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# Analysis of the experimental program MISTRAL using CASMO-4

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An experimental program "MISTRAL" was undertaken by NUPEC, CEA and their associated industrial partners to investigate the main neutronic characteristics of high moderation ALWR loaded with 100% MOX fuel. The MISTRAL program comprises four core configurations of one $UO_2$ core and three MOX cores. The analyses of the MISTRAL experiment were performed to evaluate the capability of CASMO-4 code by NUPEC. The critical keff was overestimated for MOX cores. For the fission rate distribution the results agreed well with the experimental data. For absorber worth, boron efficiency coefficient, temperature coefficient, water-hole reactivity and 2D void reactivity the results were predicted within about twice the experimental uncertainty. CASMO-4 had the same accuracy in all configurations except for the critical keff.

***KEYWORDS: MISTRAL, CASMO-4, full-MOX core, mock-up core, high moderation, critical experiment, PWR***

## 1. Introduction

From 1995 to 2000, an extensive experimental program "MISTRAL", using the EOLE critical facility at CEA Cadarache, was undertaken by NUPEC, CEA and their associated industrial partners. The aim of this program was to investigate the main neutronic characteristics of high moderation advanced light water reactors loaded with 100% MOX fuel. The analyses of the MISTRAL experiment were performed to evaluate the capability of CASMO-4 code by NUPEC.

## 2. Characteristics of the MISTRAL

The MISTRAL program comprised four core configurations of three homogeneous cores and one heterogeneous mock-up core. Fig.1 shows the configuration of the MISTRAL reference cores. The details of each reference core are described in Table 1.

**Table 1** Configuration of the MISTRAL reference cores

| Configurations | MISTRAL | | | | |
|---|---|---|---|---|---|
| | Core 1 | Core 2 | Core 3 | Core 4 | |
| Core type | Homogeneous $UO_2$ | Homogeneous MOX | Homogeneous MOX | PWR Mock-up | |
| | | | | MOX | $UO_2$ |
| Fuel rods (No.) | - <br> $UO_2$ 3.7% (744) | MOX 7.0% (1556) <br> MOX 8.7% (16) | MOX 7.0% (1388) <br> - | MOX 7.0% (1596) <br> - | MOX 7.0% (840) <br> $UO_2$ 3.7% (264) |
| Lattice pitch [cm] | 1.32 | 1.32 | 1.39 | 1.32 | 1.32 |
| H/HM (Vm/Vf) | 5.1 (1.8) | 5.2 (1.8) | 6.2 (2.1) | 5.8 (2.1) | 5.8 (2.1) |

* H/HM: atomic moderator ratino, Vm/Vf: volumetric moderator ratio

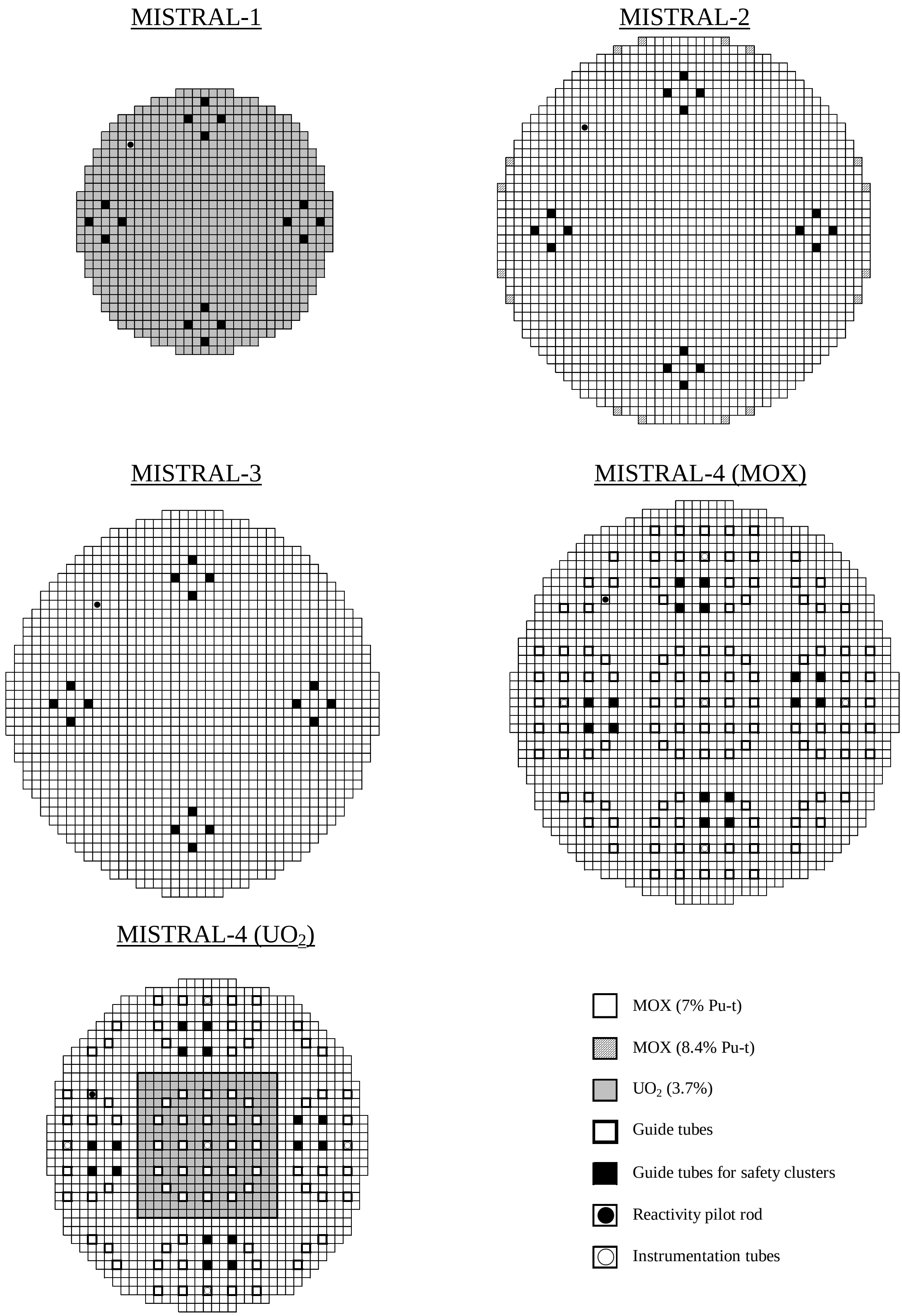


**Fig.1** Configuration of the MISTRAL reference cores

The measurement parameters of each core are listed in Table 2. The circles indicate the measurement items, of which the black circles indicate the calculation items.

In each measurement, the criticality was compensated by adjusting the soluble boron concentration for MISTRAL-1, 3 and 4, and by loading 8.7% MOX fuel pins at the peripheral of the core for MISTRAL-2.

**Table 2** Measurement and calculation parameters of the MISTRAL program

| Items | | | MISTRAL | | | |
|---|---|---|---|---|---|---|
| | | | Core 1 | Core 2 | Core 3 | Core 4 |
| Measurement Parameters | *reference core* | Critical mass | ● | ● | ● | ● |
| | | Boron Concentration | ○ | - | ○ | ○ |
| | | Power distribution (rad./axial) | ○/● | ○/● | ○/● | ○/● |
| | | Buckling(rad./axial) | ○ | ○ | ○ | - / ○ |
| | | Spectrum index and conversion factor | ○ | ○ | ○ | - |
| | | $\beta$ eff | ○ | ○ | - | - |
| | *derivative core* | Single absorber worth | ● | ● | ● | - |
| | | Absorber cluster worth | - | - | - | ● |
| | | Iso-thermal temp. coefficient | ● | ● | ● | - |
| | | Boron efficiency (differential/integral) | ● | ● | ● | ● |
| | | Water hole worth | ● | ● | - | - |
| | | 2D void worth | - | - | ● | - |

## 3. Analysis Method

CASMO-4 code is a multigroup two-dimensional transport theory code using the Characteristics method on BWR and PWR assemblies or simple pin cells. The neutron data library is based on data from ENDF/B-IV although some data come from other sources. The microscopic cross sections are constituted in 70 energy groups.

Fig.2 shows, the calculation model of CASMO-4, handling a fuel assembly or a simple pin cell in a square pitch array, is shown for the MISTRAL-1. The MISTRAL cylindrical cores were modeled using a rectangular geometry with BLACK boundary condition. The fuel pins were modeled to fuel pin cells, and the moderation capability of the moderator surrounding the real core was simulated by adjusting the amount of moderator being given in the rectangular shape outside the modeled core. Axial leakage was treated with a measured axial buckling.

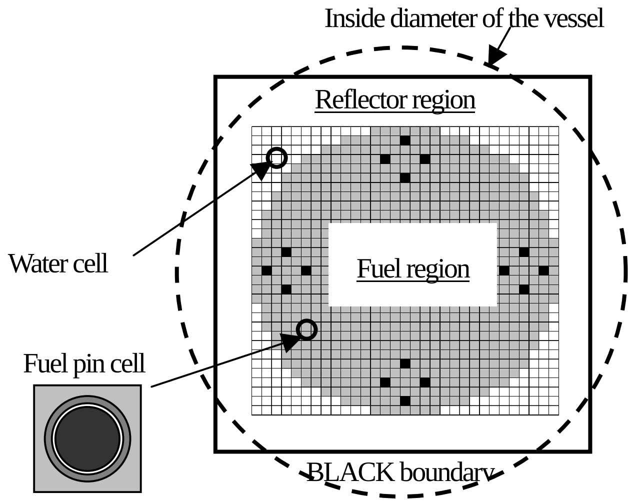


**Fig.2** Calculation model of CASMO-4

## 4. Results and Discussion

### 4.1 Critical keff

Table 3 shows the calculated critical keff with a fraction of MOX fuels in each core. For MISTRAL-4 seven mock-up configurations, loaded absorber clusters in both MOX and $UO_2$ central assemblies, were measured.

For MISTRAL-1 the calculated results show good agreement to the experimental data, while for the MISTRAL-2, 3 and 4 the results were overestimated. The results show that CASMO-4 overestimates for the MOX cores and calculation accuracy doesn't depend on the H/HM and the absorber type but the fraction of MOX fuels in the core. The cause of the overestimation seems to be the defects of the neutron data library.

**Table 3** Critical keff

| | MISTRAL | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Core 1 | Core 2 | Core 3 | Core 4 | | | | | | |
| Configuration (MOX/MOX+$UO_2$ [%]) | $UO_2$-Ref. (0) | MOX-Ref. (100) | MOX-Ref. (100) | MOX-Ref. (100) | MOX-SUS (100) | MOX-Hf (78) | MOX-AIC (75) | MOX-$B_4C$ (69) | $UO_2$-Ref. (76) | $UO_2$-$B_4C$ (60) |
| Critical keff | 1.0012 | 1.0062 | 1.0065 | 1.0075 | 1.0074 | 1.0043 | 1.0063 | 1.0042 | 1.0042 | 1.0039 |

### 4.2 Fission rate distribution

Table 4 shows the differences between calculation and measurement in fission rate distribution. The results agreed well with the experimental data within 3% in root-mean-square (RMS) error, which is evaluated from all measurement points over the cores. Considering the measurement points were different in each core, CASMO-4 seems to have the same accuracy in all configurations. Fig.3 shows the differences between the calculated and the measured fission rate distributions along a diagonal direction for MISTRAL-4 MOX core and $UO_2$ core. For $UO_2$ core, $UO_2$ fuel pins next to MOX fuel pins were overestimated, while MOX fuel pins were underestimated.

**Table 4** Fission rate distribution

| C-E/1 [%] | | MISTRAL Core 1 | MISTRAL Core 2 | MISTRAL Core 3 |
|---|---|---|---|---|
| Ref. | | 5.0 | 4.2 | 9.3 |
| | | -3.3 | -3.0 | -3.5 |
| | | 2.0 | 1.8 | 2.0 |
| Single absorber | $UO_2$-$Gd_2O_3$ | 4.9 | 2.2 | 3.5 |
| | | -2.1 | -2.1 | -2.9 |
| | | 1.4 | 0.9 | 1.5 |
| | Ag-In-Cd | 5.3 | 3.0 | - |
| | | -1.7 | -2.6 | |
| | | 1.4 | 1.2 | |
| | narural $B_4C$ | 5.2 | 2.6 | - |
| | | -1.9 | -1.7 | |
| | | 1.5 | 1.0 | |
| | enriched $B_4C$ | 4.8 | 3.3 | 3.9 |
| | | -1.7 | -2.0 | -2.9 |
| | | 1.2 | 1.0 | 1.5 |
| temperature 80°C | | 3.6 | 2.9 | 4.4 |
| | | -2.5 | -2.5 | -3.6 |
| | | 1.7 | 1.4 | 1.7 |
| water-hole | | 6.2 | 7.0 | - |
| | | -3.4 | -6.6 | |
| | | 2.2 | 3.5 | |

| C-E/1 [%] | | MISTRAL-4 MOX | $UO_2$ 17x17$UO_2$ | $UO_2$ MOX | Total |
|---|---|---|---|---|---|
| Ref. | | 3.9 | 1.9 | 3.5 | 4.2 |
| | | -4.0 | -5.8 | -6.2 | -6.8 |
| | | 1.5 | 2.7 | 2.9 | 2.4 |
| Absorber cluster | 24Hf | 4.0 | - | | |
| | | -3.5 | | | |
| | | 1.6 | | | |
| | 24AIC | 3.9 | - | | |
| | | -2.9 | | | |
| | | 1.5 | | | |
| | 24$B_4C$ | 4.8 | 2.9 | 3.2 | 4.1 |
| | | -4.5 | -5.3 | -4.0 | -4.6 |
| | | 1.9 | 2.2 | 1.7 | 1.8 |

・The differences between measurement and calculation (C-E/1[%])

| |
|---|
| Max + |
| Max - |
| RMS |

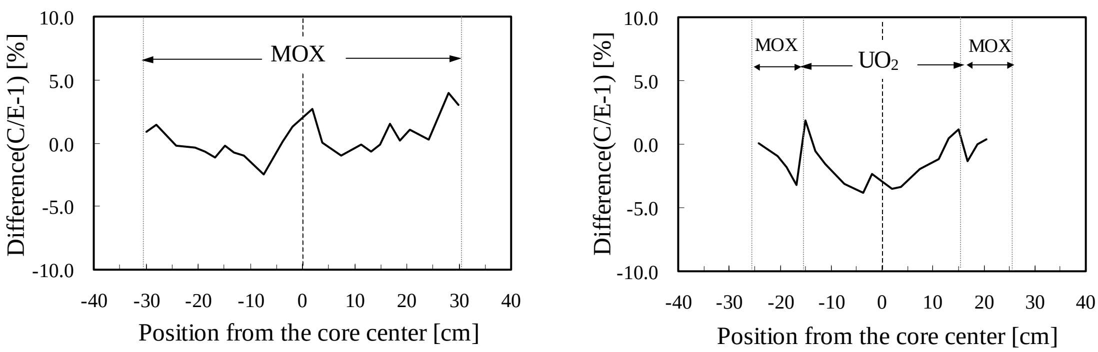


**Fig.3** Fission rate distribution along a diagonal direction

### 4.3 Single absorber and absorber cluster worth

The measurement of absorber worth was carried out for the absorbers loaded at the center of the core by using the method of soluble boron equivalence (SBE) and the Amplified Source Method (ASM). The worth of single absorber of $UO_2$-$Gd_2O_3$, Ag-In-Cd, natural $B_4C$ and enriched $B_4C$ were measured for the MISTRAL-1, 2 and 3 and the worth of absorber cluster of 12 SUS, 24 Ag-In-Cd and 24 enriched $B_4C$ were measured for the MISTRAL-4.

Table 4 shows the differences of absorber worth between calculation and measurement with measurement uncertainties. For homogeneous $UO_2$ core and MOX cores we had the same accuracy in predicting the absorber worth. The efficiency of single absorber was predicted within the error of about 10%. For the absorber cluster worth the calculated results were underestimated from about 7 to 15%. As 12 SUS cluster had a small worth, the difference seems to be large. The difference (C-E) was very small comparing other absorber clusters.

**Table 5** Single absorber and absorber cluster worth

| C/E-1 [%] (measurement uncertainty[%]) | | MISTRAL | | | | |
|---|---|---|---|---|---|---|
| | | Core 1 | Core 2 | Core 3 | | Core 4 (MOX) |
| measurement method | | SBE | ASM | SBE | ASM | ASM |
| single absorber | $UO_2$-$Gd_2O_3$ | 4.6 (3.9) | 0.9 (6.1) | 12.6 (8.2) | 1.6 (5.7) | - |
| | Ag-In-Cd | 6.3 (2.7) | 5.3 (6.1) | - | - | |
| | natural $B_4C$ | 7.2 (2.5) | -13.1 (6.1) | - | - | |
| | enriched $B_4C$ | 8.5 (1.8) | -7.1 (6.0) | 3.6 (6.3) | -5.4 (5.7) | |
| absorber cluster | 12SUS | - | | | | -14.8 (5.3) |
| | 24Hf | | | | | -9.3 (5.2) |
| | 24AIC | | | | | -9.3 (5.2) |
| | 24$B_4$C | | | | | -6.7 (5.2) |

### 4.4 Boron efficiency coefficient

The differential boron efficiency coefficient around the critical state was deduced from reactivity between two states. The measurement was carried out for four states differing from the boron concentration in a few ppm by using doubling time (DT) and ASM.

Table 6 shows the differences of differential boron efficiency coefficient between calculation and measurement with measurement uncertainties. The calculated results were overestimated for MISTRAL-1, 2 and 3 and underestimated for MISTRAL-4. The results were predicted within about twice the measurement uncertainty in all cases.

**Table 6** Differential boron efficiency coefficient

| C/E-1 [%] (measurement uncertainty[%]) | MISTRAL | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Core 1 | | Core 2 | | Core 3 | | Core 4 | |
| Measurement method | DT | ASM | DT | ASM | DT | ASM | DT | ASM |
| Boron efficiency coefficient | 4.1(11.3) | 2.3(20.0) | 1.6(4.3) | 7.3(6.4) | 6.2(4.0) | 4.4(6.1) | -15.1(5.3) | -17.1(10.3) |

### 4.5 Temperature coefficient

The temperature coefficient was deduced from reactivity between two states. The measurement was carried out at temperature ranging from 10$^{o}$C to 80$^{o}$C by using SBE, DB and ASM.

Fig.3 shows the relative value of temperature coefficient between calculation and measurement. The temperature was plotted the average temperature of two states. For MISTRAL-3 temperature coefficient by ASM was plotted except 70$^{o}$C, because this value seemed to be doubt. The calculated results agreed to the measurement value within about twice the measurement uncertainty. The difference between calculation and measurement by SBE was larger as the temperature was higher. In SBE the worth was obtained from the difference of boron concentration between two states by the differential boron efficiency coefficient. The coefficient seems to have not been used adequately at each temperature.

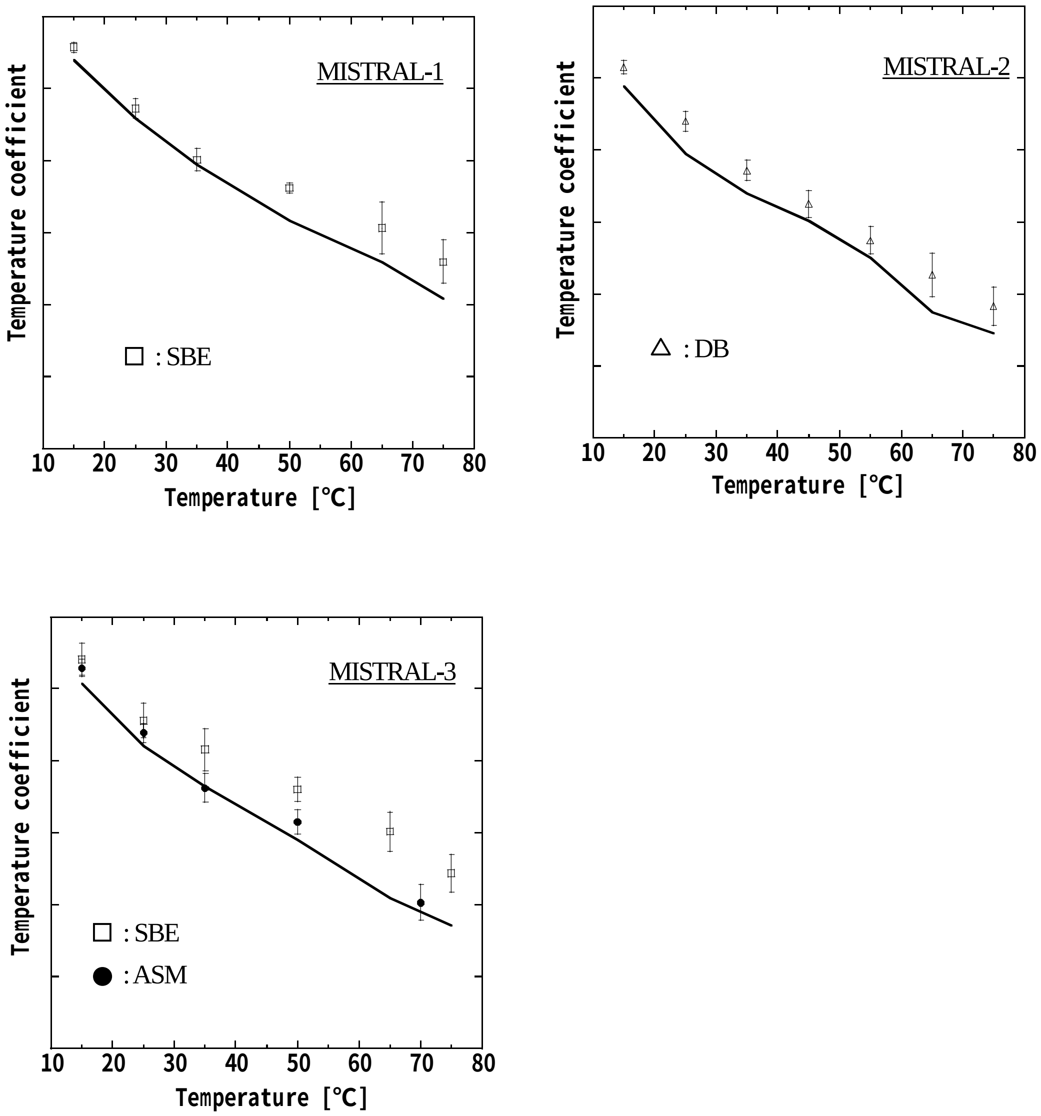


**Fig.4** Temperature coefficient

### 4.6 Water-hole reactivity

For MISTRAL-1 and 2 the reactivity effect of the substitution of 3x3 central fuel pins by water were measured by using ASM and SBE.

Table 7 shows the differences of water-hole reactivity between calculation and measurement with measurement uncertainties. The calculated results agreed well with the experimental data by ASM.

**Table 7** Water-hole reactivity

<table>
<tr><td rowspan="2">C/E-1 [%]<br>(measurement uncertainty[%])</td><td colspan="3">MISTRAL</td></tr>
<tr><td colspan="2">Core 1</td><td>Core 2</td></tr>
<tr><td>Measurement method</td><td>ASM</td><td>SBE</td><td>ASM</td></tr>
<tr><td>3x3 water-hole reactivity</td><td>-11.7(19.2)</td><td>-17.9(7.6)</td><td>-1.7(6.0)</td></tr>
</table>

### 4.7 2D void reactivity

For MISTRAL-3 the reactivity effect of the substitution of 7x7 central fuel pins by void simulation pins were measured by using ASM and SBE.

Table 8 shows the differences of 2D void reactivity between calculation and measurement with measurement uncertainties. The difference tends to be large as the void fraction increases, however the calculated results agreed well within twice the measurement uncertainty in all cases.

**Table 8** 2D void reactivity

<table>
<tr><td colspan="2" rowspan="2">C/E-1 [%]<br>(measurement uncertainty[%])</td><td colspan="2">MISTRAL-3</td></tr>
<tr><td>ASM</td><td>SBE</td></tr>
<tr><td rowspan="3">Void</td><td>40%</td><td>5.9(5.4)</td><td>7.1(5.8)</td></tr>
<tr><td>60%</td><td>6.1(5.4)</td><td>9.2(5.9)</td></tr>
<tr><td>100%</td><td>8.8 (5.%)</td><td>10.6(5.9)</td></tr>
</table>

## 5. Conclusion

The MISTRAL cores were analyzed using CASMO-4 code. The critical keff was overestimated for MOX cores. For the fission rate distribution the results agreed well with the experimental data within 3% in RMS error. For single absorber and absorber cluster worth, boron efficiency coefficient, temperature coefficient, water-hole reactivity and 2D void reactivity the results were predicted within about twice the measurement uncertainty. CASMO-4 had the same accuracy in all configurations except for the critical keff. As the cause of the overestimation seems to be the defects of the neutron data library, so we are replacing the library based on ENDF/B-IV to the neutron data library JENDL-3.3 released in 2002.

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