Core Modification for the High Burn-up to Improve Irradiation Efficiency of the Experimental Fast Reactor Joyo

S. Maeda, M. Yamamoto, T. Soga, T. Furukawa and T. Aoyama

Oarai R&D Center

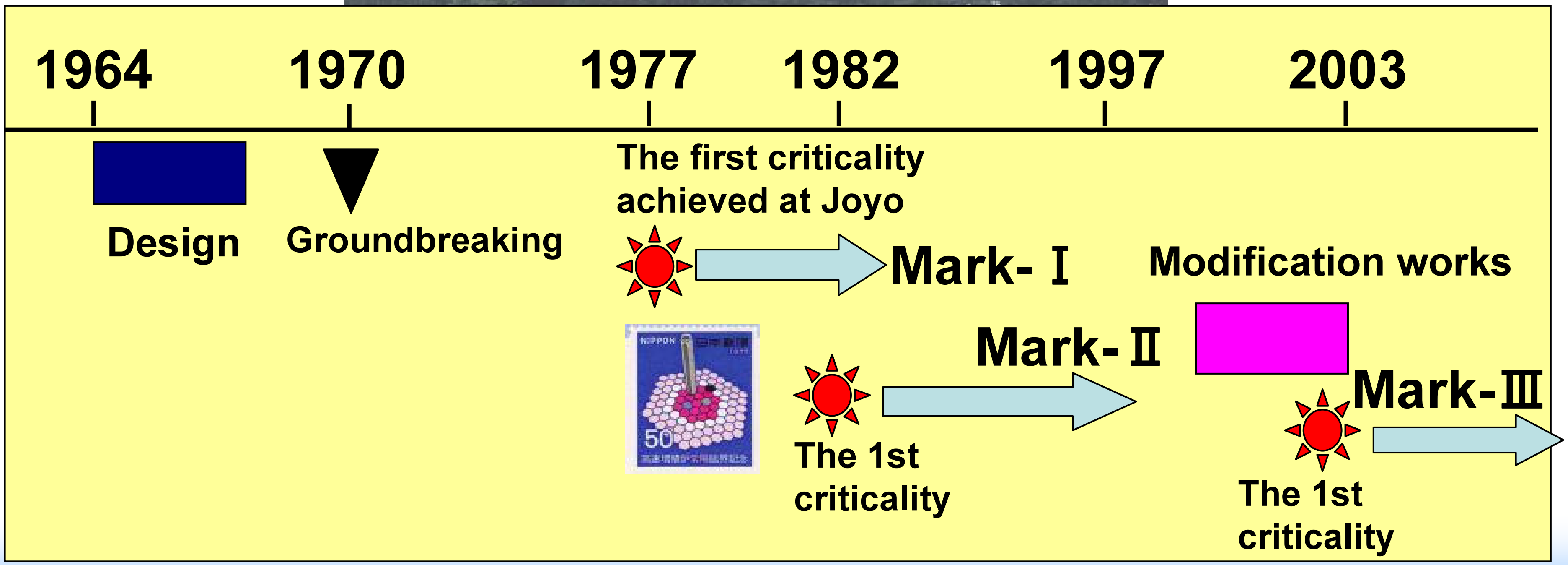
Japan Atomic Energy Agency

History of Joyo

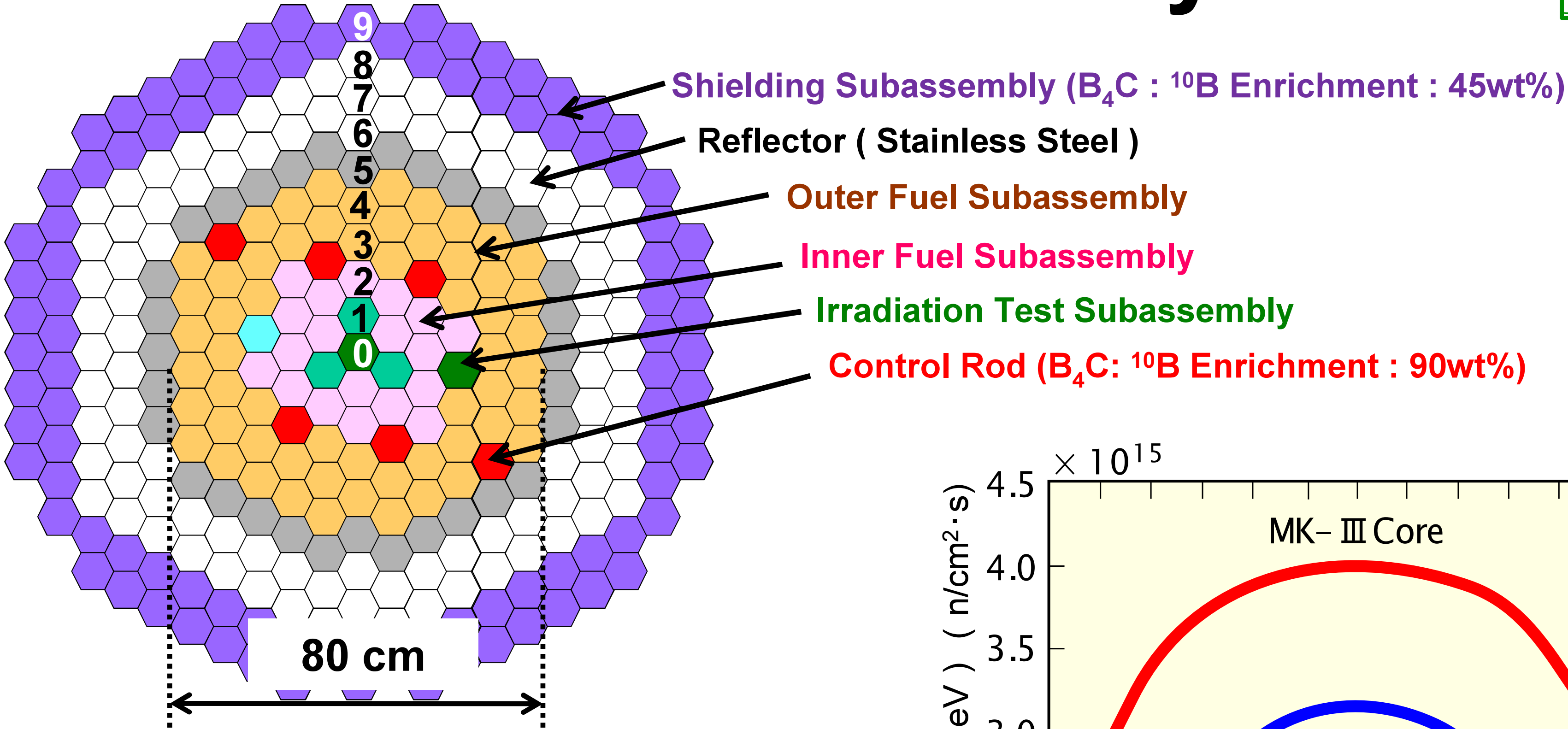
Mission

(1) To Accumulate Technical Experience of FR through planning, construction and operation

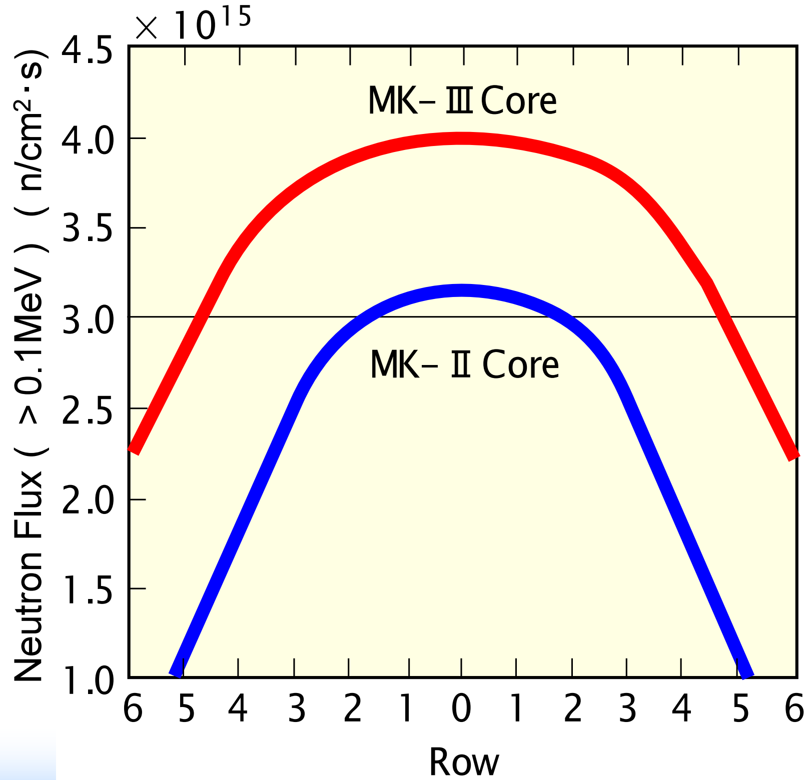
(2) Irradiation facility for FR Fuels and Materials



Introduction of Joyo



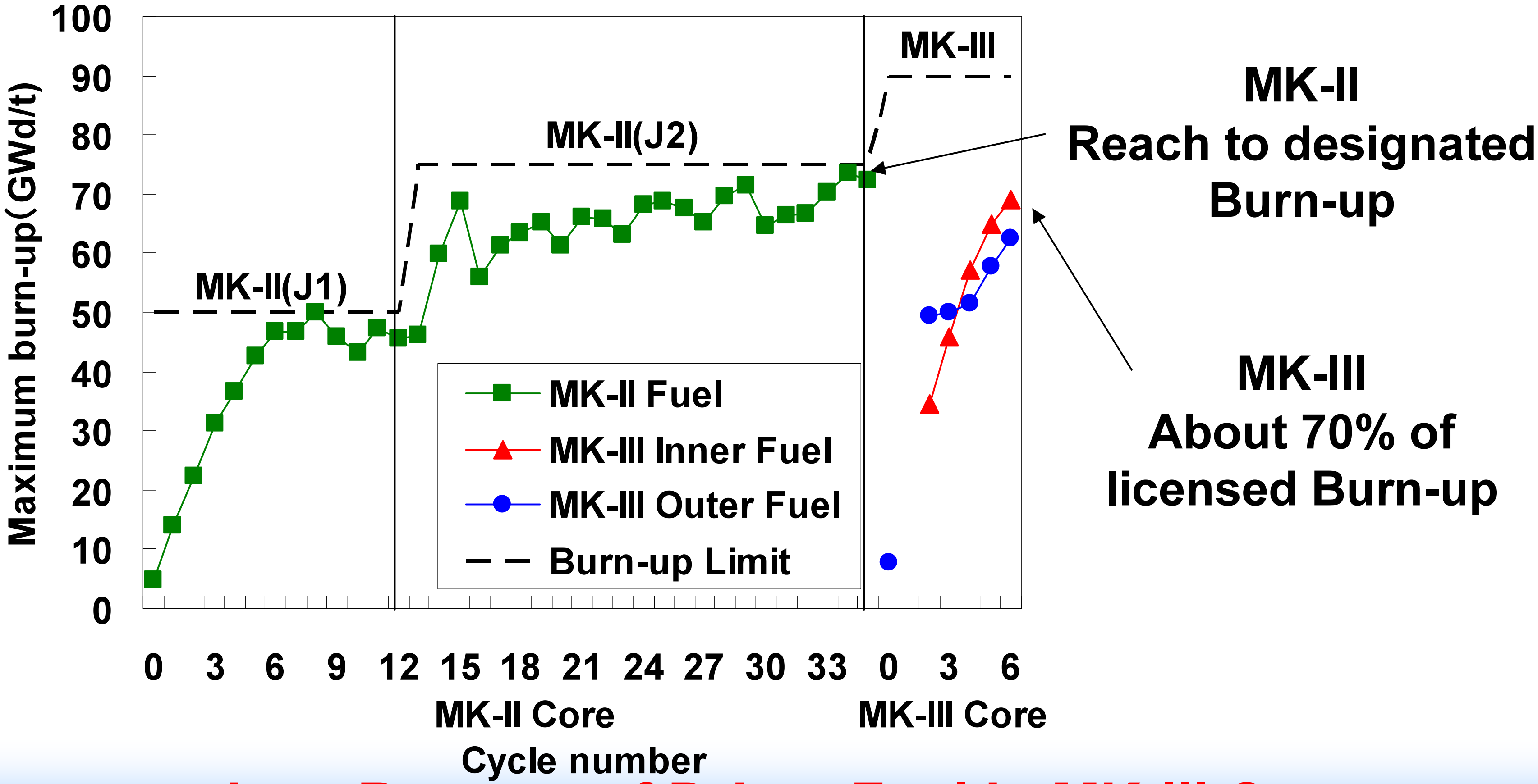
	MK-II Core	MK-III Core
Max. No. of Driver Fuel S/A	67	85
Max. No. of Test Fuel S/A	9	21
Core Diameter (cm)	73	80
Core Height (cm)	55	50
^{235}U Enrichment (wt%)	12(J1)/18(J2)	~18
Pu Content Total (wt%)	<30	<30
Fissile (Inner/Outer)	~20	~16/21
Max. Linear Heat Rate (W/cm)	400	420
Reactor Thermal Power (MWt)	100	140



Problem

The number of Irradiation test rig with little nuclear fuel Increases in MK-III.

Need to remove driver fuel at low burn-up in order to compensate excess reactivity decrease.

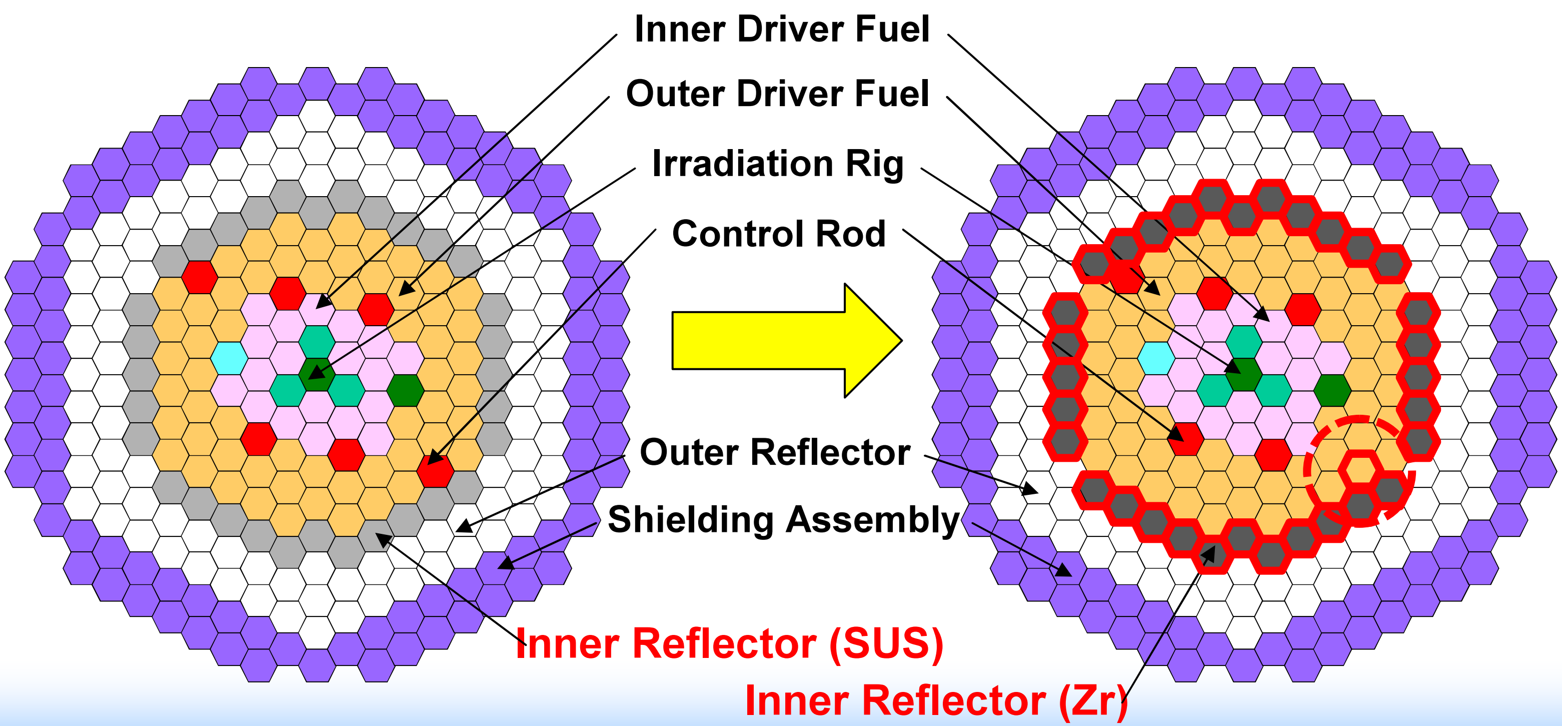


Low Burn-up of Driver Fuel in MK-III Core

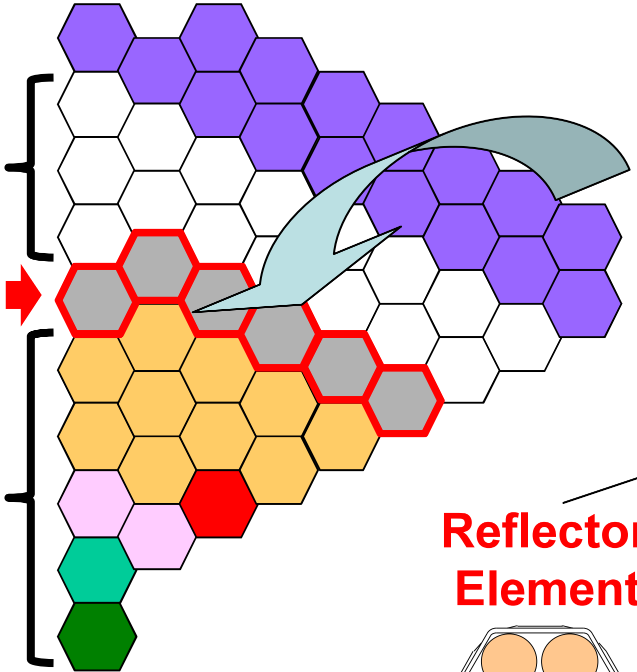
How to Increase the Core Burn-up

Core Modification to compensate the core reactivity decrease

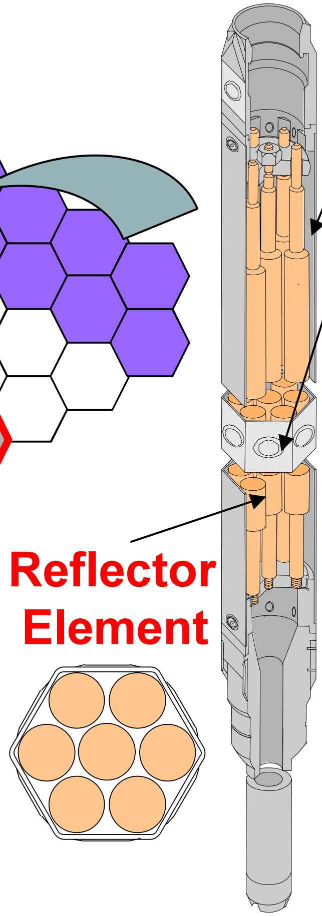
1. **Installation of zirconium reflectors around the driver fuel region to improve the neutron efficiency**
2. **Replacing one control rod with fuel to increase the fuel inventory**



Installation of zirconium reflectors



Joyo MK-III core



Specification of inner reflector

Subassembly length	2970mm
Reflector element length	650mm
Reflector material	Modified 316SS, PNC1540, Zirconium alloy
Number of elements	7
Volume ratio of the reflector material	70%

$\overline{\Sigma}_{absorption}$: Ni(0.030) > Fe(0.010) > Zr(0.008)

$\overline{\Sigma}_{scattering}$: Ni(6.6) > Fe(3.5) > Zr(2.8)

Mass num. : Zr(91.2) > Ni(58.7) ≒ Fe(55.8)

N.D. : Ni(1.0) ≒ Fe(0.94) > Zr(0.47) a.u.

Zirconium's nuclear characteristics provide a reflection of neutrons with less absorption than austenitic stainless steel or high nickel alloys

Calculation Code

JUPITER standard fast reactor analysis method

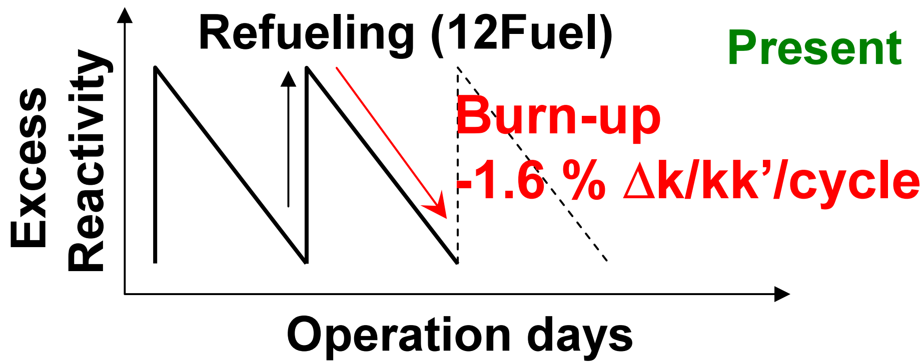
Code :	CITATION-FBR (Diffusion theory, 3D Tri-Z geometry) TRITAC (Transport theory, 3D XYZ geometry) PERKY (Perturbation theory)
Xsec set:	JFS-3-J3.2R based on JENDL-3.2
Energy Gr. :	70Gr. or 7Gr.

Applying a C/E correction method

Effect of Zr reflector

- **Excess Reactivity Change (SS -> Zr)**

+0.41 %Δk/kk'



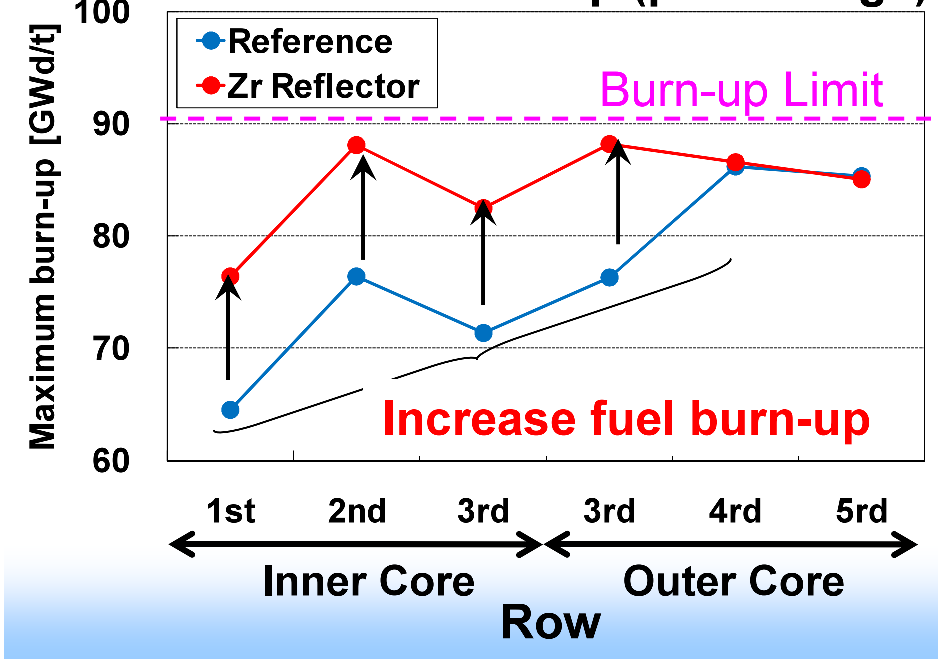
Making use of a driver fuel longer

Changing of refueling batch number

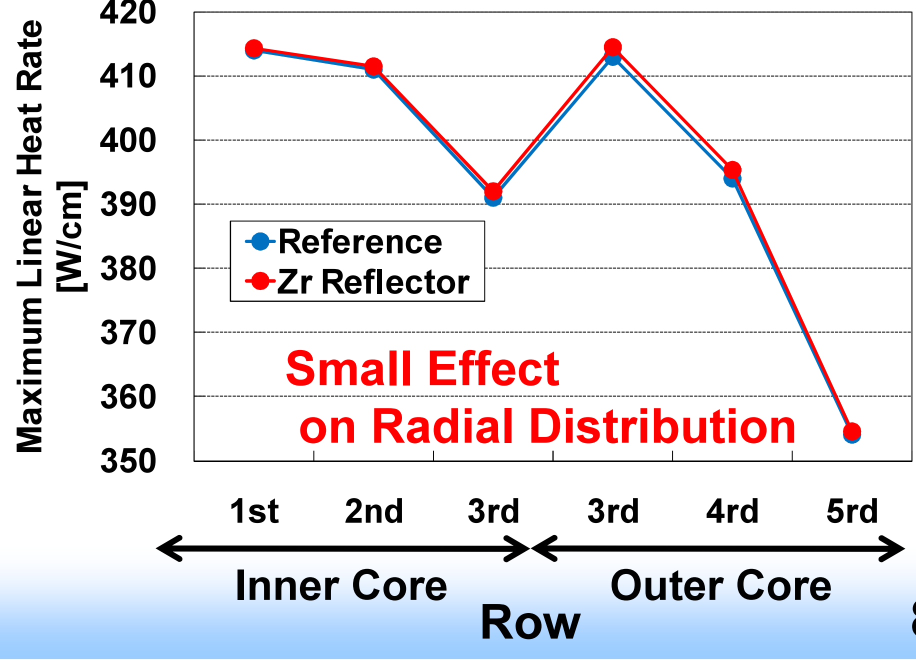
- To maximize the fuel burn-up within the licensed burn-up limitation (90 GWd/t)

Item	SS Reflector	Zr Reflector
Number of Refueling (S/As)	12	10
Maximum Fast Neutron Flux (E>0.1 MeV)(×10^{15} n/cm^2·s)	4.0	4.0

Maximum burn-up (pin average)



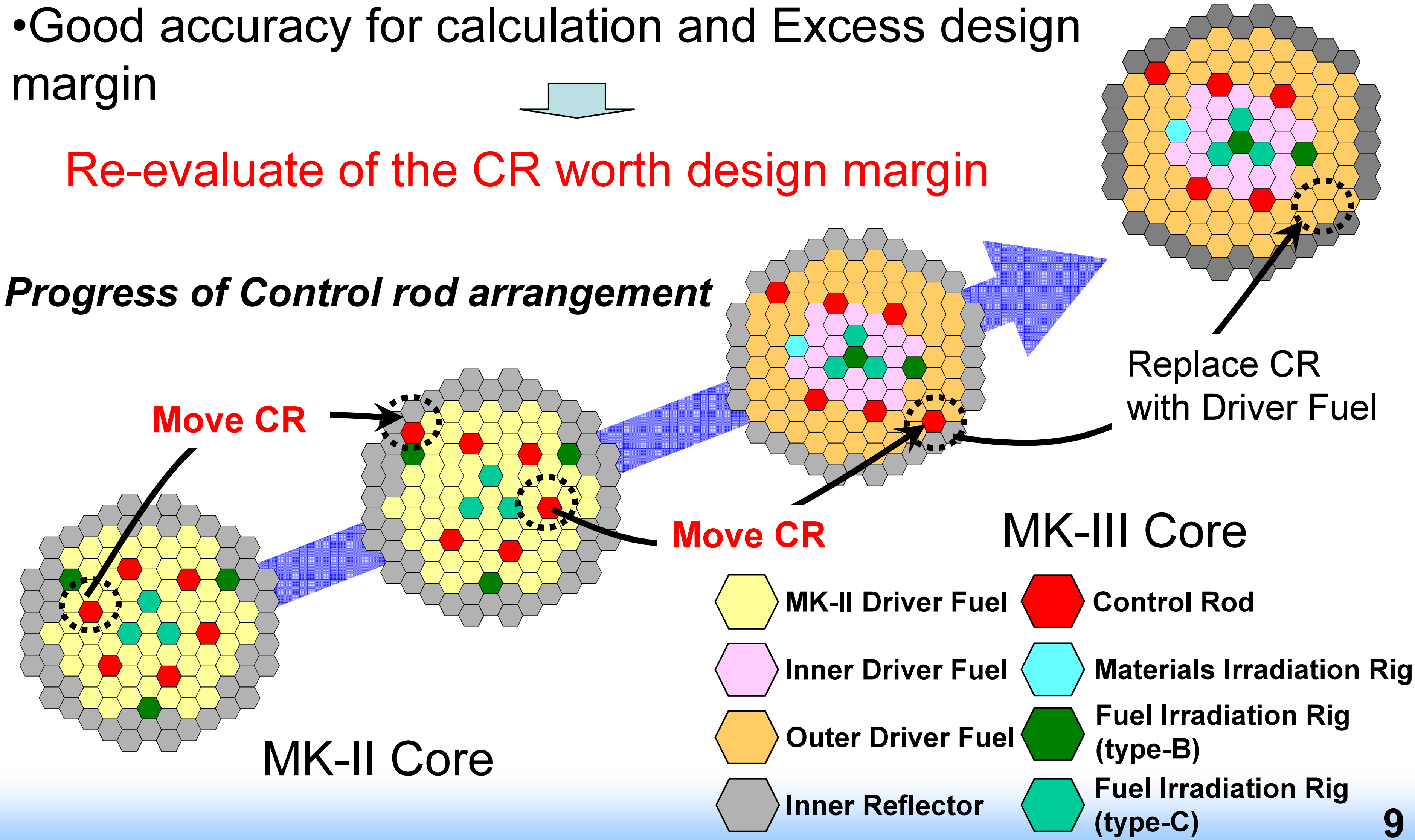
Maximum liner heat rate



Changing the control rod arrangement

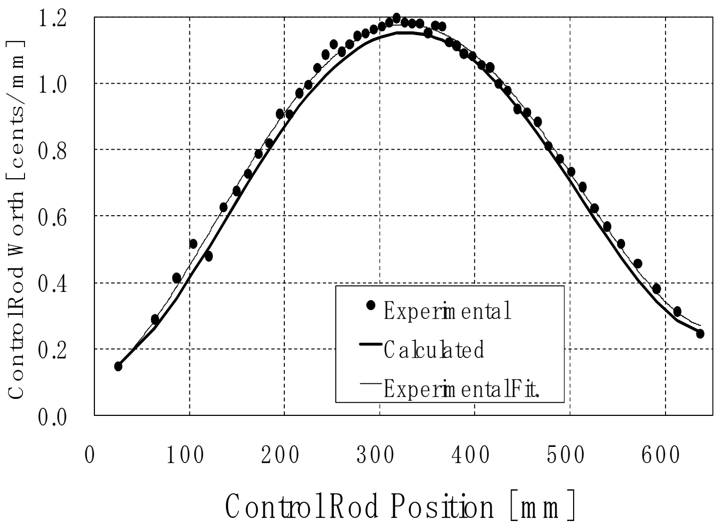
- Two experiences of changing the CR arrangement
- Good accuracy for calculation and Excess design margin

Re-evaluate of the CR worth design margin



Reduction of CR Design Margin based on the MK-III performance test

Differential rod worth profile



Measurement Error 3.2%

C/E value of control rod worth

No.	Loc.	Control Rod Worth [%Δk/kk']		C/E	Deviation of C/E (1σ)
		Exp.(E)	Biased calc. (C)		
1	3rd	2.09±0.07	2.01	0.96	< ±1%
3	3rd	2.03±0.07	1.97	0.97	
4	3rd	2.08±0.07	2.01	0.97	
6	3rd	2.06±0.07	1.97	0.96	
2	5th	0.80±0.03	0.79	0.99	< ±1%
5	5th	0.78±0.03	0.79	1.01	

Reduce the calculation error in design margin

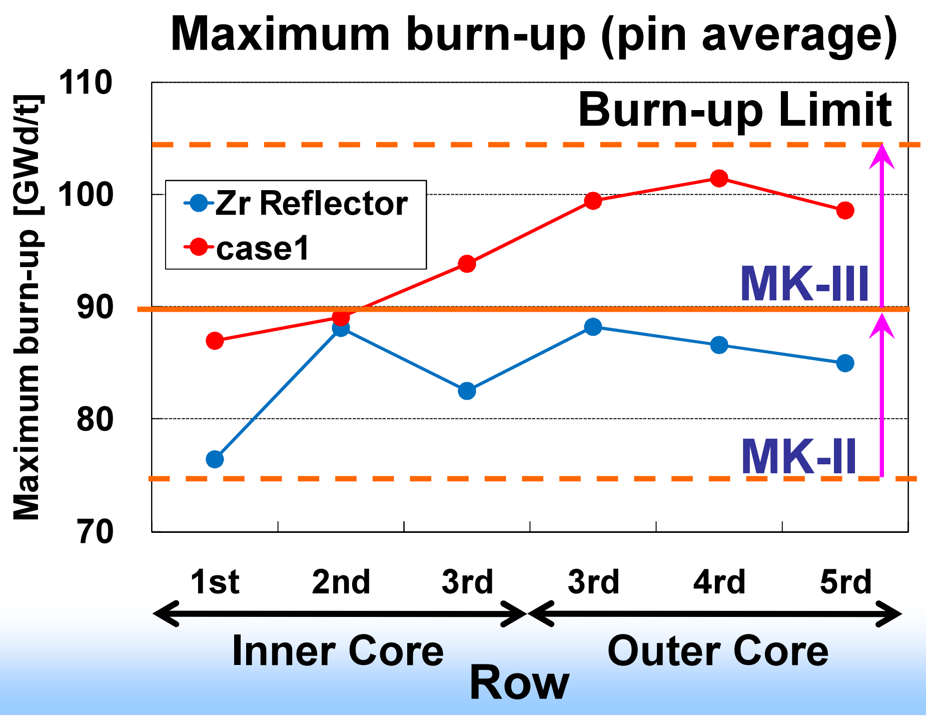
Item	Present	This study
Calculation error	± 13 %	*± 5 %*

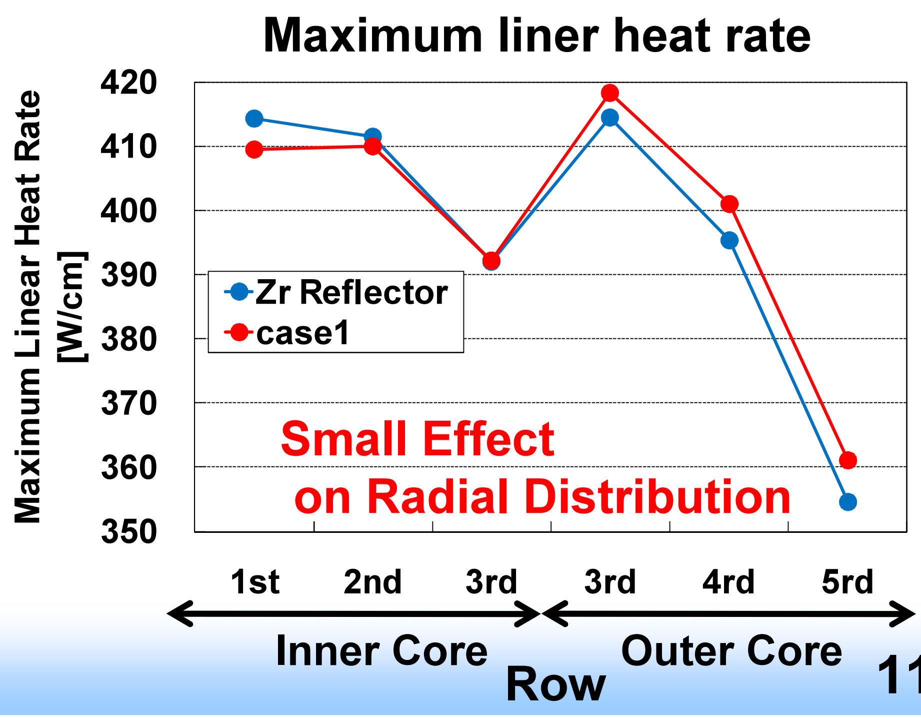
Larger deviation of C/E

Changing of refueling batch number

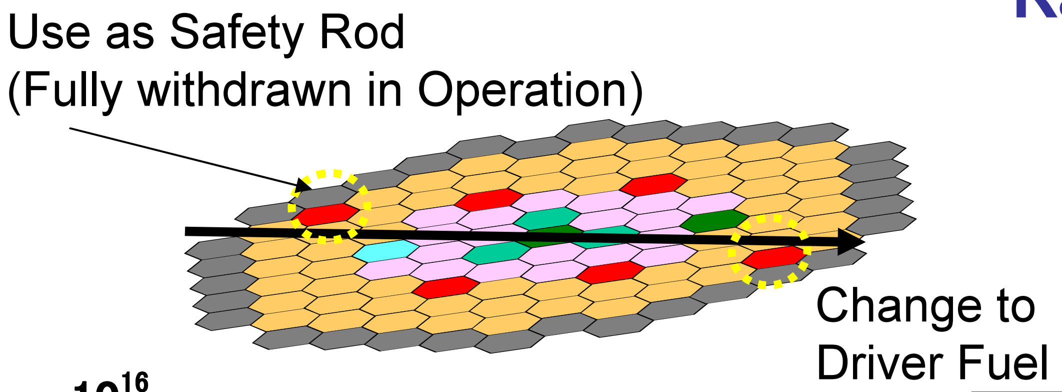
- To maximize the fuel burn-up within 105GWd/t
  (MK-II : 75GWd/t -> MK-III : 90GWd/t)

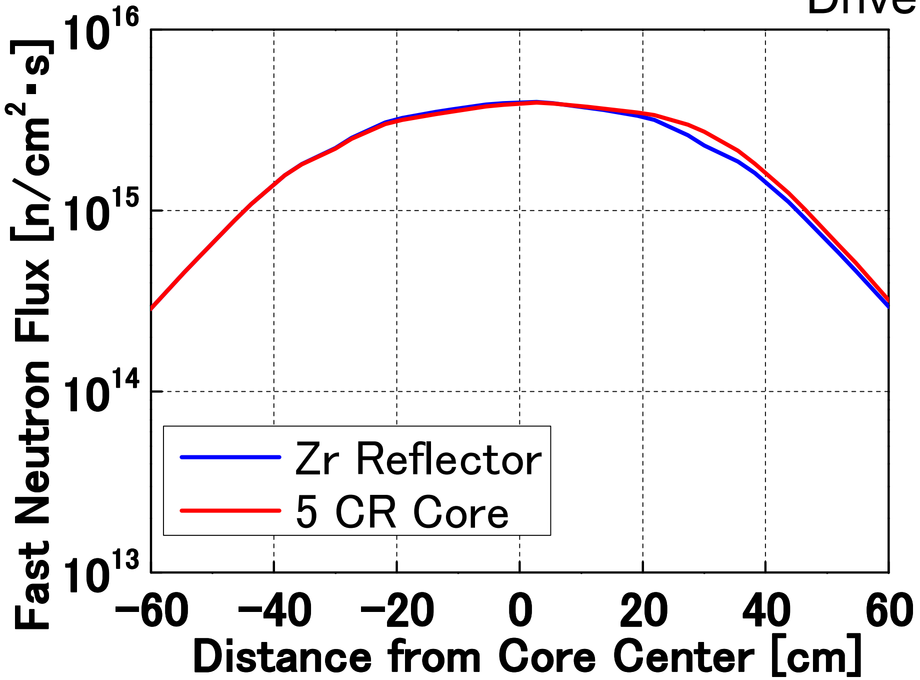
CR arrangement	3rd Row : 4 5th Row : 2	3rd Row : 4 5th Row : 1
Number of Refueling (S/As)	10	9
Maximum Fast Neutron Flux (E>0.1 MeV)($\times 10^{15}$ n/cm$^2 \cdot$s)	4.0	4.0





Effect on Flux distribution and CR worth





Radial Flux Distribution

Small Increase at the position where CR replaced with driver fuel

Control Rod Worth [%Δk/kk']

CR	Zr Ref. Core	5 CR Core	Criteria
3rd	2.16	2.15	---
5th	0.80	0.73	---
Total	10.2	9.3	> 7.6

Decrease of CR Worth is less than 10%

One Rod Stuck Margin [%Δk/kk']

Zr Ref. Core	5 CR Core	Criteria
1.97	1.17	> 1.1

No Significant effect on core characteristics

Summary

- Core modification was investigated to increase core and fuel burn-up of Joyo
  - *Installation of zirconium reflectors*
  - *Changing the control rod arrangement*

➢ Increase core and fuel burn-up up to 18%

➢ Reduce number of refueling up to 15%

⇩

More irradiation experiments

Thank you for your attention!

Supplement

Background

Irradiation test of which irradiation behavior is not well understood

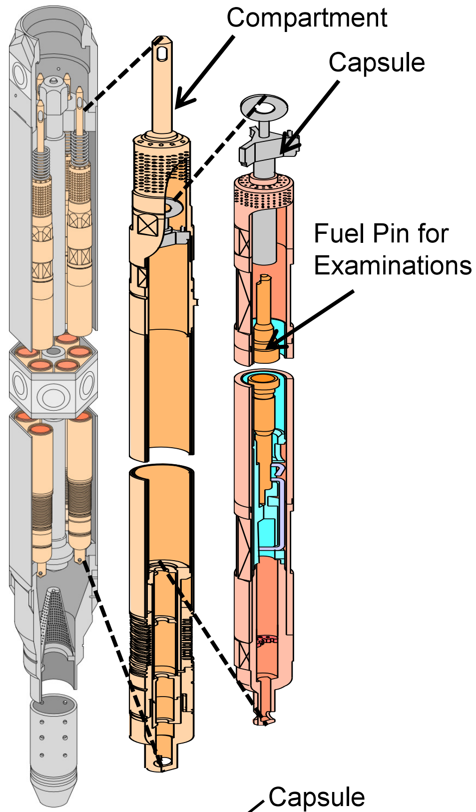
（MA bearing fuel, ODS cladding fuel, Metal fuel）

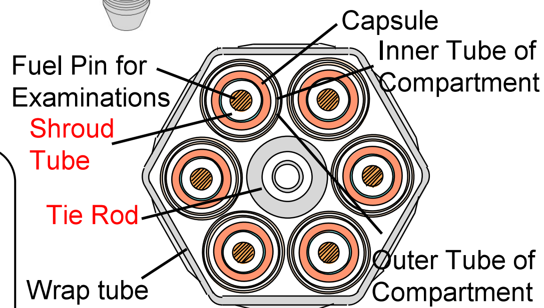
One fuel pin is loaded in the high strength capsule that endures the pressure when the fuel is damaged. (Capsule type irradiation rig)

- The number of Irradiation test rig with little nuclear fuel increases.
- We remove driver fuel at low burn-up in order to compensate excess reactivity decrease.

•Need more fresh fuel (Fuel cost increases)

•Increase spent fuel (Lack of storage space)





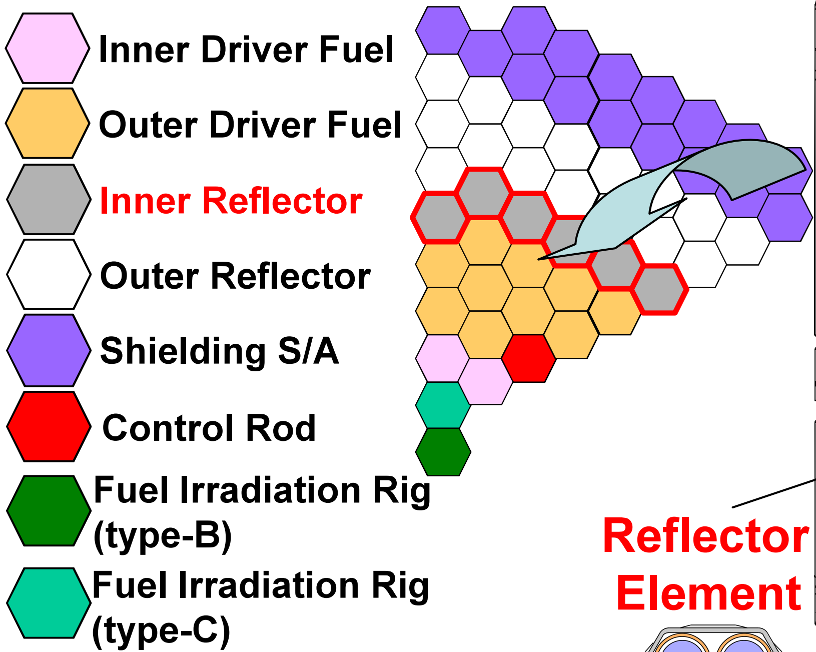
Cross Section

Capsule Type Irradiation Rig

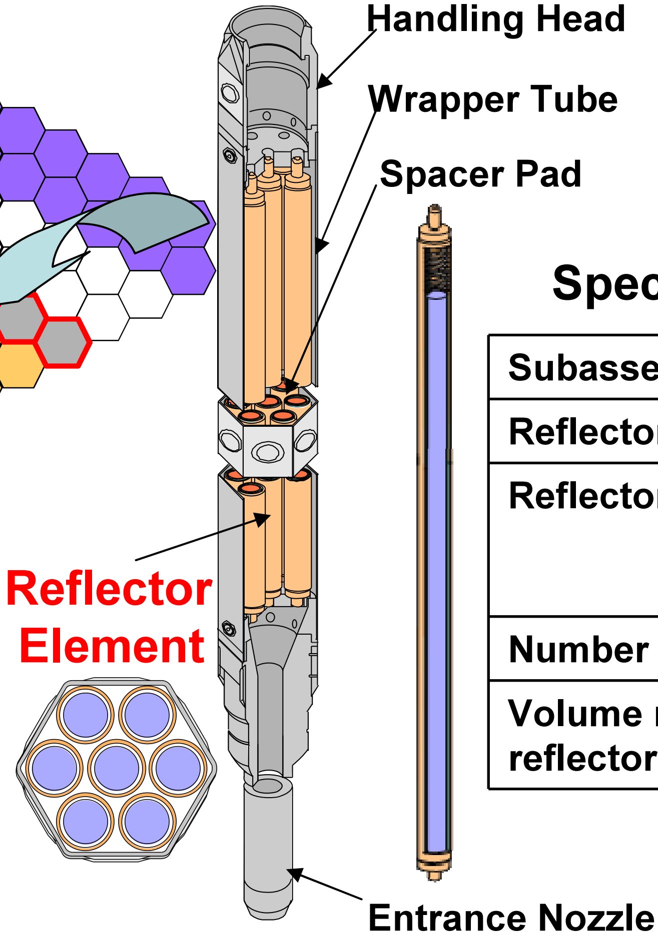
Contents

- Introduction
- Core Modification Plan
  - *Installation of zirconium radial reflectors*
  - *Changing the control rod arrangement*
- Summary

Installation of zirconium reflectors



Joyo MK-III equilibrium 1/6th core



Specification of radial reflector

Subassembly length	2970mm
Reflector element length	650mm
Reflector material	Modified 316SS, PNC1540, Zirconium alloy
Number of elements	7
Volume ratio of the reflector material	70%

$\Sigma_{absorption}$: Ni(0.030) > Fe(0.010) > Zr(0.008) a. u.

$\Sigma_{scattering}$: Ni(6.6) > Fe(3.5) > Zr(2.8) a. u.

Mass num. : Zr(91.2) > Ni(58.7) ≒ Fe(55.8)

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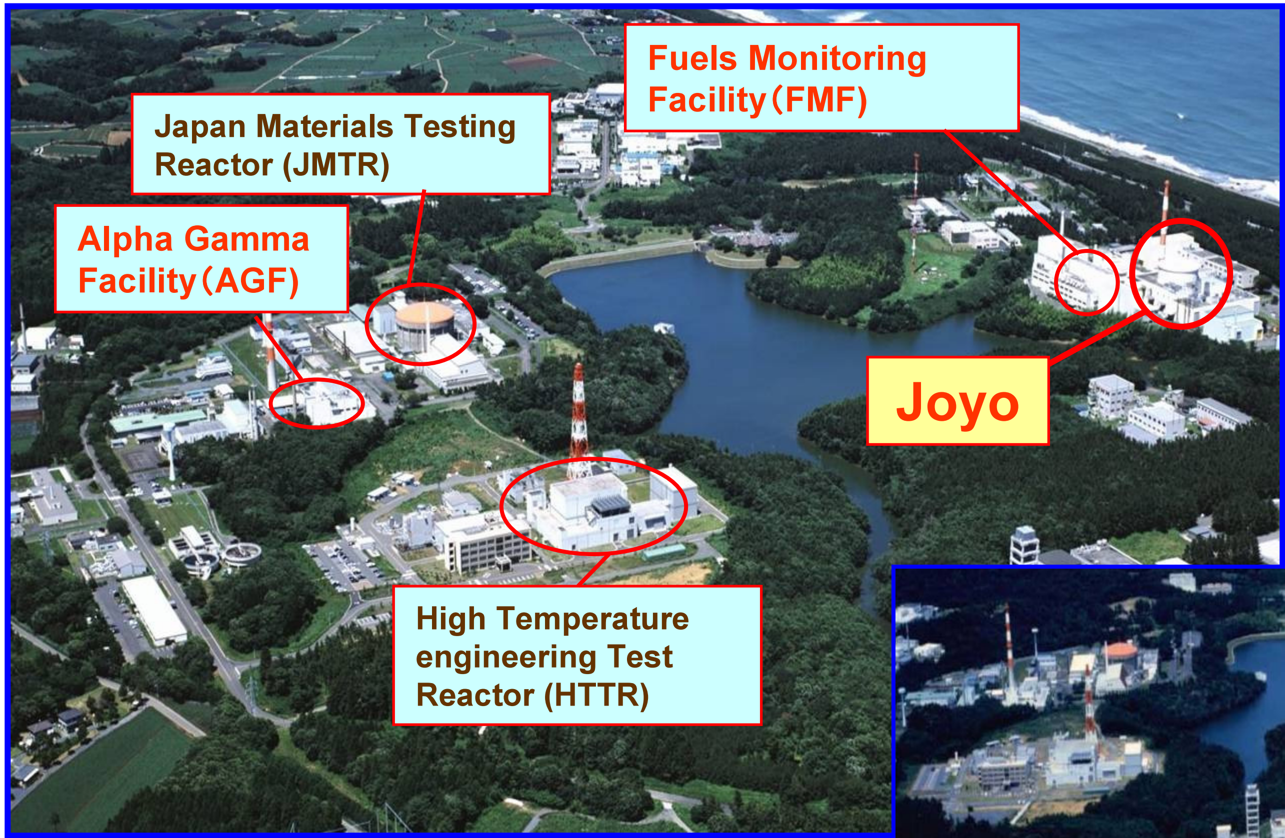
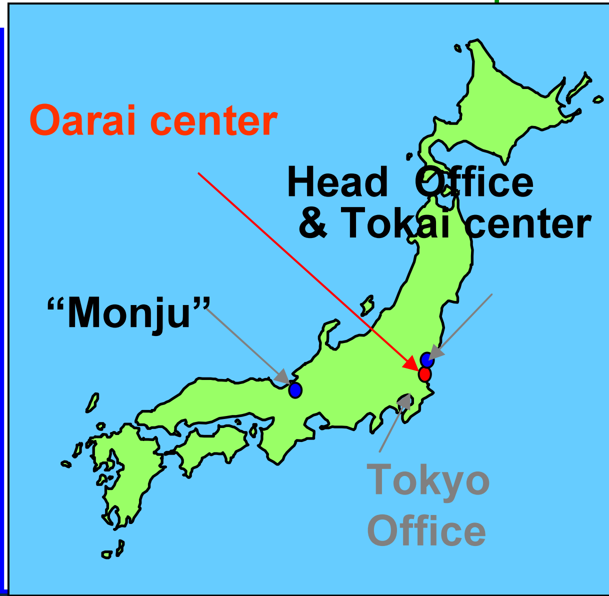
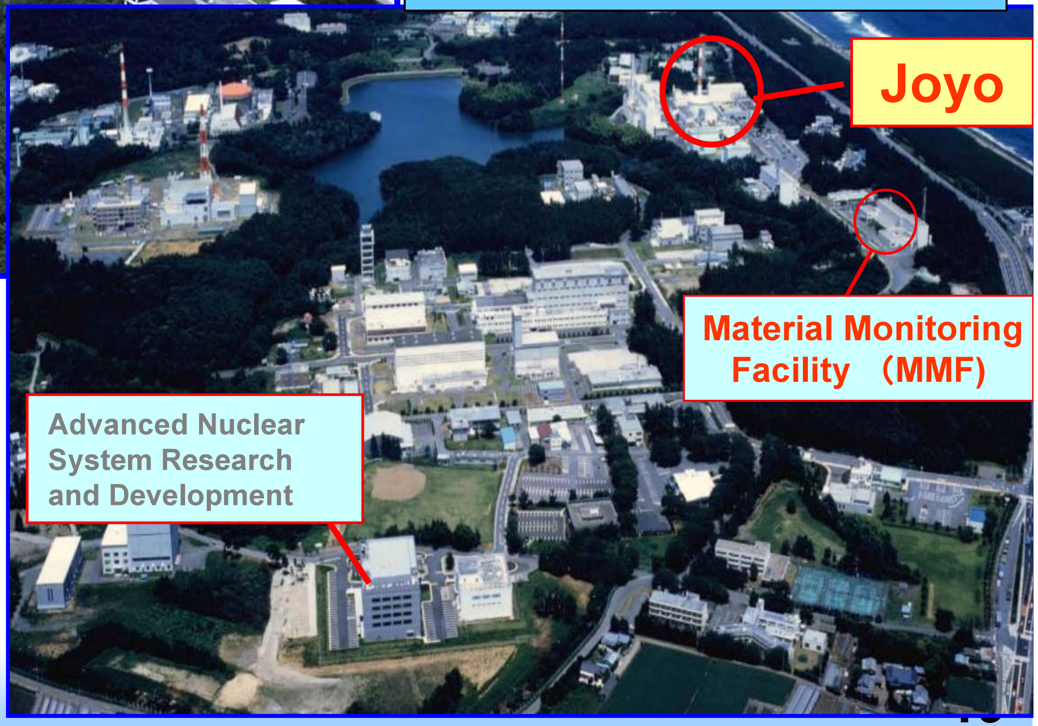
Oarai research and development center







Milestone of Joyo

MK-III

2004.5~ Rated power operation
2003.7 First Criticality of MK-III Core

MK-III Renovation

MK-II Core

2000.6
- Carbide and Nitride Fuel Irradiation（Cooperate with JAERI）
- Power-to-Melt Test（PTM）
- Fuel Failure Detection Test
- High Burnup Test（peak burnup of 144 GWd/t, Collaboration with CEA France)
- Served mainly as an Irradiation Facility for FBR Fuel and Material

1982.7 First Criticality of MK-II Core

MK-I Core

1981
- Natural Circulation Test
- Confirm Breeding Ratio
- Accumulate Technical Experience Through Planning, Construction and Operation

1977.4 Attain First Criticality

Objectives and Core Modification of MK-III

Objectives of MK-III Upgrade

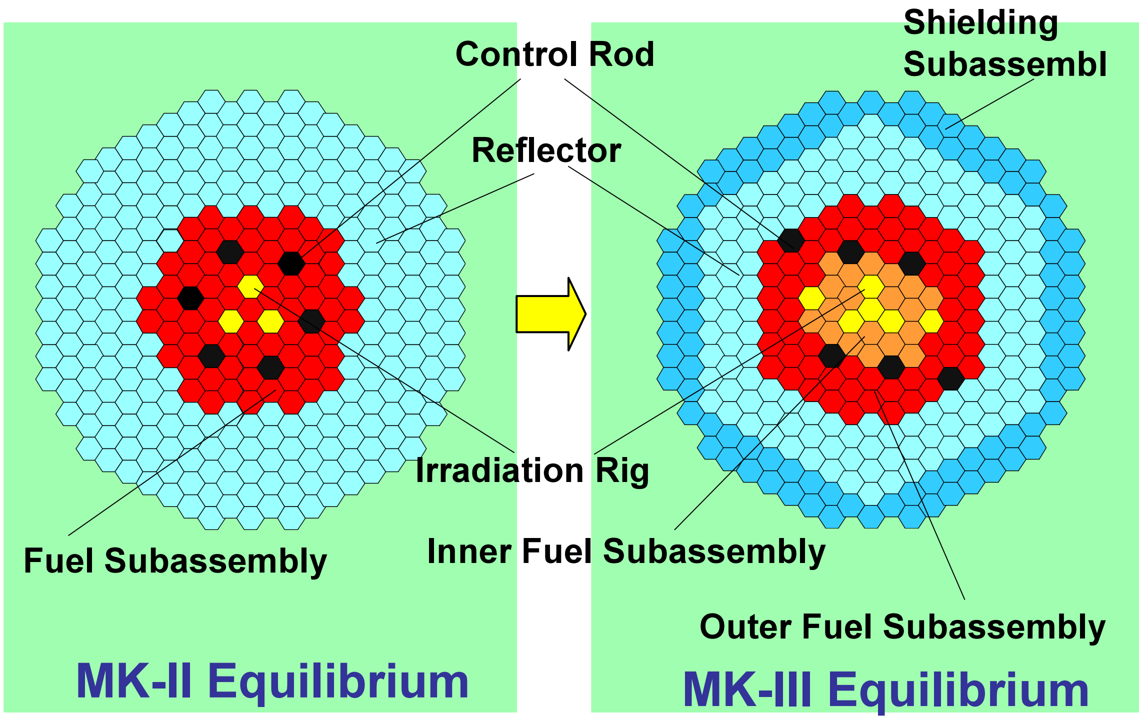
Core modification for high neutron flux

Improvement of plant availability factor

Expansion of irradiation space

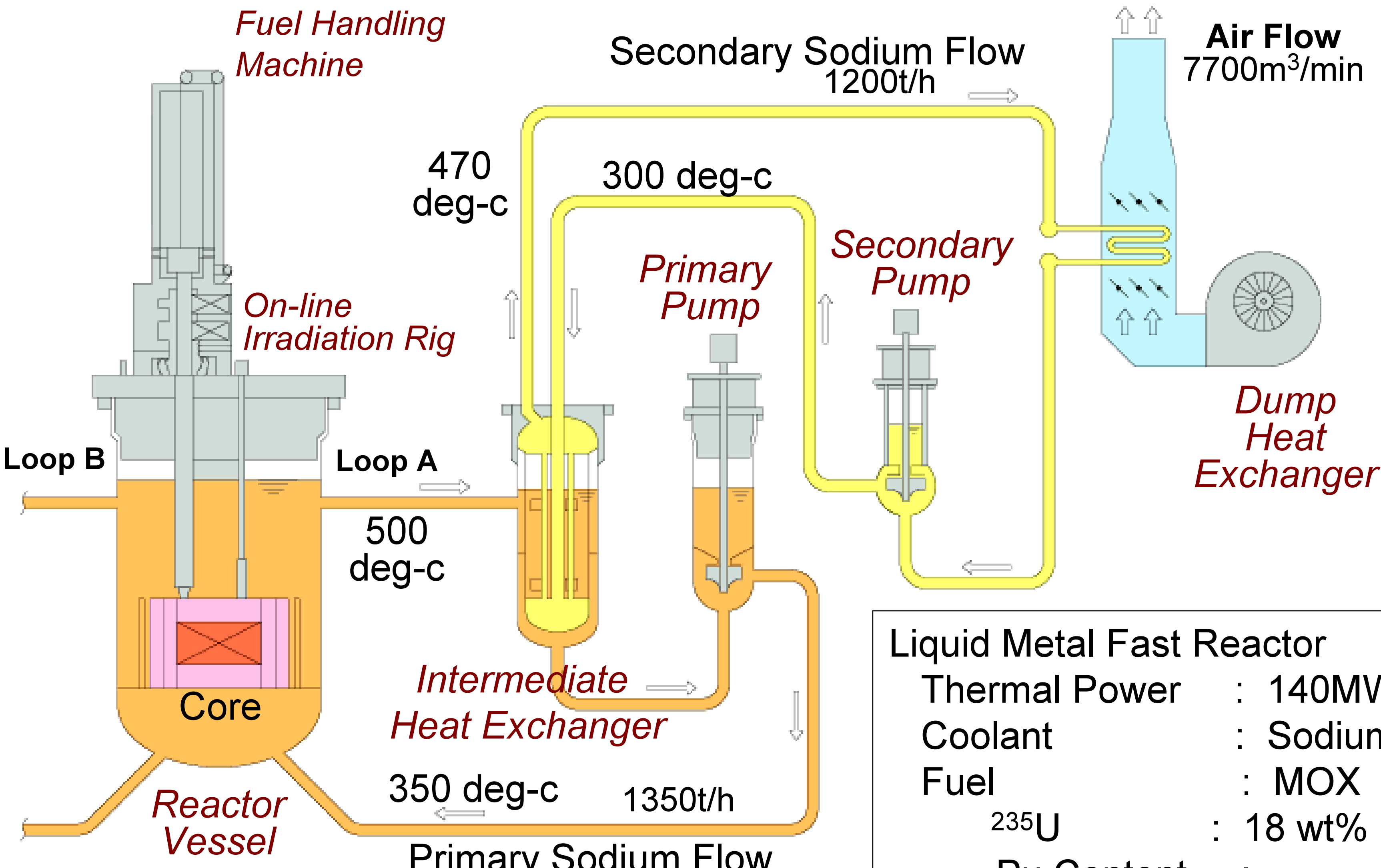
Irradiation capability enhanced 4 times

Upgrade of irradiation techniques



	MK-II		MK-III
▪ Number of Fuel Subassemblies (Max.)	67	→	85
▪ Core Height	55 cm	→	50 cm
▪ Arrangement of Control Rods	6 Control Rods in 3rd Row	→	4 Control Rods in 3rd Row 2 Control Rods in 5th Row
▪ Stainless Reflectors in 9th and 10th Row		→	Shielding S/A (B4C)
▪ Number of Irradiation Rigs (Max.)	9	→	21
▪ Fast Neutron Flux (E>0.1 MeV)	3.2×10^{15} n/cm^2/s	→	4.0×10^{15} n/cm^2/s
▪ Reactor Thermal Power	100 MW	→	140 MW

Heat transfer system

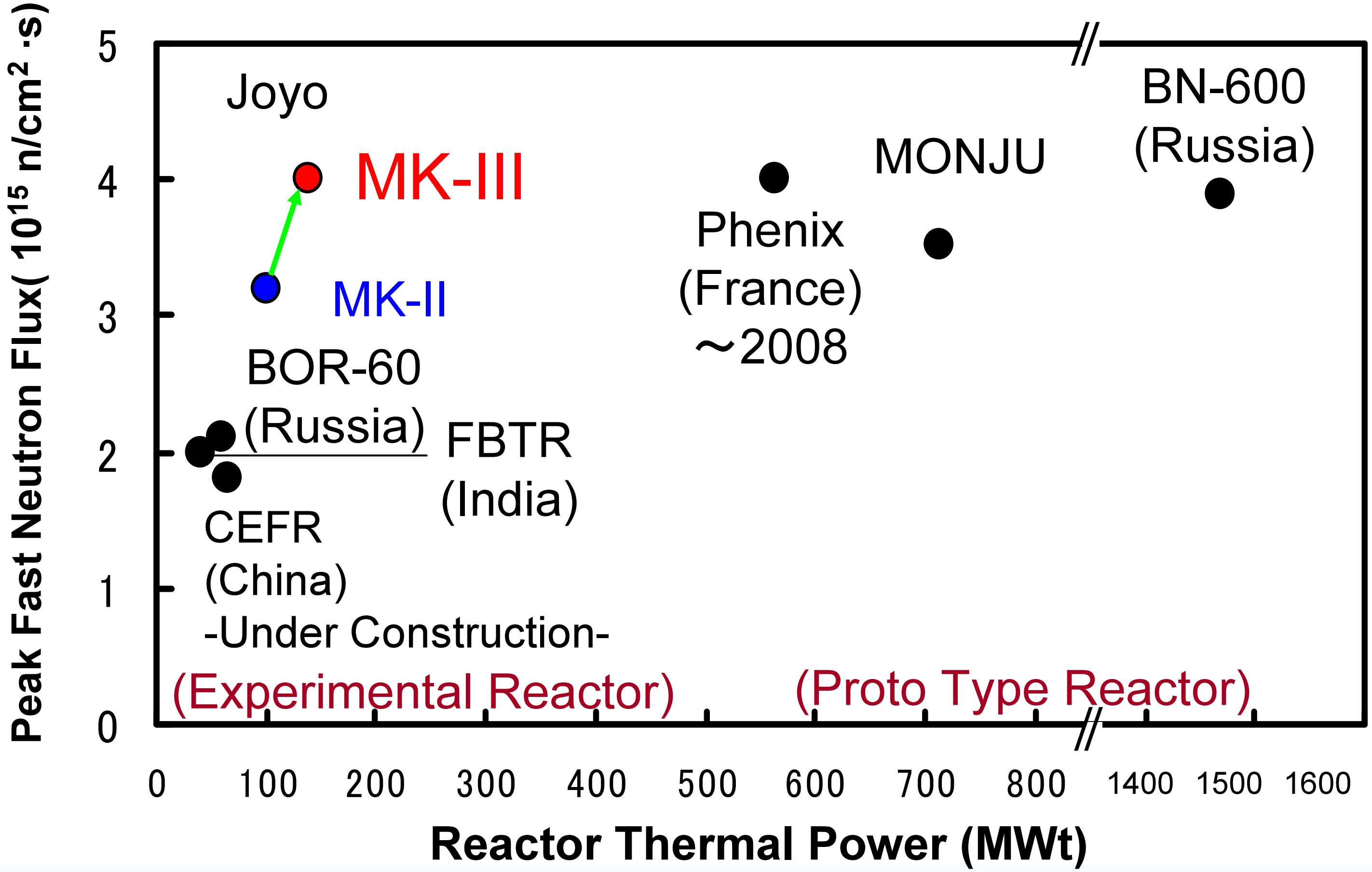


Liquid Metal Fast Reactor

Thermal Power	: 140MWt
Coolant	: Sodium
Fuel	: MOX
^{235}U	: 18 wt%
Pu Content	: ～ 30wt%

Joyo is a Powerful Fast Neutron Irradiation Facility

- World's highest fast neutron field allows accelerated fuel and material irradiation tests



Effect of Zirconium

Factor of increasing reactivity

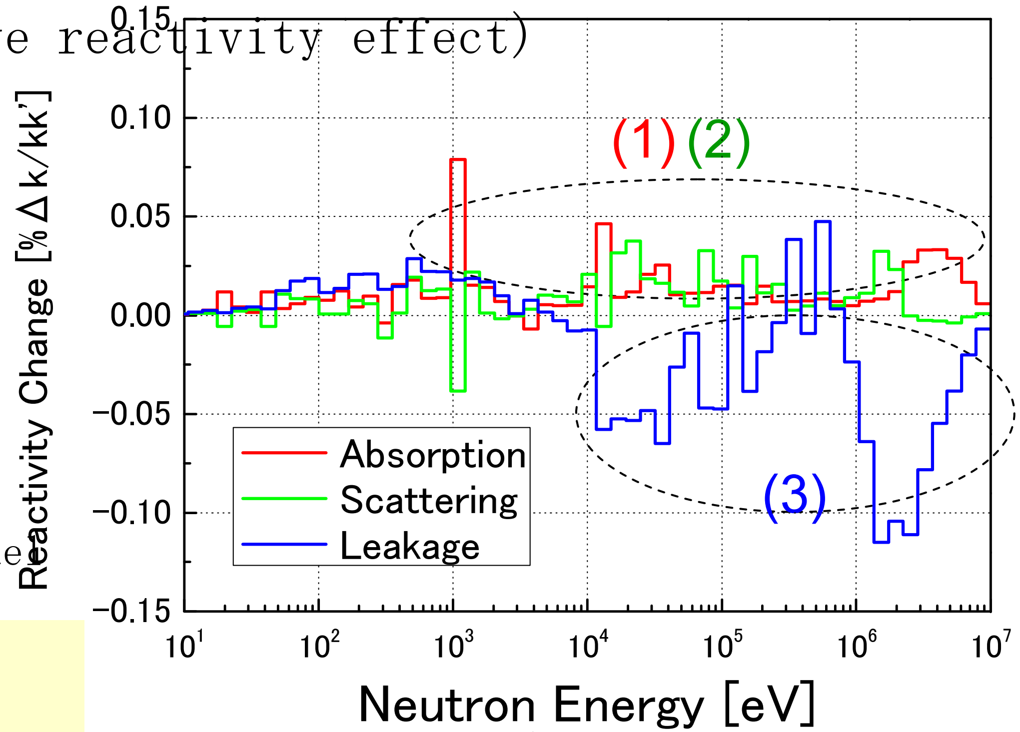
(1)Absorption　　　Zr' s neutron absorption is less than SS

(2)Scattering　　　Lower loss energy by elastic scattering than SS

(3)Leakage　Increasing neutron leakage ovew1MeV and between 10keV and 100keV(negative reactivity effect)

	Reactivity Change [%Δk/kk']
Absorption	+0.684
Scattering	+0.422
Leakage	−0.699
Total	+0.407

Corresponding to 3 fresh fue

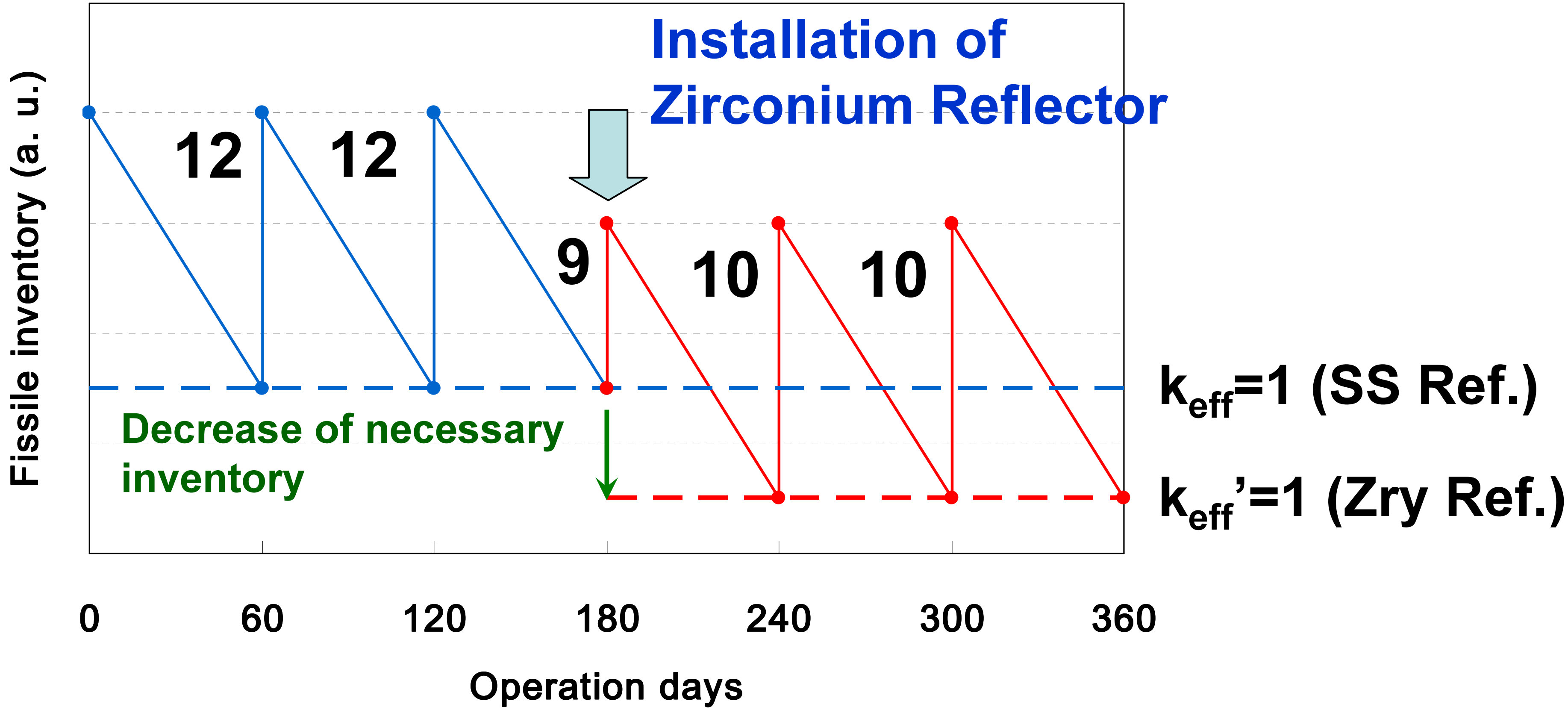


Energy and Component wise reflector replacement reactivity (Calculated using PERKY)

Experimental Result at FCA (Fast Criticality Assembly)
Reactivity Change at FCA core center (SS→Zr)
C/E=0.78

Effect of Zirconium Reflector

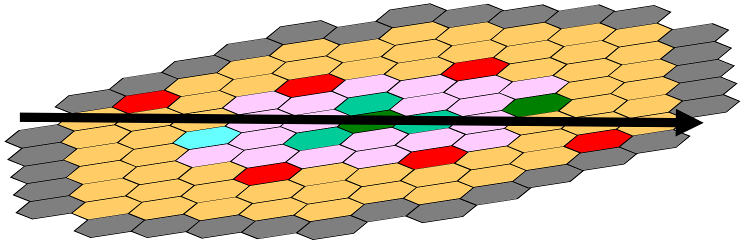
Number of refueling

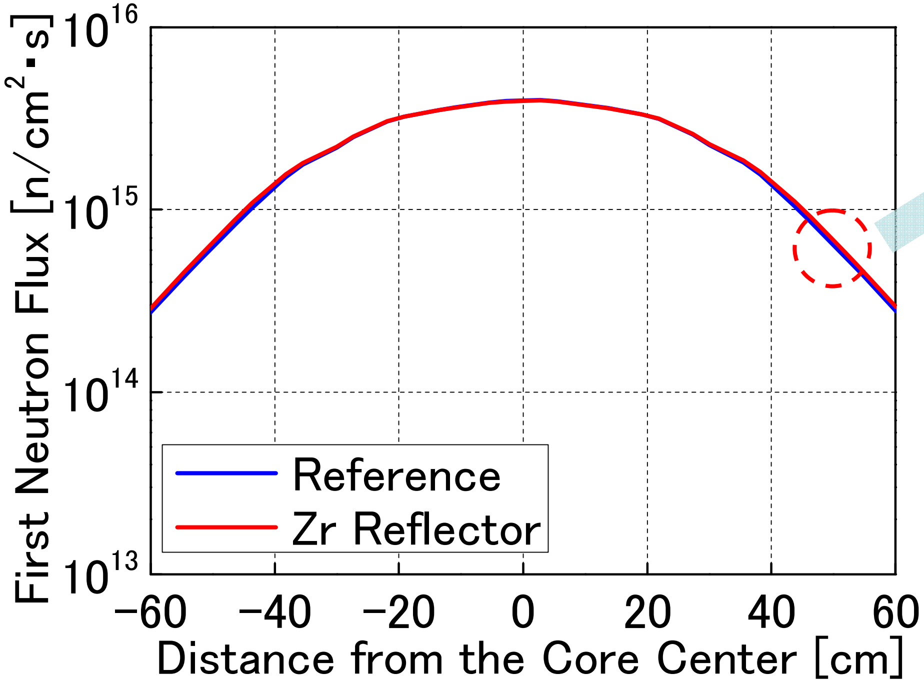


- Improve the neutron efficiency
- Decrease of necessary inventory = Long use of a driver fuel
- Increase of a burn-up of spent fuel
- Increase of reactivity change for one refueling
- Decrease of necessary number of refueling

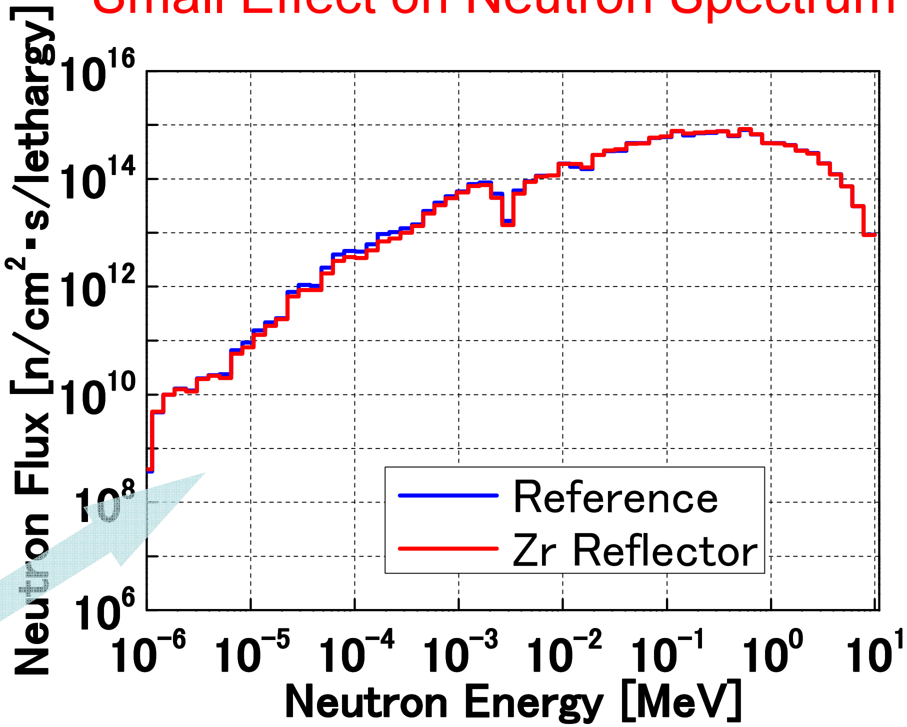
Calculation Results (Zr Ref.)

Radial Flux Distribution:
Small Increase near Reflector





Small Effect on Neutron Spectrum



Control Rod Worth [%Δk/kk']

Pos.	SUS Ref.	Zr Ref.
3rd	2.14	2.16
5th	0.78	0.80

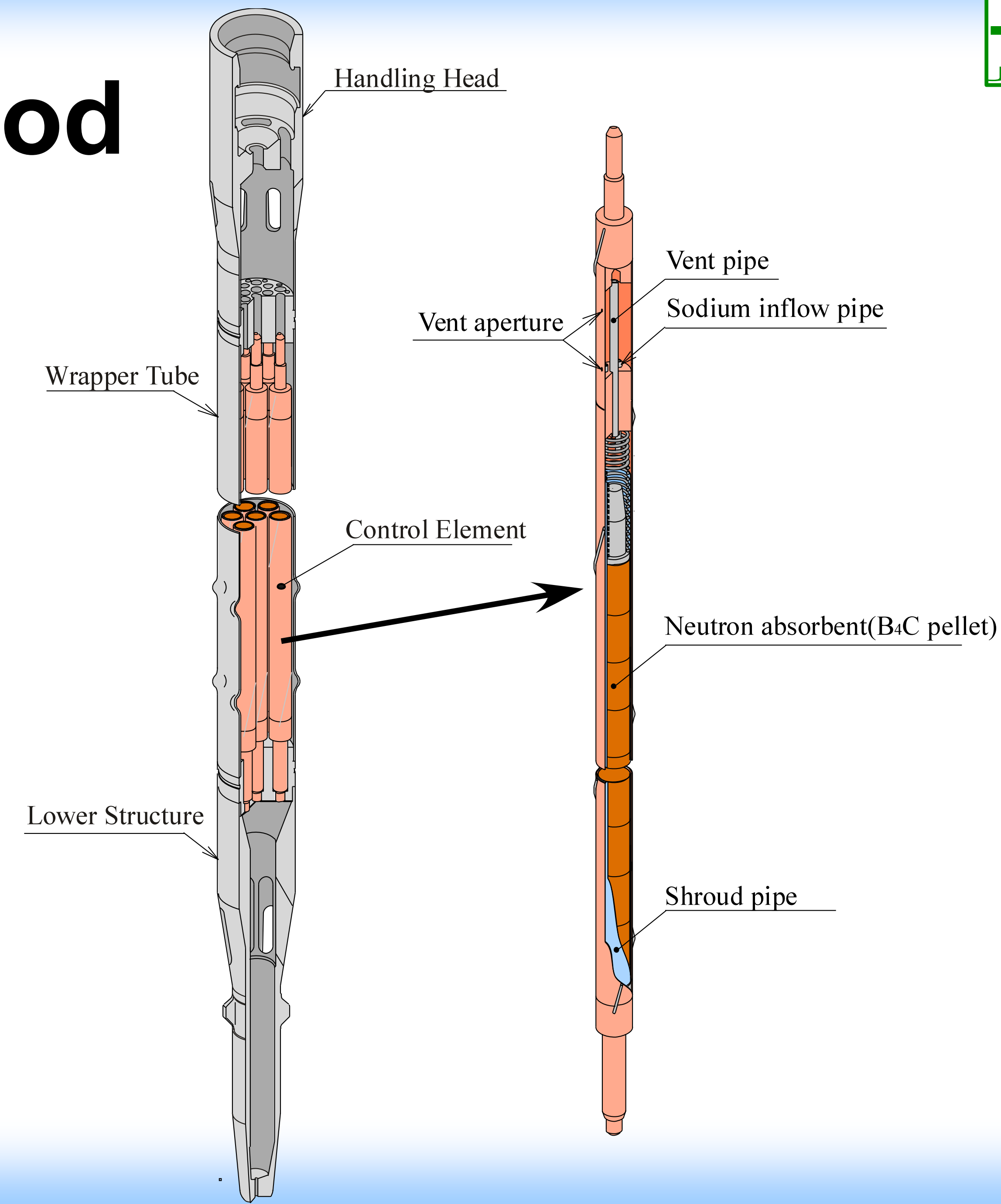
No Significant effect on core characteristics

Core physics characteristics of zirconium reflector

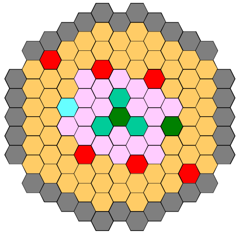
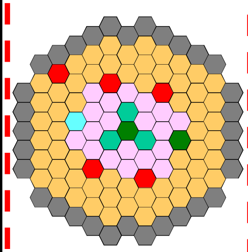
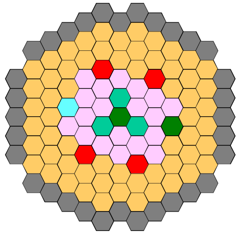
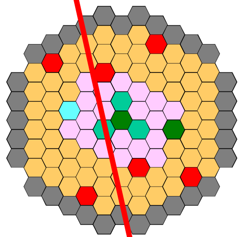
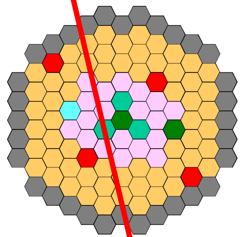
Item		Reference	Zr reflector	Criteria
Average number of fuel exchange		11.3	10.6	---
Maximum linear heat rate [W/cm]	Inner	414	414	420
	Outer	413	415	420
Power peaking factor	Total	1.64	1.62	---
	Radial	1.38	1.36	---
	Axial	1.18	1.18	---
	Local	1.01	1.01	---
Maximum neutron flux [n/cm^2・s]		4.0×10^{15}	4.0×10^{15}	---
Effect for Shielding S/A	^{10}B capture reaction rate [capture/cc・s^{-1}]	7.1×10^{13}	7.5×10^{13}	---
	Life time* [days]	2190	2080	---
Maximum pin averaged fuel burn-up [GWd/t]	Inner	76.8	88.6	90
	Outer	86.0	89.9	90
Maximum S/A averaged fuel burn-up [GWd/t]	Inner	70.0	81.1	---
	Outer	72.7	74.7	---
Control rod worth [%Δk/kk']	Average of 3rd row	2.14	2.16	---
	Average of 5th row	0.78	0.80	---
	Total	10.13	10.23	More than 7.6

* Equivalent to reach 135×10^{20} capture/cc

Control Rod


Handling Head
Wrapper Tube
Control Element
Lower Structure
Vent pipe
Vent aperture
Sodium inflow pipe
Neutron absorbent(B4C pellet)
Shroud pipe

Calculation Results (CR arrangement)

Item		Zr Ref. Core	Case 1	Case 2	Case 3	Case 4
		3rd Row: 4 5th Row: 2	3rd : 4 5th : 1	3rd : 4 5th : 0	3rd : 2 5th : 4	3rd : 2 5th : 2
						
Substitution Reactivity [%Δk/kk']		-	0.49	0.92	0.81	1.67
One Rod Stuck Margin* [%Δk/kk']	Present Design Margin	1.16	0.56	0.16	-0.55	-1.75
	Re-evaluate Design Margin 13→5%	1.90	1.22	0.75	-0.03	-

* More than 1.0

Case 1 was focused
5th Row CR was used as safety rod (fully withdrawn in operation)

Reduction of CR Design Margin based on the performance test

No.	Loc.	Control Rod Worth [%Δk/kk']				C/E	Deviation (1σ)
		Exp.(E)	Base calc.	Bias Factor	Biased calc. (C)		
1	3rd	2.09±0.07	2.07	0.97	2.01	0.96	<±1%
3	3rd	2.03±0.07	2.03	0.97	1.97	0.97	
4	3rd	2.08±0.07	2.07	0.97	2.01	0.97	
6	3rd	2.06±0.07	2.03	0.97	1.97	0.96	
2	5th	0.80±0.03	0.83	0.95	0.79	0.99	<±1%
5	5th	0.78±0.03	0.83	0.95	0.79	1.01	

Item		Error(%)
Statistic	Signal Swing of Nuclear Instruments	0.3
	Measurement Error of CR Position	
Systematic	Correction Error of Shadow Effect	1
	Error of β_{eff}	3
Total		3.2

Item			Present	Modified
orrection r base alculation	C/E		0.97	1.00
	^{10}B decrease due to burn-up		0.85	
ncertainty alculation	Core size change		±1 %	
	Asymmetrical arrangement		±2 %	
	Design margin	Fabrication tolerance of B_4C	±2 %	
		Calculation error	±13 %	±5 %
Total			±18 %	±10 %

Core physics characteristics of control rod arrangement

Item		Zr Reflector 3rd : 4 rods 5th : 2 rods	Case 1 3rd : 4 rods 5th : 1 rod	Case 2 3rd : 4 rods 5th : 0 rod	Criteria
Average number of fuel exchange		10.6	9.6	9.5	---
Maximum linear heat rate [W/cm]	Inner	414	409	402	420
	Outer	415	416	401	420
Peaking factor	Total	1.62	1.61	1.60	---
	Radial	1.36	1.36	1.36	---
	Axial	1.18	1.17	1.17	---
	Local	1.01	1.01	1.01	---
Maximum neutron flux [n/cm²・s]		4.0×10^{15}	4.0×10^{15}	3.9×10^{15}	---
Effect on Shielding S/A	^{10}B capture reaction rate [capture/cc・s^{-1}]	7.5×10^{13}	7.7×10^{13}	7.5×10^{13}	---
	Life time* [days]	2080	2040	2080	---
Control rod worth [%Δk/kk']	Average of 3rd row	2.16	2.15	2.13	---
	Average of 5th row	0.80	0.73	-	---
	Total	10.23	9.32	8.51	More than 7.6
One rod stuck margin at 100 °C [%Δk/kk']		1.97	1.22	0.75	More than 1.1

* Equivalent to reach 135×10^{20} capture/cc

R&D items to increase Joyo driver fuel burn-up

Item		Viewpoint
PIE of the MK-III driver fuel (Maximum pin averaged fuel burn-up: 86.0 GWd/t)	Visual inspection	Defect
	X-ray CT-scanning	Deformation
	Pin profilometry	Dimensional change
	Pin puncture test	FP gas release ratio
	Metallography and Elemental *analysis*	- Corrosion by sodium at outer surface of cladding tube - Fuel cladding chemical interaction (FCCI)
Re-evaluation of mechanical design method of the MK-III driver fuel based on PIE	Design criteria for strength during short term stress	(current design criteria is based on the ASME code)
	Design equation	- Sodium corrosion and FCCI - FP gas release ratio
	New design to achieve 105 GWd/t (pin averaged)	- Fuel pin and subassembly integrity - Evaluation of short term stress and CDF