Analysis of Core Physics Experiments of High Moderation Full MOX LWR

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NUPEC carried out an core physics experimental programs called MISTRAL and BASALA in order to obtain the major physics characteristics of the high moderation full MOX LWR cores from 1996 to 2002. In addition to those data, NUPEC also obtained a part of experimental results of the EPICURE program that CEA had conducted for 30 % Pu recycling in French PWRs. The analysis of those experimental data was aslo performed by NUPEC with SRAC, a deterministic code system for pin cell and core calculations, and MVP, a continuous energy Monte Carlo calculation code, based on a common nuclear data library, JENDL-3.2. A part of analysis was also done with JENDL-3.3, ENDF/B-VI and JEF-2.2 This paper summarizes the analysis results of those MOX core physics experiments referring to the published papers etc..

1. Introduction

Full MOX LWR cores are favorable since they enable a large amount of plutonium to be loaded in a small number of reactors. Higher moderation LWR cores are also favorable to enhance the consumption of plutonium and reduce the residual plutonium in burned MOX fuel. Nuclear Power Engineering Corporation (NUPEC) studied such high moderation full MOX cores[1-3] as a part of advanced LWR core concept studies from 1994 to 2003 supported by the Ministry of Economy, Trade and Industry. In order to obtain the major physics characteristics of this advanced MOX cores, high moderation full MOX LWR cores, NUPEC carried out the core physics experimental programs called MISTRAL[4-7] and BASALA[8,9] in collaboration with CEA in the EOLE critical facility of the Cadarache Center from 1996 to 2002. NUPEC also obtained a part of experimental data of the EPICURE program[10] that CEA had conducted for 30 % Pu recycling in French PWRs under the collaboration with French industrial partners. Those experimental data was transferred to Japan Nuclear Energy Safety Organization (JNES) by March 2005 for further effective utilization.

The analysis of the experimental data was performed by NUPEC from 1996 to 2003 with SRAC[11], a deterministic code system for pin cell and core calculations, and MVP[12], a continuous energy Monte Carlo calculation code, based on a common nuclear data library, JENDL-3.2.[13] A part of analysis was also done with JENDL-3.3,[14] ENDF/B-VI and JEF-2.2.

This paper summarizes the analysis results of those MOX core physics experiments that have been published in a large number of papers[4-9] and others.[15]

2. Outline of Core Physics Experimental Programs

An outline of core configurations and measurement items of EPICURE, MISTRAL and BASALA programs is shown in Table 1 and Fig. 1. The UO2 and MOX fuel rods used for the experiments other than 11 wt% MOX fuel rods have the same geometry of the standard PWR 17x17 assembly with Zry-4 claddings of an outer diameter of 9.5 mm except for the fuel effective length, about 800 mm. Those rods are sealed by Aluminum over-claddings for adjusting the core moderation ratio and protecting the rods in handling. The MOX pellets except for the 11% MOX fuel are composed of typical reactor grade plutonium with a fissile plutonium content of 60 to 70% and ^{240}Pu content larger than 20% in a depleted UO2 matrix. The total Plutonium contents of the MOX pellets are 3.0, 4.3, 7.0 and 8.7wt%.

3. Analysis Results and Discussion

Table 2 shows a summary of major analysis results obtained with SRAC-CITATION (Diffusion) and/or -TWORAN (Sn Transport) based on JENDL-3.2. Fig. 2 shows the values of critical keff of MVP with different nuclear data libraries in the order of MOX fraction in the core.

3.1 Criticality

UO2 vs MOX cores: As shown in Table 2 and Fig. 2, it is seen that the values of keff of JENDL-3.3 increase with the fraction of MOX in the core. This trend is also seen for the other libraries. The critical keff in full MOX cores seems to increase with the date of critical measurements that cause a Pu composition change by decaying of ^{241}Pu and piling of ^{241}Am in MOX fuel rods. Fig. 3 shows a correlation between the critical keff and absorption fraction of ^{241}Am in MVP analysis.

Moderation ratio: This effect is less than 0.1 %dk from comparison between MISTRAL Core 2 (H/HM=5.1) and 3 (H/HM=6.2), and BASALA Core1 (H/HM=5.0) and 2 (H/HM=9.0).

Homogeneous and Mockup: The effect in the PWR cores is 0.2 to 0.3 %dk in the from comparison between MISTRAL Core 3 (homogeneous) and 4 (mock up). The effect in BWR cores is less than 0.1 %dk as seen in MISTRAL Core 2 (homogeneous) and BASALA Core 1 (mock up).

3.2 Other Characteristics

The power distributions calculated by SRAC-CITATION with JENDL-3.2 agree well with the measurements almost within the measurement errors of 1 to 2 % in the same manner for the UO2 an the MOX cores, the conventional and the high moderation cores, the homogeneous and the mockup cores. The influence of the nuclear data libraries on the analysis results of the power distributions was surveyed with MVP for several cores and it turned out the influence is negligibly small.

The trend of C/E of spectrum index for MH1.2 is different from that of the MISTRAL cores, which may be caused from systematic error in the measurements in MH1.2.

Analysis of reactivity worth with SRAC-TWOTRAN generally shows better C/E than that of SRAC-CITATION for the absorbers, the burnable poisons, the control cluster, the control blade, the water hole/rod and the void burnable poison.

Table 1 Core configurations and measurements of EPICURE, MISTRAL and BASALA programs (M: measured item, blank: not measured)

Program	EPICURE				MISTRAL					BASALA	
Core	UH1.2	MH1.2	UM17x17 /7%	UM17x17 /11%	Core 1	Core 2	Core 3	Core4 Full MOX	Core4 UO2 zone	Core 1	Core 2
Core Config-ration	UO2 Homo-geneous	Partial MOX Homo-geneous	Partial MOX 17x17 Mockup	Partial MOX 17x17 Mockup	UO2 Homo-geneous	Full MOX Homo-geneous	Full MOX Homo-geneous	Full MOX 17x17 Mockup	UO2 17x17 Mockup in MOX	Full MOX BWR Mockup	Full MOX BWR Mockup
-Vm/Vf*[1]	1.3	1.3	1.3	1.3*[3]	1.8	1.8	2.1	2.0	2.0	1.7	3.1
-H/HM*[2]	3.7	3.7	3.7	3.7*[3]	5.1	5.1	6.2	5.8	5.8	5.0	9.0
-Fuel pitch cm	1.26	1.26	1.26	1.26	1.32	1.32	1.39	1.32	1.32	1.13 (in Assembly)	1.35 (in Assembly)
-Fuel rod type	UO2-3.7%	MOX-7.0% UO2-3.7%	MOX-7.0% UO2-3.7%	MOX-11% UO2-3.7%	UO2-3.7%	MOX-7.0, 8.7%	MOX-7.0%	MOX-7.0%	MOX-7.0% UO2-3.7%	MOX-3.0, 4.3,7.0,8.7%	MOX-3.0, 4.3,7.0,8.7%
-Core size*[4]	D=54cm	D=69cm	D=58cm	D=55cm	D=41cm	D=60cm	D=59cm	D=62cm	D=52cm	XY=61cm	XY=47cm
Measurement											
-Critical mass	M	M	M	M	M	M	M	M	M	M	M
-Critical boron	M	M	M	M	M	0 ppm	M	M	M	0 ppm	0 ppm
-Buckling*[5]	M	M			M	M	M				
-Spec. Index		M			M	M	M				
-Rad.&Axial, Distribution	M	M	M	M	M	M	M	M	M	M	M
-ITC*[6]					M	M	M				M
-Boron*[7]	M	M			M	M	M	M			M
-Absorber rod	M	M			M	M	M			M	M
-Control Cluster								M	M		
-Control blade											M
-Water hole					M	M				M	
-Void	M	M	M	M			M			M	
-Beta effective					M	M					

*[1]Volumetric ratio of moderator to fuel pellet, *[2]Hydrogen to heavy metal atomic ratio, *[3]Vm/Vf=1.7, H/HM=4.9 for 17x17 MOX region, *[4]"D" means effective diameter of cylindrical core and "XY" side length of square core, *[5]Radial buckling, *[6]Iso-thermal temperature coefficient, *[7] Differential and/or integral boron worth

Table 2 Summary of Analysis Results by SRAC and JENDL-3.2[15)]

Measurement Item	EPICURE				MISTRAL					BASALA	
	UH1.2	MH1.2	UM17×17 /7%	UM17×17 /11%	Core 1	Core 2	Core 3	Core 4 Full MOX	Core 4 UO_2 zone	Core 1	Core 2
(a) Referenc core											
- keff (C-E, Δk, CITATION/TWOTRAN)	-0.44%/+0.07%	+0.27%/+0.13%	-0.25%/+0.07%	-0.25%/+0.31%	-0.97%/-0.19%	+0.48%/+0.41%	+0.49%/+0.42%	+0.74%/+0.74%	-0.10%/+0.24%	+0.39%/+0.78%	+0.47%/+0.41%
- Power (RMS of (C-E)/E, CITATION)	0.8% (1.0%)	0.9%(1.5%)	1.1%(1.5%)	1.1%(1.5%)	2.0% (1.0%)	1.1%(1.5%)	1.3%(1.5%)	1.0%(1.5%)	1.5%(2.2%)	1.8% (1.5%)	1.6%(1.5%)
- Spectrum Index (C/E, Pij)											
U238/U235		2.45(3%)			0.67(10%)	0.91(7%)	-				
Pu239/U235		1.05(2%)			1.01(2%)	1.04(2%)	1.03(2%)				
Pu238/Pu239		0.89(3%)			-	0.94(14%)	-				
Pu240/Pu239		0.81(3%)			0.95(8%)	0.83(6%)	-				
Pu241/Pu239		0.92(2%)			0.99(3%)	0.98(3%)	0.98(3%)				
Pu242/Pu239		0.17(3%)			-	0.98(8%)	-				
Np237/Pu239		-			0.76(3%)	0.90(3%)	0.90(3%)				
- Conversion fact. (C/E, Pij)		-			1.02(3%)	1.01(1%)	1.02(1%)				
(b) Boron worth (C/E, CITATION)											
- Differential					1.09(11%)	1.08(4%)	1.12(4%)	0.90(5%)			
- Integral (Av. C/E)					-	1.00(4%)	1.01(5%)	1.07(6%)			0.98(5%)
(c) Iso-thermal Temp. Co. (C-E, $\times 10^{-5}$ △k/kk\`/℃, CITATION)					-2.0(1.7)	-1.0(0.9)	-1.3(1.1)				-0.8(1.9)
(d) Absorber/Control Cluster Worth (C/E, CITATION/TWOTRAN)					(Absober)	(Absober)	(Absober)	(Cluster)	(Cluster)	(Burnable Poison)	
$UO_2Gd_2O_3$		1.07/1.06 (7%)			1.05/1.05 (13%)	1.10/1.09 (7%)	1.15/1.13 (8%)	-	—	1.04/0.99 (6%)	1.08/1.03 (6%)
AIC	1.16/1.12 (5%)	1.13/1.05 (5%)			1.06/1.04 (12%)	1.07/1.03 (8%)	-	1.07/1.02 (6%)	—		(Control Blade)
Hf					-	-	-	1.06/1.02 (6%)	—		1.09/0.91 (6%)
natB$_4$C	1.09/1.06 (4%)	1.03/0.99 (4%)			1.08/1.04 (12%)	1.01/1.00 (7%)	-	-	—		1.07/0.97 (6%)
90%EnrichB$_4$C					1.11/1.05 (12%)	0.97/0.98 (7%)	1.01/1.04 (6%)	1.08/1.00 (6%)	1.06/0.98 (6%)		
(f) Water Hole/Rod Worth (C/E, CITATION／TWOTRAN)					(Water Hole) 0.84/1.02 (7%)	1.04/1.02 (6%)				(Water Rod) 1.12/1.12 (5%)	
(g) Void Worth (C/E, CITATION/TWOTRAN)	1.05/ - (～10%) (2D Void)	1.05/ - (～7%) (2D Void)	1.13/0.97 (～12%) (2D Void)	1.20/1.08 (13%) (3D Void)			1.09/1.05 (6%) (2D Void)			1.14/1.01 (6%) (2D Void)	
(h) Eff. Delayed Neutron Fraction (C/E, CITATION)					0.99 (2%)	0.98 (2%)					

Note: Bracket shows measurement error %(Iso-thermal Temp. Co.: measurement error in x10^{-5} △k/kk\`/℃)

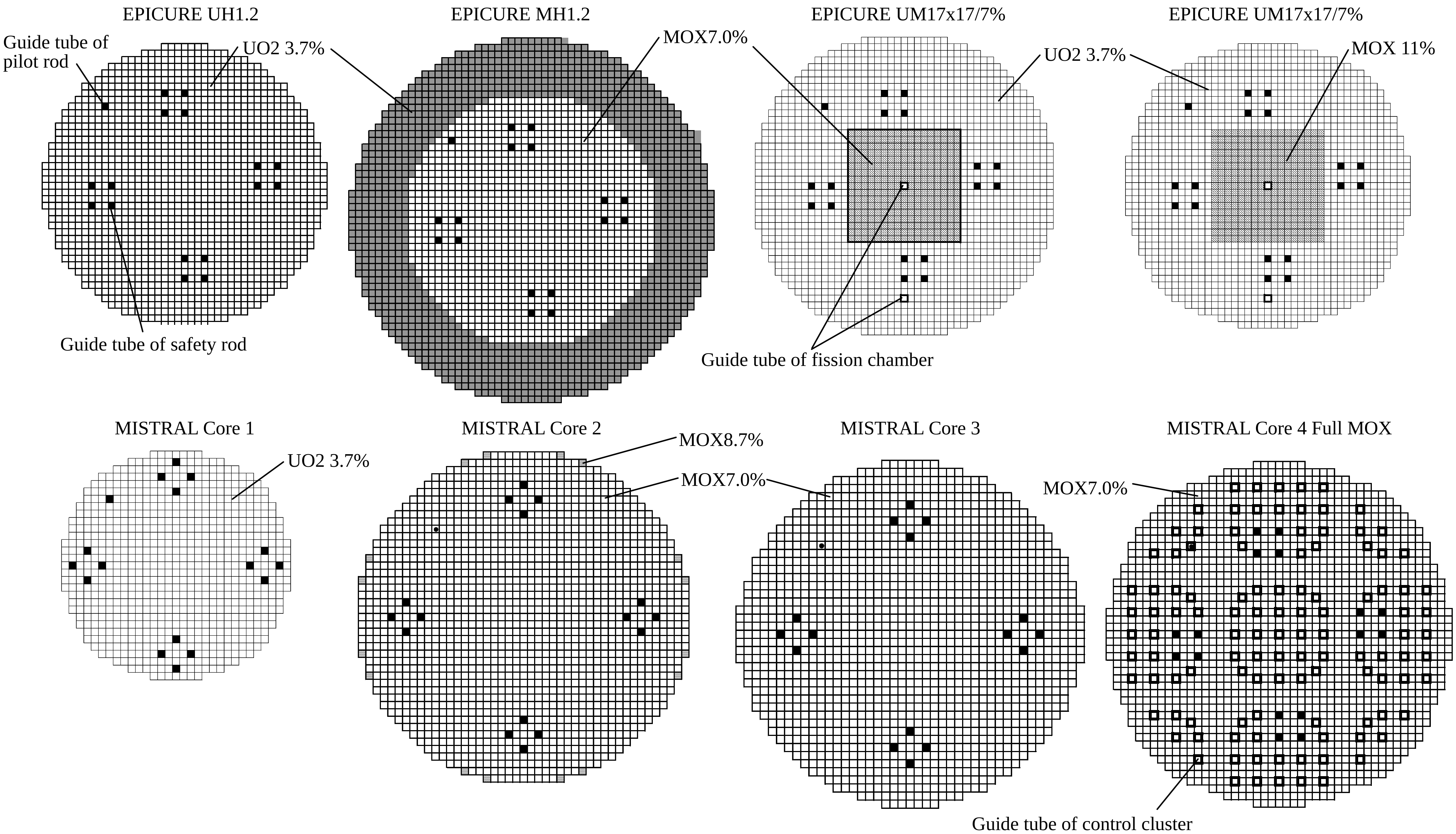

Fig. 1a Schematic Core Configuration (1)

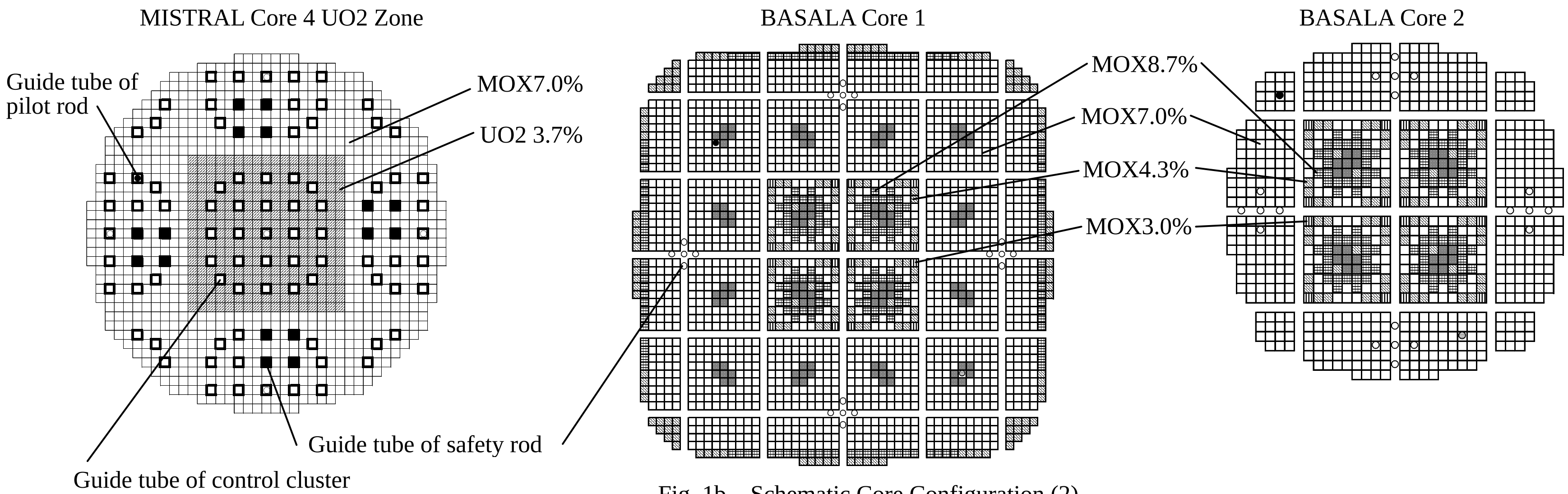

Fig. 1b Schematic Core Configuration (2)

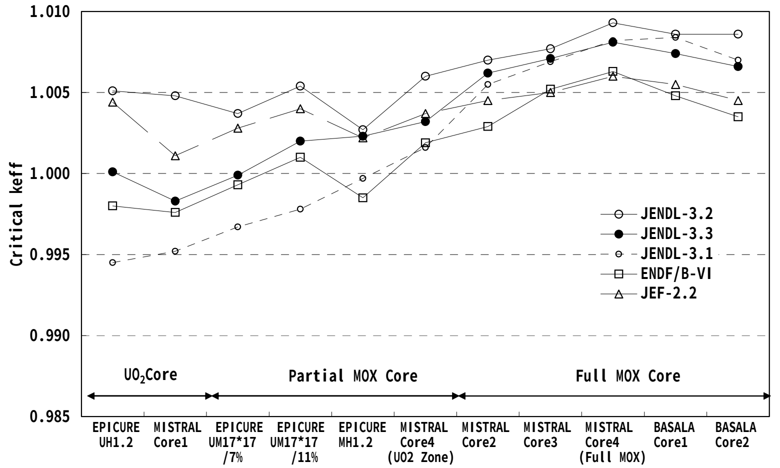

Fig. 2 Summary of Critical keff by MVP[15)]

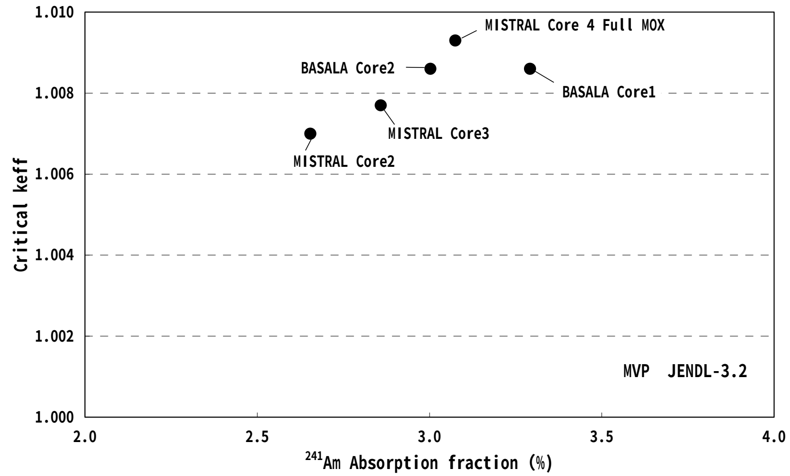

Fig. 3 Critical keff vs ^{241}Am Absorption Fraction (MVP)[15)]

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