Development of Metal Fuel Fast Reactor in CRIEPI

January 15th 2020

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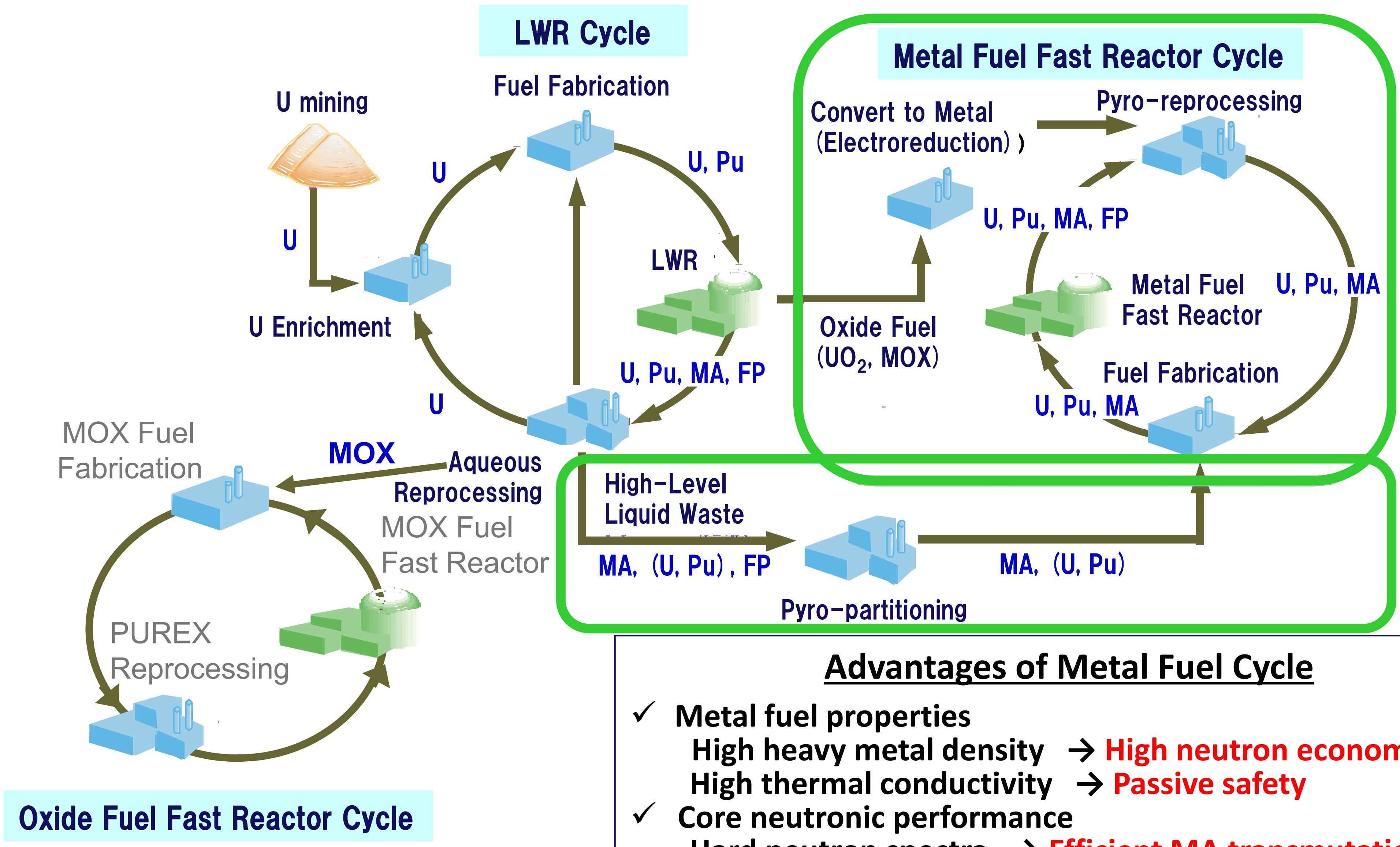
Metal Fuel Fast Reactor Cycle



Advantages of Metal Fuel Cycle

- ✓ Metal fuel properties
  - High heavy metal density → High neutron economy
  - High thermal conductivity → Passive safety
- ✓ Core neutronic performance
  - Hard neutron spectra → Efficient MA transmutation
- ✓ Pyro-reprocessing → Simultaneous collection of MA & Pu
  Economics on small scale plant
- ✓ Injection casting fuel fabrication → Remote operation

History of Metal Fuel Development

○**Adopted as experimental reactor fuels at early stage of FBR development (1940’s-)**

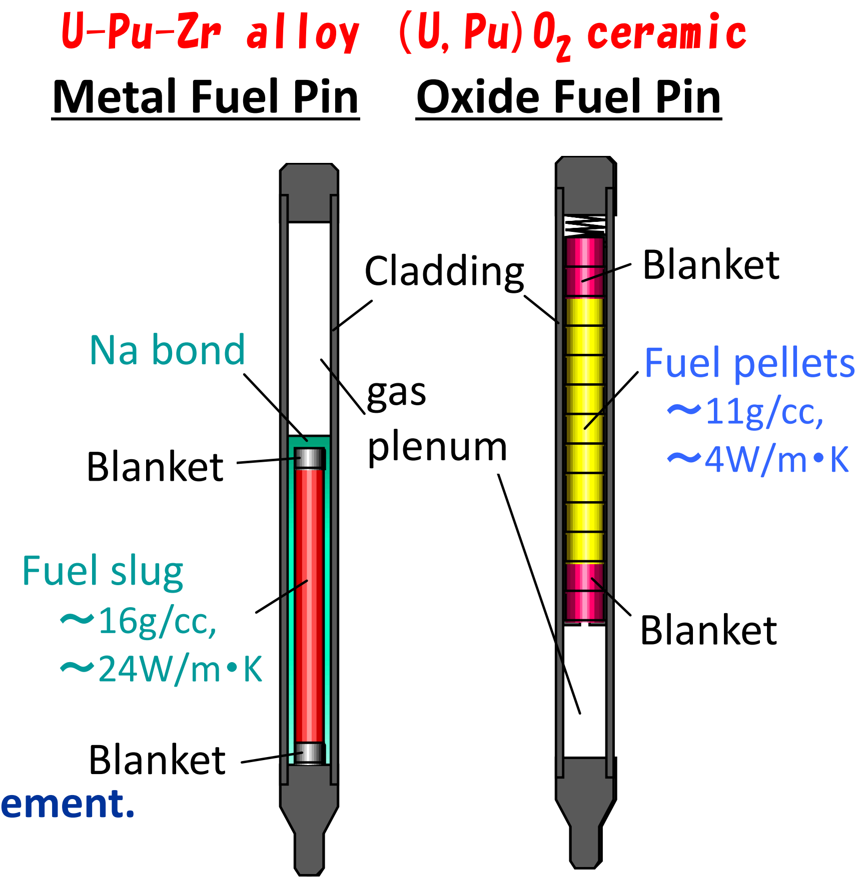
Ideal characteristics for fast reactor fuel

- High breeding due to high HM density
- High core safety due to high thermal conductivity
- Low-decontamination reprocessing is acceptable

	EBR-I (U.S.)	DFR (U.K.)	Fermi (U.S)	EBR-II (U.S.)
Operation	1951-63	1959-72	1963-72	1963-94
MWe	0.2	15	65	20
Fuel alloy	U-Zr	U-Mo	U-Mo	U-Zr

Large FCMI stress caused by fuel swelling → B.U.＜10,000MWd/t

Oxide fuel was applied for prototype & demonstration scale reactors
→ B.U.〜100,000MWd/t



○ **ANL continued R&D and achieved high burnup by design improvement.**

’84 - ’94 IFR program

- **U-Zr & U-Pu-Zr fuel development**

  ~10,000 U-Zr fuel pins & ~600 U-Pu-Zr fuel pin fabrication & irradiation were completed.
  → Max. B.U. ~200,000MWd/t
- **Inherent safety demonstration in EBR-II, TOP experiments in TREAT** → Passive safety
- **Pyro-reprocessing development** → MA recovery etc.

Requirements for Metal Fuel Development

- Metal Fuel Development in Japan

Started in 1986

Japanese utilities including CRIEPI participated in part of IFR program

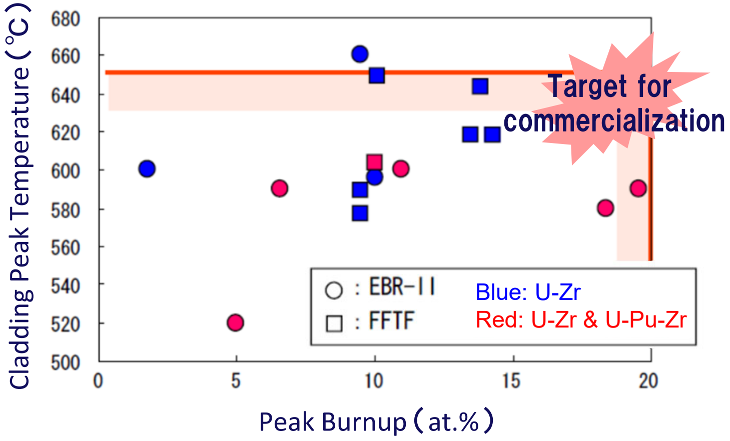
Domestic requirements for fast reactor fuel development

- Accumulation of domestic fabrication & irradiation experiences
- Feasibility of MA-containing fuels
- High temperature & high burnup use for commercialization
  （Cladding temperature ~650 ^{O}C, Peak burnup 15-20 at.%）
  → Limited irradiation data

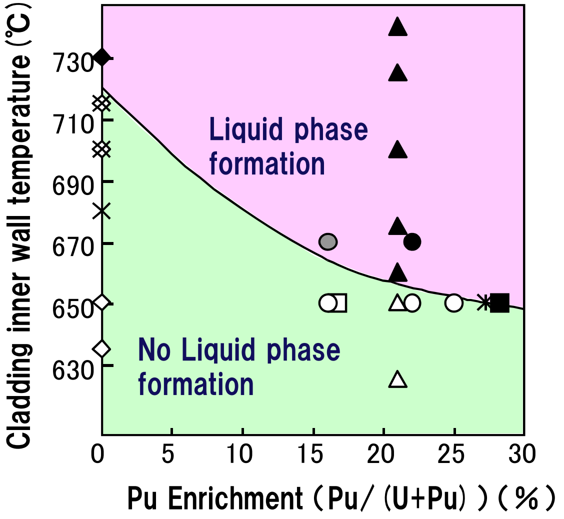
【Concerns for high temperature use】

- Liquid phase formation between fuel alloy and cladding

  Ex-reactor diffusion couple experiments suggested a liquid phase is formed at > 650 ^{O}C when Pu enrichment is < 25 %.



Irradiation experiments in the U.S. and target for commercial reactor in Japan



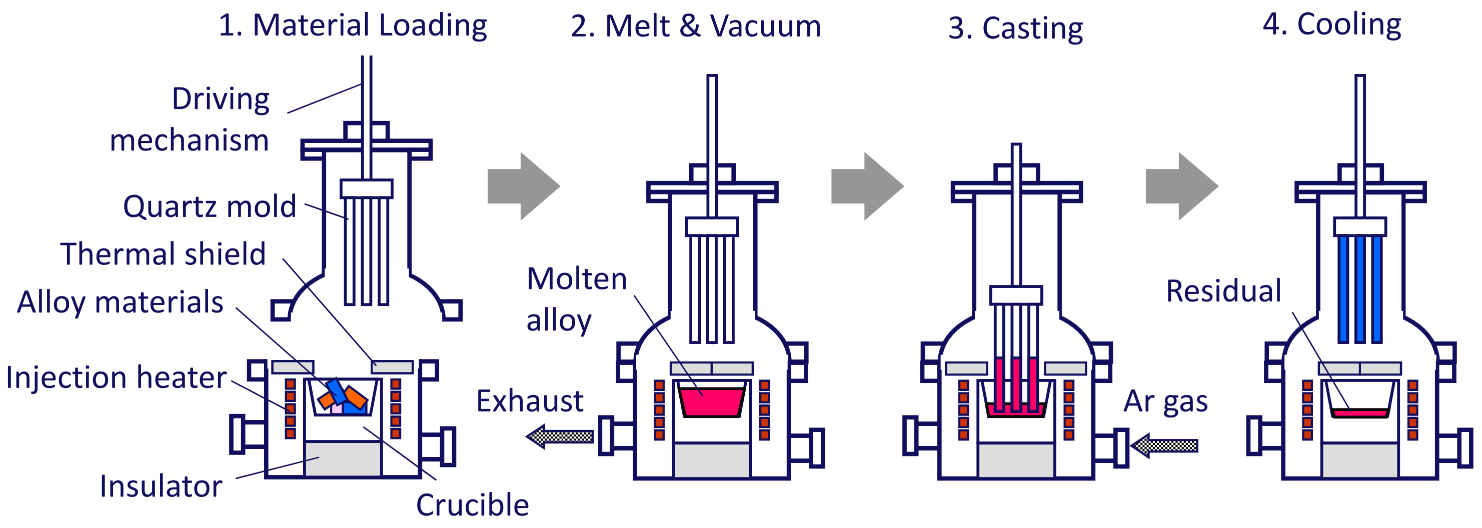
Liquid phase formation reaction between U-Pu-Zr fuel and cladding.

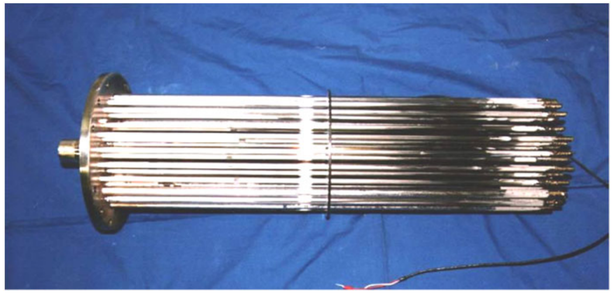
K. Nakamura et al., JNST 38(2) (2001) 112-119.

Metal Fuel Development

(1) Metal fuel fabrication (Joint Study with JAEA)

Injection Casting Fuel Fabrication



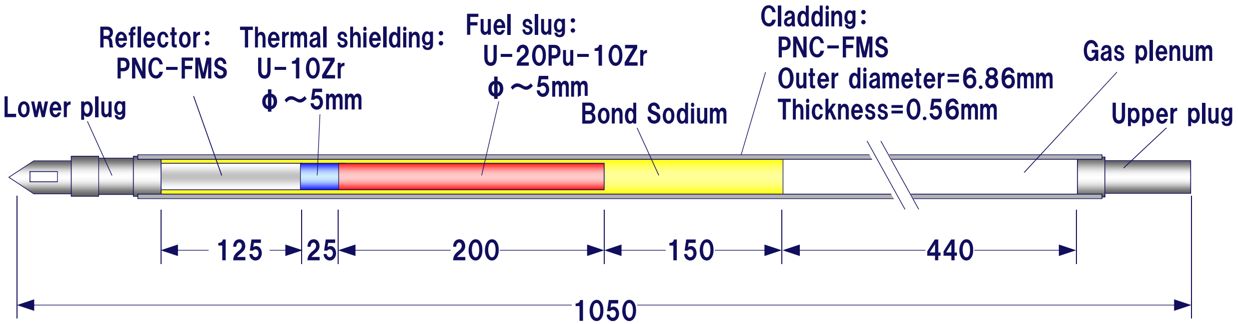


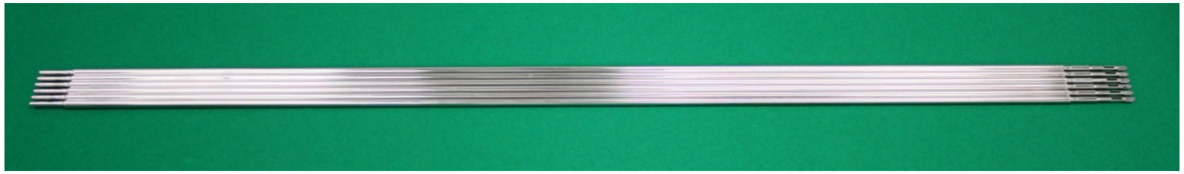
Engineering scale ~20kg/batch test

Φ= ~6mm, L= 400mm,

~500 U-Zr slugs were fabricated by injection casting.

U-Pu-Zr Fuel Pin Fabrication





U-Pu-Zr fuel pins fabricated for Irradiation experiment in Joyo

Irradiation Conditions for U-Pu-Zr fuel pins in Joyo

	Cladding temperature	Smear density	Burnup	Purposes
(1)	640℃	77.4 %	3 at.%	Confirmation of liquid phase formation
(2)	640℃	74.4 %		
(3)	620℃	77.4 %	8 at.%	Acquisition of fuel-cladding chemical Interaction data
(4)	620℃	74.4 %		
(5)	620℃	77.4 %	10 at.%	Acquisition of fuel-cladding mechanical Interaction data
(6)	620℃	74.4 %		

Maximum linear heat power : 500W/cm

- 6 U-Pu-Zr fuel pins were successfully fabricated.
- Irradiation test will be started in 2022.

T. Ogata et al., in: Proc. Nuclear Fuels and Structural Materials for the Next Generation Nuclear Reactors, Anaheim, California, June 8-12, 2008.
K. Nakamura et al., in: Proc. Global 2011, Makuhari, Japan Dec. 11-15, 2011.

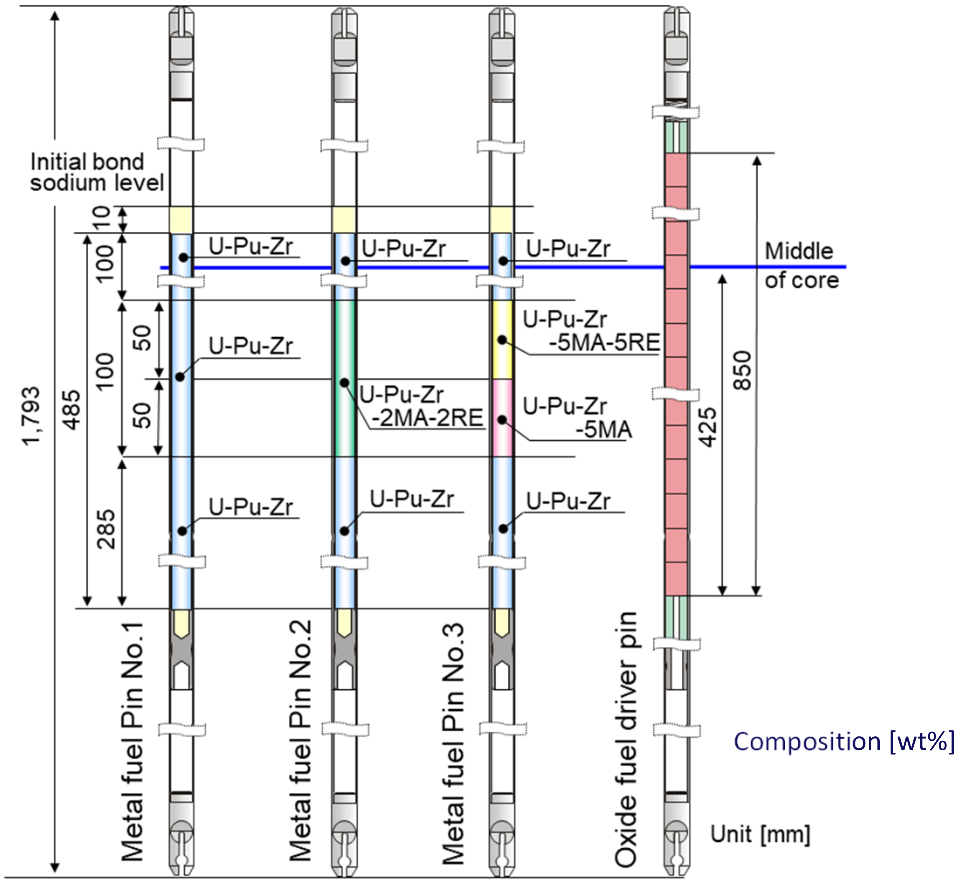
Metal Fuel Development

(2) MA-containing metal fuel irradiation experiment （1/3）

(Joint Study with JRC-Karlsruhe)

Purposes: Irradiation behavior data of MA-containing metal fuel are obtained.
MA transmutation performance with metal fuel are demonstrated.

3 types of MA-containing U-Pu-Zr fuel pins were fabricated by 1994.
3 sets of irradiation capsules were prepared to achieve different target burnups of 2.5at.%, 7at.% and 10at.%.
Irradiation experiments were performed in Phenix, France during 2003-2008.



MA-containing metal fuel pins for irradiation experiment in Phenix

- Cladding outer diameter：6.55mm
- Thickness：0.45mm
- Fuel slug diameter：4.9mm
- Total length of metal fuel = 485mm
- MA-containing segment length
  = 10mm(U-19Pu-10Zr-2MA-2RE)
  5mm(U-19Pu-10Zr-5MA-5RE)
  5mm(U-19Pu-10Zr-5MA)

MA=Np, Am, Cm
RE=Y, Ce, Nd, Gd

H. Ohta, et al., Nuclear Technology Vol.190, April 2015

Metal Fuel Development

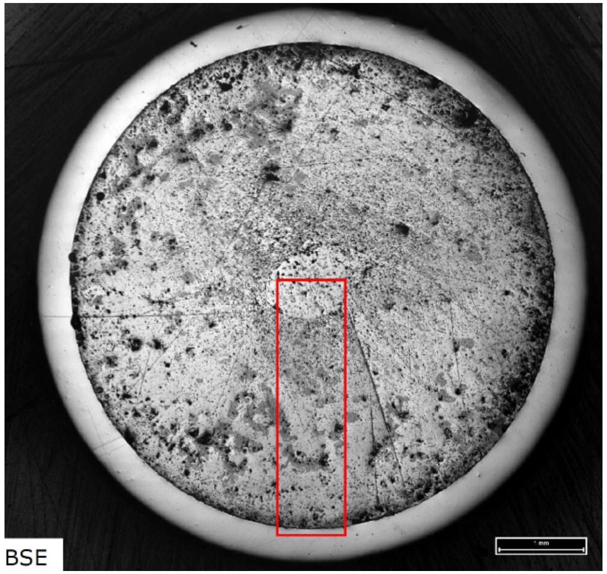
(2) MA-containing metal fuel irradiation experiment（2/3）

(Joint Study with JRC-Karlsruhe)

- Cladding peak temperature ～570°C, Peak linear power ～330W/cm
  3 different burnups were achieved with 120 EFPDs*, 360EFPDs and 600EFPDs of irradiation.
- Post-irradiation examinations of low-burnup METAPHIX-1 fuels and middle-burnup METAPHIX-2 fuels are ongoing at JRC Karlsruhe.
- High-burnup METAPHIX-3 fuel pins are stored after non-destructive tests.
- Metallography of METAPHIX-2 fuel containing 5wt% MA & RE irradiated up to ～7at.% burnup revealed that
  - radial migration of matrix elements of U and Zr occurs,
  - precipitates of Am & Cm containing RE grow to ～100μm during irradiation,
  - Am & Cm contents in precipitates ～25wt%,
  - part of MA precipitates contain noble metal FPs.

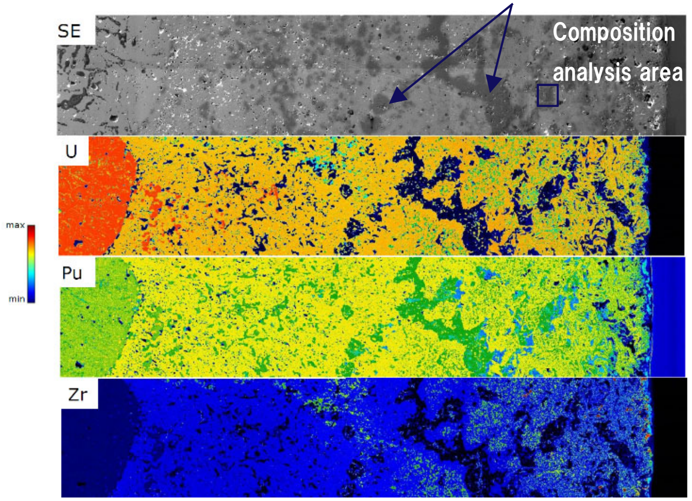
} No trace of fuel melting
fuel integrity was maintained.

*: EFPDs=effective full power days

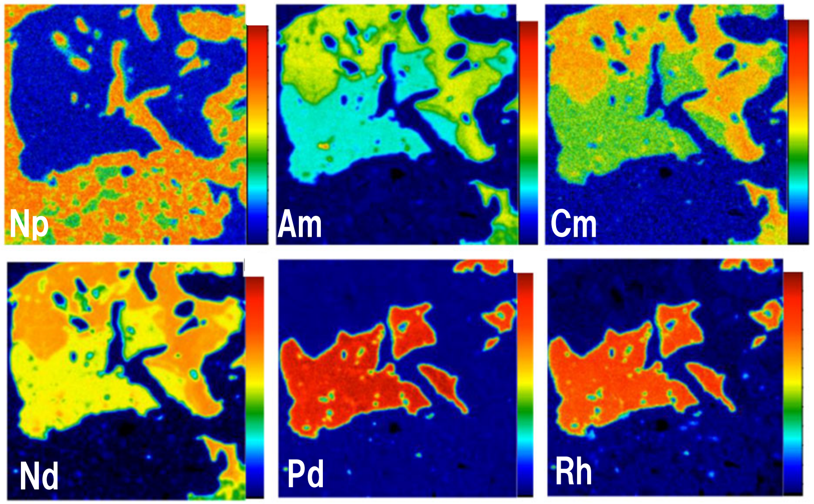


Cross sectional view of U-19Pu-10Zr-5MA-5RE

Precipitates



Radial distribution of Matrix elements



Composition analysis results of MA precipitates

S. Brémierm et al., ‘ Electron Microprobe Examination of Irradiated Metallic Fuel containing Rare Earth and Minor Actinide elements’, ANS 2017 winter meeting

Metal Fuel Development

(2) MA-containing metal fuel irradiation experiment（3/3)

(Joint Study with JRC-Karlsruhe)

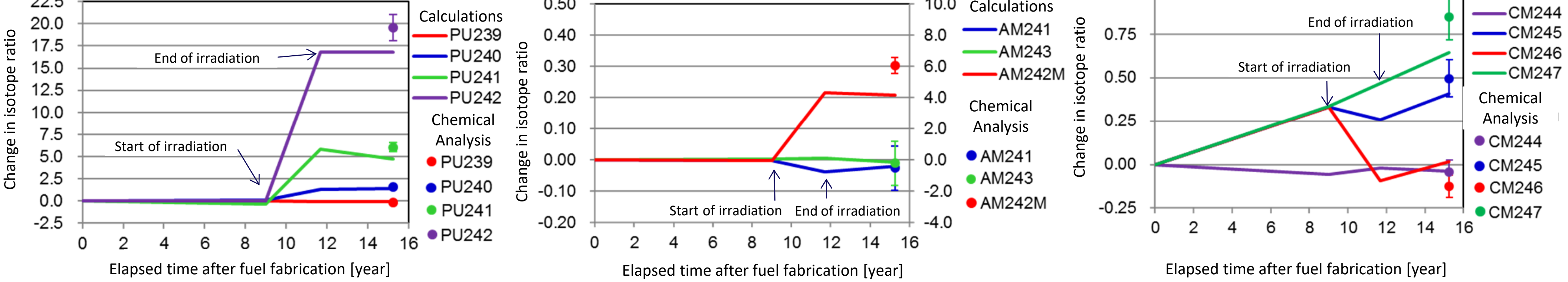
- ➢ Chemical analysis of METAPHIX-1 and METAPHIX-2 fuels
- ➢ Irradiation burnups were evaluated based on the composition analysis results.
  → Target peak burnups (METAPHIX-1 ∼2.5at.%, METAPHIX-2 ∼7at.%) were almost attained.（See Table 1）
- ➢ MA transmutation performance were evaluated from the changes in isotope ratios.
  Burnup calculation properly predicted the chemical analysis results（See Fig. 1）
  → MA transmutation performance with metal fuel were demonstrated.
- ➢MA transmutation result：19.8±5.1% （METAPHIX-2, U-Pu-Zr-5MA sample）

Table 1　Burnup evaluation based on chemical analysis results [at.%]

		METAPHIX-1			METAPHIX-2			
Sample		U-Pu-Zr	U-Pu-Zr -2MA-2RE	U-Pu-Zr -5MA	U-Pu-Zr	U-Pu-Zr -2MA-2RE	U-Pu-Zr -5MA	U-Pu-Zr -5MA-5RE
Indicator	^{148}Nd	2.1	N/A[1]	2.3	5.7	N/A[1]	5.4	N/A[1]
	^{139}La	2.2	2.5	2.5	5.9	5.8	5.3	5.6
	^{102}Ru	2.2	2.4	2.3	5.5	6.4	6.2	5.8
	^{104}Ru	2.1	2.5	2.3	5.4	6.0	5.9	5.4

[1]: Not applicable

Fig.1 Comparison between calculation and chemical analysis on changes in isotope ratios of Pu, Am and Cm after fuel fabrication
（METAPHIX-2, U-Pu-Zr-5MA sample）

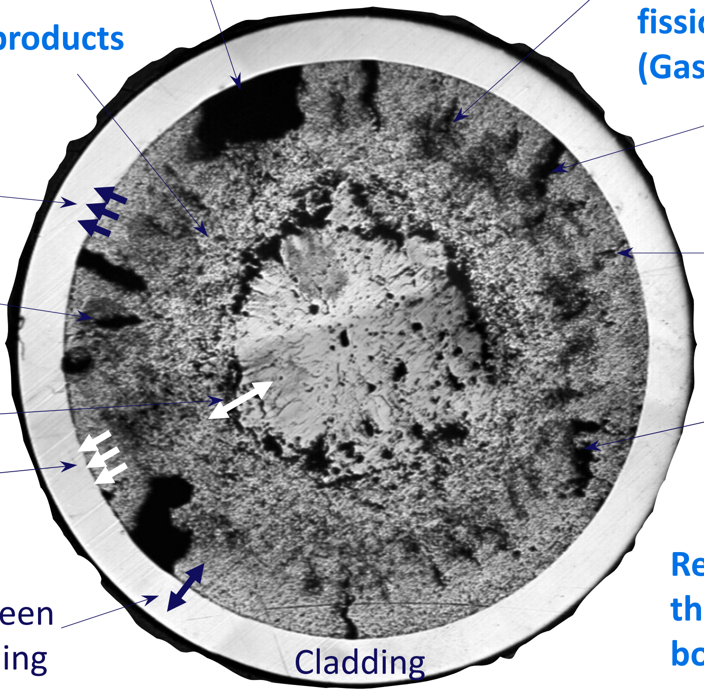


H. Ohta, et al., ‘Minor actinide transmutation in fast reactor metal fuels irradiated for 120 and 360 equivalent full-power days,’ JNST Vol.53, No. 7, 968 (2016).

Metal Fuel Development

(3) Irradiation behavior analysis code, ALFUS（1/2）

Phenomena modeled in ALFUS (ALloyed Fuel Unified Simulator)



MECHANICAL (STRUCTURAL) BEHAVIOR

Cracking

Accumulation of non-gaseous fission products (Solid FP swelling)

FCMI caused by fuel slug swelling

Mitigation of FCMI due to open pore collapse

CHEMICAL BEHAVIOR

Fuel constituent migration

Cladding attack by rare-earth fission products

Interdiffusion between fuel alloy and cladding

FISSION GAS BEHAVIOR

Gas bubble formation due to fission gas precipitation (Gas swelling)

Interconnection of gas bubbles (Open pore formation)

Fission gas release through open pore

INFLUENCE ON TEMPERATURE

Deterioration of fuel slug thermal conductivity due to gas bubble formation

Recovery of fuel slug thermal conductivity due to bond sodium ingress into open pore

T. Ogata, et al., “Development and Validation of ALFUS: An Irradiation Behavior Analysis Code for Metallic Fast Reactor Fuels,” Nucl. Technol., 128, 113 (1999).

Metal Fuel Development

(3) Irradiation behavior analysis code, ALFUS（2/2）

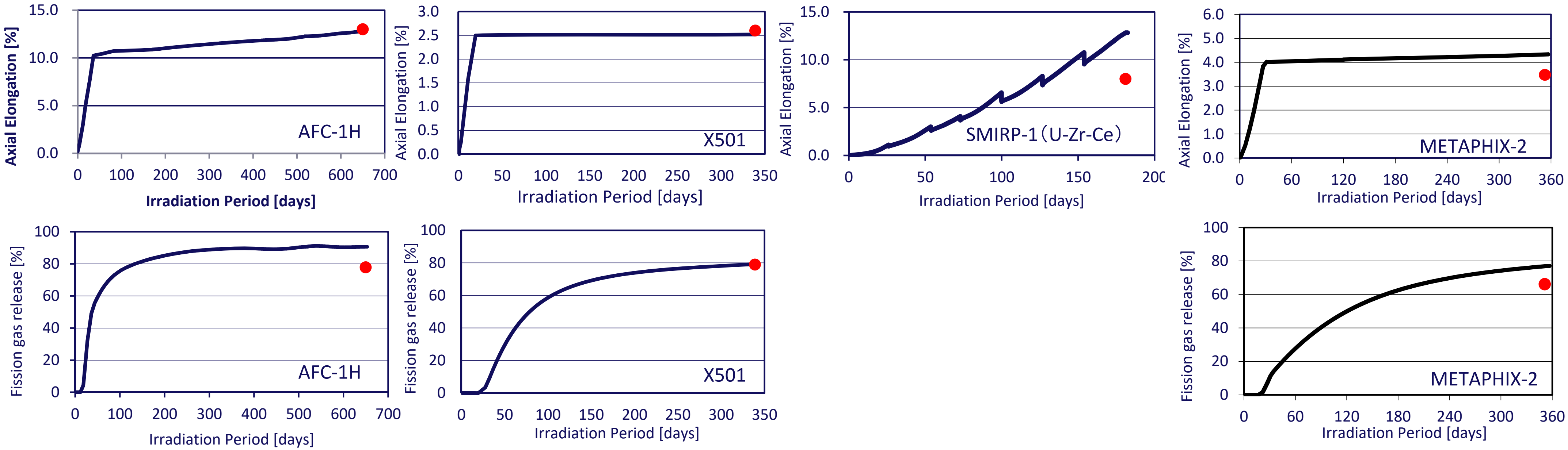
(Expert meeting of OECD/NEA)

- A mechanistic model code for metal fuel irradiation behavior analysis, ALFUS is developed in CRIEPI.
- Benchmark analysis for metal fuel irradiation experiments by expert group on innovative fuel (EGIF) organized by OECD/NEA was conducted.（See Table 1）
- ALFUS can predict metal fuel behavior in various metal fuel irradiation experiments（See Fig. 1）

Table Metal fuel irradiation experiments and analysis codes participating in benchmark analysis by EGIF

Organization	INL		KAERI	CRIEPI
Irradiation Experiment	AFC-1H	X501	SMIRP-1	METAPHIX-2
Fuel Composition	U-Pu-Zr-Np-Am	U-Pu-Zr-Np-Am	U-Zr/U-Zr-Ce	U-Pu-Zr-Np-Am-Cm-RE
Calculation Code	NON	NON	MACSIS	ALFUS

Fig. Comparison of experimental results and ALFUS analysis for metal fuel irradiation behavior of axial elongation and fission gas release



N. Chauvin, et al.,'Benchmark Study on Fuel Performance Codes for Fast Reactors', Proc. GLOBAL2019.
OECD/NEA, "Benchmark study on minor actinide bearing fuel performance codes", NEA, OECD, Paris, forth coming.

Metal Fuel Core Development

(1) Demonstration scale core design (Joint Study with JAEA)

- Design study of demonstration scale 750MWe class metal fuel core
- Irradiation behavior of metal fuel is reflected in the design.
  Reactivity change due to axial elongation of fuel slug & migration of bond sodium during irradiation were considered quantitatively.（Fig. 2）
- Reduction of coolant void reactivity to < 6$
  Flattening core shape with large diameter fuel pin (Fig. 3)

Fig. 1 750MWe class metal fuel core configuration

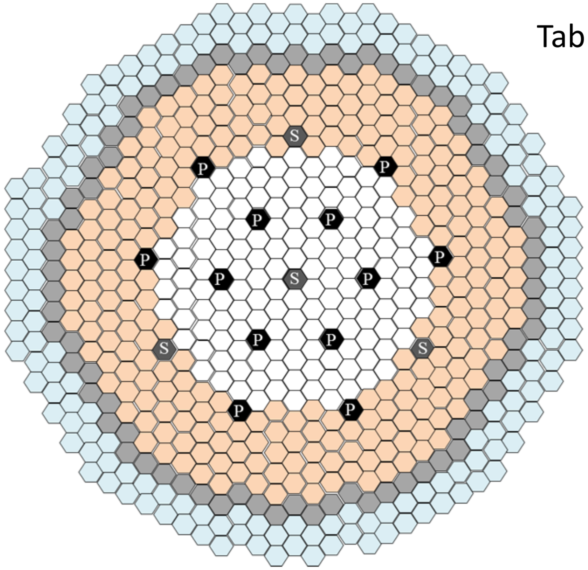
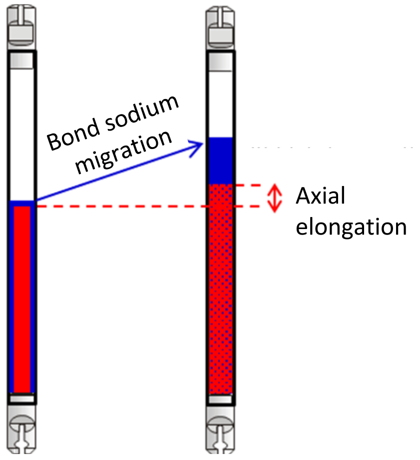


Table 1 Major Spec. of demonstration scale core

Item	Unit	value
Output	MWe	750
Outlet / inlet temperature	ºC	550/395
Cladding peak temp.	ºC	650
Cycle length	days	~700
Refueling batch	-	3
Fuel pins/assembly	-	271
Smear density	%TD	70-75
Zr content	Wt%	10-6

- Single Pu enrichment core design to suppress power distribution fluctuations during burnup period.
Single Pu enrichment
- Adjustment of the inner / outer core power with Zr content and smear density

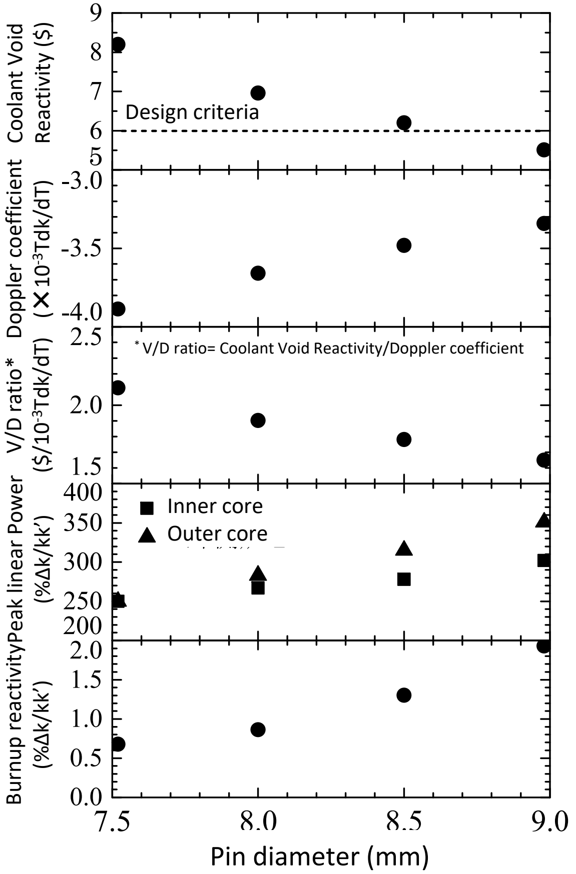
Fig. 2 Fuel slug elongation and bond sodium migration during irradiation



Before irradiation After irradiation start

Irradiation Behavior	:Reactivity Change
Axial Elongation=8%	:-2.22$
Bond Sodium Migration=90%	:+4.38$
Net	:+2.16$

Fig. 3 Core characteristic change by adjusting fuel pin diameter



Large diameter fuel pin > 8.5mm
Coolant void reactivity < 6$

K. Ohgama, 'DESIGN STUDY OF A 750 MWe JAPAN SODIUM-COOLED FAST REACTOR WITH METAL FUEL', Proc. of ICAPP 2017

Metal Fuel Core Development

(2) Flexible MA transmutation system development (MEXT project)

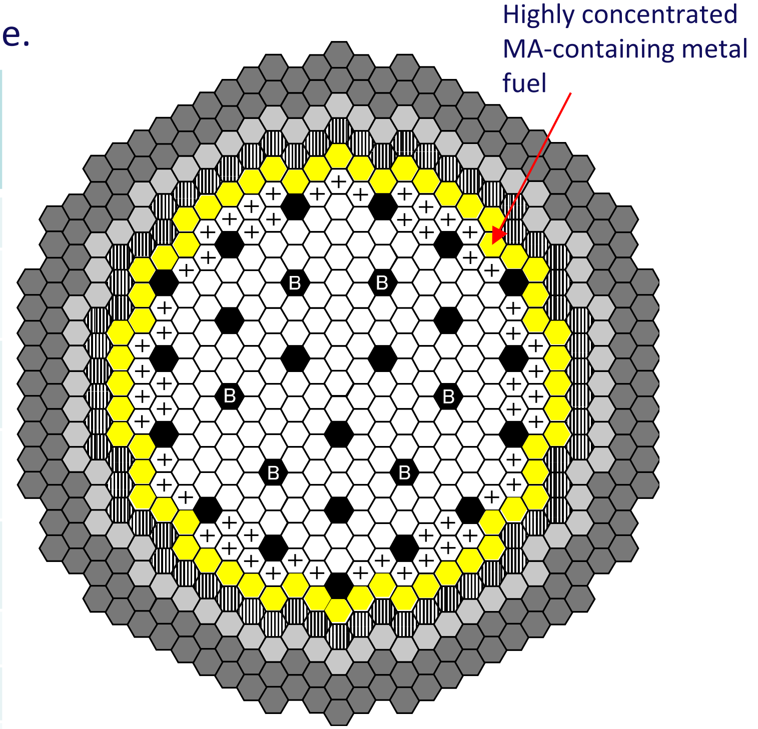
Feasibility of an efficient MA transmutation & Pu utilization systems by combining advantages of MOX fuel cycle & metal fuel cycle is investigated.

MOX fuel cycle：Long domestic R&D experiences & Abundant infrastructure

Metal fuel cycle：Suitable for MA recycling

- ➢ A MOX fuel core partially loaded with highly concentrated MA-containing metal fuel subassemblies (SAs) is design to achieve both core safety and high MA transmutation performance.

Item	unit	Homogeneously MA loaded MOX fuel core	Highly concentrated MA-containing metal fuel loaded MOX fuel core
Number of SA	-	274	274
MA-containing metal fuel SA	-	0	60
Pu enrichment IC/OC/Metal SA	wt%	18.6 / 24.6 / -	18.7 / 24.8 / 18.5
MA content IC/OC/Metal SA	wt%	3.0 / 3.0 / -	1.4 / 1.9 / 16.0
Coolant Void Reactivity	$	6.0	6.0
Doppler Coefficient	Tdk/dT	-4.6×10^{-3}	-4.4×10^{-3}
MA loading	kg/batch	175	353
MA transmutation	kg/GWe-y	53	89


Highly concentrated MA-containing metal fuel

Highly concentrated MA-containing metal fuel loaded MOX fuel core configuration

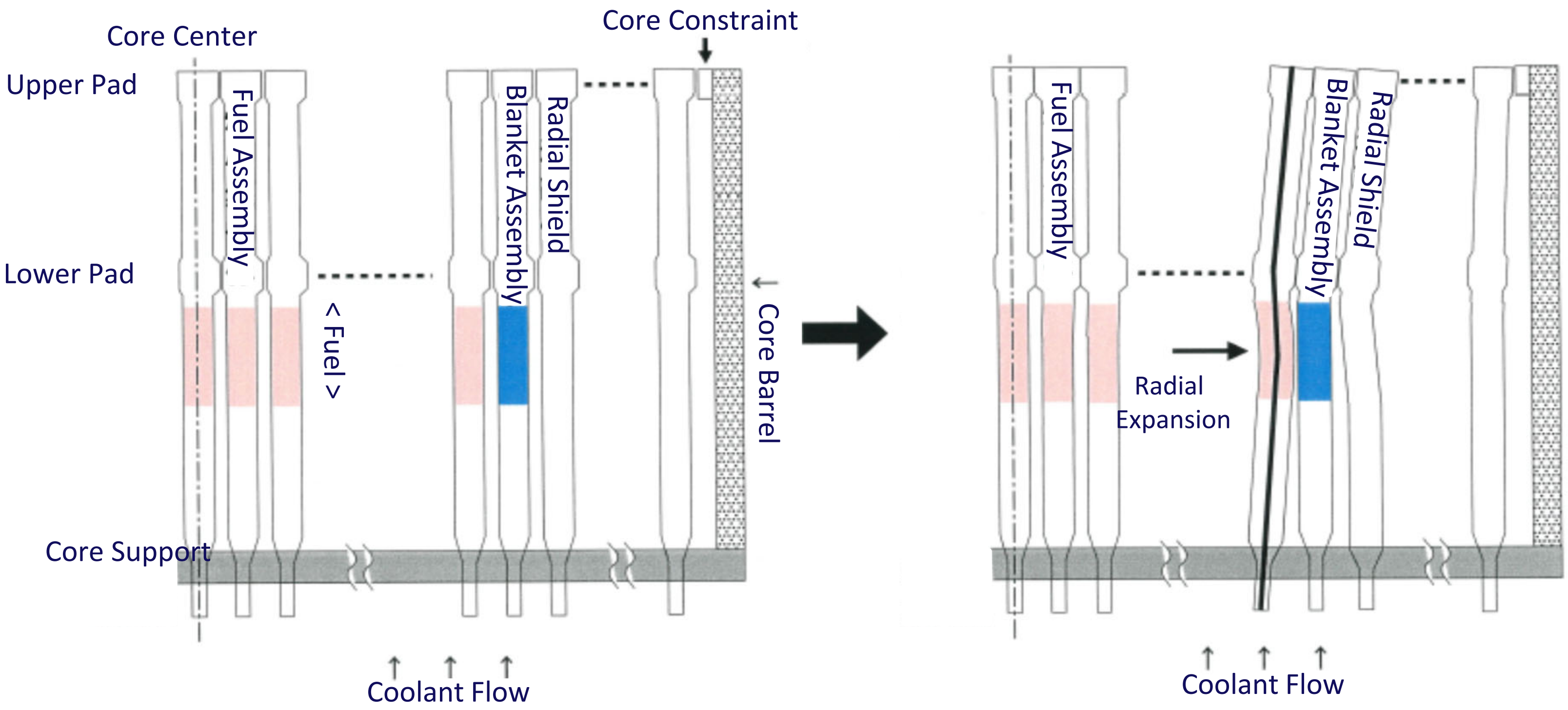
MA transmutation increases to ～160% while maintaining core safety parameters .

K. Ohgama, 'Development of highly flexible technology for recovery and transmutation of minor actinide (2) Study on a MOX fuel fast reactor core loading highly concentrated MA-containing metal fuel', *Proc. of AESJ 2017 Fall meeting*

Metal Fuel Core Development

(3) Core Safety Analysis（1/4）

Passive Safety Features of Fast Reactors: Mechanism of core radial expansion reactivity



Standby
- Subassemblies are loaded with gap
- Without temperature gradient

Normal operation
- Interpad gap closing due to thermal expansion
- Assembly deformation due to irradiation & temperature gradient

Accident conditions
- Rapid increase in temperature
  → Increase in thermal expansion
- Changes in thermal bowing of assemblies
- Radial expansion of core → negative reactivity

Passive shutdown & core damage prevention

When and how much negative reactivity is inserted depends on the core shape during normal operation, i.e., remaining gap width and assembly contact conditions.

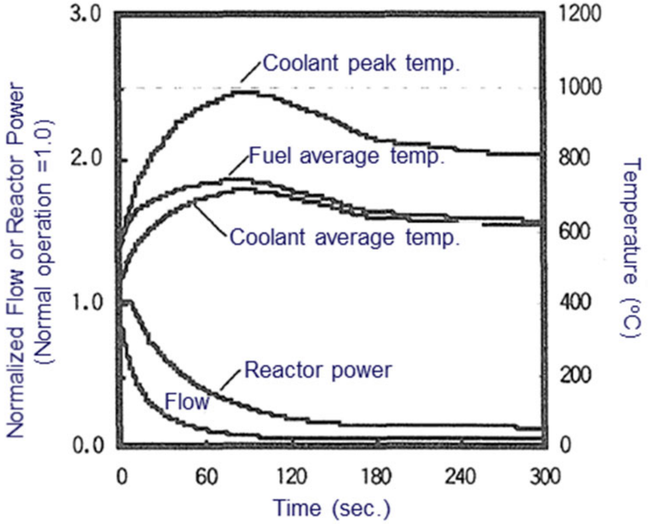
Metal Fuel Core Development

(3) Core Safety Analysis（2/4）

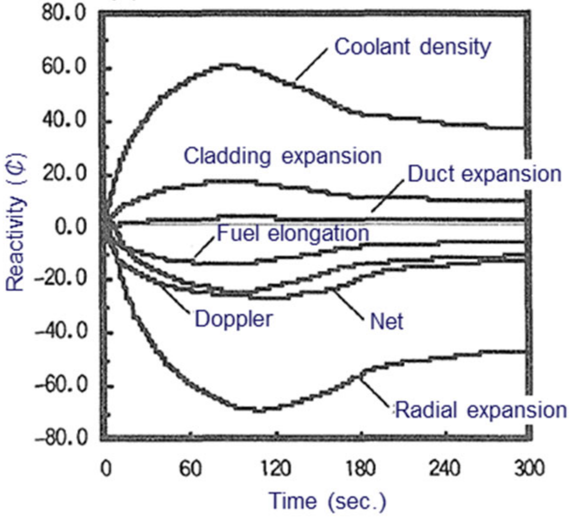
ULOF event analysis for large scale metal & oxide fuel fast reactors

Pump coast down (Flow halving time) = 10 sec.

Metal Fuel Core

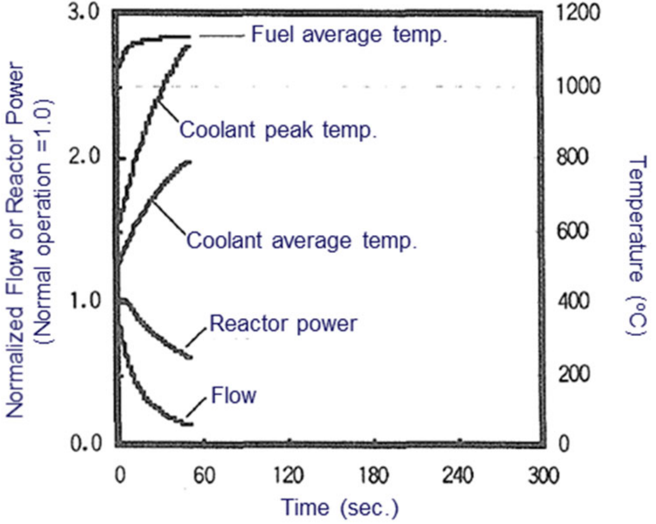


(a) History of flow, power and temperature

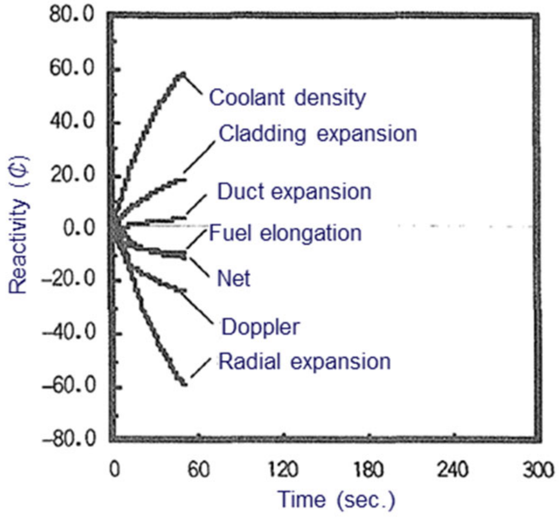


(b) Reactivity balance during ULOF event

Oxide Fuel Core



(a) History of flow, power and temperature



(b) Reactivity balance during ULOF event

Potential to avoid coolant boiling in metal fuel core due to large negative feedback reactivity by radial expansion.

→ Precise core deformation analysis is required.

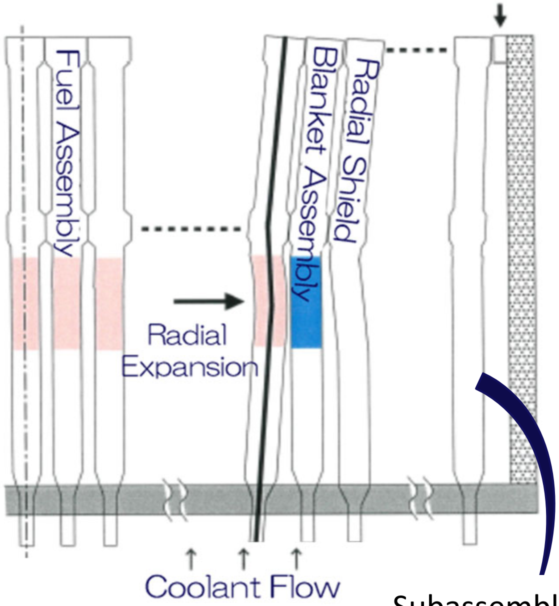
T. Yokoo, et al., 'Design study of 1500 MWe high burnup metal and oxide fuel FBR cores', CRIEPI report T97040 in Japanese.

Metal Fuel Core Development

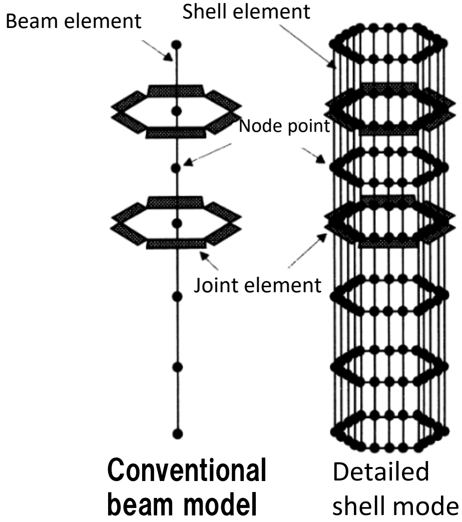
(3) Core Safety Analysis（3/4） (METI project*/CNWG NE08)

A detailed core bowing analysis code required for precise evaluation of the radial expansion reactivity expected as one of the core damage prevention measures is developed.

Radial expansion reactivity: Thermal expansion & deformation of subassemblies (SA) due to temperature increase
→ Radial expansion of core → Negative reactivity insertion



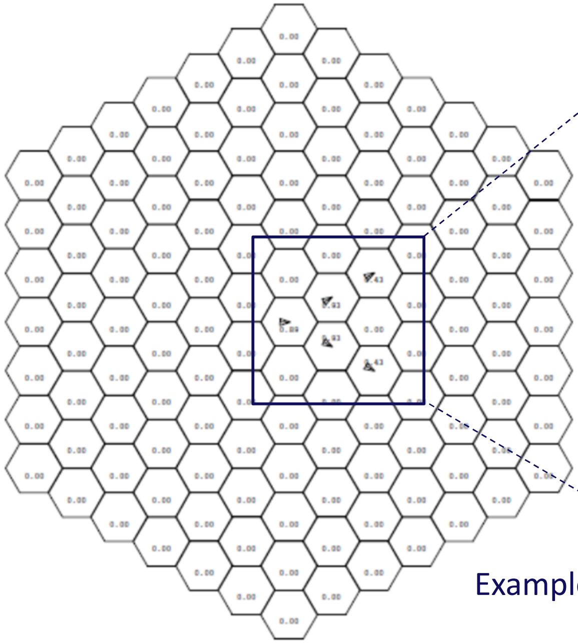
Subassembly model

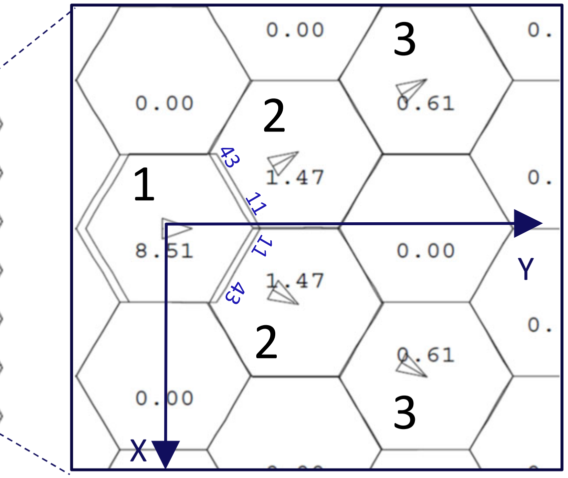


Conventional beam model

Detailed shell model → ARKAS_cellule

Duct wall deformation and load distribution are explicitly considered using thin shell elements.





Example-3A: Deformation of 127 SAs cluster

Verification of ARKAS_cellule by IAEA benchmark problem analysis

	Displacements [mm]			Loads [kgf]	
SA number	1	2	3	1-2	2-3
ARKAS_cellule	8.51	1.47	0.61	54(43+11)	0
IAEA report	8.54	1.52	0.66	53	0

ARKAS_cellule model was verified with IAEA benchmark problems analysis

Expansion of applicability to practical reactor core analysis →1000 SAs

H. Ohta, ‘VERIFICATION OF DETAILED CORE-BOWING ANALYSIS CODE ARKAS_CELLULE WITH IAEA BENCHMARK PROBLEMS’, Proc. of GLOBAL 2019.

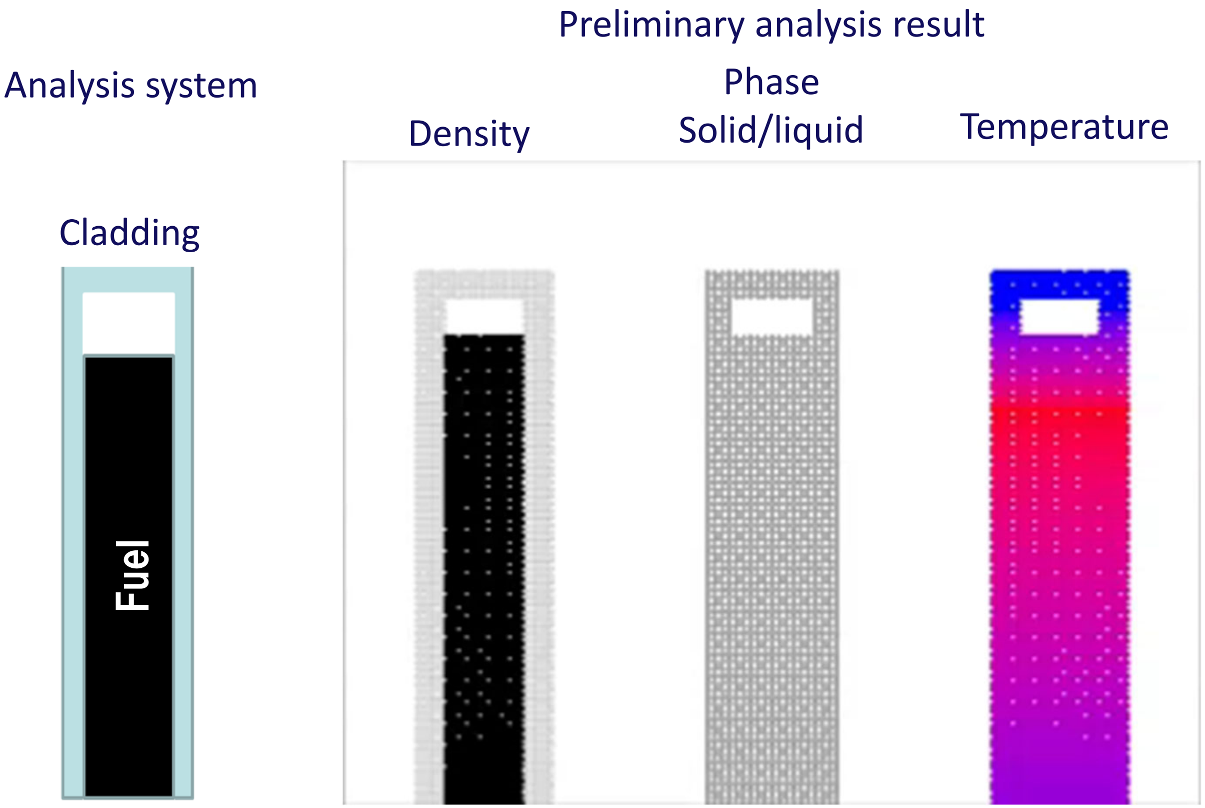
Metal Fuel Core Development

(3) Core Safety Analysis（4/4） (METI project*/CNWG NE08)

- A multi-physics particle method* (MPPM) code is developed that can simulate the metal fuel failure behavior such as local melting, breakage, dispersion and solidification, reflecting the shape of the fuel pins.

※ Particle method：A numerical analysis method that can handle melting, solidification, large deformation, and large movement of materials.

- Metal fuel failure behavior considering eutectic reaction between fuel and cladding was preliminary analyzed. Feasibility of melt-solidification reaction analysis involving eutectic reaction was confirmed.
- Multi-pin bundle failure behavior will be analyzed.



Summary

Development of metal fuel fast reactors in Japan has been conducted since 1986 according to the domestic fast reactor development targets.

1. Metal Fuel Development

- The applicable conditions for metal fuels, i.e. $T_{clad} < 650\ ^{O}C$, Pu enrichment < 25 %, were experimentally determined.
- ~500 U-Zr slugs were fabricated by injection casting.
- Six U-Pu-Zr metal fuel pins were successfully fabricated for the purpose of irradiation experiment in Joyo.
- Irradiation experiment of MA-containing metal fuel pins were completed to target burnups of ~2.5at.%, 6at.% and ~10at.%.
- PIEs for low burnup and middle burnup fuels are ongoing.
- An irradiation behavior analysis code, ALFUS has been developed.

2. Metal Fuel Core Development

- A demonstration scale metal fuel core was designed.
- A MOX fuel core partially loaded with highly concentrated MA-containing metal fuel SAs was design to achieve both core safety and high MA transmutation performance.
- Advanced analysis codes have been developed for improving core safety.
  ex.) ARKAS_cellule, MPPM, etc.

Various R&D activities are being promoted with the cooperation of domestic and international research institutes and the financial support by national projects.

- JAEA, METI, MEXT,
- ANL, INL, JRC-Karlsruhe, etc.

Thank you for your attention!!