ANALYSES OF MISTRAL AND EPICURE EXPERIMENTS WITH SRAC AND MVP CODE SYSTEMS

Koki Hibi
Nuclear Energy Systems Engineering Center, Mitsubishi Heavy Industries, Ltd.
3-1, Minatomirai 3-chome, Nishi-ku, Yokohama, 220-8401, Japan
hibi@atom.hq.mhi.co.jp

Masahiro Tatsumi
PWR Fuel Division, Nuclear Fuel Industries, Ltd.
950, Ohaza Noda, Kumatori-cho, Sennan-gun, Osaka, 590-0481, Japan
tatsumi@nfi.co.jp

Takuya Umano
Nuclear Engineering Laboratory, Toshiba Corporation
4-1, Ukishima-cho, Kawasaki-ku, Kawasaki, 210, Japan
takuya.umano@toshiba.co.jp

Atsushi Fushimi
Power & Industrial Systems R & D Laboratory, Hitachi, Ltd.
7-2-1, Omika-cho, Hitachi-shi, Ibaraki-ken, 319-1221, Japan
fusimi@erl.hitachi.co.jp

Toru Yamamoto, Masao Ueji, Yutaka Iwata
Systems Safety Department, Nuclear Power Engineering Corporation
17-1, 3-chome, Toranomon, Minato-ku, Tokyo, 105-0001, Japan
t-yamamoto@nupec.or.jp, ueji@nupec.or.jp, iwata@nupec.or.jp

ABSTRACT

An extensive experimental program, MISTRAL[1],[2], is undertaken by NUPEC and CEA in order to measure the main core physics parameters of high moderation 100 % mixed oxide plutonium fuel (MOX). NUPEC has also obtained the experimental data of conventional moderation cores of the EPICURE program[3]. NUPEC has been analyzing the experimental results with diffusion calculations by the SRAC code system[4] and Monte Carlo calculations by the MVP code system[5]. The differences between the results of calculations and experiments are approximately in the same range of the experimental uncertainty and this is common for both calculations. Both code systems calculate the nuclear core characteristics correctly for the six cores of MISTRAL

and EPICURE. These calculation results show no apparent trend among the cores with hydrogen to heavy metal atom number ratios (H/HMs) of 3.7 and 5 for the UO2 and the MOX cores.

1. INTRODUCTION

Recycling of plutonium is one of the key issues for energy security in Japan. Since LWRs are expected to play the major role in nuclear power, plutonium will be recycled in LWRs for several decades. It is also important not to have excess plutonium stocks from the view point of nuclear non-proliferation. In this situation, full MOX cores are attractive since it decreases a number of reactors for plutonium recycling.

An extensive experimental program, MISTRAL, is being performed in a framework of cooperation between NUPEC and CEA and their industrial partners. The MISTRAL program is being undertaken in the EOLE facility of the Cadarache research center in France for measurement of main core physics parameters. The H/HMs are from 5.1 to 6.2. The experimental data are utilized for the verification and improvements of the current calculation methods for high moderation full MOX cores. NUPEC has been conducting this study on behalf of the Japanese Ministry of International Trade and Industry (MITI). The MISTRAL program consists of four high moderation cores. NUPEC has also obtained the experimental data of four conventional moderation cores (H/HM=3.7) of the EPICURE program, which had been conducted in the EOLE facility.

This paper presents the results of analyses for the first two cores of MISTRAL and above four cores of EPICURE. Following items are reported for nuclear core characteristics in this paper:

- Criticality,
- Radial fission rate distribution,
- Conversion factor of MISTRAL-1 and 2,
- Fission spectrum index of MISTRAL-1 and 2,
- Absorber worth of MH1.2, MISTRAL-1 and 2,
- Isothermal temperature coefficient of MISTRAL-1 and 2,
- Differential boron efficiency of MISTRAL-1 and 2,
- Integral boron efficiency of MISTRAL-2.

2. OUTLINE OF EXPERIMENTAL PROGRAM

The MISTRAL program consists of four high moderation cores described below:

MISTRAL-1: A homogeneous enriched UO_2 core (H/HM=5.1) with a square fuel pin pitch of 1.32cm,

MISTRAL-2: A homogeneous full MOX core (H/HM=5.2) with the same fuel pin pitch as that of MISTRAL-1,

MISTRAL-3: A homogeneous full MOX core (H/HM=6.2) with a larger fuel pin pitch than that of MISTRAL-2, MISTRAL-4: A mock-up core simulating a full MOX PWR (H/HM=5.8) with 17x17 sub-assemblies and 25 guide-tubes.

The experiments for MISTRAL-1, -2 and -3 had already finished for the last three years. MISTRAL-4 program is being executed at the present time and plans to be completed on July this year.

Four EPICURE cores which NUPEC has analyzed have a square fuel pin pitch of 1.26cm and are:

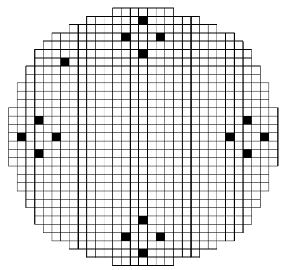
- UH1.2: A homogeneous enriched UO_2 core,
- MH1.2: A homogeneous MOX core surrounded UO_2 driver fuel pins,
- UM17x17/7%: A mock-up core simulating a MOX PWR 17x17 sub-assembly (Pu-total=7%, no guide-tubes) surrounded UO_2 fuel pins,
- UM17x17/11%: A mock-up core simulating a MOX PWR 17x17 sub-assembly (Pu-total=11%, no guide-tubes) surrounded UO_2 fuel pins.

Table2-1 shows core characteristics and measurement items for each core. The core configurations for MISTRAl and EPICURE are shown in Fig.2-1 and Fig.2-2, respectively.

Table2-1 Core Characteristics and Measurement Items for Each Core

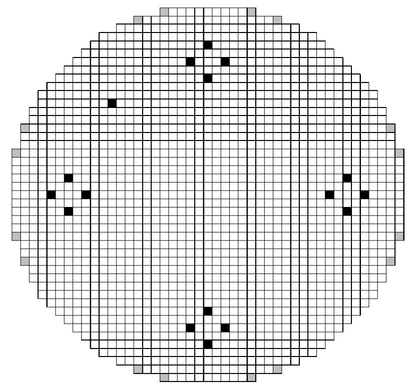
	MISTRAL				EPICURE			
	core 1	core 2	core 3	core 4	UH1.2	MH1.2	UM17x17 /7%	UM17x17 /11%
H/HM	5.1	5.2	6.2	5.8	3.7	3.7	3.7	3.7
Volumetric moderator ratio (Vm/Vf)	1.8	1.8	2.1	2.0	1.3	1.3	1.3	1.3
Pin pitch (cm)	1.32	1.32	1.39	1.32	1.26	1.26	1.26	1.26
Main loaded fuel	UO2 3.7 %	MOX 7.0 %	MOX 7.0 %	MOX 7.0 %	UO2 3.7 %	MOX 7.0 %	MOX 7.0 %	MOX 11 %
Equivalent core radius (cm)	41	60	59	62	54	69	58	55
Measurement items								
Critical Mass	x	x	x	x	x	x	x	x
Buckling	x	x	x		x	x		
Boron concentration	x	x	x	x	x	x	x	x
Spectral index	x	x	x			x		
Radial power distribution	x	x	x	x	x	x	x	x
Axial power distribution	x	x	x	x			x	x
Iso-thermal coefficient	x	x	x					
Boron efficiency	x	x	x	x				
Absorber worth	x	x	x		x	x		
Fuel pin substitution (Water Hole worth)	x	x						
Absorber cluster worth				x				
2D void effect			x		x	x		
3D void effect							x	x
βeff	x	x						

x : measurement item



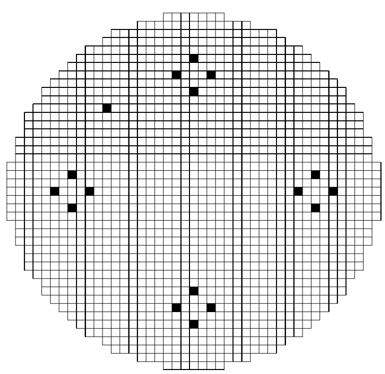
□ MOX(7.0%) fuel rod
■ Guide tube for safty and control rod

MISTRAL-1



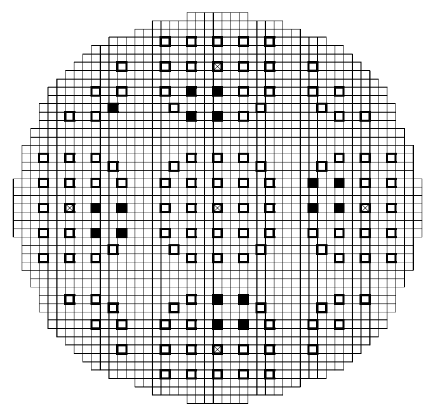
□ MOX(7.0%) fuel rod
▒ MOX(8.7%) fuel rod
■ Guide tube for safty and control rod

MISTRAL-2



□ MOX(7.0%) fuel rod
■ Guide tube for safty and control rod

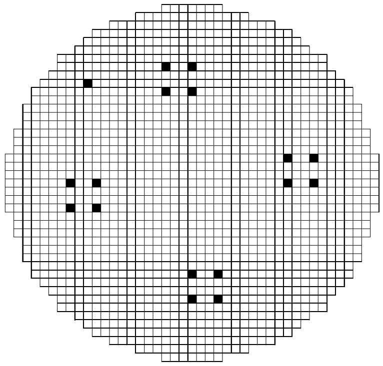
MISTRAL-3



□ MOX(7.0%) fuel rod
□ Mock-up thimble tube
⊠ Instrumentation tube
■ Guide tube for safty and control rod

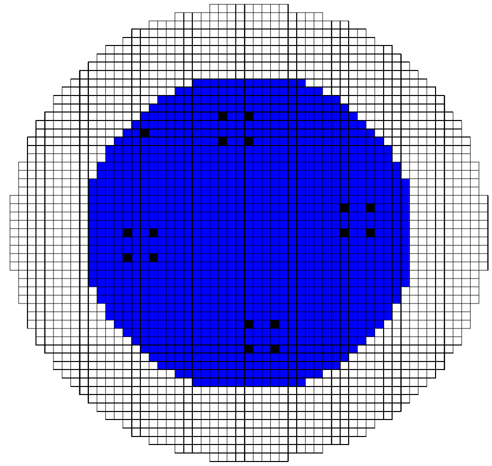
MISTRAL-4 (MOX Reference)

Fig.2-1 Core Configuration in MISTRAL Experimental Program



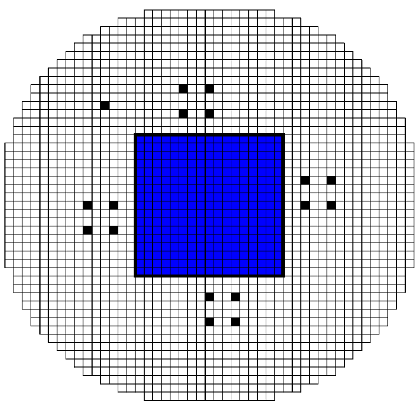
□ UO2 (3.7%) fuel rod
■ Guide tube for safty and control rod

UH1.2



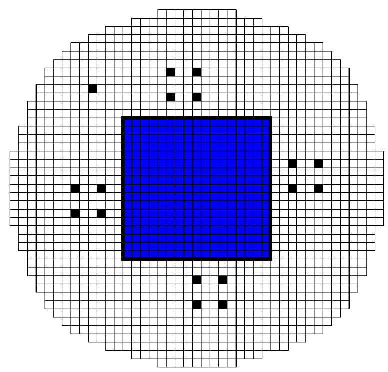
■ MOX(7.0%) fuel rod
□ UO2 (3.7%) fuel rod
■ Guide tube for safty and control rod

MH1.2



■ MOX(7.0%) fuel rod
□ UO2 (3.7%) fuel rod
■ Guide tube for safty and control rod

UM17x17(7%)



■ MOX(11%) fuel rod
□ UO2 (3.7%) fuel rod
■ Guide tube for safty and control rod

UM17x17(11%)

Fig.2-2 Core Configuration in EPICURE Experimental Program

3. ANALYSIS METHOD

NUPEC has been analyzing the experimental results with SRAC and MVP code systems. The former system performs pin cell and core calculations with the deterministic method and the later system does a core calculation with the Monte Carlo method. Both systems have been developed by Japan Atomic Energy Research Institute (JAERI).

The three libraries equipped with the SRAC code system were used in our analyses. These libraries correspond to the fast, thermal and resonance energy ranges and were generated from the nuclear data files, JENDL-3.2[6]. The resonance library was used in PEACO module of SRAC to treat resonance shielding in detail. The boundary energies of the resonance library in our analyses are 1.8554eV and 961.12eV that were determined by parameter surveys with a single cell model of the 7% enrichment MOX fuel pin (7%-MOX pin) used in EPICURE.

The collision probability calculation (Pij-calculation) for each specific cell configuration was performed by SRAC to prepare 107-group cell averaged cross sections and coarse-group macro cross sections for the diffusion and discrete ordinates transport core calculations. These core calculations were performed using CITATION and TWOTRAN modules in the SRAC code system. The two-dimensional XY-calculation with 16-group structure using SRAC-CITATION was employed for the analyses of criticality, absorber worth, differential boron efficiency, peripheral rod worth, water hole worth and isothermal temperature coefficient. For the analyses of criticality, absorber worth, water hole worth and peripheral rod worth, SRAC-TWOTRAN was used with XY geometry and 16-group. Fig.3-1 shows the representative core calculation model with the two-dimensional XY geometry.

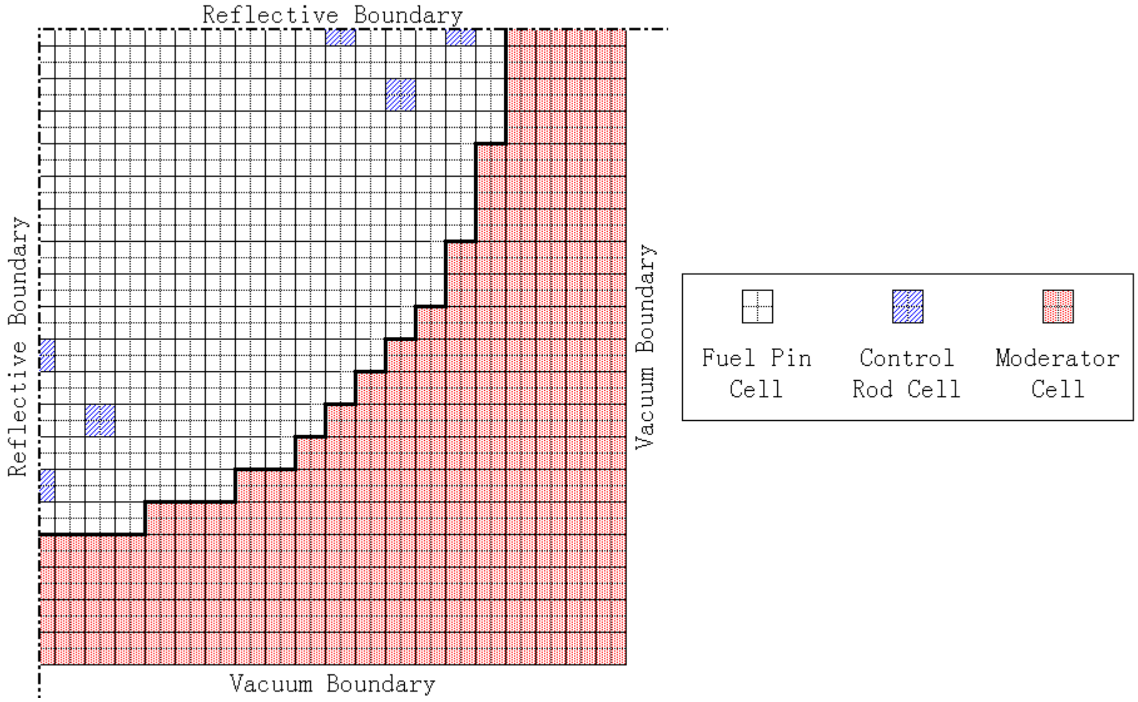


Fig.3-1 Conceptual Illustration of Core Calculation Model for SRAC

Analyses for conversion factor and spectrum index were performed only by cell calculations. For the analyses of spectral indices, a 5x5 cell model shown in Fig.3-2 was employed. It has a fission chamber pin at a corner of the multi-cell with 24 fuel rods using reflective conditions on its boundaries. As for the analyses of absorber worth, heterogeneous macro cross section for each absorber pin was calculated using a 5x5 cell model which has a central absorber rod with eight fuel rods using reflective conditions on its boundaries. The model is shown in Fig.3-3. Integral boron efficiency and βeff were analyzed by SRAC-CITATION with three-dimensional XYZ geometry. Number of energy group is 16 for integral boron efficiency and 21 for βeff.

Additionally, three-dimensional continuos-energy Monte Calro calculations (MC-calculations) were performed by the MVP code with more detail treatment of geometry and neutron energy using MVP's library processed from JENDL-3.2. The number of simulated particles was 10000 per batch, and 1000 batches calculation was performed. Therefore, total history number was ten millions.

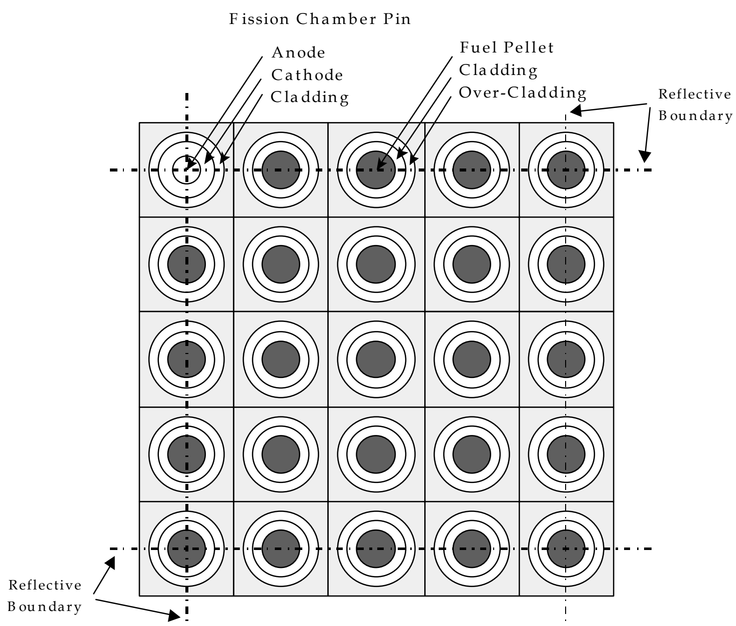


Fig.3-2 5x5 Multi-Cell Model for Spectral Index Calculation

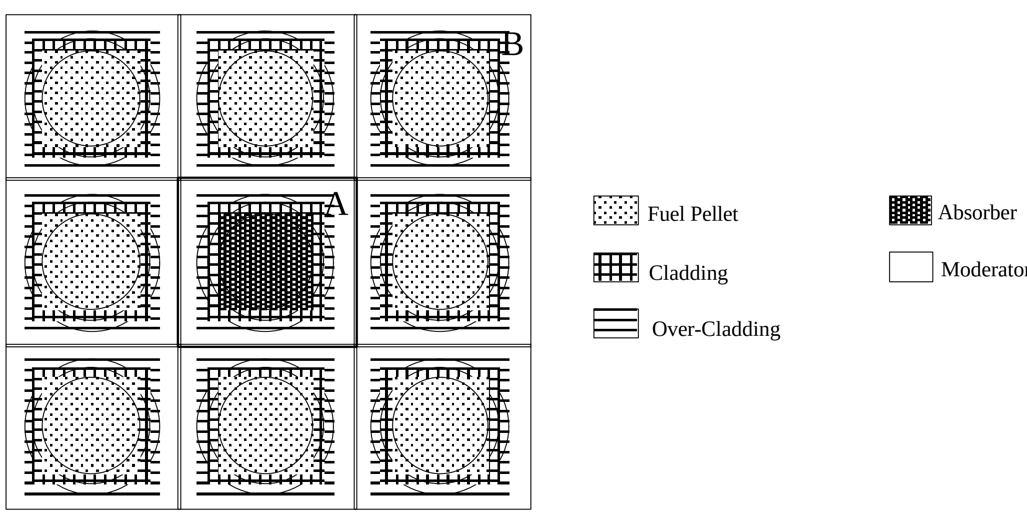


Fig.3-3 3x3 Multi-Cell Model for Absorber Worth Calculation

4. RESULTS OF EXPERIMENTAL ANALYSIS

4.1 CRITICALITY AND RADIAL FISSION RATE DISTRIBUTION

The differences between calculated and measured k_{eff}'s for the each core are shown in Table 4.1-1. The results of calculation with SRAC-TWOTRAN overestimate the experimental results by 0.1~0.4 %Δk except MISTRAL-1. In MISTRAL-1, the transport effect is very large because the equivalent radius of the core is smaller than the other cores. The results with MVP show overestimation by 0.3~0.7 %Δk among all cores including MISTRAL-1. The statistical errors for these calculations are about $\pm$0.02 %Δk and are small enough for the calculations to be validated. Additionally, the calculated results of the total fission rate for the each core are presented in Table4.1-2 and Fig4.1-1. The table and figure show that the differences for most of the positions in the cores are the same level as the uncertainties of the measurements.

Table4.1-1 Difference of Criticality between Calculation and Measurement

unit:Δk

	SRAC		MVP
	CITATION	TWOTRAN	
MISTRAL			
MISTRAL 1	-0.0097	-0.0019	0.0048 ±0.0003
MISTRAL 2	0.0048	0.0040	0.0070 ±0.0002
EPICURE			
UH1.2	-0.0044	0.0007	0.0051 ±0.0002
MH1.2	0.0026	0.0012	0.0026 ±0.0002
UM17×17/7%	-0.0025	0.0007	0.0037 ±0.0002
UM17×17/11%	-0.0025	0.0031	0.0054 ±0.0002

Table4.1-2 Root Mean Square of Difference of Radial Fission Rate Distribution between Calculation and Measurement

unit:%

	SRAC-CITATION	MVP	Experimental Uncertainty(1σ)
MISTRAL			
MISTRAL 1	2.0	1.7	±1.0
MISTRAL 2	1.1	1.7	±1.5
EPICURE			
UH1.2	0.8	1.0	±1.0
MH1.2	0.9	1.2	±1.5
UM17×17/7%	2.9	2.0	±2.5
UM17×17/11%	1.1	1.4	±1.2

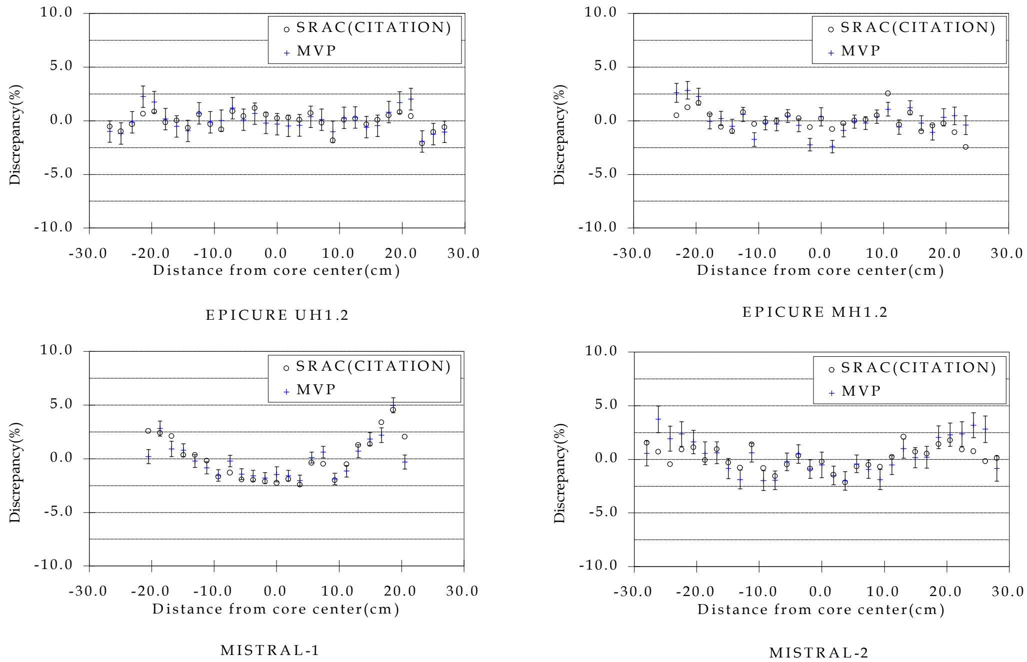


Fig.4.1-1 Difference of Radial fission rate between calculation and measurement

4.2 CONVERSION FACTOR

Calculations for conversion factors were performed by Pij calculations in SRAC within the 107-group structure in infinite lattice geometry. The 3.7%-UO_2 cell and the 7.0%-MOX cell were chosen for MISTRAL-1 and 2, respectively. Collapsed reaction rates of heavy nuclides in the fuel region were calculated to calculated conversion factors. Table 4.2-1 gives C/E value of conversion factors.

Table 4.2-1 Comparisons of Conversion Factors

	C/E	S.D (%)
MISTRAL-1	1.02	3.0
MISTRAL-2	1.01	1.4

4.3 FISSION SPECTRUM INDEX

Calculations for spectrum indices were performed by Pij-calculation within the 107-group structure in a 5x5 multi-cell geometry. A cell simulating a detector is placed at the corner of the array, which virtually makes a 9x9 infinite lattice system, as shown in Fig.3.2. Effective cross sections of the normal fuel pins and the detector pin were calculated independently by the Pij-calculation module in SRAC with detail treatment of resonance shielding by PEACO. The detector cell is surrounded by 3.7wt% UO2 fuel pins in MISTRAL-1 while by 7.0wt% MOX pins in MISTRAL-2. The deposits on the anode in the detector were simulated by containing a very little amount of heavy nuclides, such as 235U, 239Pu and so on, in the anode region in the calculation geometry so that effective cross sections of those nuclides may be considered as infinitely diluted.

Collapsed reaction rates of heavy nuclides in the anode were calculated to estimate spectrum indices. Table 4.3-1 summarize the calculation results of the spectrum index for UO2 spectrum and MOX spectrum.

Table 4.3-1 Comparisons of Spectrum Indices in MISTRAL-1 and 2

Spectrum Index	MISTRAL-1 (UO_2 Spectrum)		MISTRAL-2 (MOX Spectrum)	
	C/E	S.D (%)	C/E	S.D (%)
U-238/U-235	0.73	10	0.90	6.7
Pu-239/U-235	1.01	2.4	1.04	2.4
Pu-238/Pu-239	---	---	0.94	13.7
Pu-240/Pu-239	1.04	7.5	0.83	5.9
Pu-241/Pu-239	0.99	2.7	0.98	2.7
Pu-242/Pu-239	---	---	0.98	7.6
Np-237/Pu-239	0.83	3.2	0.90	3.2

4.4 ABSORBER WORTH

(1) Critical states

The critical states with an absorber rod at the center of the core were measured for EPICURE UH1.2, MH1.2 and MISTRAL-1, 2. In the measurements, the soluble boron concentration was adjusted for UH1.2, MH1.2 and MISTRAL-1, and the number of peripheral fuel rods was adjusted for MISTRAL-2, to attain criticality. The critical k_{eff}'s of these states were calculated with SRAC-CITATION and SRAC-TWOTRAN. In the analyses, homogenized cross sections of the absorber cell were generated by Pij calculations with 3x3 multi-cell model. The core calculations employed the same two-dimensional XY geometry as adopted in the criticality analysis. When SRAC-TWOTRAN was used, the difference in critical k_{eff} between the reference configuration (with no absorber) and the absorber one was less than 0.03%Δk for EPICURE UH1.2 and MH1.2, 0.06%Δk for MISTRAL-1 and 0.04%Δk for MISTRAL-2.

(2)Absorber worth

To measure the absorber worth, four different methods, namely, the boron equivalence method, the peripheral rod equivalence method, the amplified source method (ASM) and the rod drop method were used. In the former two methods, the reactivity worth of an absorber rod are obtained from the difference in boron concentration or the number of fuel rods between the reference configuration and the absorber one under the critical condition. In the analysis, the absorber worths were calculated as the differences in reactivity between the central absorber configuration and the no-absorber configuration with the same core condition (temperature, boron concentration, etc). In Table 4.4-1, the calculated values are compared with the experiment. The experimental values in Table 4.4-1 were those obtained by the rod drop method for UH1.2, by the ASM for MH1.2, by the boron equivalence method for MISTRAL-1, and by the peripheral rod equivalence method for MISTRAL-2. As shown in Table 4.4-1, the differences between the calculated and the measured values were smaller than 10% for all cases when SRAC-TWOTRAN is used.

(3)Radial Power Distribution

In addition to the absorber worth, the total fission rate distributions were analyzed for the central absorber configurations with SRAC-CITATION. Fig. 4.4-1 shows the fission rate distributions for MISTRAL-2 with an enriched B_4C rod at the center. Table 4.4-2 gives comparisons of the root-mean-square of the relative differences between the measured and calculated fission rate distributions. In Table 4.4-2, except for MISTRAL-1, the root-mean-square of the relative differences were within the experimental uncertainties. For MISTRAL-1, which has a smaller core radius and larger absorber worths compared with the other cores, its root-mean-square difference was twice the experimental uncertainty.

Table 4.4-1 Comparison of Calculation/Experiment Ratio for Absorber Worth

Core	Absorber	C/E	
		SRAC-CITATION	SRAC-TWOTRAN
UH1.2	Pyrex	0.99	0.98
	Ag-In-Cd	1.11	1.07
	Natural B_4C	1.04	0.98
MH1.2	UO_2-Gd_2O_3	0.97	0.96
	Pyrex	1.05	1.04
	Ag-In-Cd	1.13	1.06
	Natural B4C	1.08	0.99
MISTRAL-1	UO_2-Gd_2O_3	1.05	1.05
	Ag-In-Cd	1.06	1.04
	Natural B4C	1.08	1.04
	Enriched B4C	1.11	1.05
MISTRAL-2	UO_2-Gd_2O_3	1.09	1.09
	Ag-In-Cd	1.07	1.03
	Natural B4C	1.01	0.96
	Enriched B4C	0.97	0.90

Table4.4-2 Comparison of Root-Mean-Square Difference

Absorber	UH1.2	MH1.2	MISTRAL-1	MISTRAL-2
Pyrex	0.3%	1.2%	-	-
UO2-Gd2O3	-	-	1.9%	0.6%
Ag-In-Cd	-	1.1%	1.8%	0.9%
Natural B4C	-	1.1%	1.9%	1.0%
Enriched B4C	-	-	1.8%	1.1%
Experimental Uncertainty(1δ)	1.0%	1.5%	1.0%	1.5%

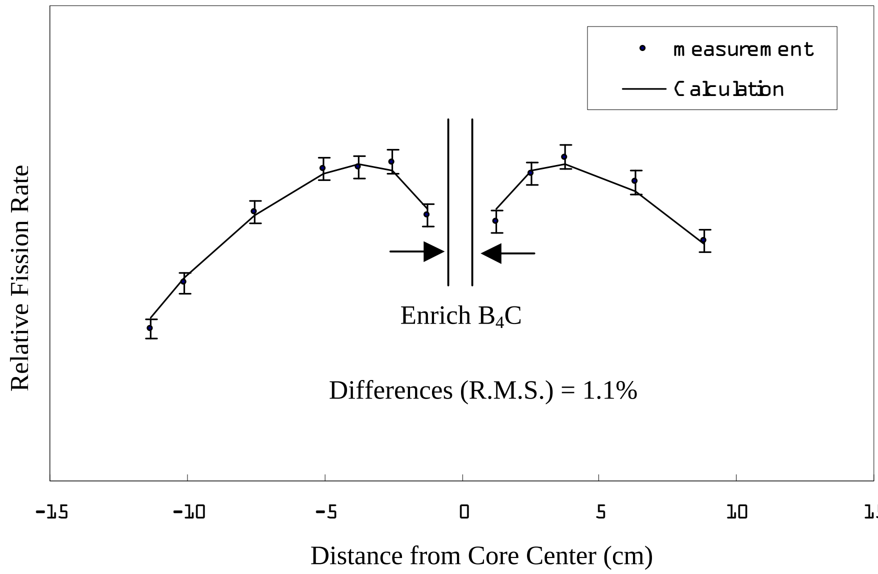


Fig.4.4-1 Radial Fission Rate Distribution for Enriched B4C in MISTRAL-2

4.5 ISOTHERMAL TEMPERATURE COEFFICIENT

Isothermal temperature coefficients were measured in MISTRAL-1 and MISTRAL-2. In this section, the methods in experiments and analyses for the coefficients are described for each core since the experimental methods were different for the two cores.

The core reactivity of MISTRAL-1 was mainly controlled with the concentration of soluble boric acid in the moderator. The isothermal temperature coefficients were estimated with measurement data among each temperature point from 5 oC to 80 oC. A reactivity loss due to temperature rise was compensated mainly by dilution of the soluble boron in the moderator so as to keep criticality at each temperature condition. Note that the uncertainty of the measured value was estimated including that of the differential boron coefficients. The core reactivity of MISTRAL-2 was usually controlled by the critical size. Therefore a reactivity loss due to temperature rise was compensated by addition of 8.7%-MOX pins in the core peripheral. The isothermal temperature coefficients of the core were evaluated with the reactivity worth of added peripheral 8.7%-MOX pins that were calculated by transport calculations.

The analyses of the isothermal temperature coefficients employed two-dimensional XY diffusion calculations. Effective cross sections for each temperature were calculated under the conditions measured in the experiments such as its system temperature, concentration of soluble boron in the moderator, etc. The isothermal temperature coefficients were calculated from the net reactivity change due to the temperature change, dividing by the temperature difference.

The isothermal temperature coefficients below 20 oC where cross section data are not available in JENDL-3.2 were reconstructed from the following three contributions:

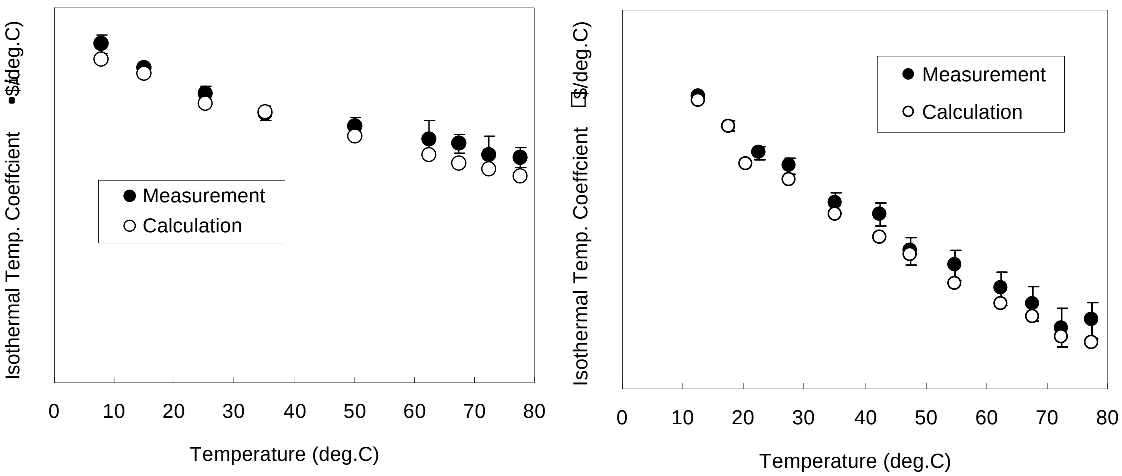
1)A reactivity change due to the Doppler effect,

2)A reactivity change due to changes of scattering kernel,
3)A reactivity change due to changes of the moderator density

Those components were calculated independently with the following conditions.
For case 1): Fixed temperatures except in a fuel pellet region and fixed moderator densities.
For case 2): Fixed temperatures except in a moderator region and fixed moderator densities.
For case 3): Fixed temperatures for all regions and different moderator densities

Reactivity changes by those contributions were interpolated with the linear function for the former two components and with the quadratic function for the last component, and finally synthesized to derive the isothermal temperature coefficients on lower temperature conditions.

Figure 4.5-1 shows comparisons of the measured and calculated values of isothermal temperature coefficients in MISTRAL-1 and 2. Both figure have the same scale on Y-axis so that those can be compared. Observe that MISTRAL-2 had larger and deeper temperature coefficients compared to MISTRAL-1. Calculated values agreed with measured values within the range of 2 standard deviations.



(a) MISTRAL-1 (b) MISTRAL-2

Fig. 4.5-1 Comparison of Isothermal Temperature Coefficient

4.6 PERIPHERAL ROD WORTH

The reactivity worth of eight peripheral UO_2 pins for MISTRAL-1, and those of 8, 24, 40 and 48 peripheral MOX pins for MISTRAL-2 were calculated using both SRAC-CITATION and SRAC-TWOTRAN. In Table 4.6-1, the calculated peripheral rod worths per rod are compared with experiments. The differences between the results with SRAC-TWOTRAN and the experiments were within 4 % and smaller than the experimental uncertainties for both MISTRAL-1 and 2. For the results with SRAC-CITATION, the differences between the calculated values and the measured values are within the experimental uncertainties for MISTRAL-2, but the calculated values for MISTRAL-1 is condiderably underestimated.

Table 4.6-1 Comparison for Peripheral Rod Worth

Core	Number of Peripheral Rod *)	C/E	
		SRAC-CITATION	SRAC-TWOTRAN
MISTRAL-1	8	0.74	1.04
MISTRAL-2	8	1.07	1.03
	24	1.03	0.99
	40	1.05	1.02
	48	1.07	1.04
	Ave.	1.05	1.02

*) 3.7%-UO_2 rod for MISTRAL-1 and 8.7%-MOX rod for MISTRAL-2

4.7 Differential Boron Efficiency

(1) MISTRAL-1

The core reactivity of MISTRAL-1 was controlled by the concentration of boric acid in the moderator. The differential efficiency of soluble boron was measured with changing its concentration within plus/minus 3 ppm around the critical concentration of 294.2 ppm Differential boron coefficients were estimated with the divergence method where the residual reactivity in each states was estimated through the doubling time and in-hour equation.

As for the analyses, the differential boron efficiencies were calculated with the range of 240 ~ 300 ppm so that the calculation results were utilized for the estimation of absorber efficiency. Two-dimensional diffusion calculations were performed using the effective cross sections prepared on the B1 approximation.

In order to make sure of the effects by the changes of the moderator density, additional analyses for two temperature points (65 and 80 ^{o}C) were performed. On each temperature condition, keff (the effective multiplication factor) values in different boron concentrations were calculated and the differential boron efficiencies were estimated. Because the dependency of the efficiency on the concentrations was about 3% and this was not so large, the only one coefficient for each temperature condition was determined through averaging all the differential boron efficiencies between the successive two boron conditions. Those results of the efficiencies have no significant discrepancies and through averaging, they were processed to derive the final value of the differential boron efficiency.

Table 4.7-1 summarizes the calculated and measured values of the differential boron efficiencies. The calculated value shows good agreements with the measured ones within their experimental uncertainties.

Table 4.7-1 Comparison of Differential Boron Efficiency for MISTRAL-1

Differential Boron Efficiency	Divergence Method	ASM Method
Relative Difference	8.7 %	7.1 %
Measurement Uncertainty (1σ)	11.3 %	19.7 %

Relative Difference =(C-E) / E$\times$100 (%)

(2) MISTRAL-2

The core reactivity of MISTRAL-2 was controlled by the number of peripheral 8.7%-MOX pins, and the reference boron concentration in the moderator was 0 ppm. For the differential boron efficiency experiments, the boron concentration was changed from 0 ppm to 3.3 ppm, 6.0 ppm and finally 0 ppm. At every four state of the boron concentration, the core consisted of 1572 of 7%-MOX pins and 92 of 8.7%-MOX pins and the criticality was achieved at each state. The differential boron efficiency was experimentally determined with the residual reactivity through the doubling time and the in-hour equation, so called the divergence method.

In addition to the divergence method, the Amplified Source Method (ASM) was also adopted. When this method was applied, the number of peripheral 8.7%-MOX pins was 76 to keep the core subcritical.

In order to analyze the differential boron efficiency, two-dimensional diffusion calculations were performed with SRAC-CITATION. The axial buckling for the axial leakage was fixed to be the same as the reference core one.

To validate the calculation method, k_{eff} values of the four critical states were compared. The calculations were performed with the core configuration of 92 of peripheral 8.7%-MOX pins. The calculation results agreed well with each other within 6 pcm.

After comparing each critical k_{eff} value of the calculation, additional calculations were performed to determine the differential boron efficiency around 0 ppm. For example, without changing any other conditions in the calculations, the boron concentration was changed from 0 ppm to 3.3 ppm to determine the differential boron efficiency. And the calculated βeff value was utilized as the unit value for the dollar.

The comparisons of the calculation results and measurements are shown in Table 4.7-2 . The calculation result shows good agreement to those of the divergence method and the ASM within roughly twice of experimental uncertainties.

Table 4.7-2 Comparison of Differential Boron Efficiency for MISTRAL-2

Differential Boron Efficiency	Divergence Method	ASM Method
Relative Difference	7.8 %	13.7 %
Measurement Uncertainty (1σ)	6.5 %	6.4 %

Relative Difference =(C-E) / E$\times$100 (%)

4.8 Integral Boron efficiency

In MISTRAL-2, integral boron efficiency measurements were performed with changing the boron concentration in the moderator from 0 ppm to 250, 400, 500, and 600 ppm. In this experiment, the subcritical levels of the core were measured with using a subcritical method, so called the Amplified Source Method (ASM). Before this experiment, CEA and NUPEC have studied the alteration of the effective efficiency of neutron detectors according to the boron concentration, and concluded to use three neutron detectors at the different core positions, two were core inside, and the other one was core peripheral outside. The correction factor for the effective efficiency for each detector at every boron concentration was precisely calculated by CEA. All data including counting rates of the neutron detectors were carefully processed with these factors. Therefore, this experiment method can be called a modified neutron source method (MSM) . The core consisted of 1570 of 7%-MOX pins and 72 of 8.7%-MOX pins and the core temperature was 20 ^{o}C.

For the analyses of the integral boron efficiency, three-dimensional diffusion calculations were performed with SRAC-CITATION because the axial buckling was unknown for each subcritical core state. The core configuration for the calculations was made of 1571 of 7%-MOX pins and 72 of 8.7%-MOX pins because the calculations were performed in 1/4 symmetry and the only neutron detector at the core center position was able to be explicitly treated. At each boron concentration, the k_{eff} (the effective multiplication factor) was calculated and processed to obtain the subcritical level of the core. For the unit value for the dollar, the calculated value of βeff was utilized. Table 4.8-1 and Fig.4.8-1 show comparisons between the calculated values and the measurements. As shown in Fig.4.8-1, although the very slight tendency of calculated values can be seen on a curve with the increase of boron concentration, the agreement between two is very good and within the experimental uncertainties.

Table 4.8-1 Comparison of Integral Boron Efficiency

Boron Concentration	Relative Difference	Measurement Uncertainty (1δ)
0 ppm	-	-
250 ppm	4.2 %	3.8 %
400 ppm	- 0.2 %	3.8 %
500 ppm	- 1.4 %	3.9 %
600 ppm	- 3.4 %	3.8 %

Relative Difference = (C-E) / E × 100 (%)

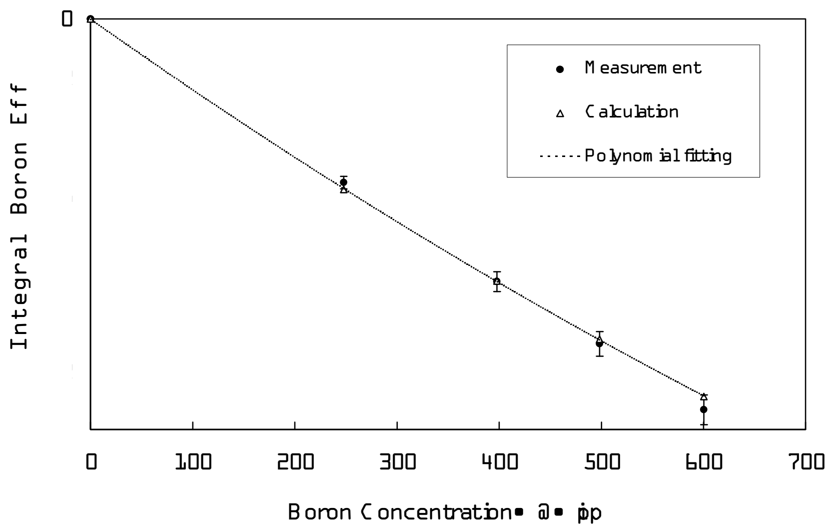


Fig.4.8-1 Comparison of Integral Boron Efficiency

4.9 WATER HOLE WORTH

(1) Critical states

The critical states with a 3x3 central water hole were measured for MISTRAL-1 and 2. The critical k_{eff}'s of these states were calculated with SRAC-CITATION and SRAC-TWOTRAN. In the analyses, homogenized cross sections of the water hole cell were generated by Pij calculations with a single water cell model. The core calculations were the same two-dimensional one as in the criticality analysis. The differences in critical k_{eff} between the reference configuration and the water hole one were less than 0.02%Δk for both MISTRAL-1 and 2 when SRAC-TWOTRAN was used.

(2) Water Hole worth

The water hole worths were calculated as the differences in reactivity between the central water hole configurations and the reference configurations with the same core condition (temperature, boron concentration, etc). In Table 4.9-1, the calculated values are compared with the experiment. As shown in Table 4.9-1, for the resultes of SRAC-TWOTRAN, the differences between the calculations and the measurements were 2% for both MISTRAL-1 and 2.

Table 4.9-1 Comparison of Calculation/Experiment Ratio for Water Hole Worth

Core	C/E	
	SRAC-CITATION	SRAC-TWOTRAN
MISTRAL-1	1.02	0.84
MISTRAL-2	1.02	1.04

(3) Radial Power Distribution

The total fission rate distributions were analyzed for the water hole configurations with SRAC-CITATION. Fig. 4.9-1 shows the fission rate distributions for MISTRAL-2 with a central 3x3 water hole. Table 4.9-2 gives comparisons of the root-mean-square of the relative differences between the measured and calculated fission rate distributions. As shown in Table 4.9-2, their differences were slightly large compared with the experimental uncertainties, but within 2% for both MISTRAL-1 and 2.

Table.4.9-2 Comparison of Root-Mean-Square Difference of Radial Fission Rate Distribution for Water Hole Configuration

Core	Root-Mean-Square Difference	Experimental Uncertainty (1δ)
MISTRAL-1	1.5 %	1.0 %
MISTRAL-2	1.9 %	1.5 %

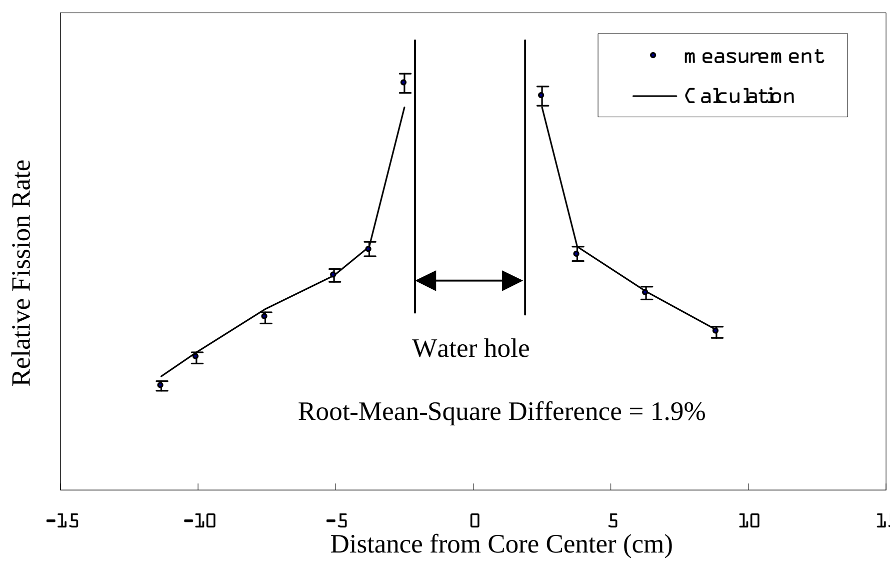


Fig.4.9-1 Radial Fission Rate Distribution for Water Hole Configuration in MISTRAL-2

4.10 βeff (Effective Delayed Neutron Fraction)

In the MISTRAL program, the measurements of βeff were performed with a core noise analysis method. The signals from the two well calibrated fission detectors installed at core peripheral positions were processed based on a core noise theory. The value of the absolute total fission rate of a core was measured. And the processed value and the total fission rate value were combined to determine the βeff value.

The analyses of βeff's (the effective delayed neutron fraction) for MISTRAL-1 and MISTRAL-2 were made based on the first order diffusion perturbation theory. Calculations were performed with SRAC-CITATION. For the core calculation, a three-dimensional model was utilized to take into account of the normal and adjoint fluxes of the whole core area. In addition, the 21-group neutron energy structure was adopted to treat the delayed neutron spectra more precisely. As for MISTRAL-1, the calculation conditions were the same as the reference case ones. The core consisted of 744 of 3.7%-UO_2 pins, the core temperature was 20 ^{o}C and the boron concentration was 294.2 ppm. As for MISTRAL-2, the calculation conditions were determined with considering the experiment dates and the core configuration. The core temperature was 20 ^{o}C. The core consisted of 1571 of 7%-MOX pins and 88 of peripheral 8.7%-MOX pins because the fission chamber was installed at the core center.

Table 4.10-1 shows the comparison between the calculated values (C) and the measured ones (E). As for MISTRAL-1, the relative difference is less than the measurement uncertainty (1σ), the agreement between two values is very good. As for MISTRAL-2, the calculations became more complicated than that of MISTRAL-1 because the number of nuclides in the fuel were increased and there were two types of MOX pins. However, the agreement between the calculation and the measurement seems to be comparable.

Table 4.10-1 Comparison of Calculated and Measured βeff Value

Core	Measurement Uncertainty (1σ)	Relative difference ((C-E)/E)
MISTRAL-1	± 1.5 %	- 0.8 %
MISTRAL-2	± 1.6 %	- 2.5 %

CONCLUSIONS

The differences between calculation and experiment are approximately same range of the experimental uncertainty and this is common for both diffusion and Monte Carlo calculations. SRAC and MVP calculate the nuclear core characteristics correctly for the six cores of MISTRAL and EPICURE. These calculation results show no apparent trend among the cores with H/HMs of 3.7 and 5 for the UO_2 and the MOX cores.

ACKNOWLEDGEMENTS

The authors thank Prof. Kanda of Kyoto Univ., and other members of the implementation committee of "Study of Advanced LWR Cores for Effective Use of Plutonium," in NUPEC for their technical advice and suggestions.

REFERENCES

1. Yamamoto, T., *et al*., “CORE PHYSICS EXPERIMENT OF 100% MOX CORE: MISTRAL,” *Proc. of Int. Conf. On Future Nuclear Systems, Global’97*, Vol.1, pp395 (1997)

2. Sakurada, K., *et al*., “STUDY ON ADVANCED LWR CORES FOR EFFECTIVE USE OF PLUTONIUM AND ANALYSIS OF MOX PHYSICS EXPERIMENTS,” *Proc. of Int. Conf. On Future Nuclear Systems, Global’99* (1999)

3. Mondot, J., *et al*., “EPICURE: An Experimental Programme Devoted to Validation of the Calculational Schemes for Plutonium Recycling in PWRs,” *Proc. of Int. Conf. Physics of Reactor Operation, Design and Computation, PHYSOR’90,* Vol.1 ppVI-53 (1990)

4. Tsuchihashi, K., *et al*., “Revised SRAC Code System,” JAERI-1302.(1986)

5. Mori, T., *et al*., “Vectorization of Continuous Energy Monte Carlo Method for Neutron Transport Calculation,” *J. Nucl. Sci. Technol*., 29, pp325 (1992)

6. Nakagawa, T., *et al*. “JENDL-3.2,” *J. Nucl. Sci. Technol*., 32(12), pp1259 (1995)