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ImPACT Symposium

JAEA's R&D Activities on Transmutation Technology for Long-lived Nuclear Wastes

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Background (1/3)

- Sustainable use of nuclear power depends on:
  - Safety - Non-proliferation - Radioactive waste - Economy
- To reduce the burden of radioactive waste management, the **Partitioning and Transmutation (P&T) Technology** has been actively studied in Japan for more than 30 years.
  - **Japan Atomic Energy Agency (JAEA)** has been studying this technology since the era of the former institutions; JAERI and PNC/JNC.
  - In Japan, the **OMEGA Project** was initiated in 1988. Two Check & Reviews (C&Rs) were carried out by the Atomic Energy Commission (AEC) in 2000 and 2009.
  - Since the first C&R, JAEA has been mainly studying P&T of **Minor Actinides (MAs)**, while P&T of **Long-Lived Fission Products (LLFPs)** was mainly studied by universities.

Background (2/3)

- After the **accident of Fukushima Daiichi Nuclear Power Plant** in 2011, public concern to **spent fuel management** increased in Japan.

➔ **P&T** for long-lived nuclides, therefore, drew the attention from public, media and politicians.

- In 2014, Japanese Government issued the "**Strategic Energy Plan**", where the importance of research and development (R&D) on **volume reduction and mitigation of degree of harmfulness of radioactive waste (i. e. P&T) by fast reactor and/or accelerator** was described.

Background (3/3)

- **Up to now, candidate site for the deep geological repository has not yet been nominated**, while the "Map of Scientific Characteristics" was released in July, 2017.

- In July, 2018, Japanese Government revised the "**Strategic Energy Plan**", where promotion of R&D on P&T was mentioned again.

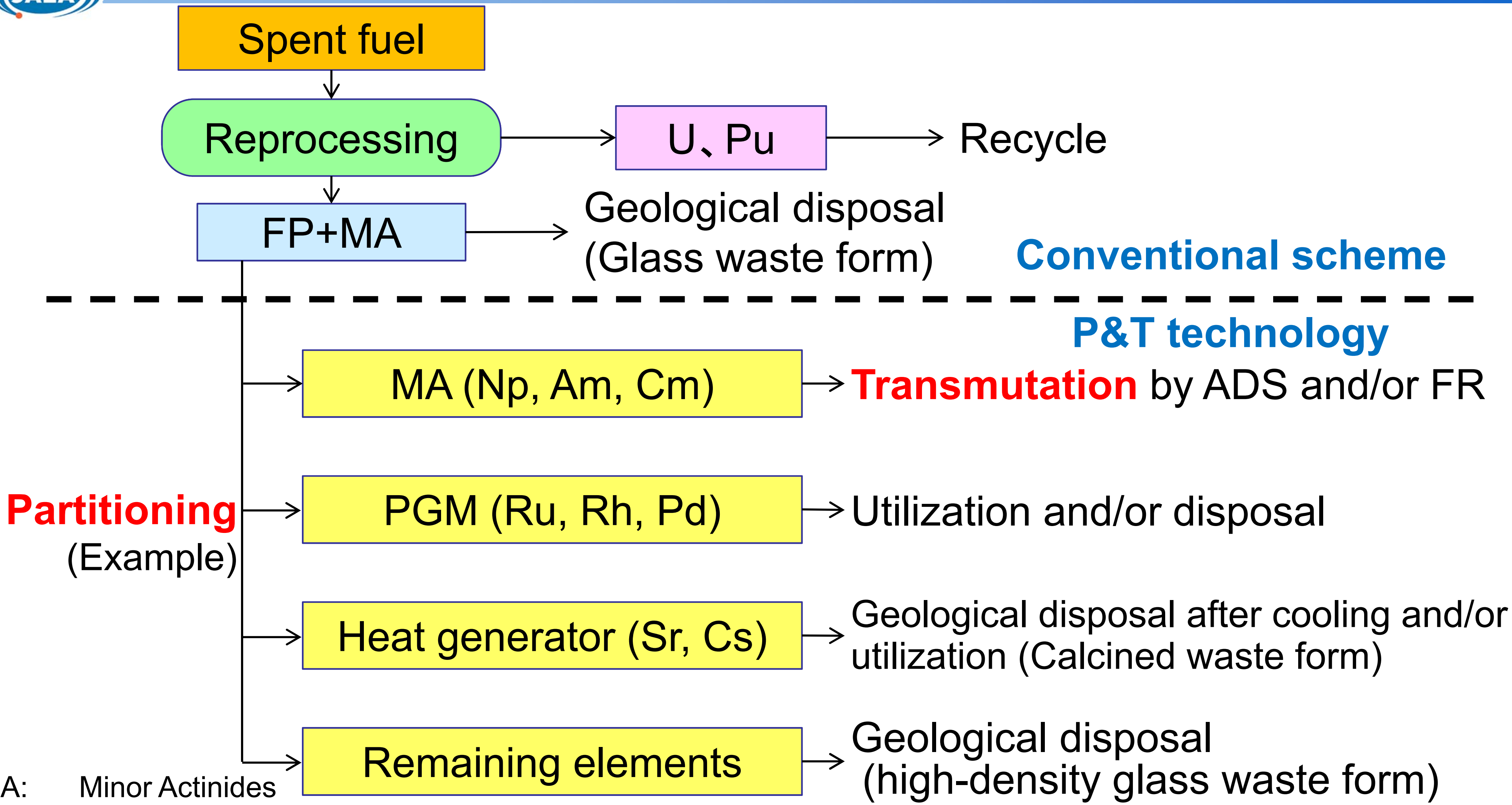
Present Status around P&T in JAEA

- In December, 2016, Japanese Government decided the **shut-down of the prototype fast breeder reactor "MONJU"**.

- JAEA released a middle and long-term plan for facility management, where **44 out of 89 facilities** (including JMTR and FCA) **will be closed**.

- The Japan Proton Accelerator Research Complex (**J-PARC**) **achieved 1-MW operation (~ 1hr.)** in July, 2018. Nevertheless, construction of the **Transmutation Experimental Facility (TEF)** of J-PARC is **still pending**.

JAEA's Strategy on P&T



MA: Minor Actinides
FP: Fission Products
PGM: Platinum Group Metal
FR: Fast Reactor
ADS: Accelerator Driven System

Major Long-lived Nuclides in Spent Nuclear Fuel

JAEA

Actinides

Nuclide	Half-life (year)	Dose coefficient (μSv/kBq)	Mass (per 1tHM)
U-235	0.7B	47	10kg
U-238	4.5B	45	930kg

Trans-uranic elements (TRU)

Nuclide	Half-life (year)	Dose coefficient (μSv/kBq)	Mass (per 1tHM)
Pu-238	87.7	**230**	0.3kg
Pu-239	24k	**250**	6kg
Pu-240	6.6k	**250**	3kg
Pu-241	14.3	4.8	1kg

Minor actinides (MA)

Nuclide	Half-life (year)	Dose coefficient (μSv/kBq)	Mass (per 1tHM)
Np-237	2.14M	**110**	0.6kg
Am-241	432	**200**	0.4kg
Am-243	7.4k	**200**	0.2kg
Cm-244	18.1	**120**	60g

Fission products (FP)

Nuclide	Half-life (year)	Dose coefficient (μSv/kBq)	Mass (per 1tHM)
Se-79	0.3M	2.9	6g
Sr-90	28.8	28	0.6kg
Zr-93	1.53M	1.1	1kg
Tc-99	0.21M	0.64	1kg
Pd-107	6.5M	0.037	0.3kg
Sn-126	0.1M	4.7	30g
I-129	15.7M	**110**	0.2kg
Cs-135	2.3M	2.0	0.5kg
Cs-137	30.1	13	1.5kg

The other 30~40kg of FPs are stable or short-lived ones

Dose Coefficient:

Committed dose (Sv) per unit intake (Bq), indicating the magnitude of influence of radioactivity to human body. α-activity is more influential than β,γ-activity.

Examples of "Reduced Half-life"

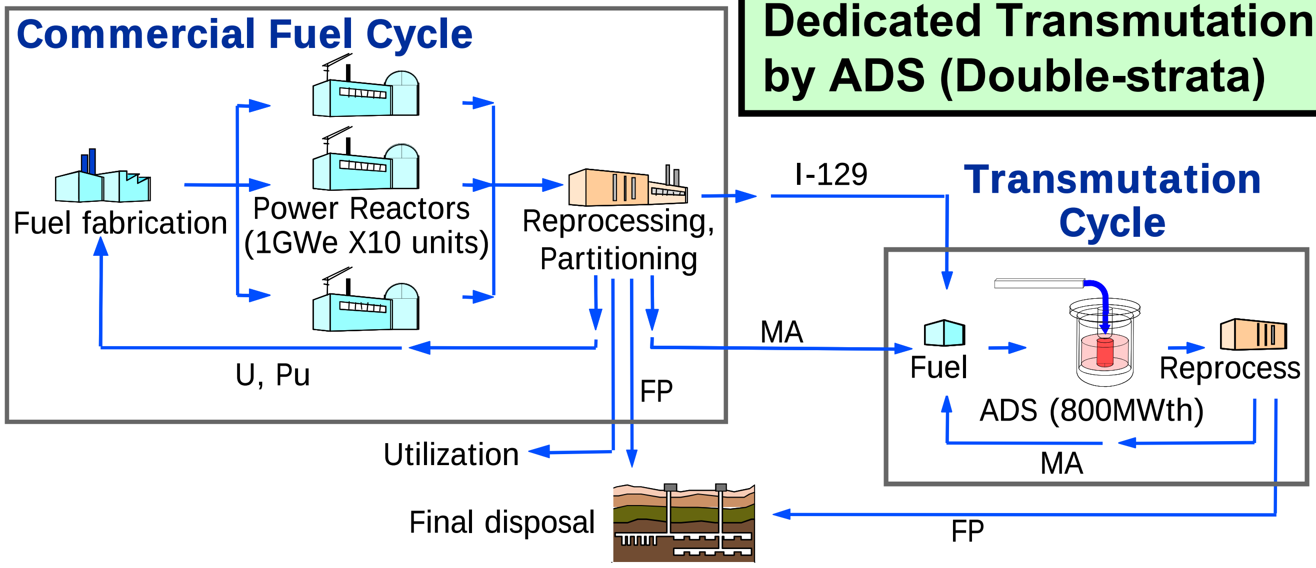
"Reduced Half-life" can be written as $T_{1/2} = \ln 2 / (\varphi \cdot \sigma)$, if there is no competitive reaction nor production reaction, where φ is neutron flux and σ is reaction cross section.

Nuclide	Half-life (year)	Reaction	Neutron energy	Cross section σ (JENDL-4.0) (barn=$10^{-24}cm^2$)	Neutron flux φ ($/cm^2/s$)		
					10^{13}	10^{14}	10^{15}
					Reduced half-life (year)		
Np-237	2.14M	n,f	Fiss. Spec.	1.336	1,600	160	16
Am-241	432	n,f	Fiss. Spec.	1.378	1,600	160	16
Tc-99	211k	n,γ	Maxwell	23.68	93	9.3	0.93
Sn-126	230k	n,γ	Maxwell	0.09	24,000	2,400	240
I-129	15.7M	n,γ	Maxwell	30.33	72	7.2	0.72
Cs-135	2.3M	n,γ	Maxwell	8.304	260	26	2.6
Cs-137	30.1	n,γ	Maxwell	0.27	8,100	810	81

Condition of realistic transmutation: $\varphi \cdot \sigma > 10^{15}$ ($barn/cm^2/s$)

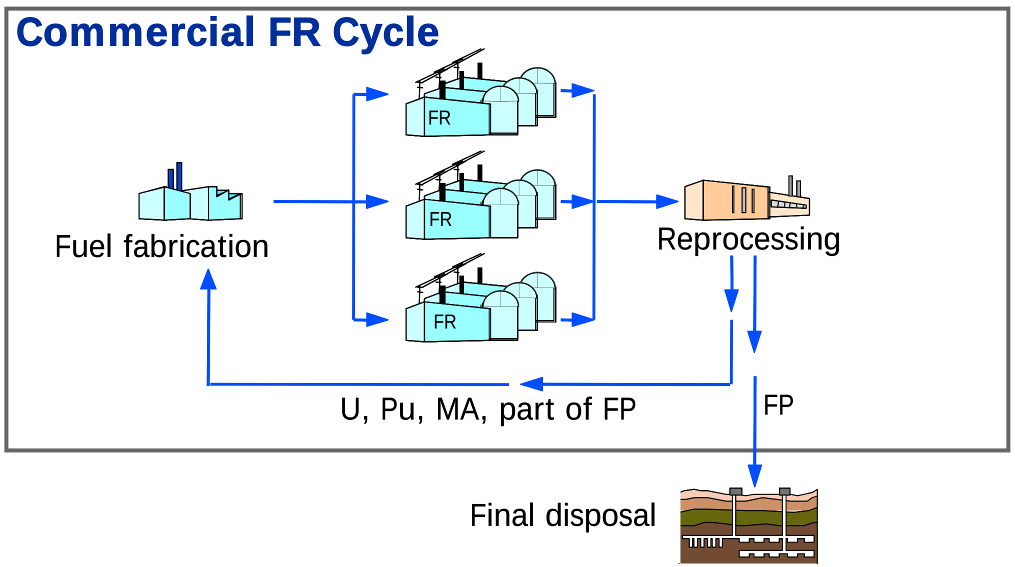
Two Types of Fuel Cycles for P&T

Dedicated Transmutation by ADS (Double-strata)



- Transmutation cycle is attached to commercial cycle.
- ADS or ABR is used as dedicated transmutation system.
- MA can be confined into a small cycle and transmuted efficiently.

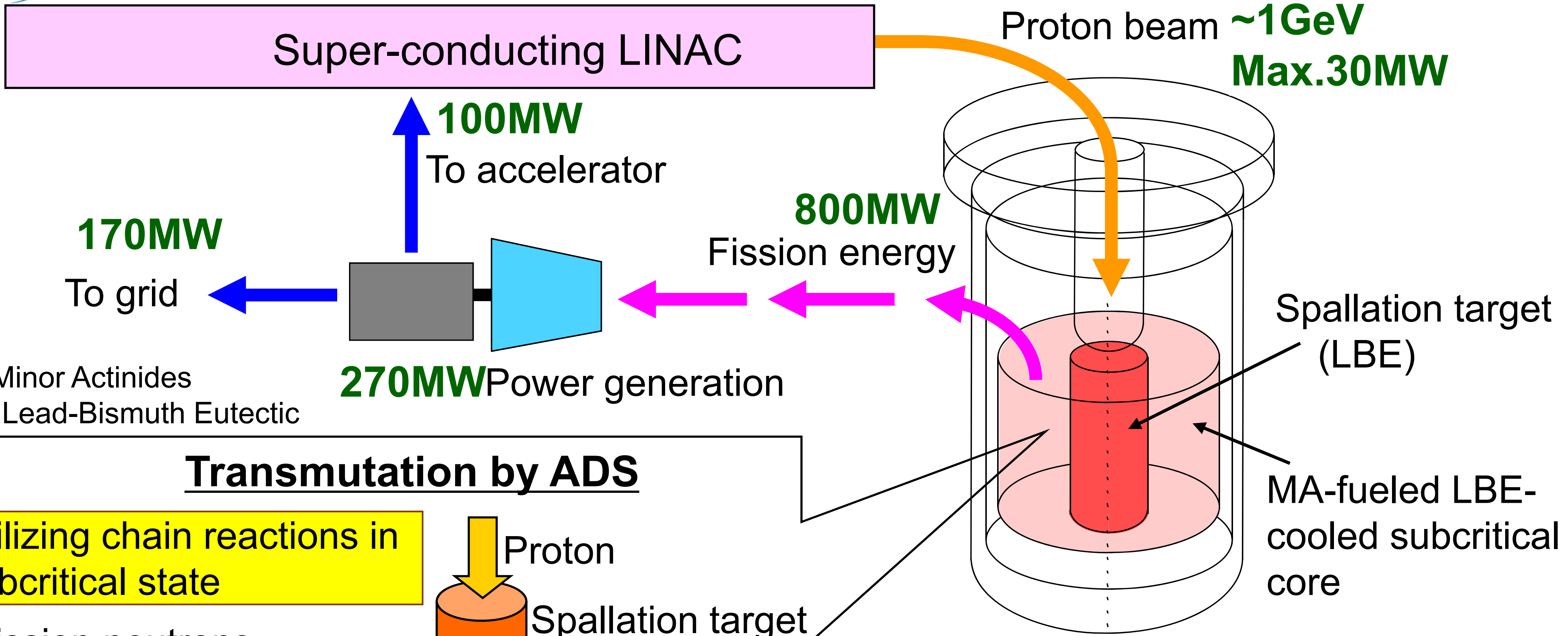
Homogeneous Recycle in FR



- MA is transmuted by commercial FR power plants.
- 5% MA (max.) is added to conventional FR fuel (MOX, Metal, ...)

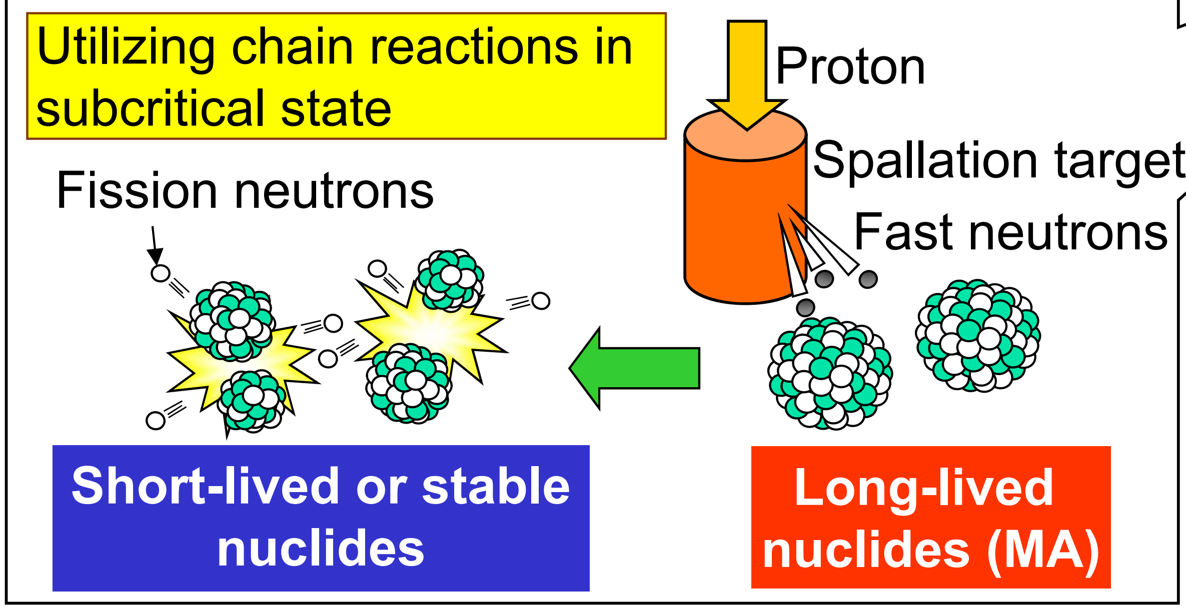
FP: Fission Product
MA: Minor Actinide (Np, Am, Cm)
ADS: Accelerator-Driven System
ABR: Actinide Burner Reactor
FR: Fast Reactor

Accelerator Driven System (ADS)



MA: Minor Actinides
LBE: Lead-Bismuth Eutectic

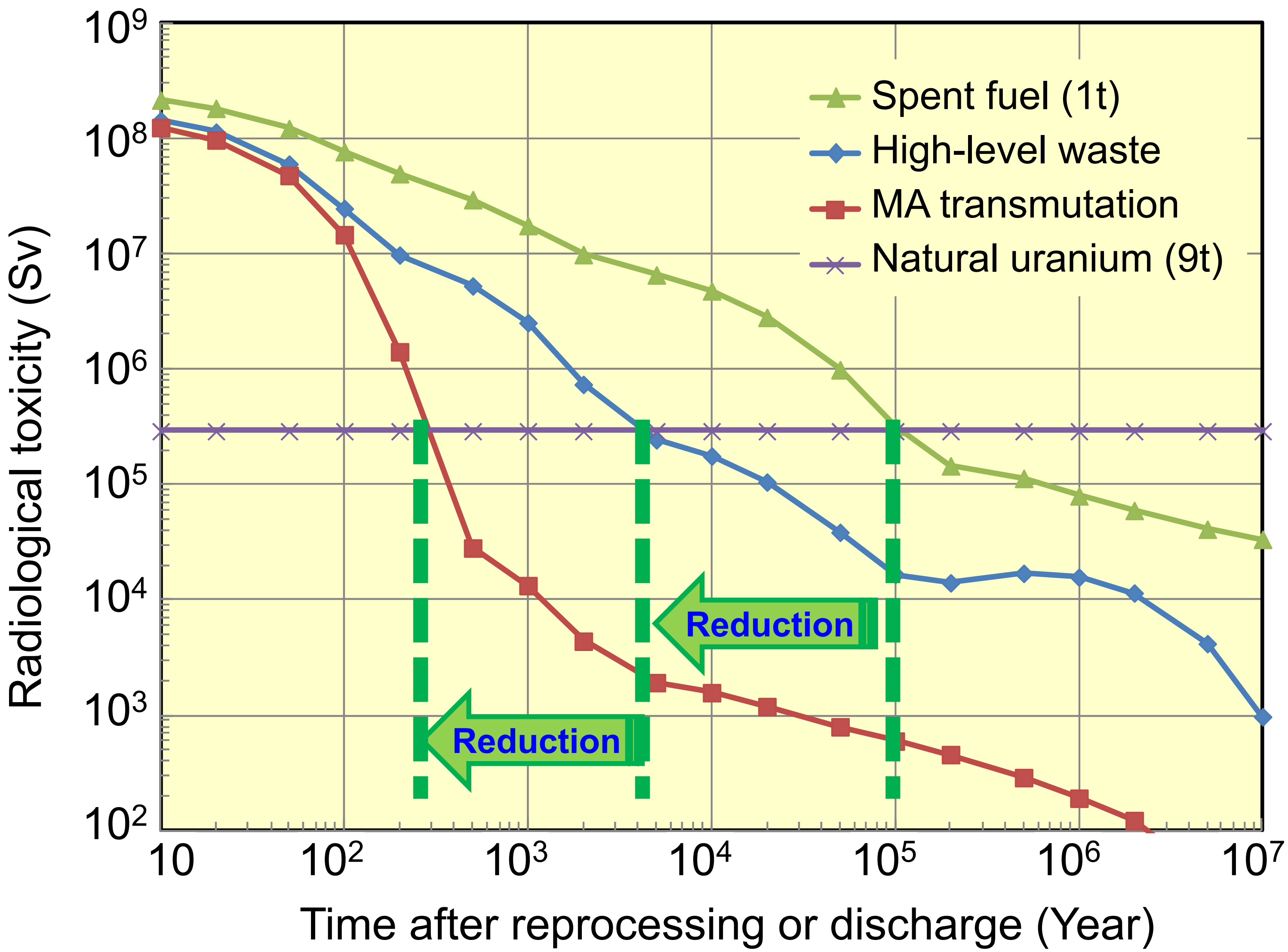
Transmutation by ADS



Characteristics of ADS:

- Chain reactions stop when the accelerator is turned off.
- LBE is chemically stable.
  ➔ **High safety can be expected.**
- High MA-bearing fuel can be used.
  ➔ MA from **10 LWRs** can be transmuted.

Reduction of Radiological Toxicity by P&T



Radiological Toxicity:
Amount of radioactivity weighted by dose coefficient of each nuclide.

- Normalized by 1t of spent fuel.
- 9t of natural uranium (NU) is raw material of 1t of low-enriched uranium including daughter nuclides.

Time period to decay below the NU level:

- Spent fuel **100,000y**

↓

- High-level waste **5,000y**

↓

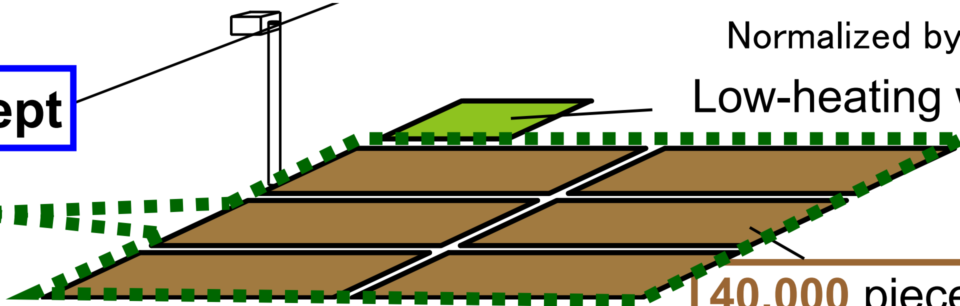
- MA transmutation **300y**

Compact Disposal by Coupling with Long-term Storage

Normalized by 32,000tHM of 45GWd/t spent fuel

Conventional Concept

1.8 km²



Low-heating wastes (0.13km²)

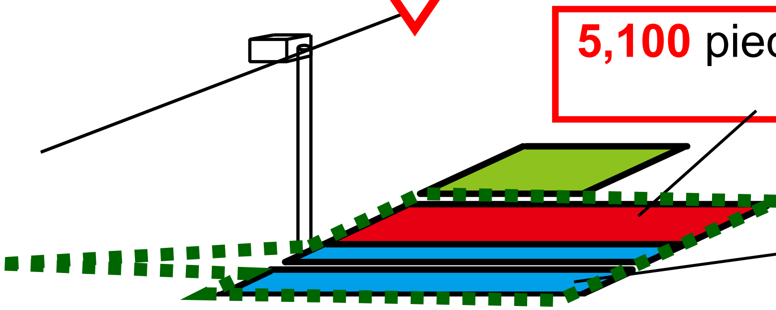
CT: Cooling time before disposal

40,000 pieces of **glass waste forms** (1.8km²)
(CT: **50** y)

(Vertical emplacement in crystalline rock)

MA transmutation
+
FP Partitioning

0.41 km²

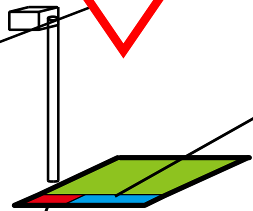


5,100 pieces of **Sr-Cs** calcined forms (0.23km²)
(CT: **130** y)

8,300 pieces of **highly-loaded glass** waste forms (0.18km²)
(CT: **5** y)

MA transmutation
+
FP Partitioning
+
Long-term storage of Sr+Cs

0.015 km²



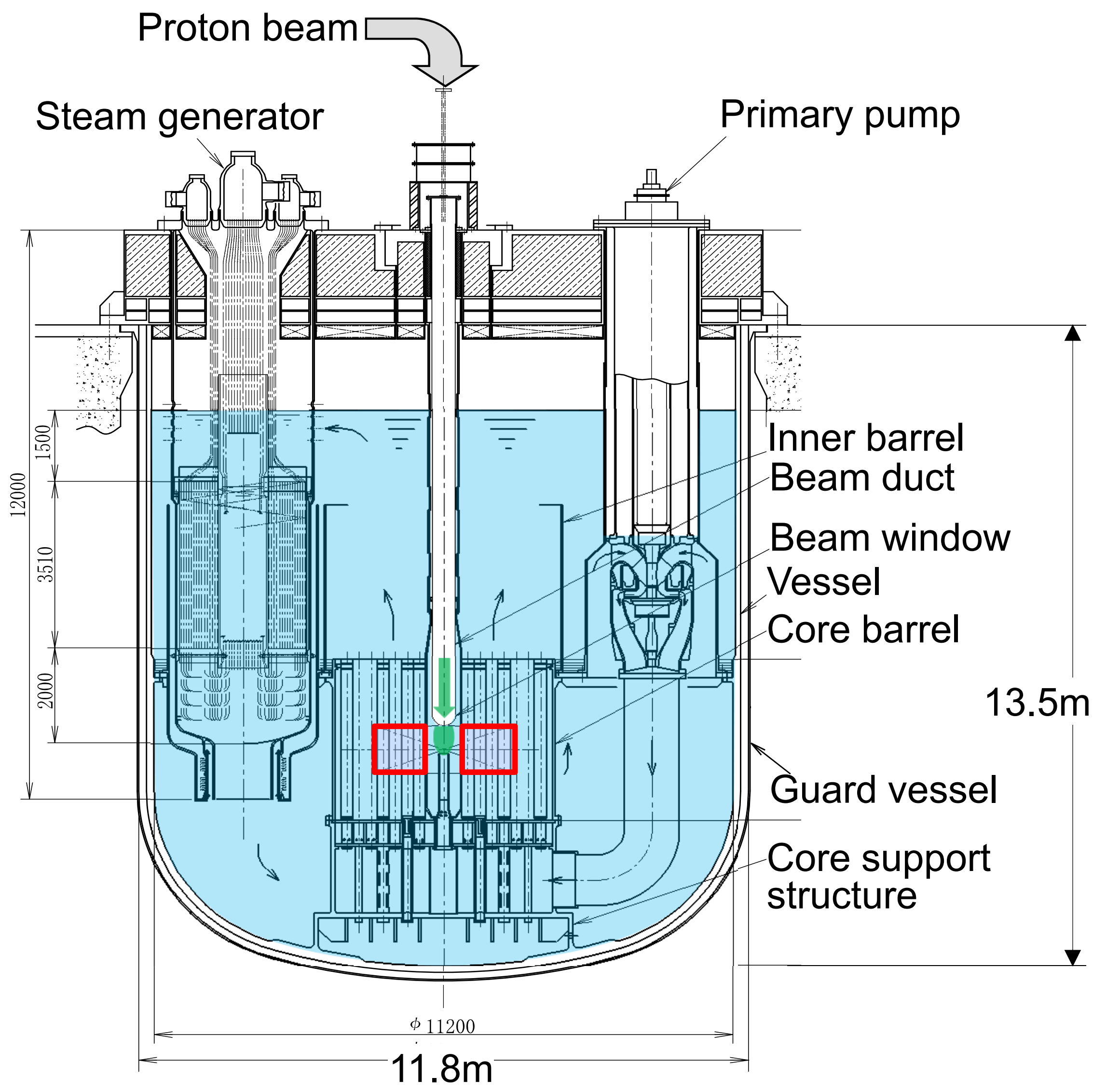
8,300 pieces of **highly-loaded glass** waste forms (0.01km²)
(CT: **45** y)

5,100 pieces of **Sr-Cs** calcined forms (0.005km²)
(CT: **320** y)

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).

Conceptual Specification and View of ADS

- Proton beam: 1.5GeV
- Spallation target: Pb-Bi
- Coolant: Pb-Bi
  Inlet: 300℃, Outlet: 407℃
- Maximum $k_{eff} = 0.97$
- Thermal output: 800MWt
- MA initial inventory: 2.5t
- Fuel composition:
  (MA +Pu)N + ZrN
- Transmutation rate:
  10%MA / y
- Fuel exchange:
  600EFPD, 1batch
- Primary pump: 2 units
- Steam generator: 4 units
- Decay heat removal system:
  3 units



Requirements for Accelerator

High reliability:

・In the case of a saturated stream turbine cycle.

- Trip longer than 5s may cause thermal stress.
- Trip longer than 300s may cause turbine stop.

High efficiency:

・ In the case of k_{sub} = 0.95, 800MWth is achievable by 27MW

→ 250MWe can be generated.

→ **At least 15%, preferably more than 30% efficiency is necessary to obtain positive energy balance.**

High cost performance:

・Compact design is preferable.

Low beam loss

・To keep accessibility for maintenance, 1W/m loss is maximum.

JAEA's first candidate is Superconducting proton LINAC

・High efficiency in CW mode. ・High magnetic field is achievable.

・Large-size duct is applicable.

Japan Proton Accelerator Research Complex: J-PARC

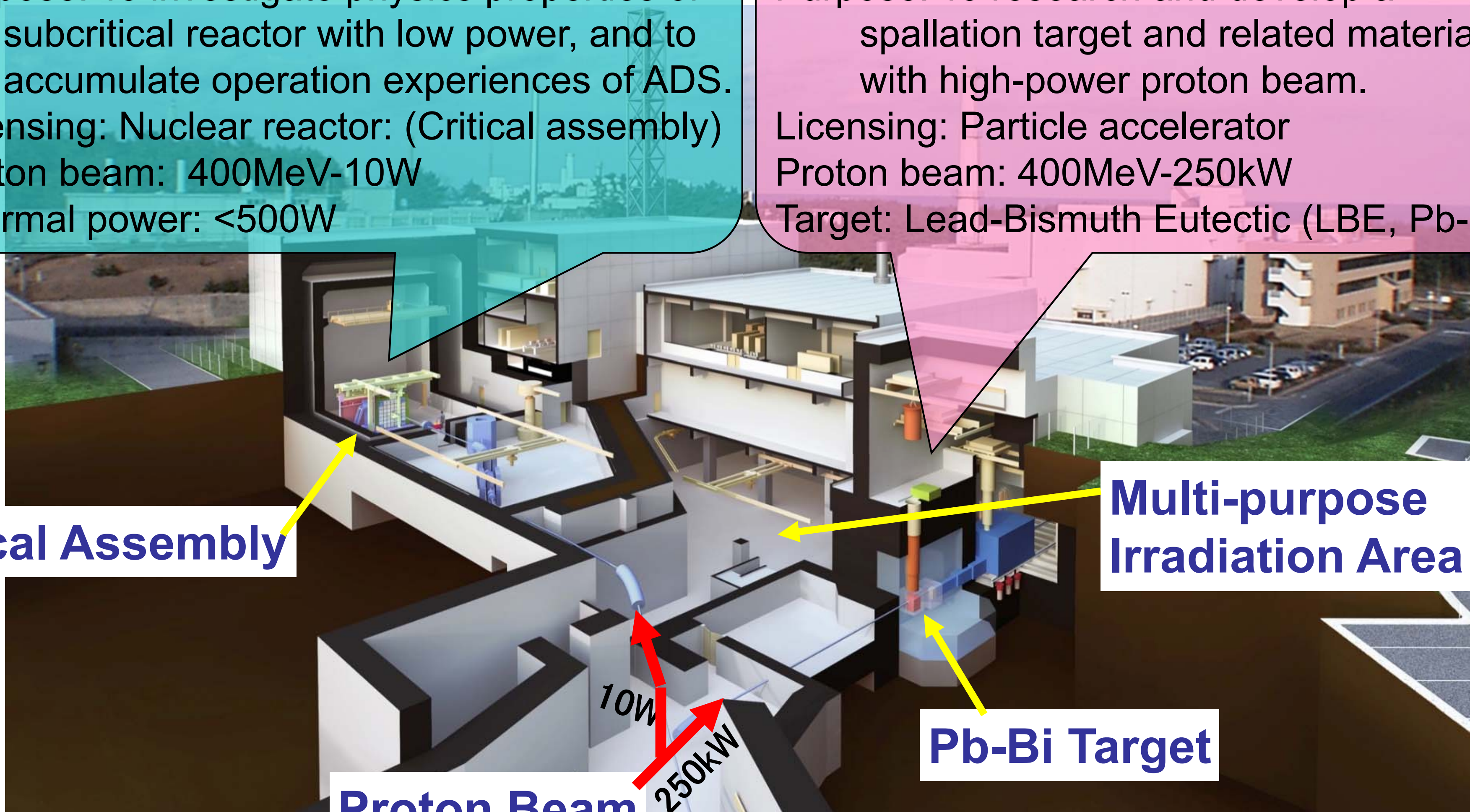
Transmutation Experimental Facility (TEF) of J-PARC

Transmutation Physics Experimental Facility: TEF-P

Purpose: To investigate physics properties of subcritical reactor with low power, and to accumulate operation experiences of ADS.
Licensing: Nuclear reactor: (Critical assembly)
Proton beam: 400MeV-10W
Thermal power: <500W

ADS Target Test Facility：TEF-T

Purpose: To research and develop a spallation target and related materials with high-power proton beam.
Licensing: Particle accelerator
Proton beam: 400MeV-250kW
Target: Lead-Bismuth Eutectic (LBE, Pb-Bi)



ADS Target Test Facility (TEF-T)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J-PARC 核変換実験施設 技術設計書
— ADS ターゲット試験施設 (TEF-T) —
Technical Design Report on J-PARC Transmutation Experimental Facility
— ADS Target Test Facility (TEF-T) —

核変換ディビジョン
Nuclear Transmutation Division

原子力科学研究部門
J-PARC センター
J-PARC Center
Sector of Nuclear Science Research

March 2017
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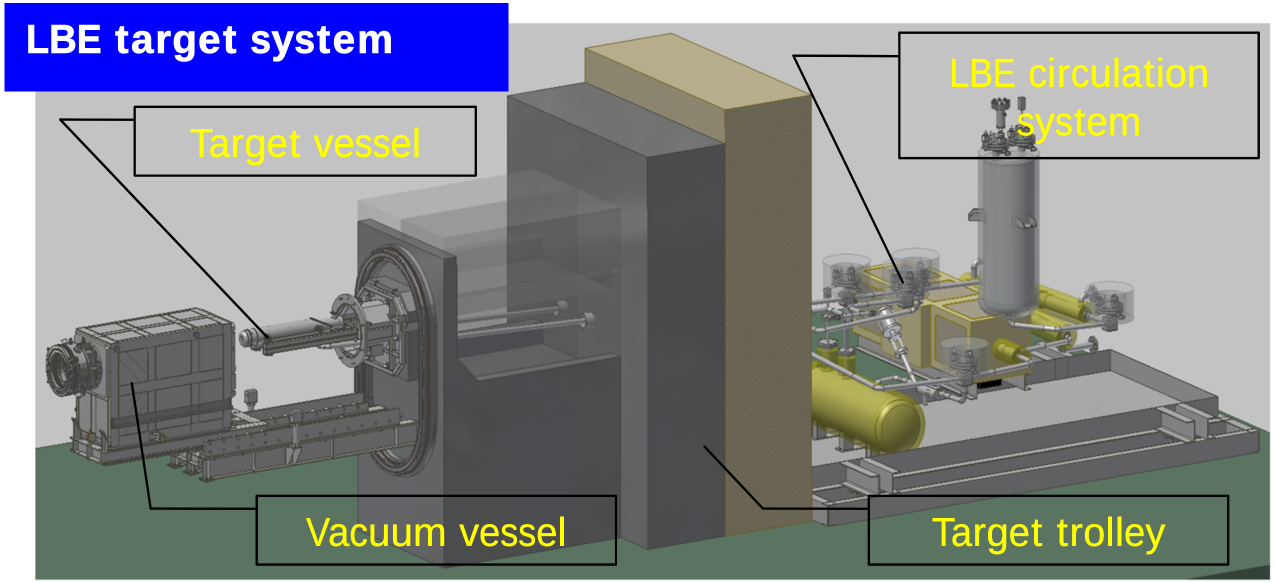

- Design of all TEF-T components has been made with considering operation and maintenance procedure.
  - LBE target system
  - Target station
  - PIE facilities
  - Waste management system
  - Proton beam transport
  - Ancillary facilities & building
  - Safety, etc.
- The basic design has been compiled in a report.

JAEA-Technology 2017-003 (sorry, in Japanese)

R&D for TEF-T

- **IMMORTAL**
  - Purpose: Demonstration of TEF-T target operation
  - LBE circulation tests at the max. temp. (500℃), and those with simulating heat input by the proton beam and its removal by operating HX were succeeded.
  - System transient exp. and analysis are to be performed.
- **OLLOCHI**
  - Purpose: Acquirement of materials corrosion data in flowing LBE under static conditions and in-situ loading of mechanical stress
  - The loop is under commissioning.

Integrated Multi-functional Mockup for TEF-T Real-scale Target Loop

Oxygen concentration sensors under development

Remote handling cutting and welding of LBE piping for the target vessel replacement

Oxygen-controlled LBE Loop for Corrosion tests in High temperature

Road map of ADS materials to realize 1st ADS

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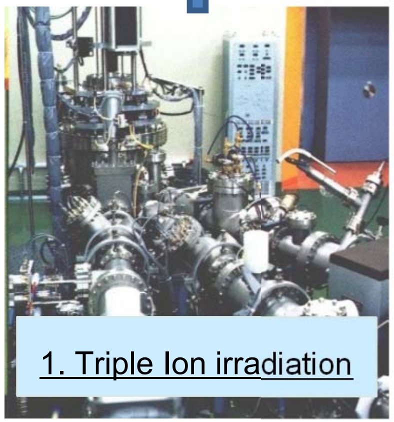

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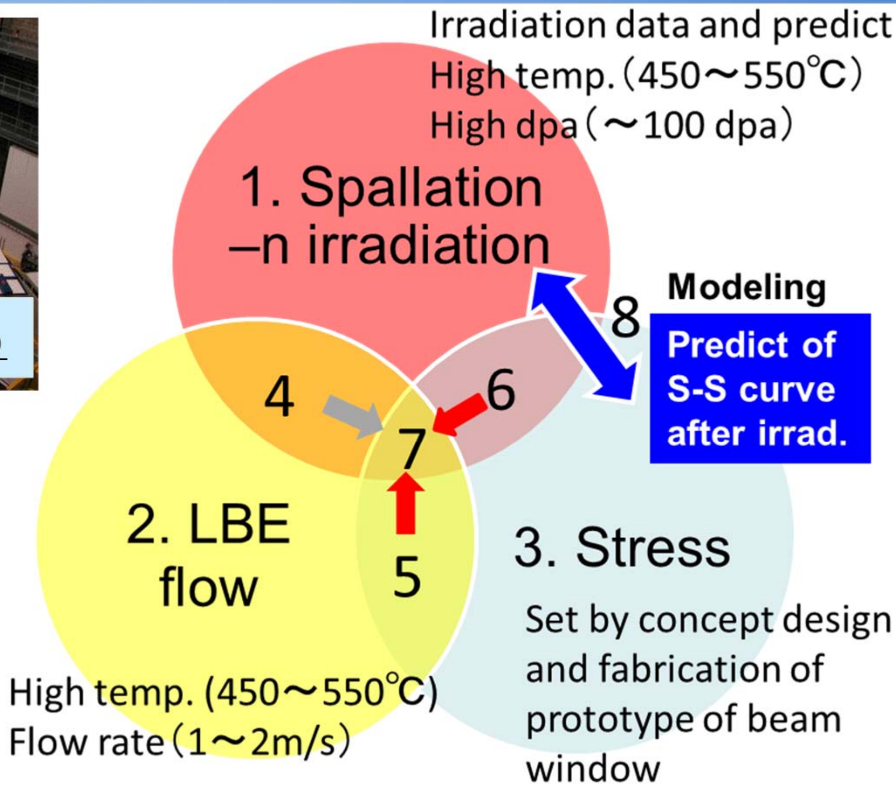


Fig. Three factors exposed for ADS materials

Irradiation in foreign reactor and PIE

Modeling
Irradiation effects
LME
LM corrosion

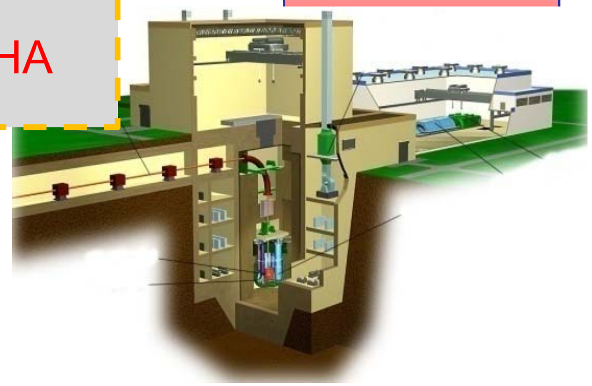
Usage of existing facility and apparatus

1. Spallation-n irradiation (STIP)
   - Ion irradiation (TIARA, QST)
   - Neutron irradiation (BR-2, etc.)
2. High temp. corrosion loop
3. Mechanical tests in LBE
5. Corrosion test in LBE flow
6. New PIE facility

4,7 Demonstration facility

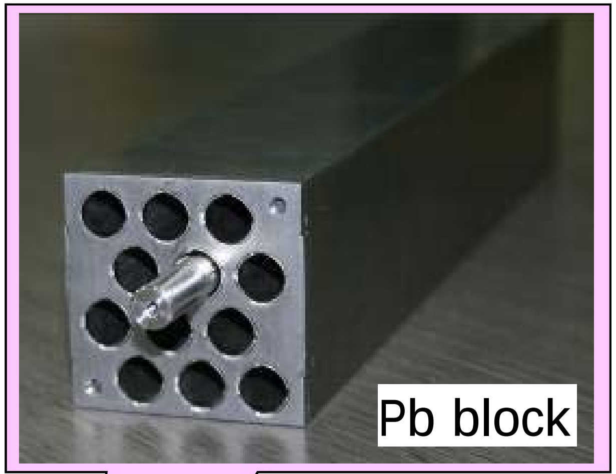
- ADS irradiation facility
- MYRRHA
- ･･･

7. 1st ADS

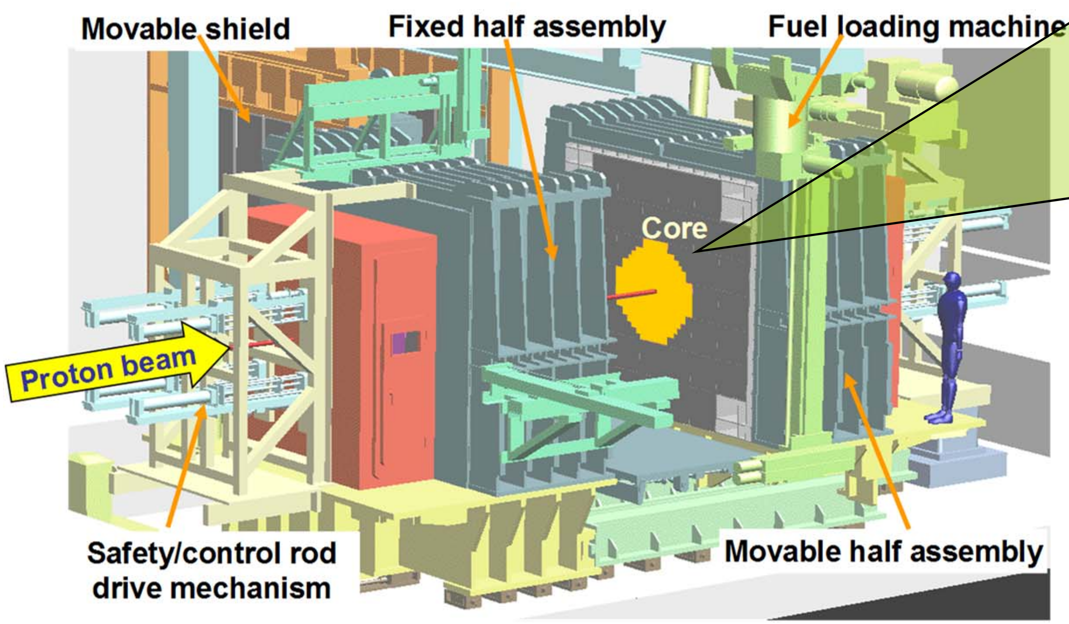


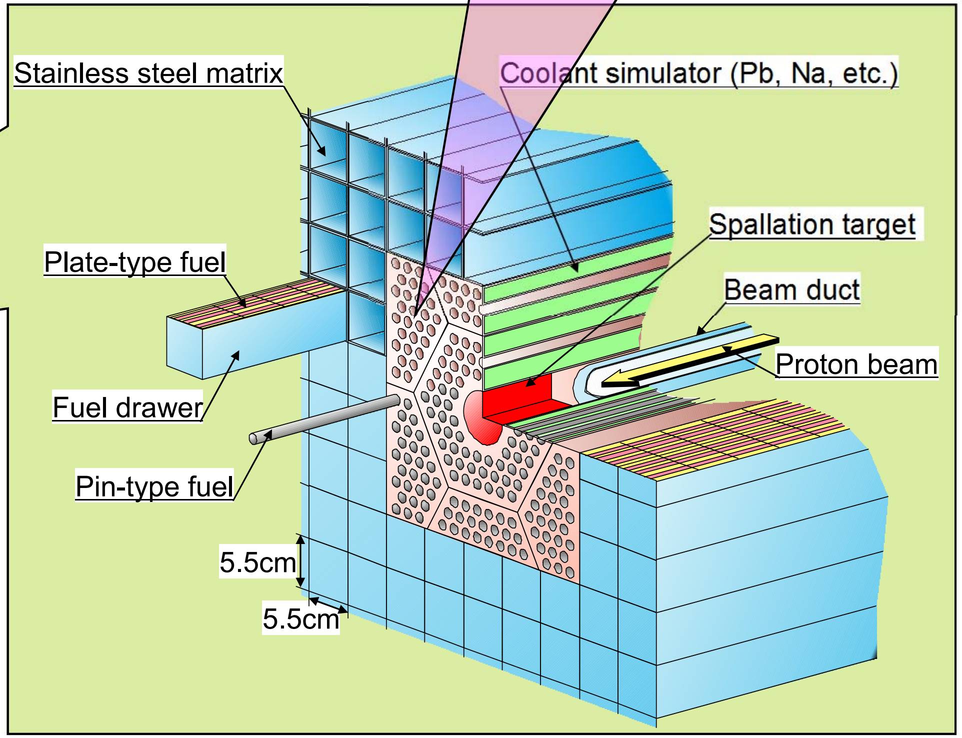
Transmutation Physics Experimental Facility (TEF-P)

- **Critical facility for reactor physics and nuclear data of transmutation systems: both ADS and FBR.**
- **Neutron source: 10^{12}n/s, 25Hz. 1ns pulsed beam is available by laser charge exchange technique.**
- **Pin-type MA fuel can be used with appropriate cooling and remote handling.**



Maximum thermal power : 500W





Safety Design Report of TEF-P

Safety design report of TEF-P was issued.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J-PARC核変換物理実験施設(TEF-P)安全設計書
Safety Design Report on J-PARC Transmutation Physics Experimental Facility (TEF-P)

分離変換技術開発ディビジョン
Partitioning and Transmutation Technology Division

原子力科学研究部門
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Nuclear Science and Engineering Center
Sector of Nuclear Science Research

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Japan Atomic Energy Agency
日本原子力研究開発機構

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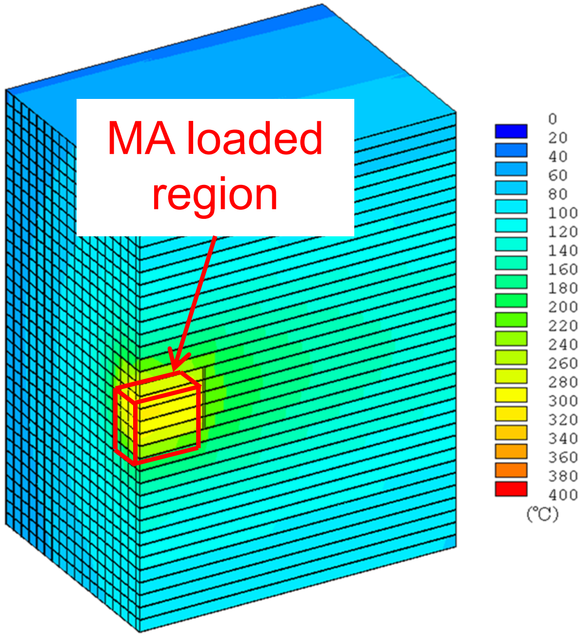
An example of safety analysis



Temperature distribution of TEF–P without *Cooling*

Maximum temp. 303℃
< Melting Point of Pb

Radioactive exposure to circumference public :
< 5 mSv even without *Stop*, *Cool*, *Confine*

TEF–P facility was classified as Class B

Concluding Remarks

- Management of radioactive waste is one of the most challenging issues in the utilization of nuclear power.
- JAEA puts its priority of R&D on the **transmutation of MAs**, but **management of Pu** also becomes a very important issue, considering the current status of FR development.
- **Transmutation and utilization of FP** can change the paradigm; "**From waste to resource**", if the ImPACT Program is successfully realized.
- **Synergy among various fields of science and technology, and also among countries**, is of great importance to tackle this issue.

  - Accelerator - Material - Separation - Remote handling, etc.