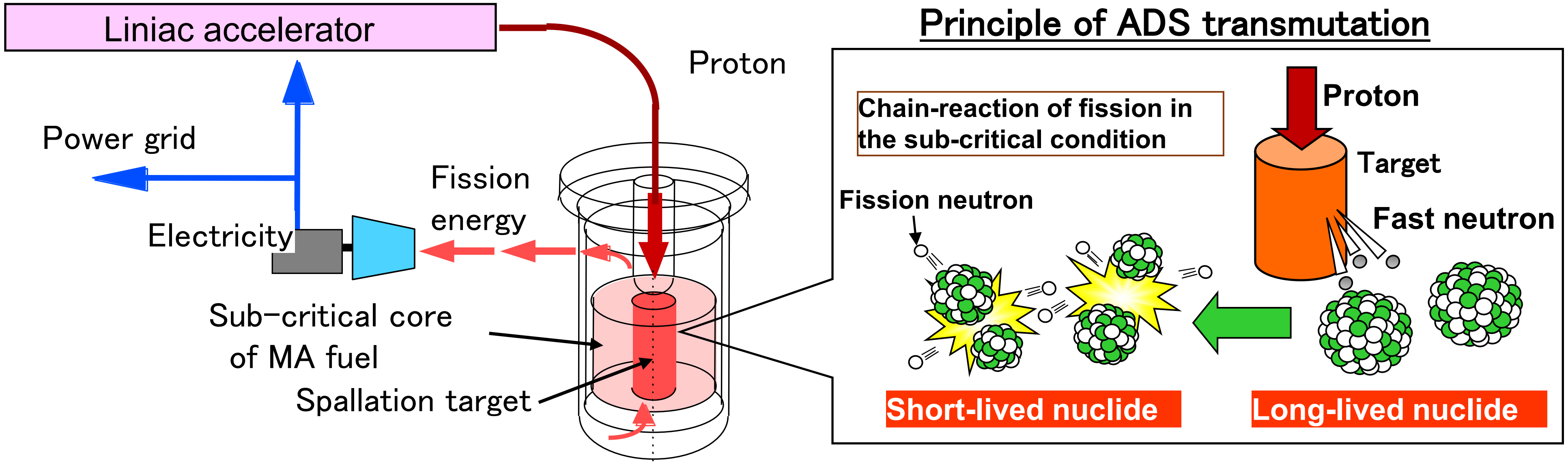
Nuclear cross section of Np-237 and Am-241 which are typical MA

Although fission XS in thermal energy region are much smaller than capture reactions, fission reaction will occur for MA in fast energy region.

◈Utilization of chain reaction by fast neutron is effective for MA transmutation.



# Accelerator Driven System (ADS)



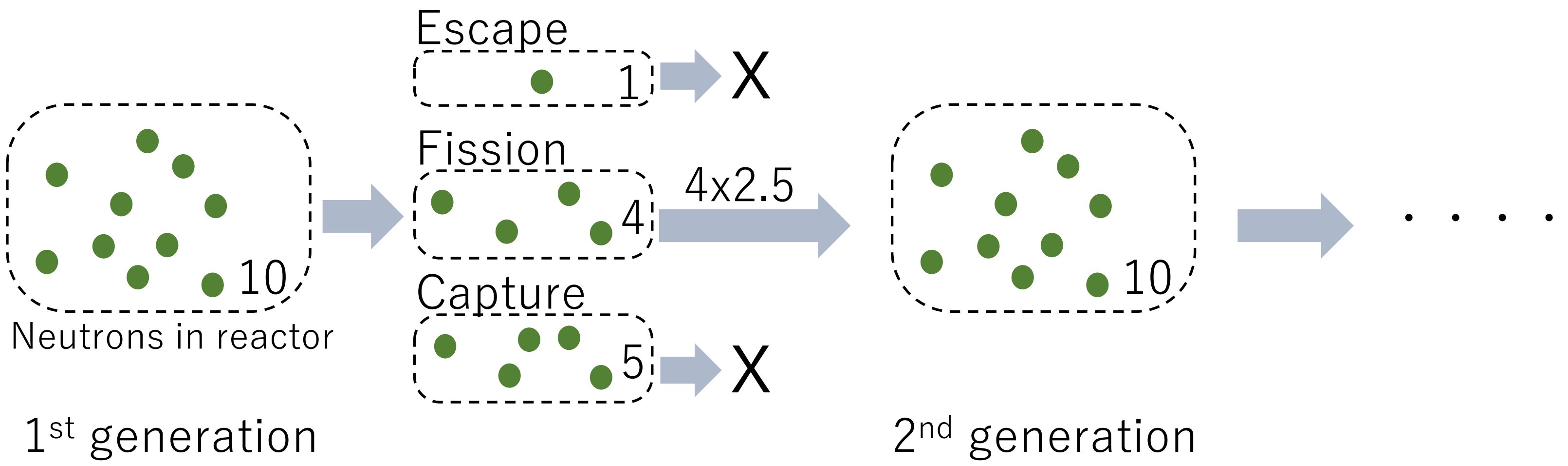

***Mechanism of ADS***

- Proton beam which is accelerated by the **superconducting LINAC** is injected to ADS.
- High intensity proton generates massive neutrons by **spallation reaction** with **heavy metal target** (~40neutrons/proton).
- Fission reactions of **MA** are caused by spallation neutrons. Neutrons by fission reactions lead to the next transmutation.

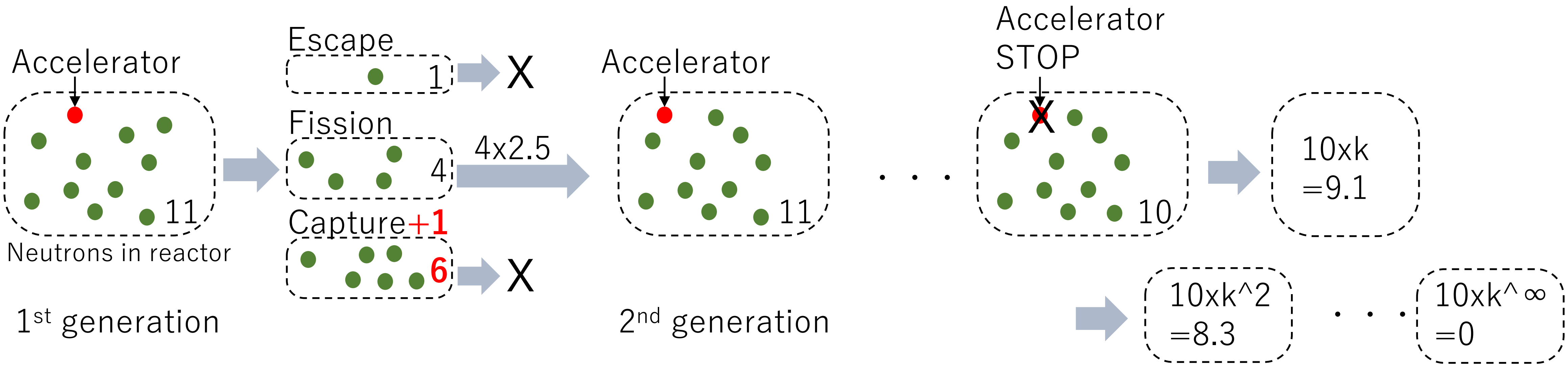
  →Number of neutron is increased 20～50-times by the **chain-reaction**.

# Critical vs. Sub-critical

**Critical** Multiplication factor (k) =10/10=1

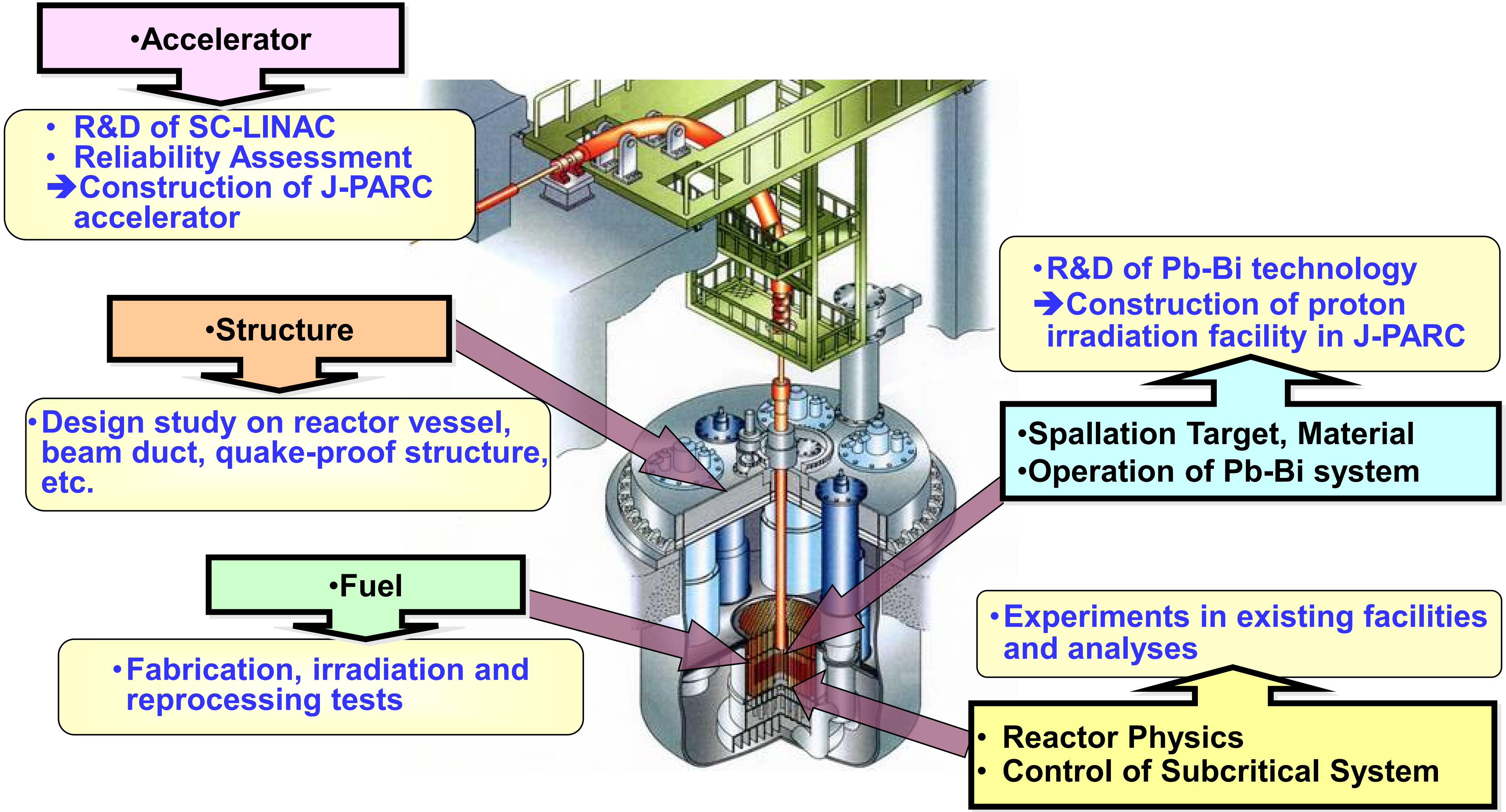



**Sub-critical** Multiplication factor (k) =10/11=0.91



R&D Activities for development of ADS :

# Technical Issues of ADS

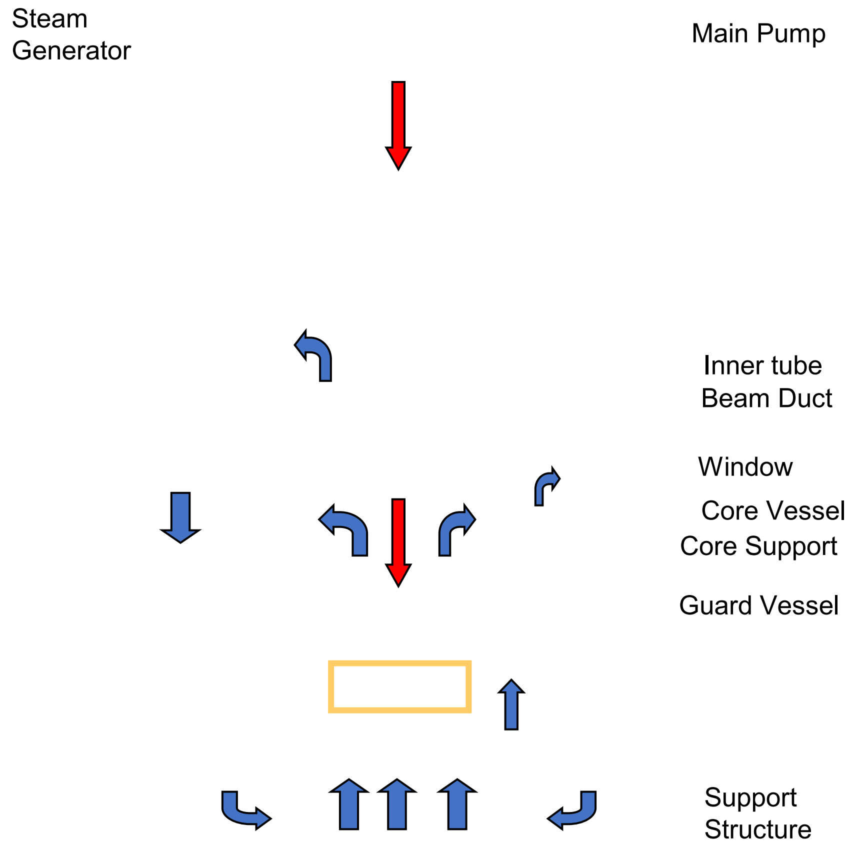


Accelerator-Driven System (ADS) for MA Transmutation :

# Conceptual Design of ADS in JAEA

## Purpose : MA transmutation

- Proton beam : 1.5GeV ~20MW
- Spallation target : LBE
- Coolant : LBE
- Subcriticality : $k_{eff} = 0.97$
- Thermal output : 800MWt
- Core height : 1000mm
- Core diameter : 2440 mm
- Fuel inventory : 4.2t (MA:2.5t)
- Fuel composition :
  (MA + Pu)N+ZrN (Mono-nitride)
  Inner : 70%MA+30%Pu
  Outer : 54%MA+42%Pu
- Transmutation rate :
  250kg(MA) / 300EFPD




K. Tsujimoto, H.Oigawa, K.Kikuchi, et. al, "Feasibility of Lead-Bismuth-Cooled accelerator-Driven System for Minor-Actinide Transmutation", *Nucl. Tech.* 161, 315-328 (2008).

Accelerator-Driven System (ADS) for MA Transmutation :

# Typical Nuclear Reaction for Neutron Source

| Process | Example | Yield | Energy deposition (MeV/n) |
|---|---|---|---|
| DT solid target | 400 keV deutrons on T in titanium | $40 \times 10^{-5}$ n/d | 10000 |
| Deutron stripping (Be(d,n), Li(d,n)) | 35 MeV D on Liquid Li | $2.5 \times 10^{-3}$ n/d | 10000 |
| Electron bremsstrahlung photoneutron ((e$^-$,$\gamma$)($\gamma$,n)) | 100 MeV e$^-$ on $^{238}$U | $5 \times 10^{-2}$ n/e | 2000 |
| Fission | $^{235}$U(n,f) | 2~3 n/fission | 180 |
| Spallation | 1.5 GeV protons on Pb | 40 n/proton | 30 |
| DT CTR | Laser or ion-beam imploded pellet | 1 n/fusion | 3 |

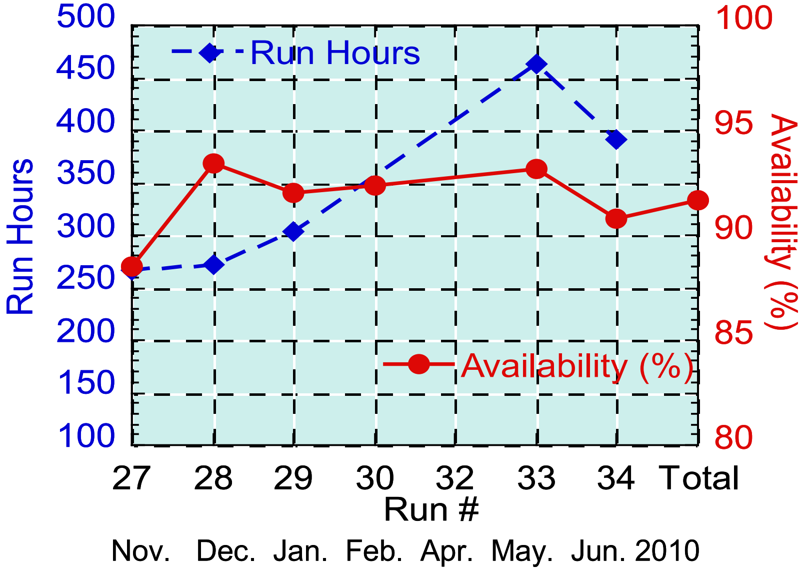
R&D Activities in JAEA :

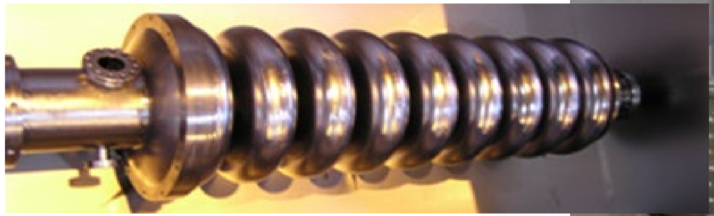
# R&D Activities for Superconducting LINAC

- **Prototype of cryomodule , which was designed to accept 927MHz RF wave, was made and tested.**
  - Two cavity excitation was successfully performed at the design field of 10MV/m, repetition rate of 25Hz and pulse length of 1ms.
- Information on **J-PARC LINAC (181MeV at present, 400MeV in the future)** will be included for the accelerator design study.
  - The LINAC had been operated stably for injection to the following 3 GeV synchrotron since October, 2007.

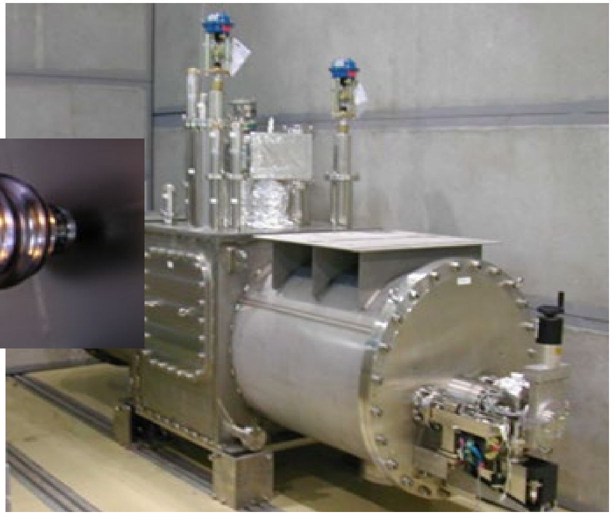
Photograph of J-PARC LINAC

Statics [ Run #27 (Nov. 2009) -- #34 (Jun. 2010)]



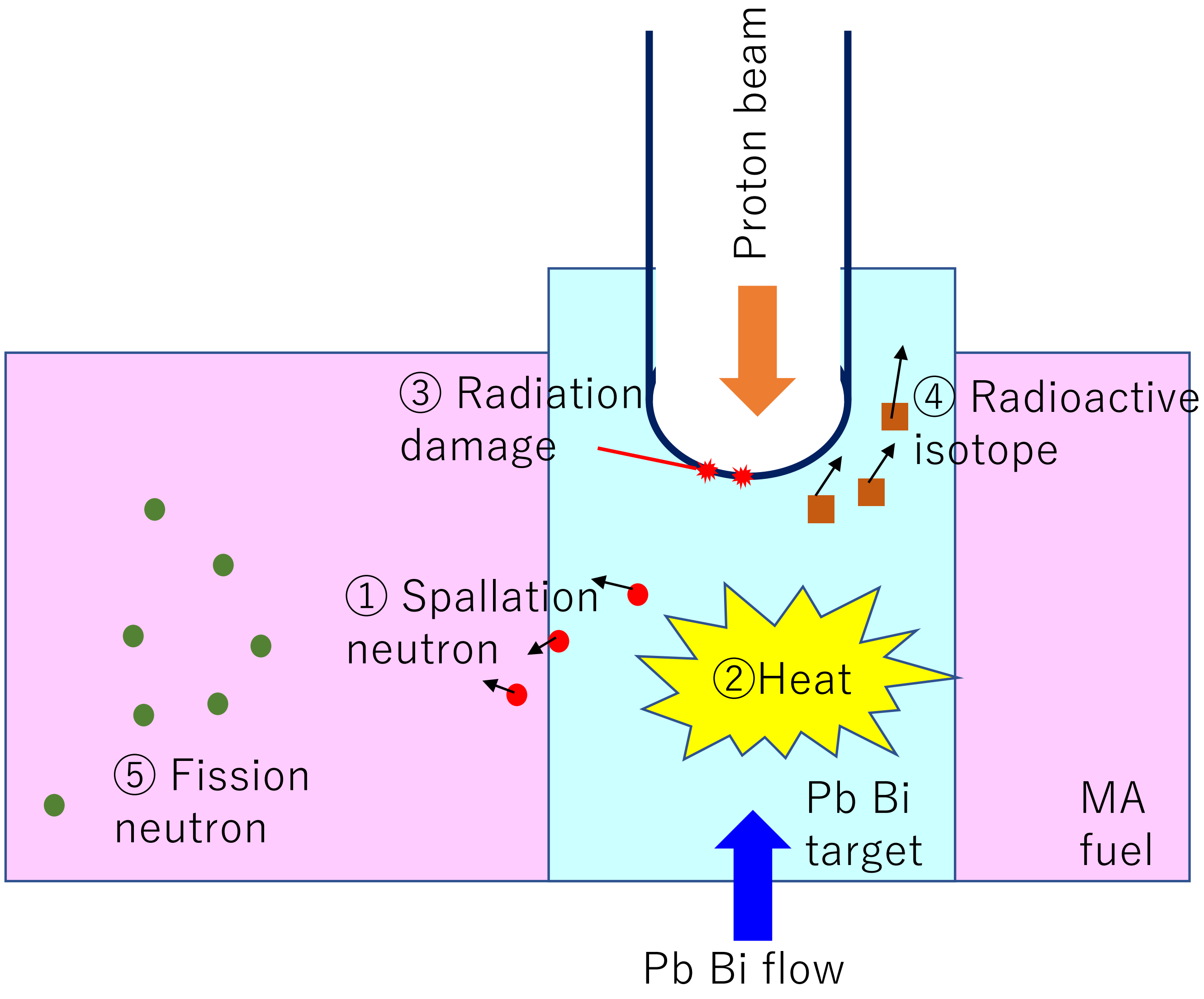
**Superconducting cavity**



**Cryomodule**

# 3. Nuclear data in ADS design

# Nuclear reactions in ADS




① Number and energy of spallation neutron production determines necessary proton beam current.

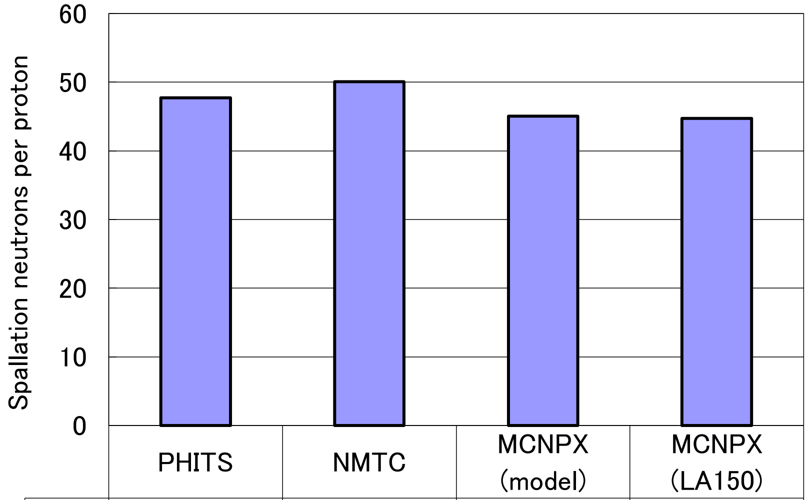
② Heat generation in PbBi target affects thermal hydraulics design

③ Radiation damage by proton on beam window material (steal), i.e. DPA and H/He production, influence material lifetime.

④ Radioactive isotopes generated by spallation reaction causes dose on operator and becomes waste.

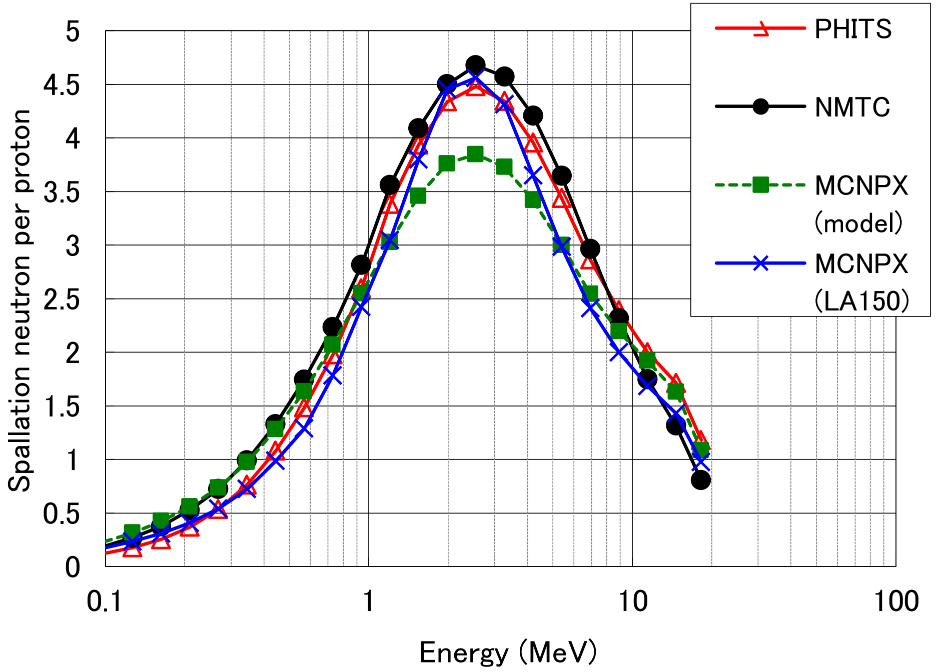
⑤ Behavior of fission neutrons in MA fuel affects on: total fission power, heat distribution, depletion of MA, power evolution in accident, ….

# ① Spallation neutron




| | PHITS | NMTC | MCNPX (model) | MCNPX (LA150) |
|---|---|---|---|---|
| N/P | 47.72 | 50.06 | 45.04 | 44.71 |
| MeV | 4.10 | 3.70 | 3.95 | 3.88 |

Number of spallation neutron generated at energy < 20MeV.

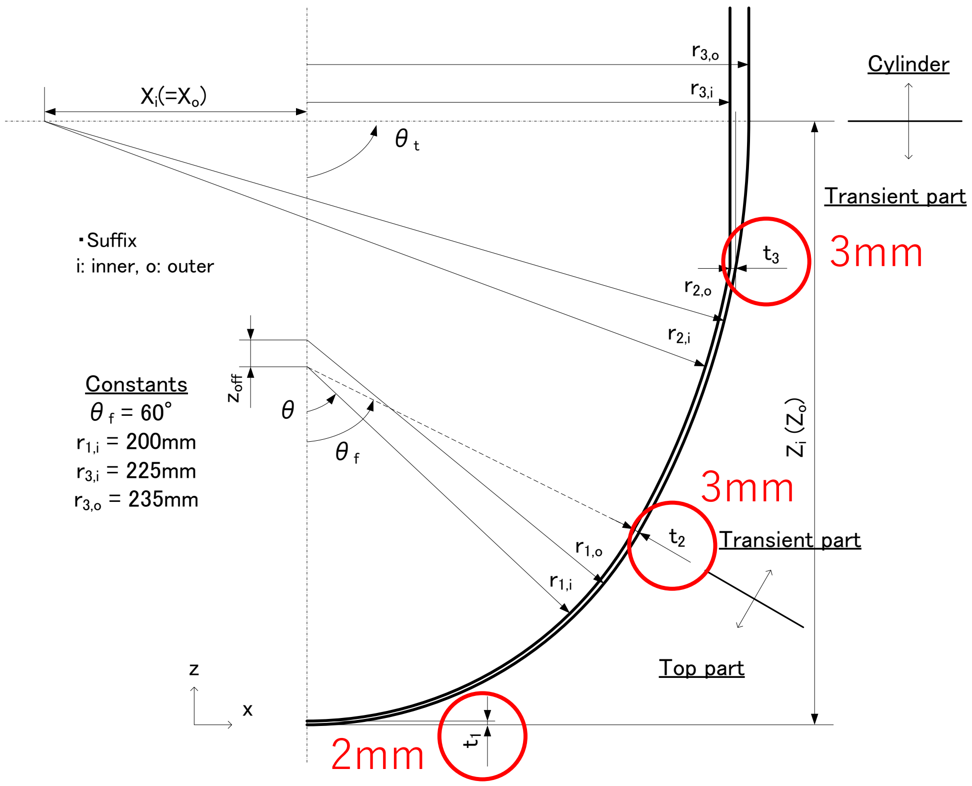



Spectrum of spallation neutron < 20MeV

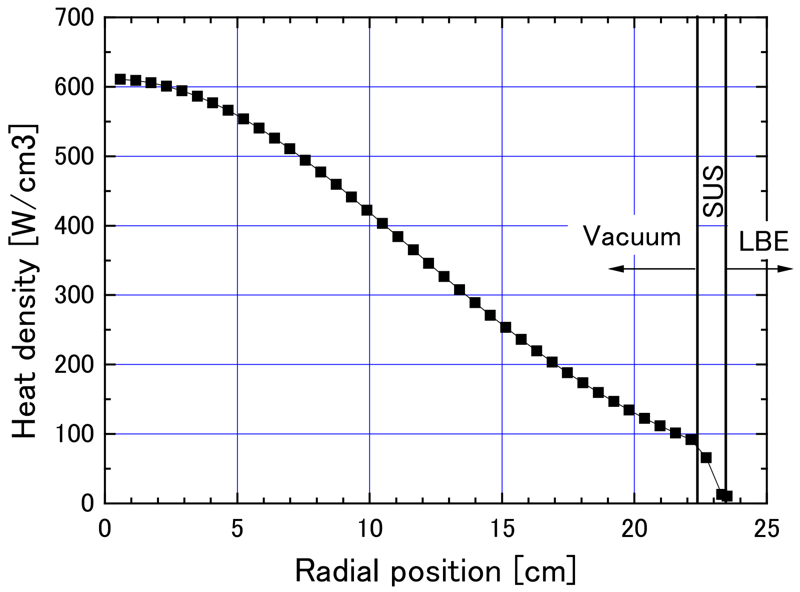
Power of ADS is proportional to number of spallation neutrons.
Uncertainty of 5% in number results in 800 ± 40 MWt.

$$Power \propto \frac{k}{1-k} S \qquad k \sim 0.97\ (multiplication\ factor), \quad S\text{: number of spallation source}$$

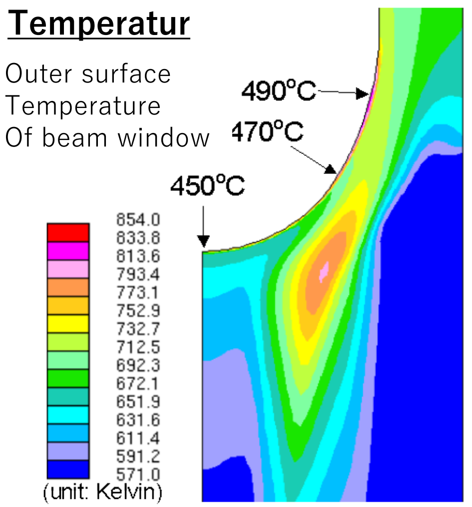
# ② Heat




Beam window
(Thin wall between Pb-Bi target and vacuum)




Heat density in beam window




Temperature in Pb-Bi

# ③ DPA (Displacement per atom)

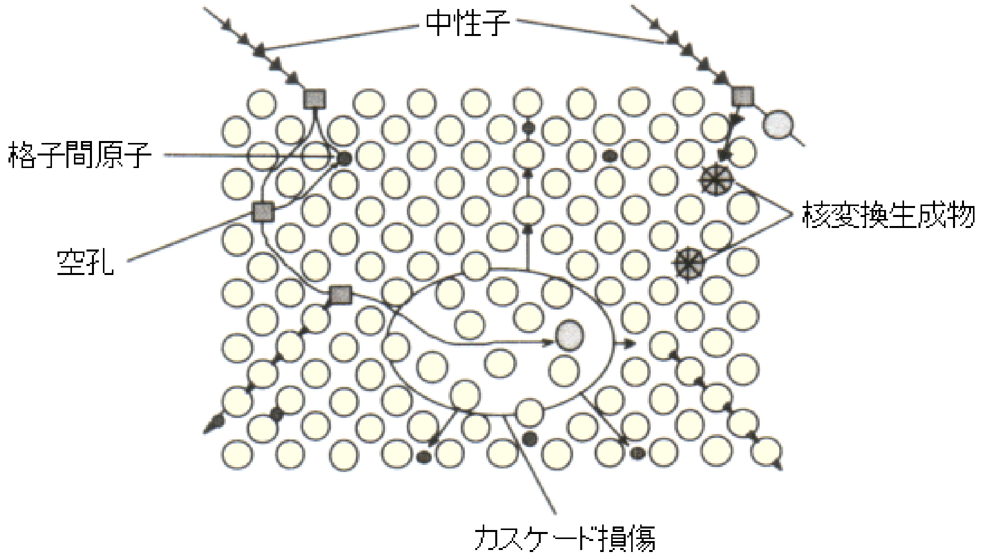
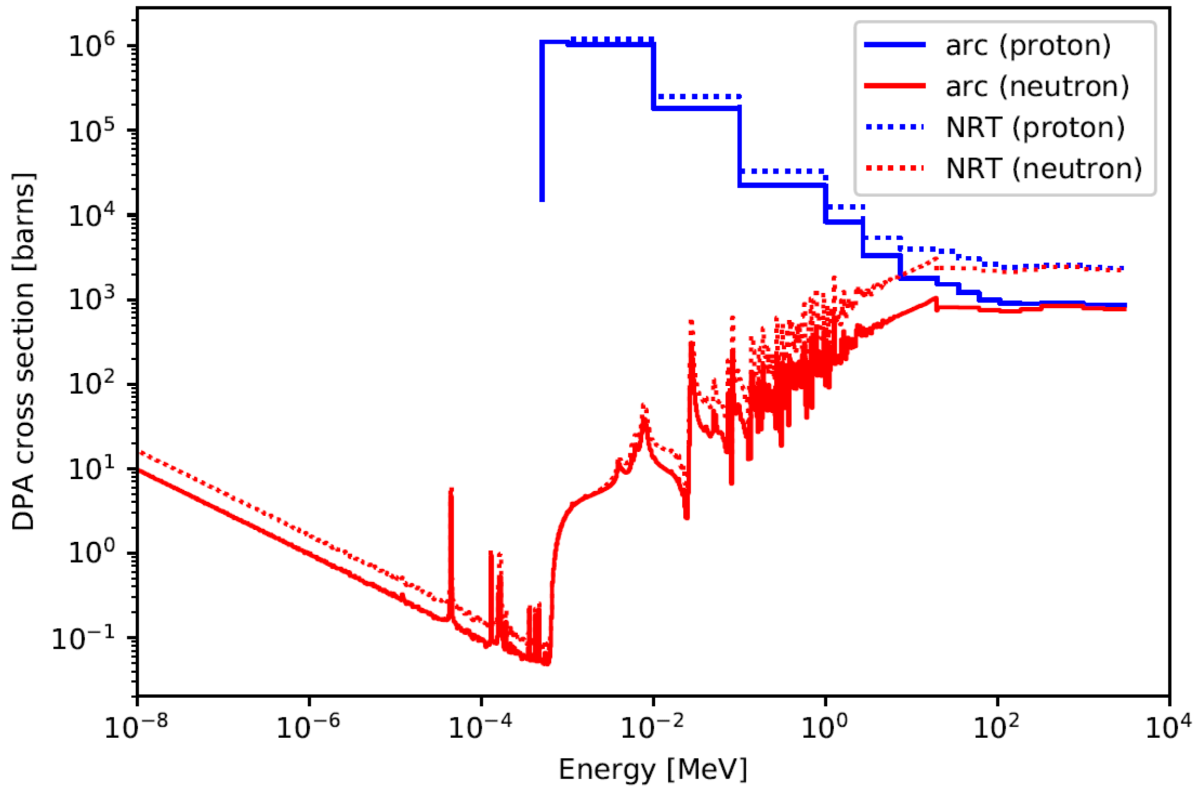



図1　中性子照射を受けた材料に起こる損傷の素過程（模式図）

Process of neutron-induced damage on material

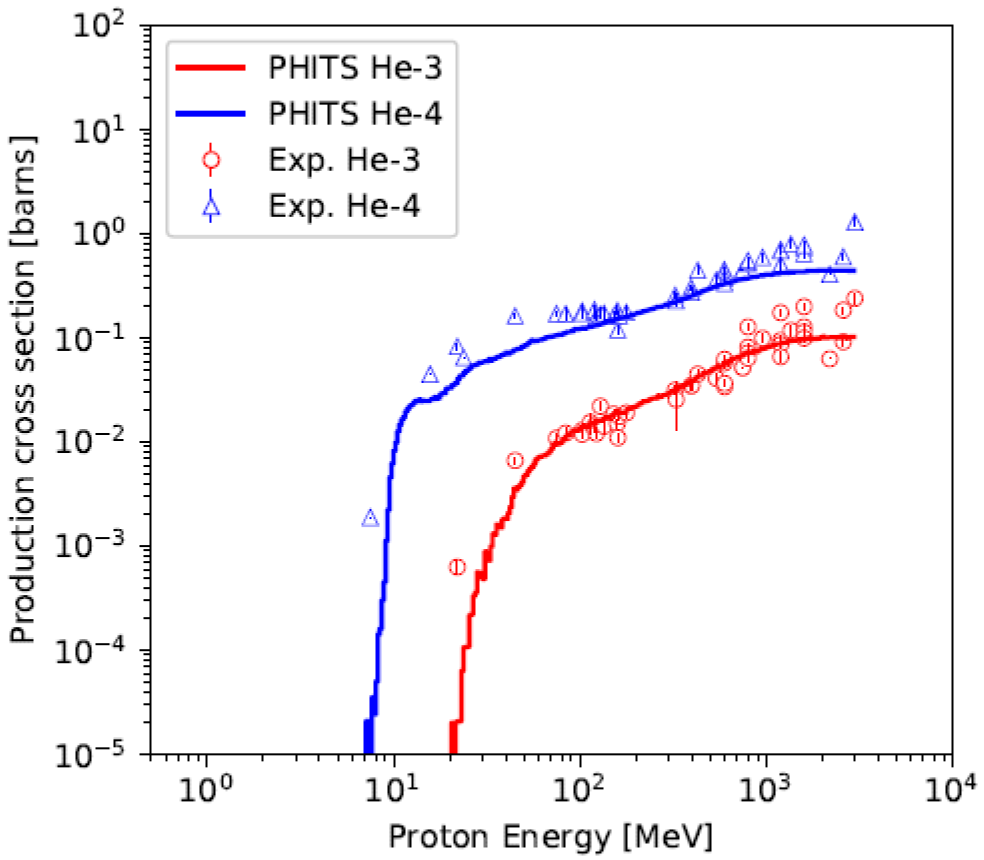
ATOMICA



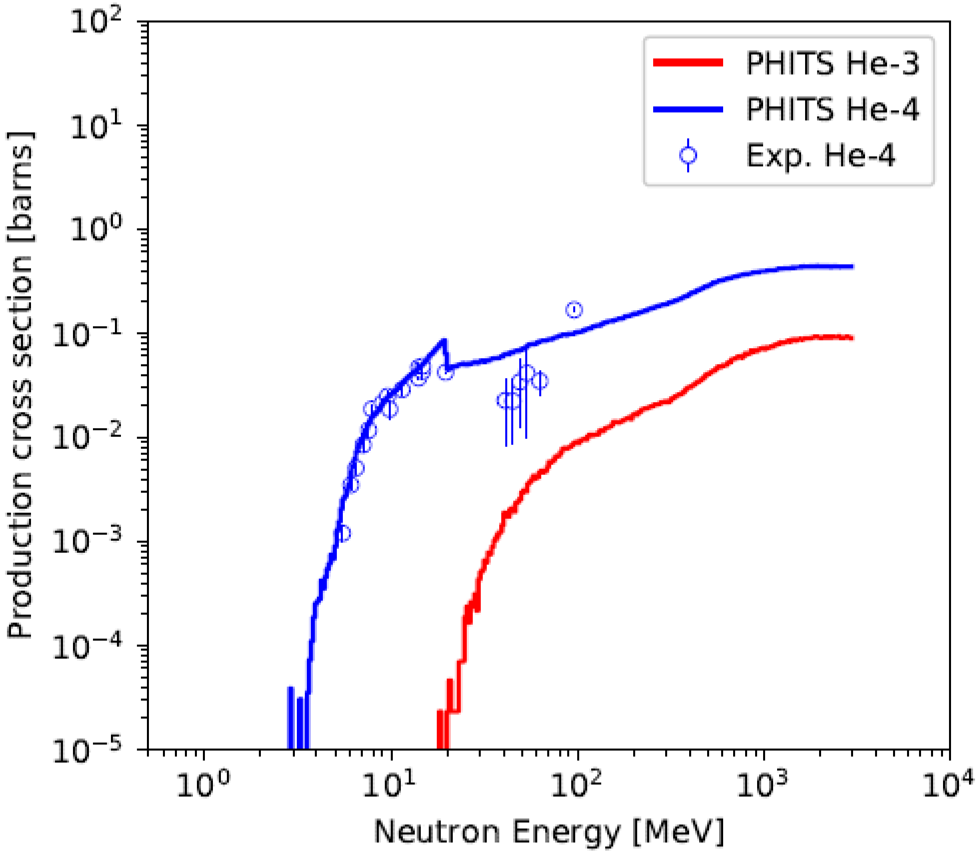

DPA cross section

K. Nakano, et al “Neutronic analysis of beam window and LBE of an accelerator-driven system” ( to be published)

# ③ Gas production in material



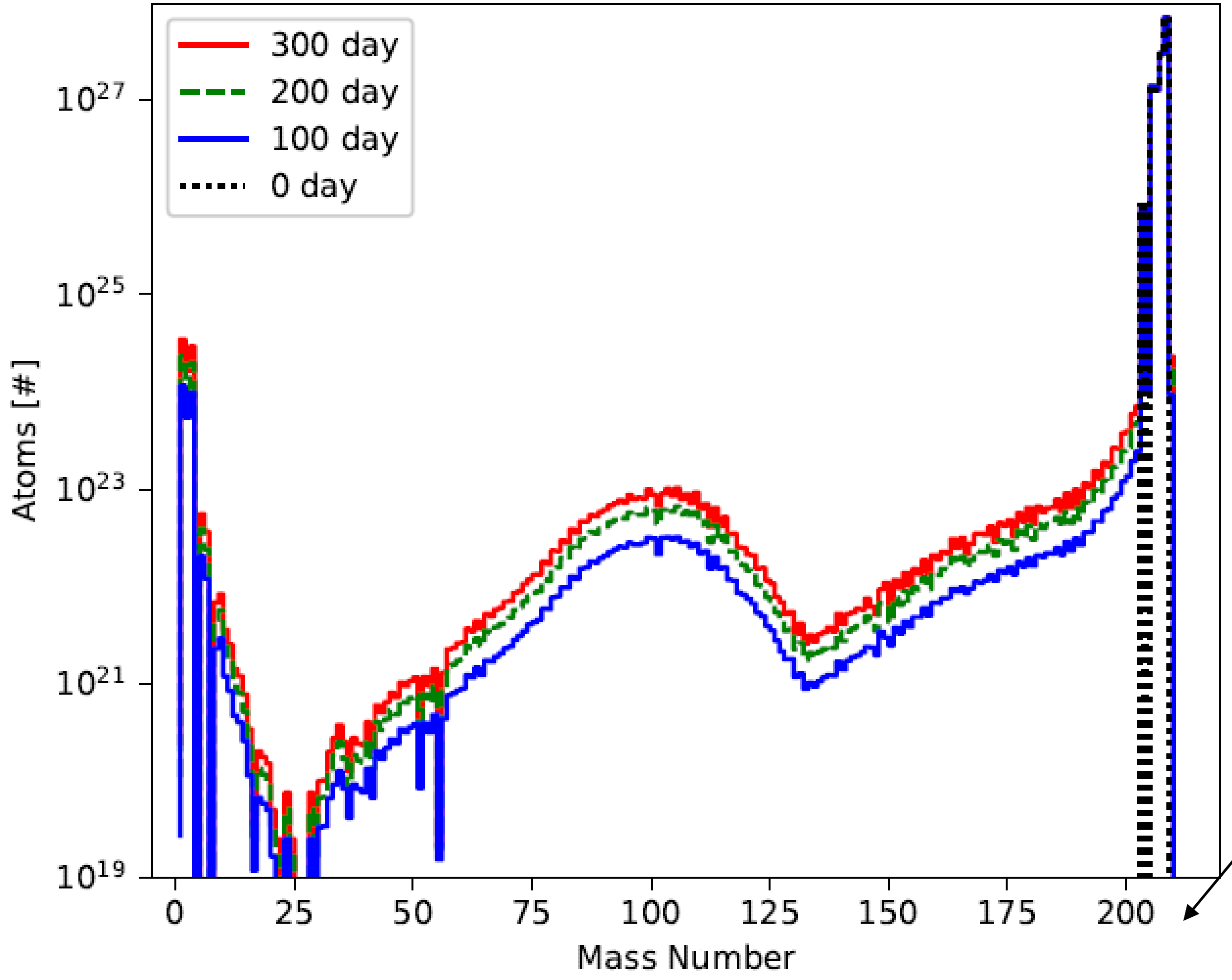

He production cross section (proton)




He production cross section (neutron)

K. Nakano, et al "Neutronic analysis of beam window and LBE of an accelerator-driven system" ( to be published)

# ④Radioactive isotopes generated in Pb-Bi




Mass of Pb-Bi (206~209)

K. Nakano, et al "Neutronic analysis of beam window and LBE of an accelerator-driven system"
( to be published)

# ⑤ Fission neutron: Benchmark

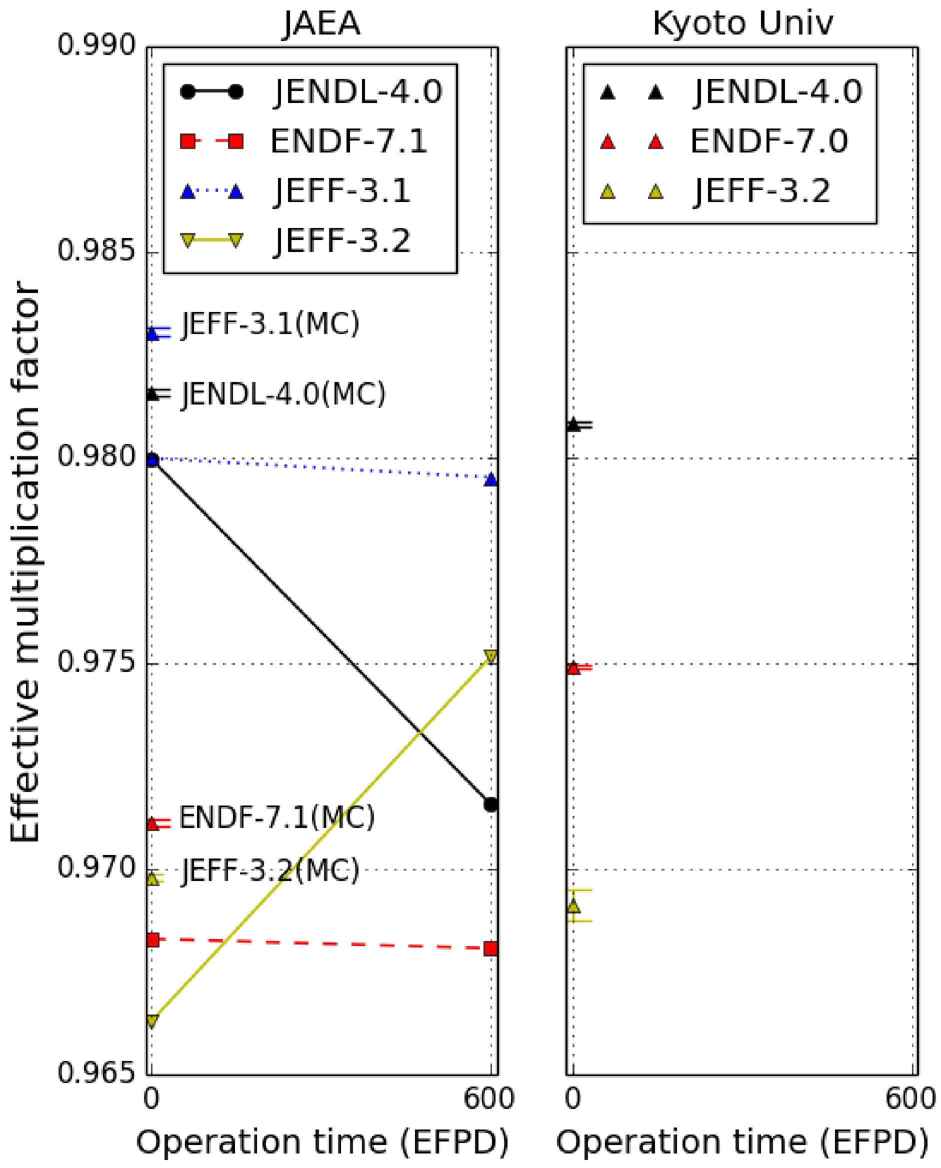
- k-effective at beginning and end of the burn-up cycle
- Isotopic composition after burn-up
- Uncertainty deduced from covariance data prepared in nuclear data library

Table : Contributors

| Participant | Calculation code (method) | Nuclear data library |
|---|---|---|
| JAEA | ADS3D (deterministic)<br>MVP (Monte-Carlo, only k-eff calculation) | JENDL-4.0<br>ENDF/B-VII.1<br>JEFF-3.1<br>JEFF-3.2 |
| KIT | ERANOS (BISTRO/VARIANT) (deterministic) | JEFF-3.1 |
| Kyoto univ. (KU) | MVP/MVP-BURN (Monte-Carlo) | JENDL-4.0<br>ENDF/B-VII.0 |

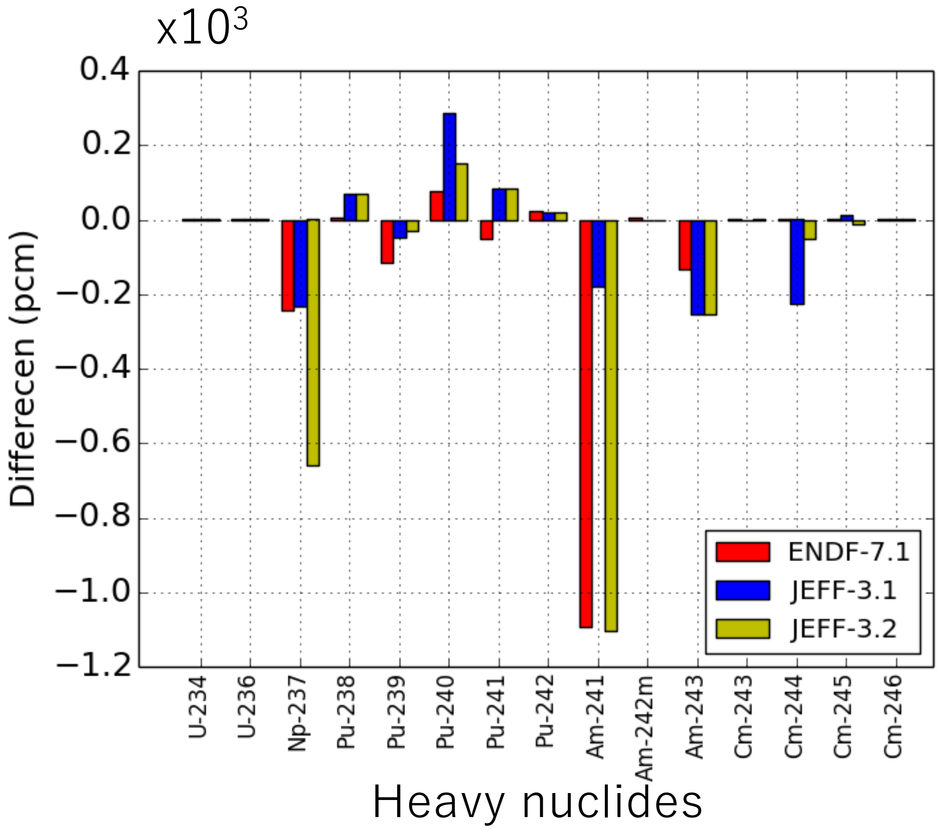
# ⑤ Multiplication factor

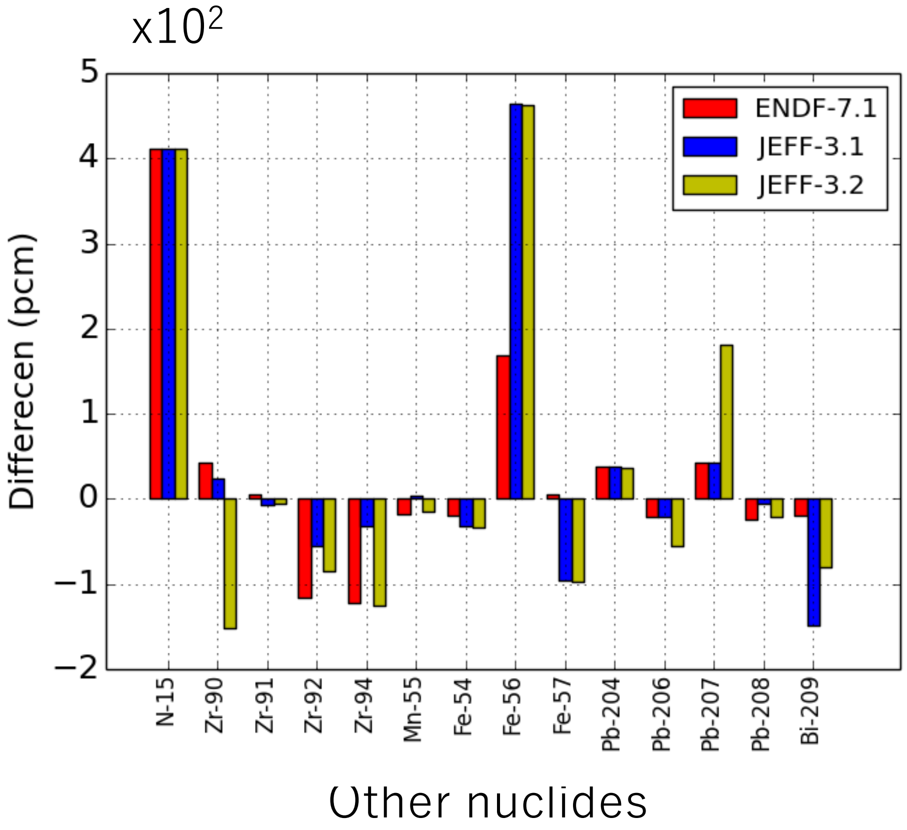
- Keff diverse from 0.965 to 0.985.
- Total fission power is proportional to $\frac{k_{eff}}{1-k_{eff}}$, which diverse from 29 to 67.
- Time evolution during operation behaves difference in JEFF, JENDL and ENDF.




Sugawara, et al,TCADS-4, Antwerpen, Belgium,14-17 October 2019

# ⑤ Cause of difference (k-eff)




- ENDF-7.1: Np-237, Am-241, N-15
- JEFF-3.1: Np-237, Pu-240, N-15, Fe-56
- JEFF-3.2: Np-237, Am-241, N-15, Fe-56, Pb-207

Difference = k-eff(x) – k-eff(J40).
ADS3D code was used for calculation

# Summary

1. Role of ADS :
   - Japanese situation and HLW issue
   - Partitioning & Transmutation for HLW reduction
2. Principle of ADS for MA transmutation
   - Transmutation of minor actinide by fission reaction
   - ADS concept
3. Nuclear data in ADS design
   - High energy >20MeV (neutron production, heat, damage, radioactive isotope)
   - Low energy <20MeV (criticality)

Thank you for your attention!