DEVELOPMENT OF MINOR ACTINIDE TRANSMUTATION BY CRIEPI

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Metal Fuel FBR & Pyro-process

Innovative fuel cycle system is under development in CRIEPI

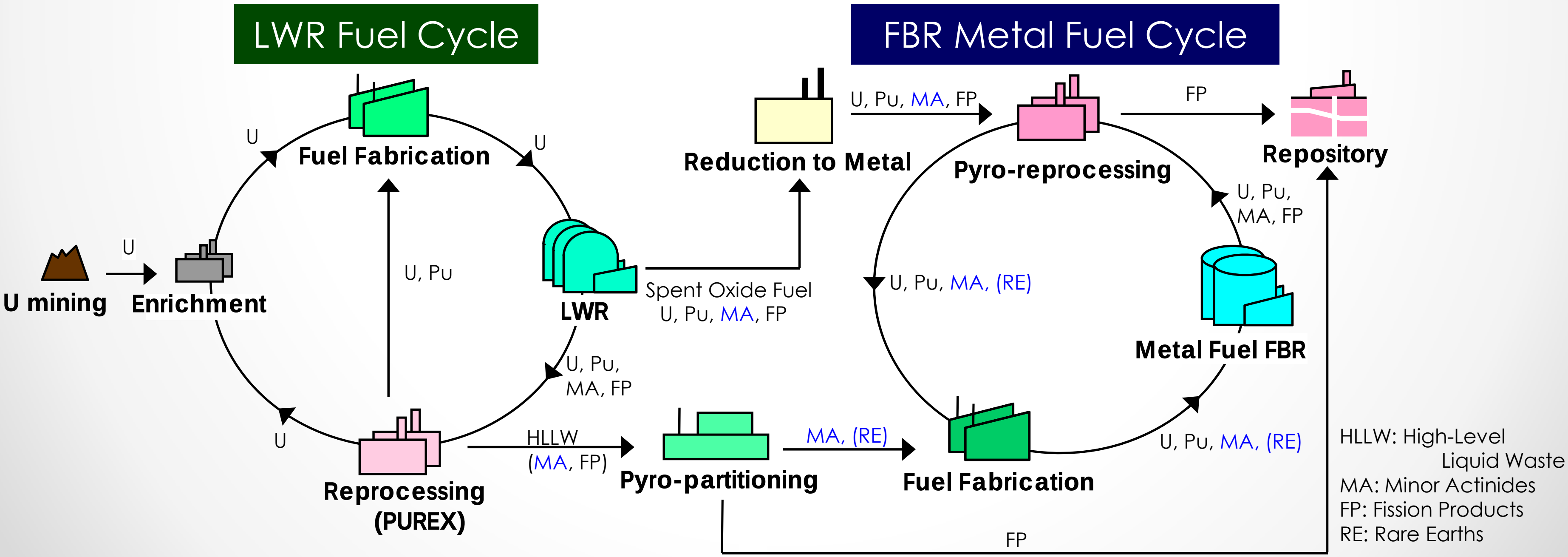
U-Pu-Zr Fuel FBR : Excellent nuclear performances & safety features

Pyro-reprocessing : Simultaneous recovery of MA with U and Pu

Injection Casting Fuel Fabrication : Simple remote-control operation

Goals:

Security of the long-term energy supply,
Reduction of the amount and the toxicity of radioactive waste,
Improvement of the proliferation resistance.



MA-Containing Metal Fuel Development

- How much content of MA should be loaded in metal fuel FBR?

  Evaluation of expected fuel compositions

  Burnup and recycle calculations of MA & RE in metal fuel FBR cycle

  Mass flow analysis based on the future fuel cycle scenario

- How about the effect of MA addition in metal fuel?

  Development of MA- and RE-containing U-Pu-Zr alloys

  Ex-reactor experiments
Irradiation experiment
postirradiation examinations } Characterization of U-Pu-Zr-MA-RE

Various experimental studies on U-Pu-Zr-MA(-RE) alloys are performed in cooperation with JRC-ITU.

MA Burnup Performance in Metal Fuel FBR

Large-scale & high-burnup metal fuel core design is assumed as a model of commercial FBR.

Output	1,500MWe / 3,900MWt
Core residence time	6years
Coolant temp. inlet / outlet	355 / 510°C
Max. cladding temp.	650°C
Max. linear power	500W/cm
Ave. discharge burnup	150GWd/t

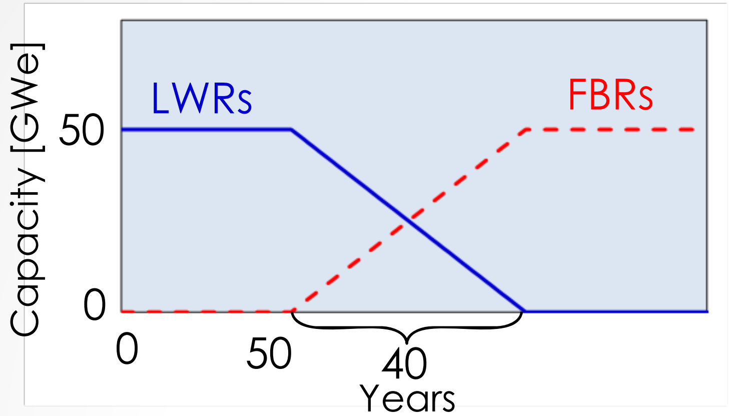
Feed compositions and core performance parameters

	No-MA-makeup	MA-enriched	
MA content, wt%	0.8	2.0	5.0
RE content [1], wt%	0.5	1.5	3.5
Pu enrichment, wt%	16.6	16.4	15.8
Makeup MA ratio [2], %	-	37	53
Doppler const., *Tdk/dT*	-2.3×10^{-3}	-2.2×10^{-3}	-2.1×10^{-3}
Coolant coeff., *¢/°C*	0.254	0.273	0.310

[1]: D.F. = 10, [2]: (MA from LWR) / (MA in FBR fuel)

Mass Flow Evaluation (1)

Transition Scenario from LWRs to FBRs



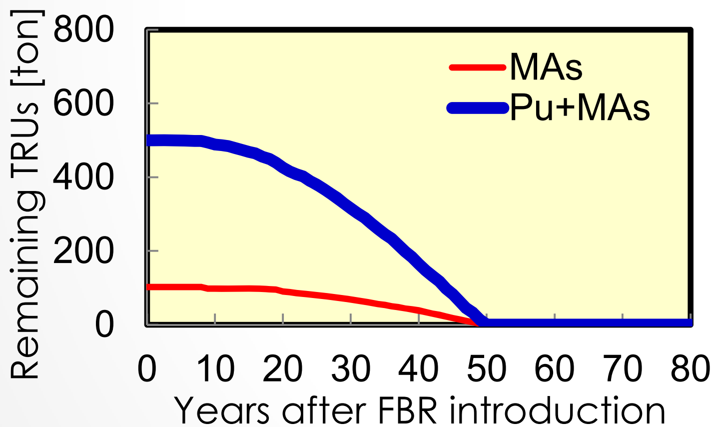
Assumptions

50GWe of LWRs are operated for 50years before FBR introduction,

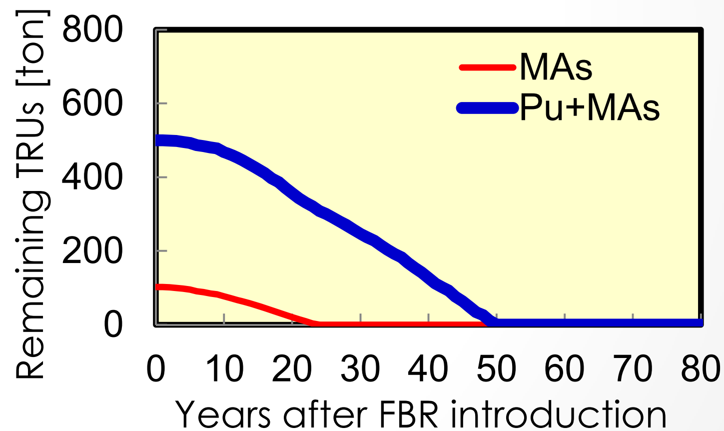
Reactor lifetime is 40 years,

MA content in the feed is 2 or 5wt%.

Mass Balance of Pu & MA



MA content=2wt%



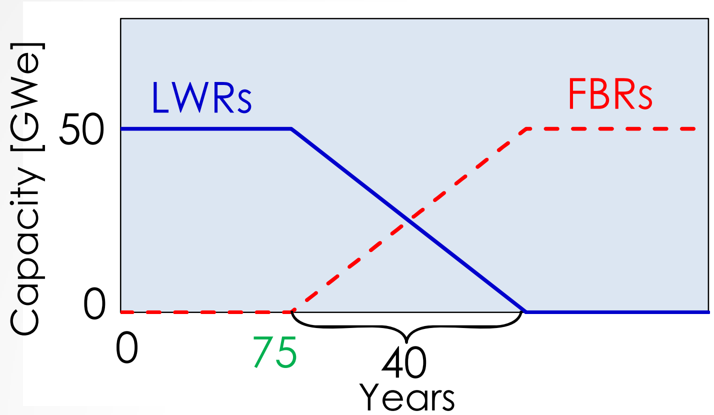
MA content=5wt%

LWR operation=50years

MA content of 2wt%: MA & Pu are recycled at the almost same time,
5wt%: MA can be consumed in shorter-term.

Mass Flow Evaluation (2)

Transition Scenario from LWRs to FBRs (2)



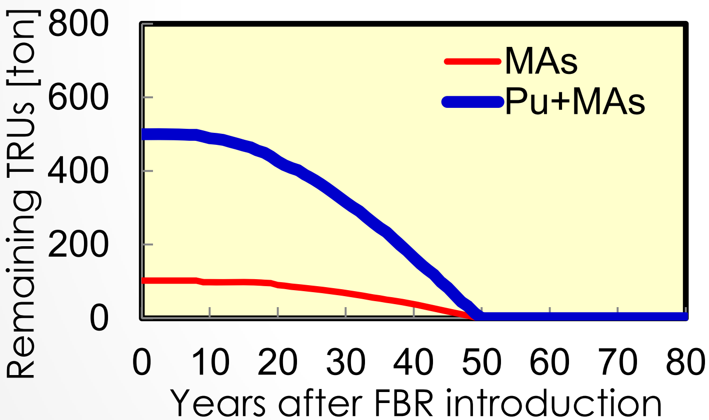
Assumptions

50GWe of LWRs are operated for 75years before FBR introduction,

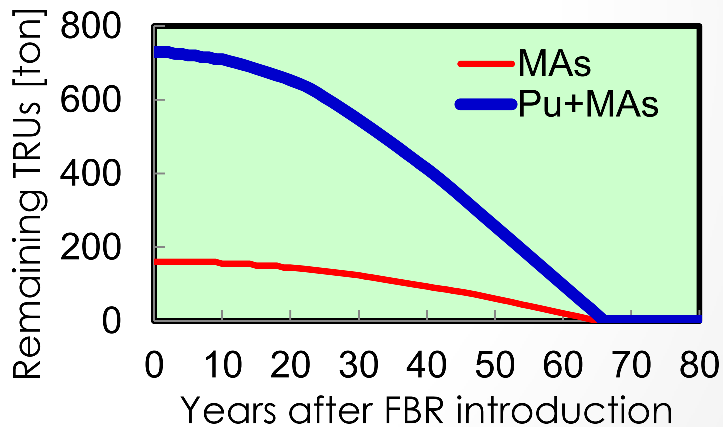
Reactor lifetime is 40 years,

MA content in the feed is 2wt%.

Mass Balance of Pu & MA



LWR operation=50years



LWR operation=75years

MA content=2wt%

MA content of 2wt%: MA & Pu are balanced.

Miscibilities among U-Pu-Zr-MA-RE

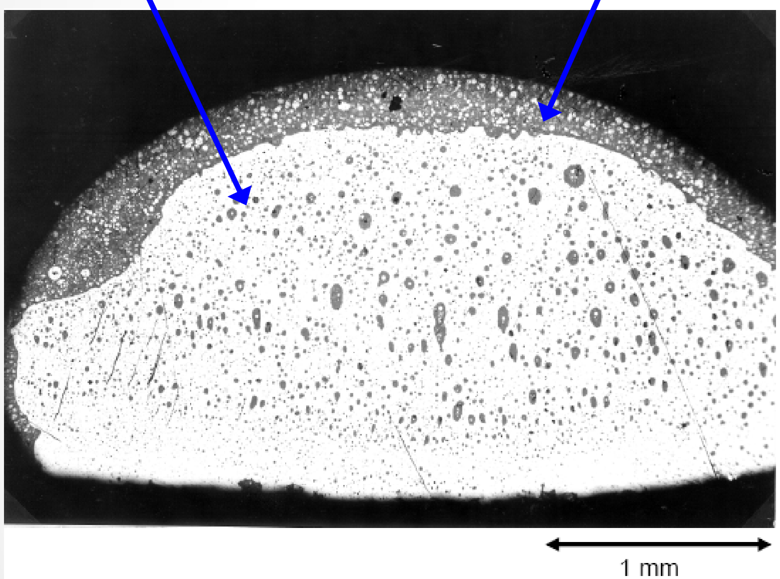
U-Pu-Zr-MA-RE alloys of different compositions were mixed by arc-melting.

→ U-Pu-Zr-MA alloys without RE can be blended homogeneously.

44U-18Pu-10Zr-9Np-5Am-3Ce-10Nd (wt%)

U-Pu-Zr-Np phase

Pu-Am-RE phase

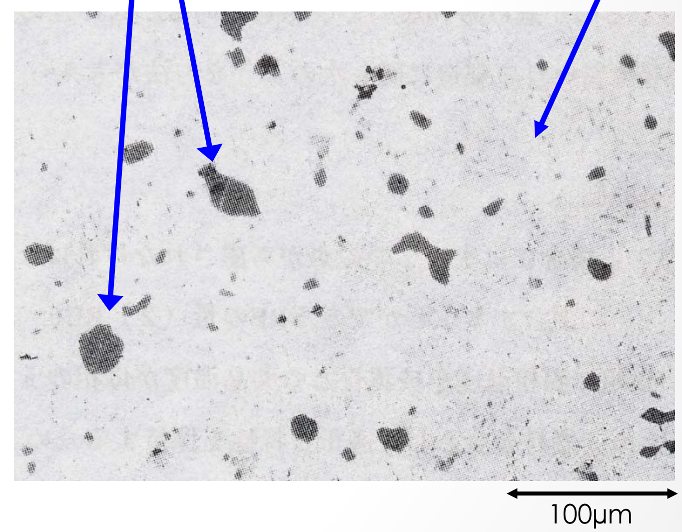


In the alloys of high RE content,
→ Matrix segregates into upper and lower parts.

39U-22Pu-12Zr-15Np-10Am-0.6Ce-1.8Nd

Pu-Am-RE precipitates

U-Pu-Zr-Np phase



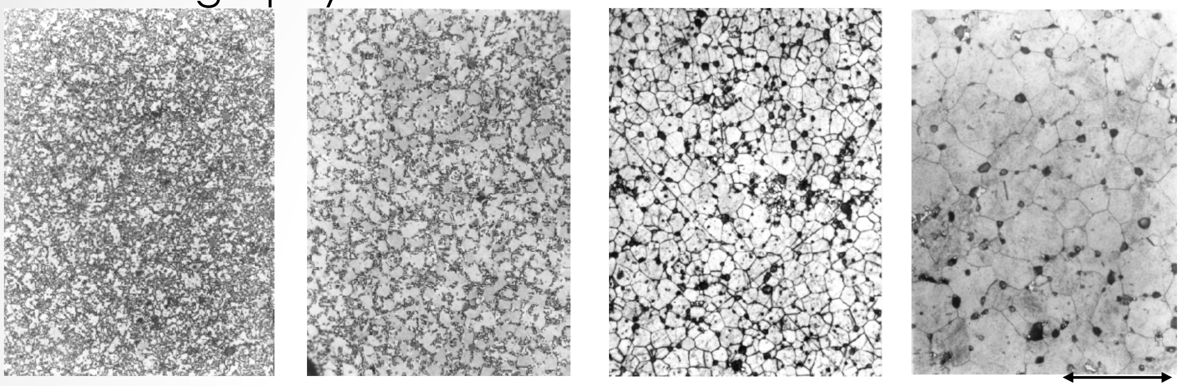
In the alloys of low RE content (≤5%),
→ RE-rich precipitates were uniformly dispersed.

RE ≤ 5% can be mixed in U-Pu-Zr-MA matrix.

Phase Structures of annealed U-Pu-Zr-MA-RE

U-Pu-Zr-MA-RE alloys were annealed and quenched.

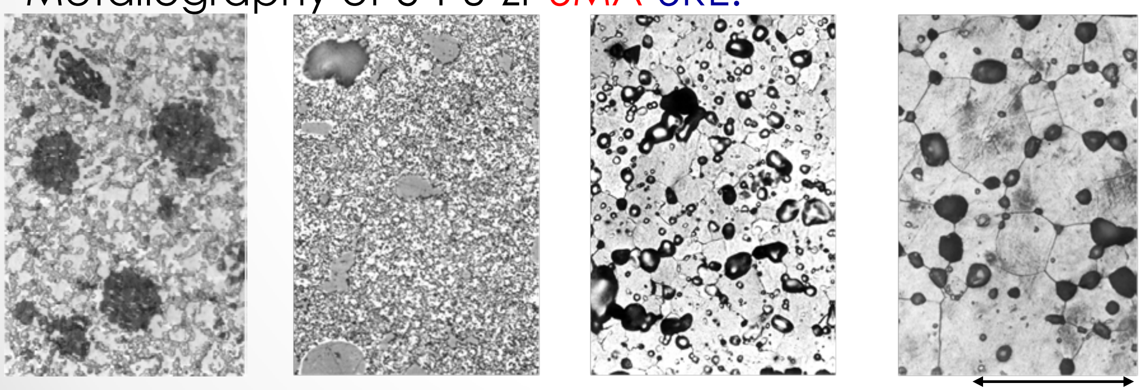
Metallography of U-Pu-Zr-2MA-2RE.



50mm

500°C 600°C 700°C 850°C

Metallography of U-Pu-Zr-5MA-5RE.



50mm

500°C 600°C 700°C 850°C

Matrix phase

- $\leq$ 600°C: Two phase structures
  - $\zeta+\delta$ at 500°C
  - $\gamma+\delta$ (or $\zeta+\delta$) at 600°C
- $\geq$ 700°C: Single γ-phase

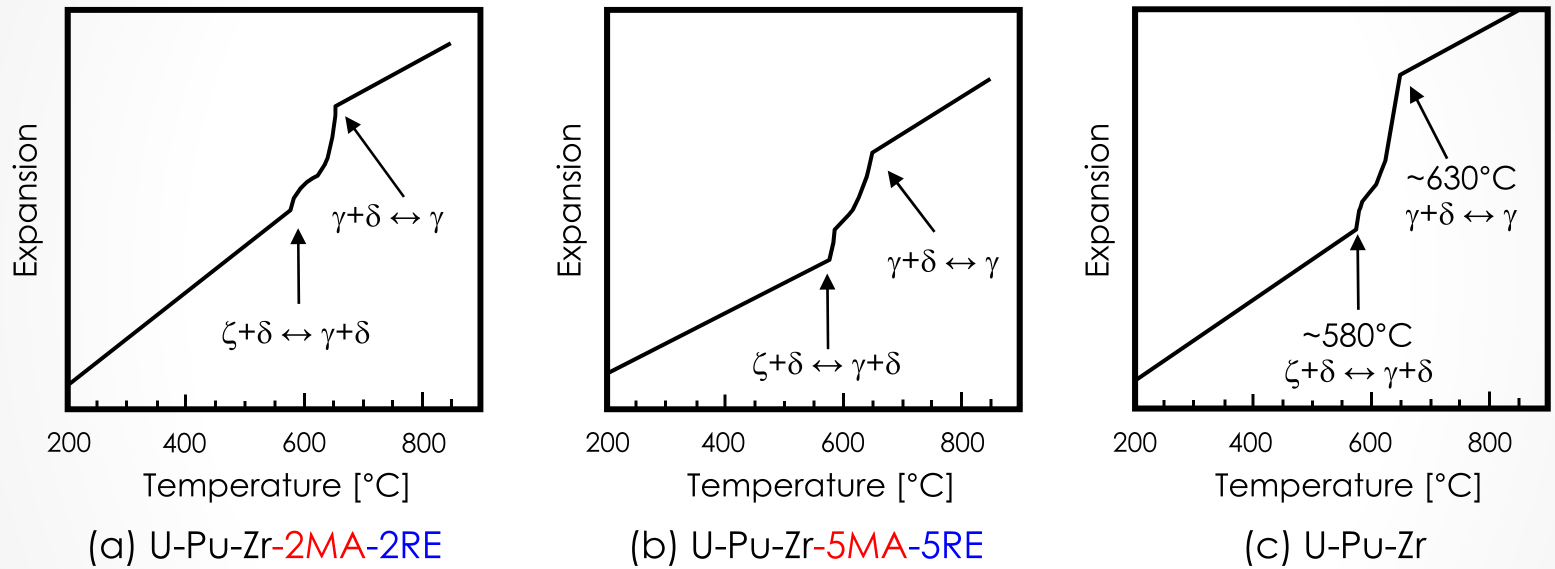
Am & RE-rich precipitates

- Uniformly dispersing
- Cohesion at grain boundary ($\geq$700°C)
- ~3μm (-2MA-2RE),
- $\geq$10μm (-5MA-5RE)

Phase transition temperature

Phase transition temperature of U-Pu-Zr(-MA-RE) were measured by dilatometry method.

Dilatometric curves



For all samples,

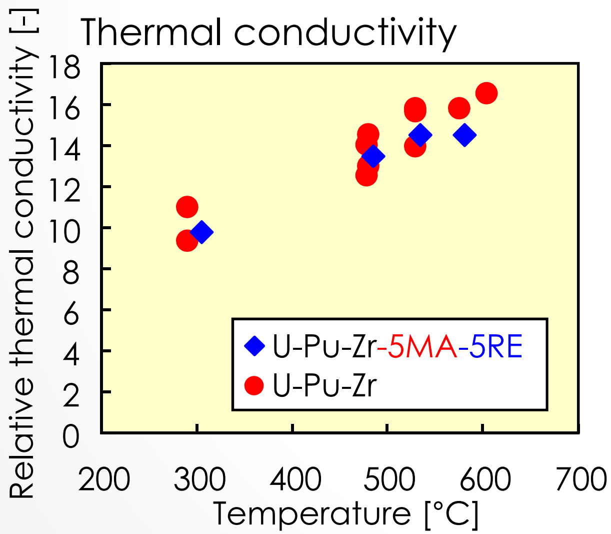
two distinctive phase transition temperatures at ~580°C & ~630°C

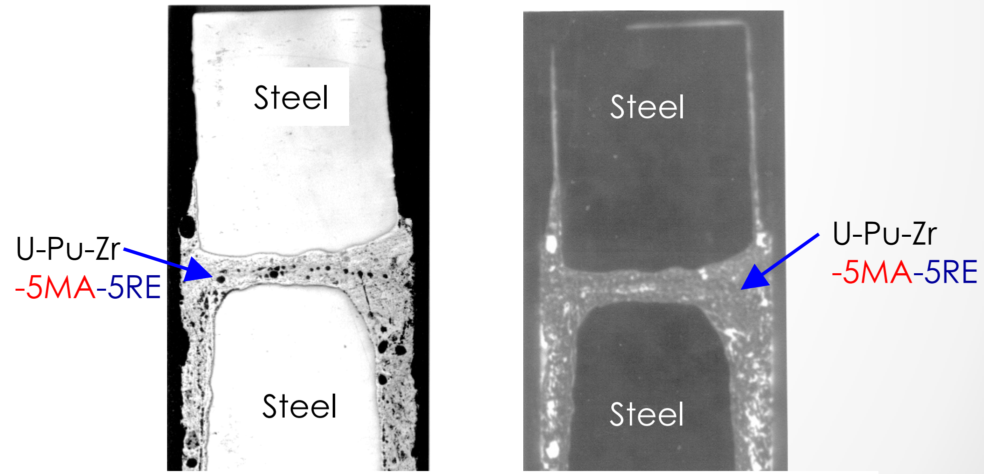
→ Insignificant influence of MA and RE addition up to 5wt%

Other properties

	U-19Pu-10Zr -5MA-5RE	U-19Pu-10Zr	Reported U-19Pu-10Zr
Melting point [°C]	1207±10	1217±10	1214±75 [2]
Elasticity Young's modulus [GPa] Shear modulus [GPa] Poisson's ratio	 93.31 35.39 0.32	 85.22 32.65 0.31	
Compatibility with SS * [1]	920-960	970-990	

*: Metallurgical reaction temperature between the alloy and stainless steel.





Optical metallography   a-autoradiography

Diffusion couple of U-Pu-Zr-5MA-5RE / SS

Influence of MA and RE addition ≤ 5wt% is not significant.

[1] C. Sari, etal, J. Nucl. Mater., 208 (1994) 201.
[2] M.C. Billon, etal., Int. Conf. on Reliable Fuels for Liquid Metal Reactors, (1986).

Fabrication of MA-containing Metal Fuel

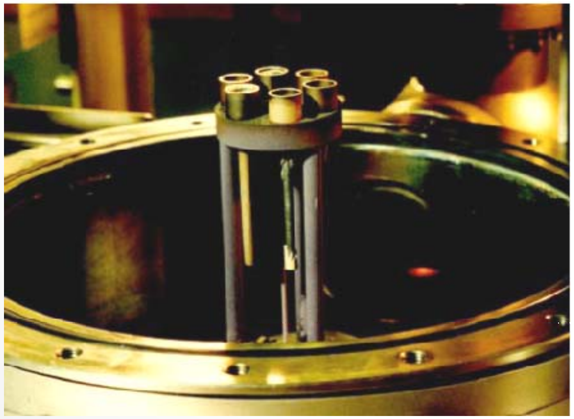
Fuel Fabrication:

U-19Pu-10Zr-2MA-2RE, U-19Pu-10Zr-5MA,
U-19Pu-10Zr-5MA-5RE and U-19Pu-10Zr

MA=60Np-30Am-10Cm, RE=10Y-10Ce-70Nd-10Gd.

Fuel Rod diameter	4.9 mm
Fuel Rod lengths	20-50 mm
Density	
U-19Pu-10Zr-2MA-2RE	14.73 g/cm^3
U-19Pu-10Zr-5MA-5RE	14.66 g/cm^3
U-19Pu-10Zr-5MA	15.31 g/cm^3
U-19Pu-10Zr	15.77 g/cm^3*

*: Reported value =15.8g/cm^3, J.H.Kittel, et al., *N.E.D.* 15 (1971)



Yttria molds used for fuel rod casting

Cast fuel rods

Irradiation Experiment

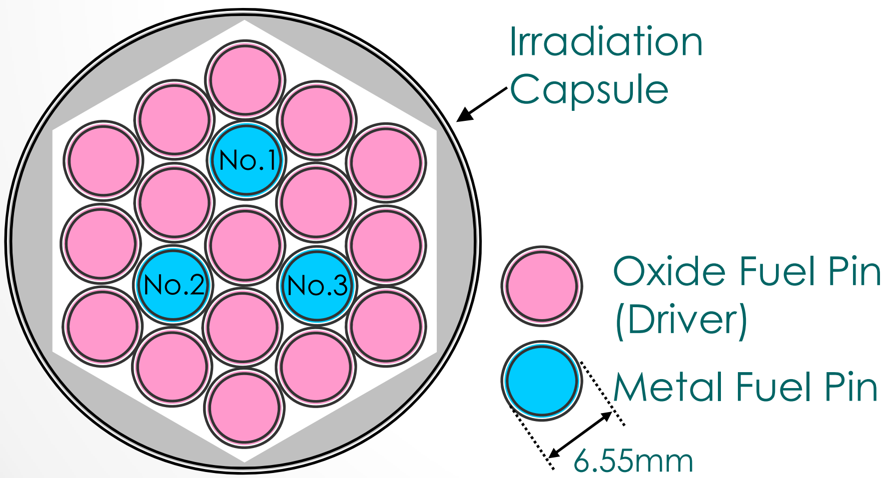
MA-containing alloys were irradiated in Phénix.

3 metal fuel pins & 16 oxide fuel pins were arranged in an capsule.

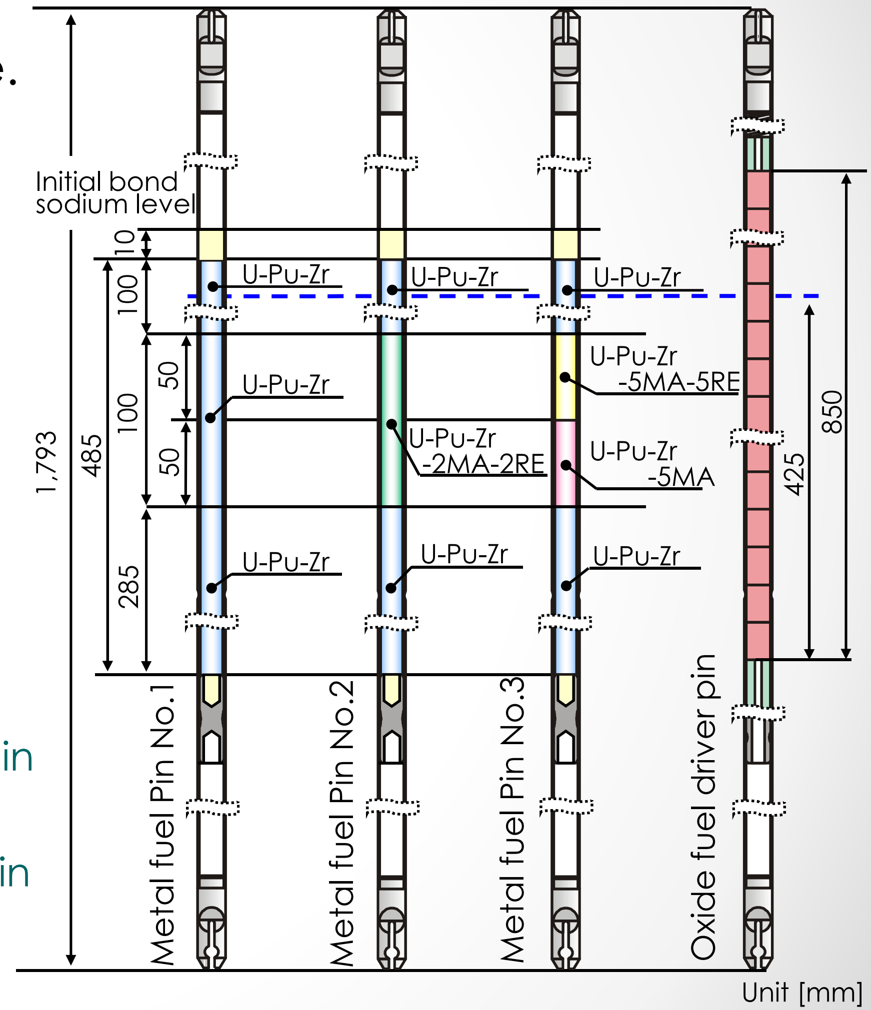
- Pin No.1 : U-19Pu-10Zr
- Pin No.2 : U-19Pu-10Zr-2MA-2RE
- Pin No.3 : U-19Pu-10Zr-5MA / -5MA-5RE

Cladding material : 15-15Ti

Burnup goals ~2.5at.% (METAPHIX-1), ~ 7at.% (METAPHIX-2), ~10at.% (METAPHIX-3).

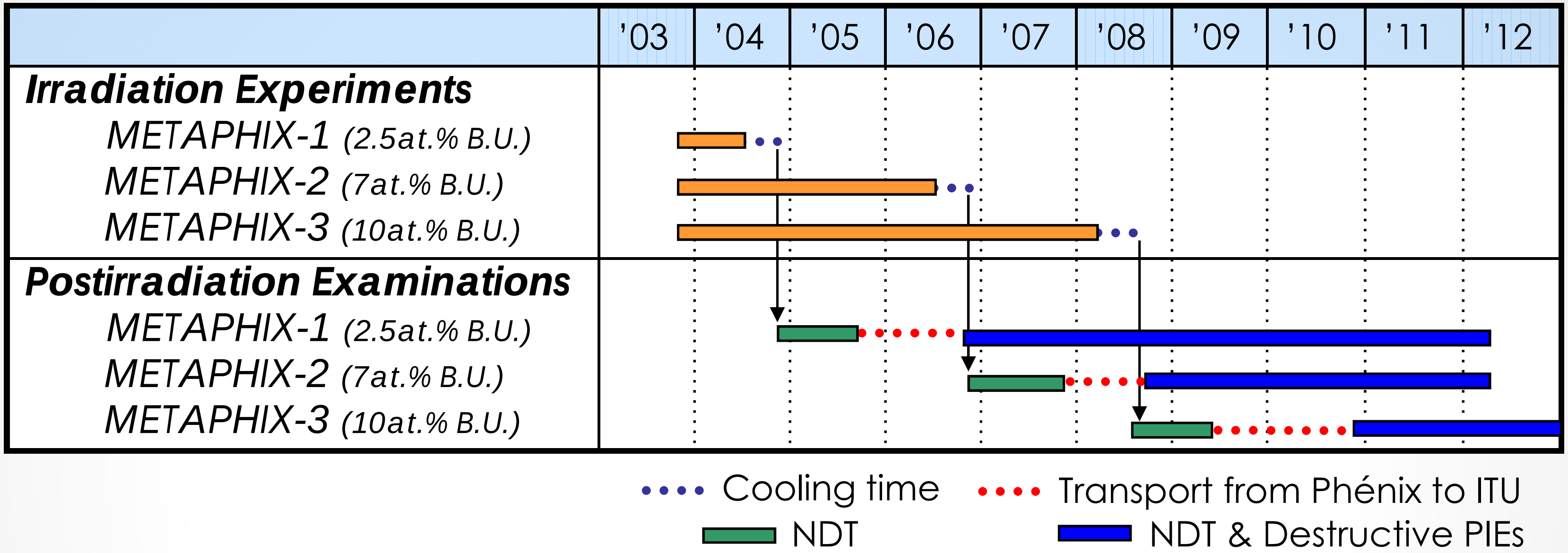


Fuel pin arrangement in irradiation capsule.



Schematic views of irradiated fuel pins.

METAPHIX Program



- Irradiation experiments were carried out from Dec. 2003 to May 2008 in Phénix.
- After cooling, NDT were carried out.

  No excessive damage due to neutron irradiation was observed.
- Irradiated fuel pins are transported to ITU for nondestructive & destructive PIE.
- After the PIE, pyro-reprocessing experiment is planned.

Irradiation Conditions

Irradiation parameters were analyzed taking account of the operation diagram of the Phénix reactor.

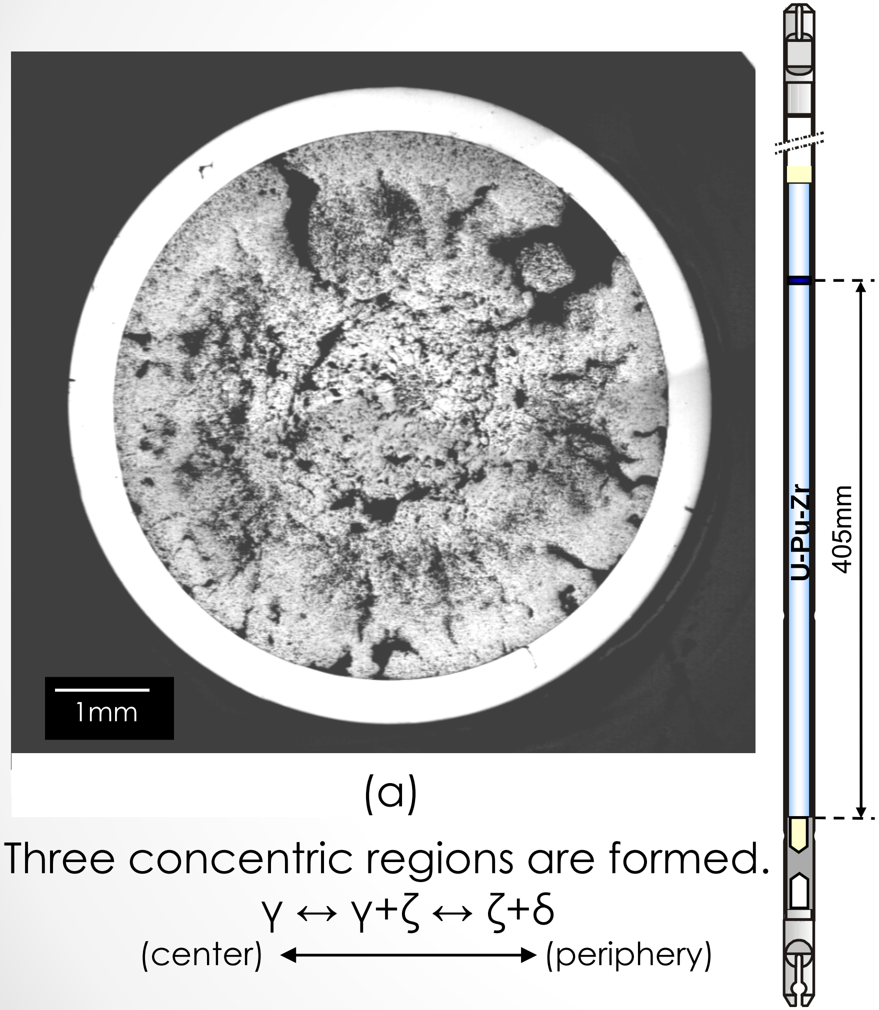
Projected Irradiation Conditions for METAPHIX Experiment

	Pin No.1 *U-19Pu-10Zr*	*Pin No.2* *U-19Pu-10Zr* *+2MA+2RE*	*Pin No.3(lower)* *U-19Pu-10Zr* *+5MA*	*Pin No.3(upper)* *U-19Pu-10Zr* *+5MA+5RE*
Begin of Irradiation *Max. Linear Power [1] [W/cm]* *Max. Cladding Temp. [2] [°C]*	350 581	327 581	343 581	332 ←
End of METAPHIX-1 (120EFPD [3]) *Max. Linear Power [1] [W/cm]* *Max. Cladding Temp. [2] [°C]* *Max. Burnup [at.%]*	330 572 2.4	308 572 2.5	325 572 2.4	313 ← 2.6
End of METAPHIX-2 (360EFPD [3]) *Max. Linear Power [1] [W/cm]* *Max. Cladding Temp. [2] [°C]* *Max. Burnup [at.%]*	295 556 6.9	276 556 7.1	294 556 7.0	282 ← 7.5
End of METAPHIX-3 (900EFPD [3]) *Max. Linear Power [1] [W/cm]* *Max. Cladding Temp. [2] [°C]* *Max. Burnup [at.%]*	268 543 10.9	251 543 11.2	269 543 11.2	256 ← 11.9

[1]: Top of the test alloy, [2]: Top of the fuel stack, [3]: EFPD=Effective Full Power Days.

Metallography (1)

METAPHIX-1, U-19Pu-10Zr

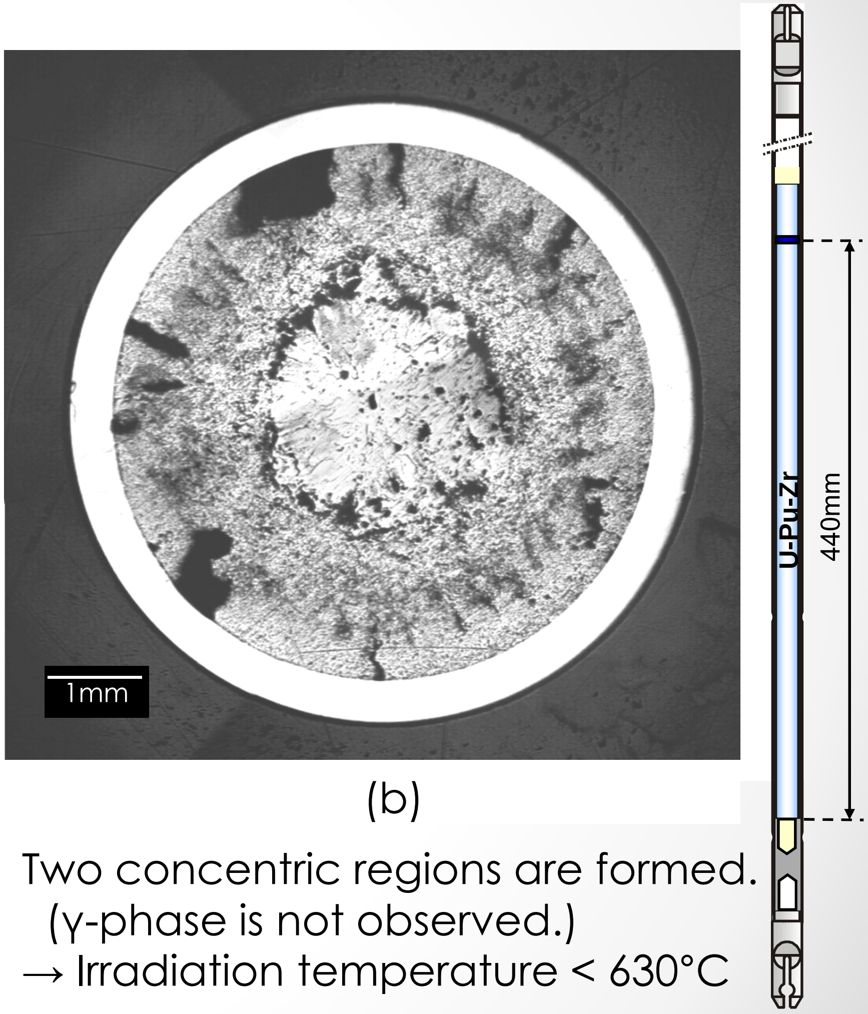


(a)

Three concentric regions are formed.

γ ↔ γ+ζ ↔ ζ+δ

(center) ⟵⟶ (periphery)



(b)

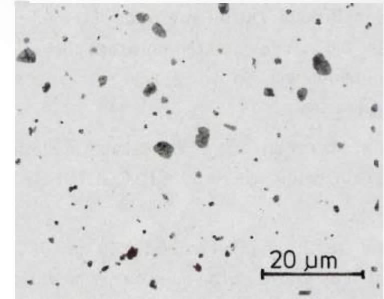
Two concentric regions are formed.

(γ-phase is not observed.)

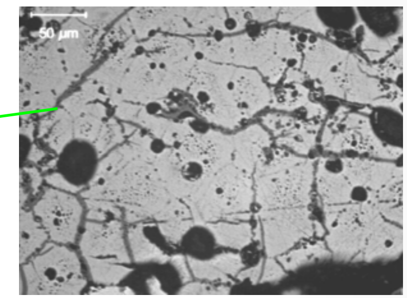
→ Irradiation temperature < 630°C

Metallography (2)

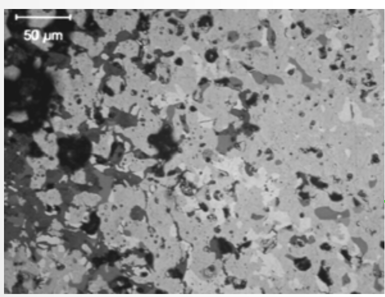
METAPHIX-1, U-19Pu-10Zr-2MA-2RE



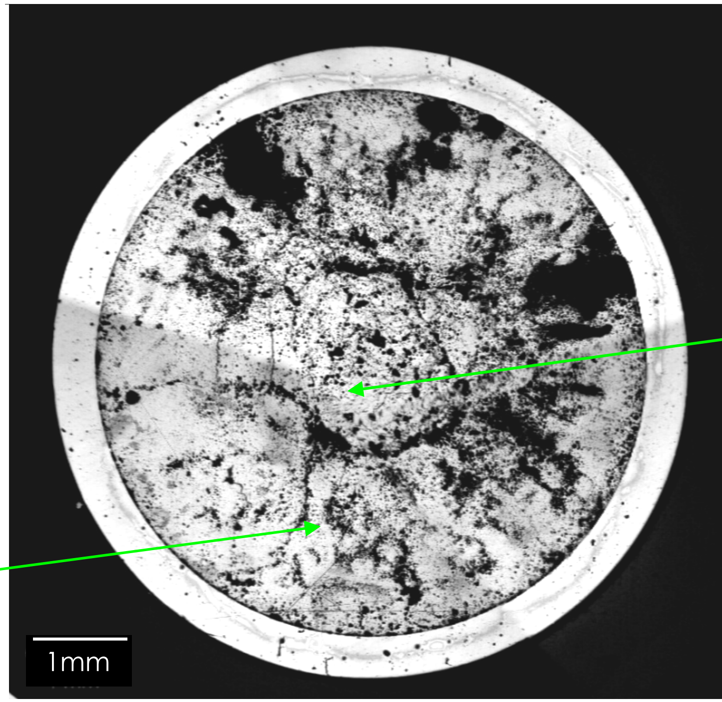
Unirradiated U-Pu-Zr-2MA-2RE



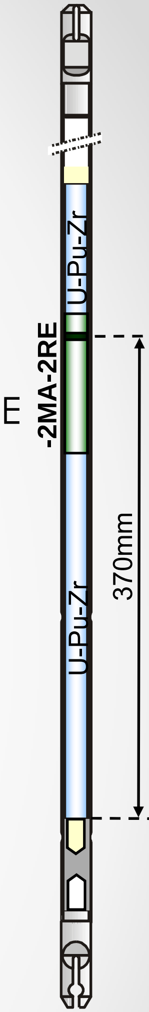
Central Zone 100µm
Dense phase
→ (γ+ζ)-phases



100µm
Intermediate Zone



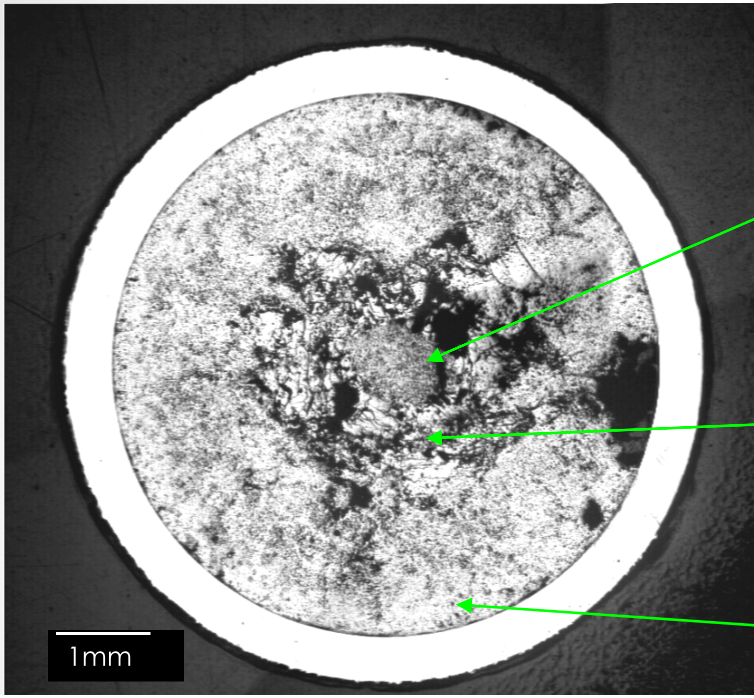
Cross-Sectional Overview



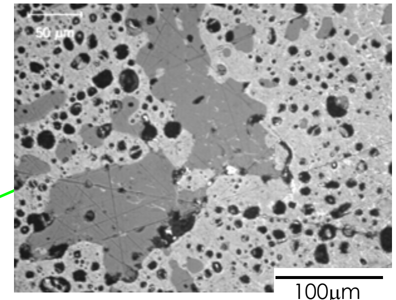
Matrix morphology is similar to that of U-Pu-Zr fuel (b).
Some narrow layered phases (MA-RE inclusions) spread along grain boundaries in γ+ζ zone.
In low-temperature region, some dark spots (MA and RE inclusions) are visible.

Metallography (3)

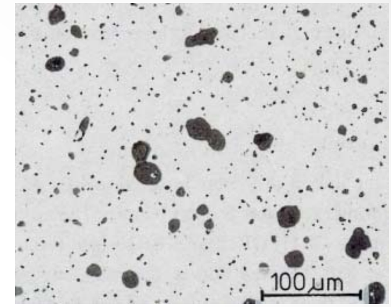
METAPHIX-1, U-19Pu-10Zr-5MA-5RE



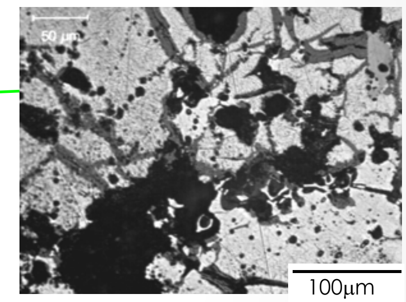
Cross-Sectional Overview



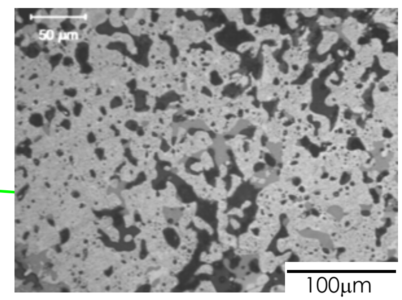
Central Zone
Porous phase
→ γ-phase



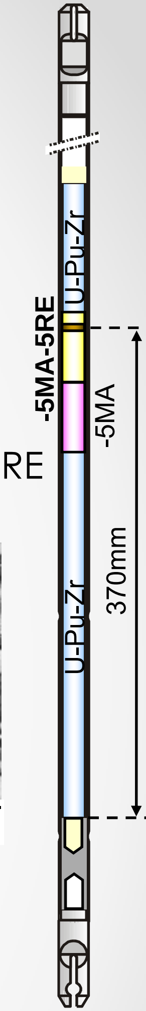
Unirradiated U-Pu-Zr-5MA-5RE



Intermediate Zone
Dense phase
→ (γ+ζ)-phases



Peripheral Zone



Matrix morphology is similar to that of U-Pu-Zr fuel (a).
Large precipitates (MA and RE inclusions) appear in γ phase zone.
Some narrow layered phases (MA-RE inclusions) spread along grain boundaries in γ+ζ zone.
In low-temperature region, small dark spots (MA and RE inclusions) are observed.

Characteristics of Irradiated MA-Containing Metal Fuel

1. The radial distribution of fuel matrix morphology is similar to that of U-Pu-Zr ternary fuels.

2. Some large precipitates (MA and RE inclusions) appear in the high-temperature phase.

3. In the dense matrix zone, some narrow layered phases (MA and RE inclusions) spread along grain boundaries.

4. In low-temperature region, some dark spots (MA and RE inclusions) are visible.

Summary

Mass flow of Pu and MA was analyzed for future LWR-FBR transition scenario.

MA content in the FBR fuel was estimated to be 2wt%.

With using 5wt% MA content fuel, MAs recycling from LWRs can be accelerated for several decades.

Relevant characteristics of U-Pu-Zr-MA-RE were examined.

In the case of ≤ 5wt% MA and ≤ 5wt% RE additions,

- Am-RE-rich precipitates are dispersed almost uniformly in the alloy,
- Basic properties are practically unchanged.

MA-containing U-Pu-Zr alloys were irradiated in Phénix.

- Compositions: U-19Pu-10Zr, U-19Pu-10Zr-2MA-2RE, U-19Pu-10Zr-5MA(-5RE)
- Peak burnups: ~2.5at.%, ~7at.% and ~10at.%.

NDT of the METAPHIX-1, -2 & -3 pins

- No critical damage had occurred during irradiation.

Metallography of METAPHIX-1

- Matrix structure is similar to that of U-Pu-Zr fuels.
- Large precipitates appear in γ-phase zone.
- Some layered phase spread along grain boundaries in γ+ζ phase region.

Quantitative analyses are being carried out.

- Fuel constituent redistribution,
- MA transmutation performance

Thank you for your attention!!

Compositions of Metal Fuel Alloys

4 types of metal fuel alloy were prepared.

Average Compositions of Fabricated Metal Fuel Alloys [wt%]

Target	71U-19Pu-10Zr	67U-19Pu-10Zr +2MA+2RE	66U-19Pu-10Zr +5MA	61U-19Pu-10Zr +5MA+5RE
U	71.00	66.85	66.30	63.50
Pu	18.93	19.80	19.35	19.75
Zr	10.19	9.46	8.97	8.19
MA	0.03	2.08	4.74	4.78
Np	*-*	*1.23*	*2.97*	*3.04*
Am	*0.03*	*0.67*	*1.45*	*1.52*
Cm	*-*	*0.18*	*0.32*	*0.31*
RE	-	1.73	-	3.40
Y	*-*	*0.12*	*-*	*0.31*
Ce	*-*	*0.20*	*-*	*0.45*
Nd	*-*	*1.25*	*-*	*2.30*
Gd	*-*	*0.16*	*-*	*0.32*

Impurities < 0.3wt%

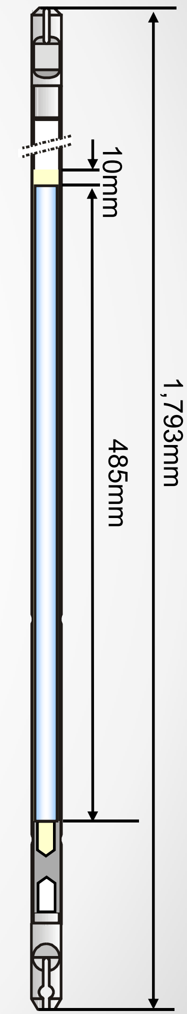
Specifications of Metal Fuel Pins

Fuel pins were manufactured according to Phénix geometry.

Fuel Pin Specifications in this Irradiation Experiments

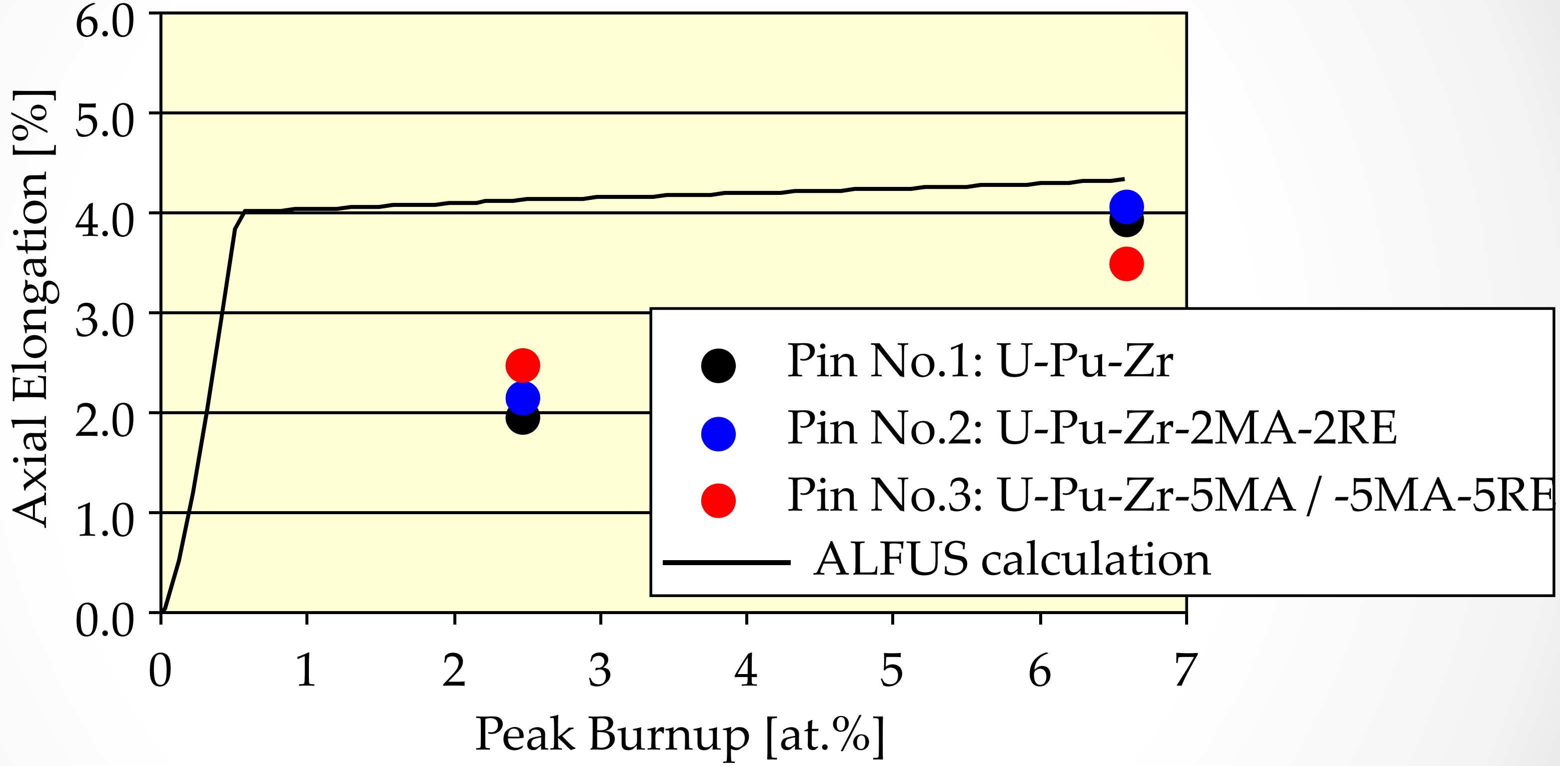
Pin length [mm]	*1,793*
Outer cladding diameter [mm]	*6.55*
Cladding material	*15-15 Ti*
Fuel length [mm]	*485*
Fuel diameter [mm]	*4.9*
Initial fuel-cladding gap [mm]	*0.375*
Fuel smear density [%]	*75.2*
Sodium level above fuel [mm]*	*~10*
Plenum length [mm]	*464*

* : Sodium is filled into fuel-cladding gap as thermal bonding.



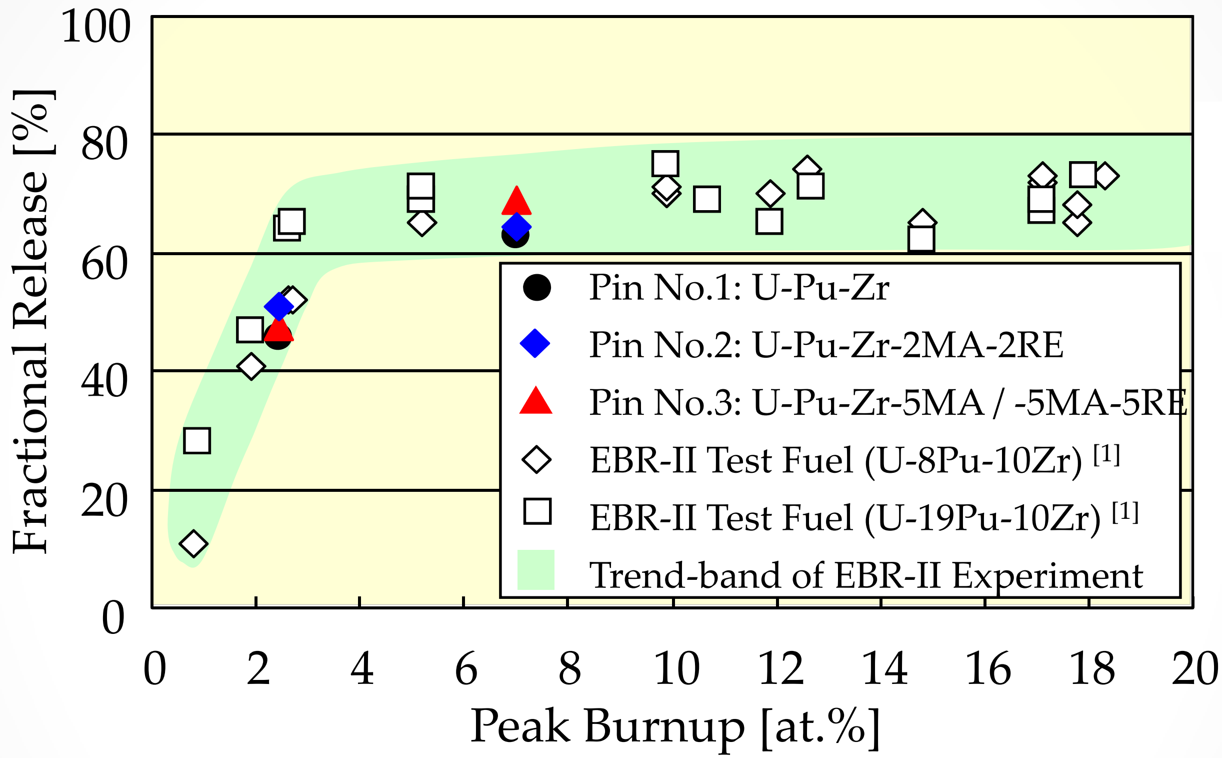
Axial Swelling of Fuel alloy

Fuel stack position was estimated by axial gamma-ray distribution from ^{106}Ru.



Fuel elongation behavior is independent of MA and RE additions.
Axial swelling of METAPHIX fuels is within the range of the prediction.

Fission Gas Release

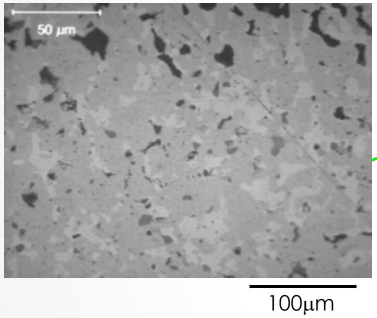


FP gas release fraction of MA & RE-containing fuel pins is the same level as that of U-Pu-Zr alloy fuel pins, and consistent with EBR-II ternary test fuel data.

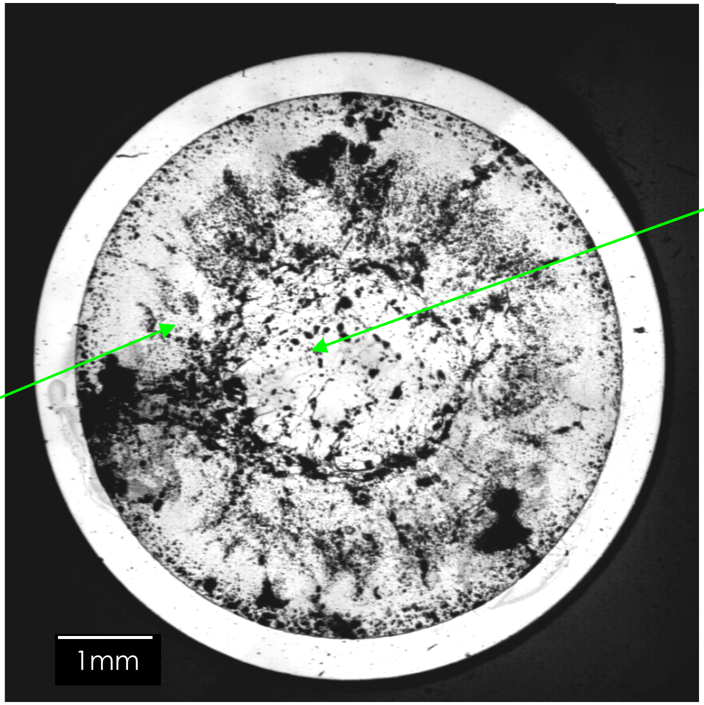
[1] : R. G. Pahl, etal., *Proc. Int. Fast Reactor Safety Meeting*, Session 2 Vol. IV, 129 (1990).

Metallography (3')

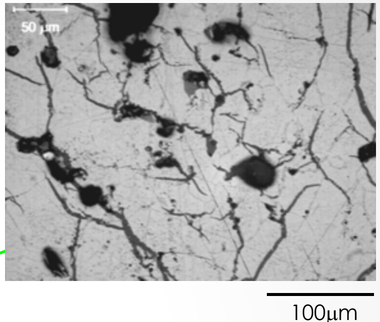
METAPHIX-1, U-19Pu-10Zr-5MA



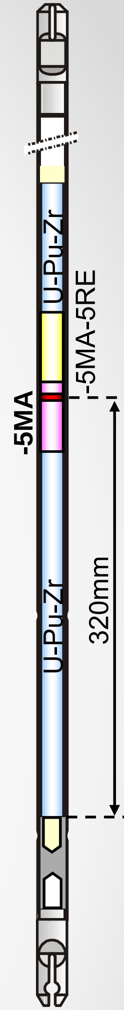
Intermediate Zone



Cross-Sectional Overview

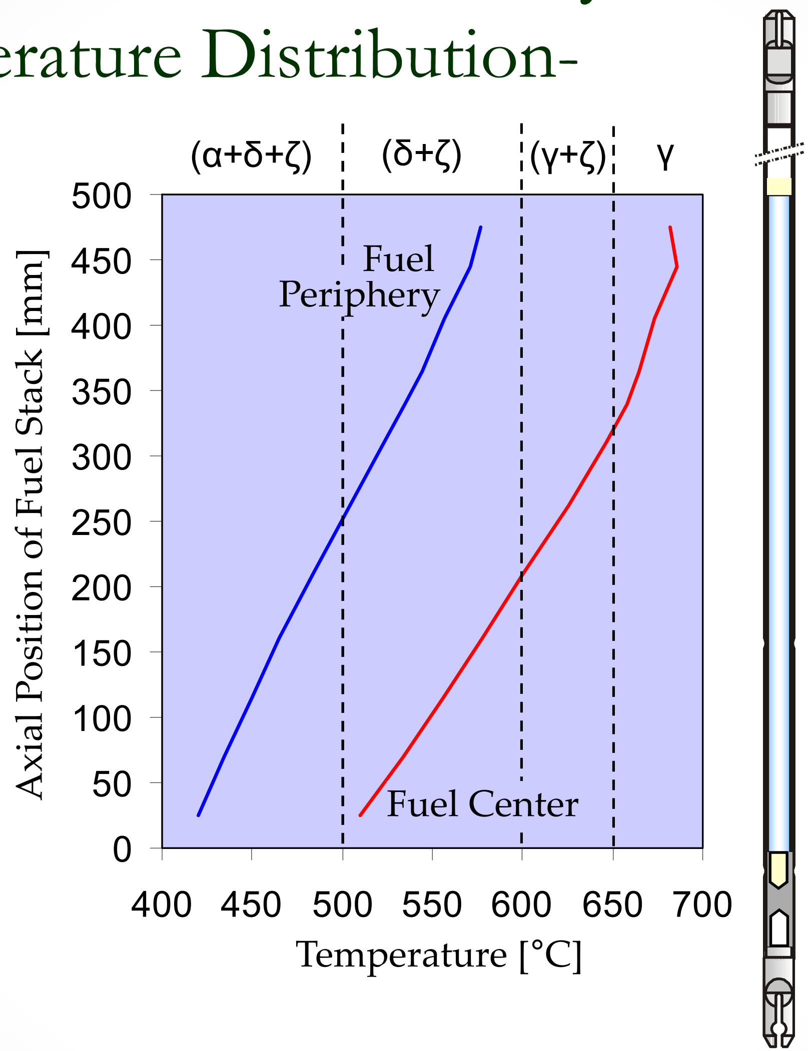


Central Zone
Dense phase
→ (γ+ζ)-phases



Matrix morphology is similar to that of U-Pu-Zr fuel (b).
Some narrow layered phases (MA-RE inclusions) spread along grain boundaries in γ+ζ zone.
In low-temperature region, small dark spots (MA and RE inclusions) are dispersed.

Irradiation Behavior Analysis
-Fuel Temperature Distribution-



420ºC < Temp. < 685ºC

Fig. Evaluated irradiation temperature for METAPHIX-1 fuel pin at EOI (Pin No.1: U-19Pu-10Zr).

Discussion - Irradiation Temperature -

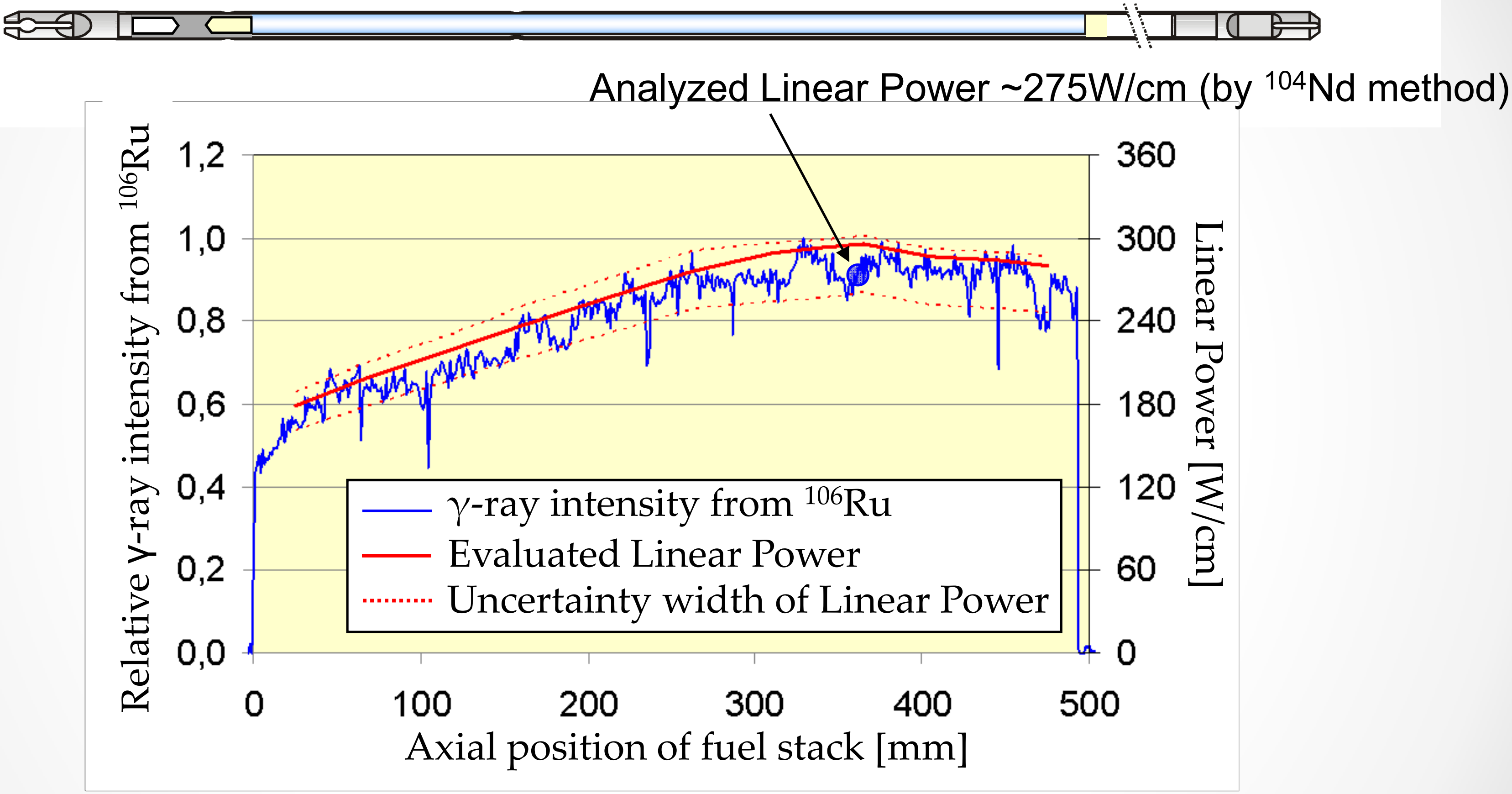


Fig. Relative γ-ray intensity emitted from ^{106}Ru and axial power profile of Pin No. 1

Discussion - Irradiation Temperature -

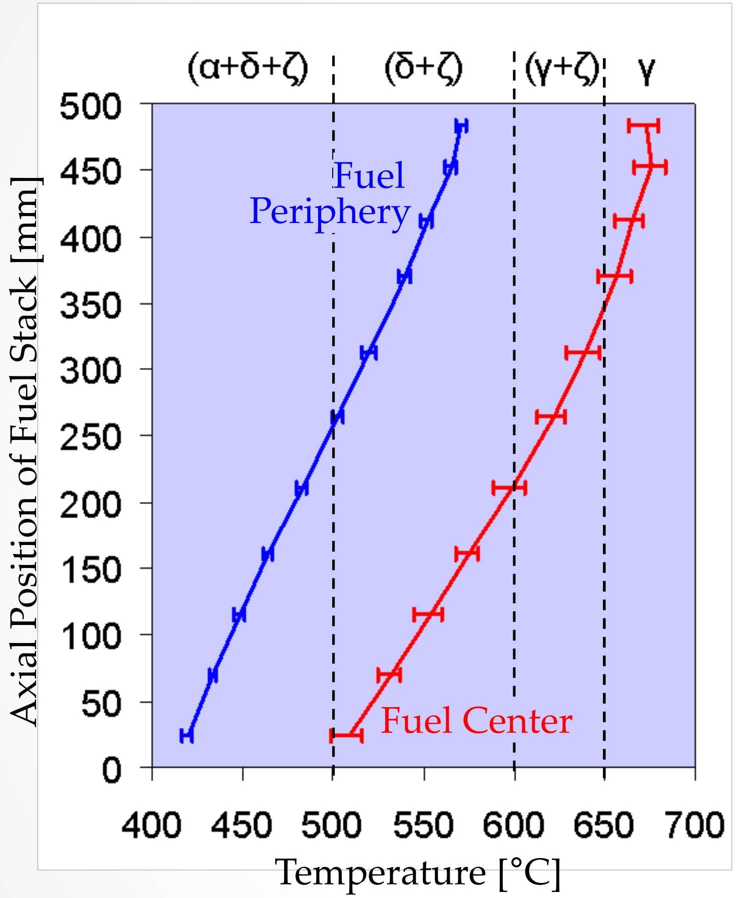


Fig. Evaluated irradiation temperature for METAPHIX-1 fuel pins,
taking account of the uncertainties of linear power.

Due to the uncertainty of linear power,

-Temperature fluctuation for each fuel rod reaches ~20°C at the fuel center,
→Irradiation temperature at higher axial level
can be lower than that at lower level,

-The highest temperature can be ~660°C.
→High-temperature γ-phase appears at only limited fuel rods.