Analysis of MISTRAL Experiments with JENDL-3.2

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NUPEC and CEA have launched an extensive experimental program called MISTRAL to study highly moderated MOX cores for the advanced LWRs. The analyses using the SRAC system and the MVP code with the JENDL-3.2 library are in progress on the experiments of the MISTRAL program and also the EPICURE program that was carried out by CEA before the MISTRAL program. Various comparisons have been made between the calculation results and the measurement values.

1. Introduction

Nuclear Power Engineering Corporation (NUPEC), French Atomic Commission (CEA) and CEA's industrial partners have launched an extensive experimental program called MISTRAL (MOX: Investigation of Systems Technically Relevant of Advanced Light water reactors) [1,2,3,4,5] in order to obtain the basic core physical parameters of the highly moderated MOX cores that will be used to validate and improve core analysis methods. This experimental program was conducted in the EOLE facility at the Cadarache center and successfully completed in July 2000. As a part of the MISTRAL program, NUPEC also obtained some of the experimental data of the EPICURE program that CEA had conducted for 30% MOX loading in PWRs.

2. EOLE critical facility

The experiments have been performed in the EOLE facility that is a tank type critical facility. A cylindrical Aluminum vessel (diameter = 2.3 m, height = 3m) is installed with a cylindrical core tank (diameter = 1.0 m, height = 1.0 m) and stainless steel over structures. Fuel pins used in the facility are a standard PWR type and the active length of the pins is about 80 cm. Four types of enrichment are prepared for MOX pins and one type for UO_2 pins. The reactivity of the core is mainly controlled with the boron (boric acid) concentration in water and the core size. Core excess reactivity is determined through the in-hour equation with measuring the doubling time after the withdrawal of the pilot rod.

3. Core configurations and measurements in the MISTRAL program

The core configuration of MISTRAL-1 is shown in Figure 1. It consisted of about 750 regular enriched UO_2 (3.7% in ^{235}U) fuel pins in a lattice pitch of 1.32 cm and was designed as a reference for the highly moderated MOX cores. The core configuration of MISTRAL-2 is shown in Figure 2. This is a highly moderated full-MOX core consisting of about 1600 MOX (7% enrichment) fuel pins with the same lattice pitch of MISTRAL-1. Figure 3 shows the core configuration of MISTRAL-4 which is a PWR mock-up configuration. The UO_2-Reference configuration in MISTRAL-4 is shown in Figure 4. In this configuration the 17×17 type of UO_2 zone was installed at the center of the core, and on account of the large reactivity of UO_2 pins, the core size was smaller than that of the full-MOX cores. Measurement items were carefully selected from the followings :

(1) Critical mass and boron concentration (2) Boron worth
(3) Buckling measurement using reaction rate distribution measurements
(4) Spectrum indices (5) Modified conversion factor : 238U capture/total fission
(6) Isothermal temperature coefficients
(7) Reactivity worth and associated reaction rate distribution of a single absorber (Natural B_4C, enriched B_4C, Ag-In-Cd alloy, and UO_2-Gd_2O_3) at the center of the core)
(8) Reactivity worth and associated reaction rate distribution of a cluster absorber
(9) Reactivity worth and associated reaction rate distribution of the substitution of 9 central fuel pins by water holes / Void coefficient
(10) β eff

4. Experimental methods

The number of fuel pins, the core temperature, the boron concentration and the doubling time were measured to determine the core critical mass. The neutron source multiplication method (the sub-critical method) was utilized for the reactivity measurement. The integral gamma scanning method was applied to determine the fission distributions of the fuel pins. The miniature fission chambers of several kinds of isotopes were adopted for the determination of energy dependent neutron flux and also for the spectrum index measurements. The effective delayed neutron fraction of the core (β eff) was measured using of the core noise method which had been utilized in the international benchmark of β eff's at the MASURCA and the FCA facilities.

5. Calculation methods

The analysis has been performed using the SRAC system and the MVP code that have been developed at Japan Atomic Energy Research Institute (JAERI) with the JENDL-3.2 library. The SRAC system consists of deterministic codes. A processed nuclear data library with 107-energy group structure is prepared for it. MVP is a continuous energy Monte Carlo code that is utilized to obtain reference calculation results for the SRAC system such as core eigen-values. In the SRAC system, the collision probability method is applied for generating the 16-group collapsed and homogenized unit cell cross sections. The neutron energy spectrum affected by the neutron leakage is calculated with the B1 approximation taking into account the measured geometrical buckling. The resonance absorption of Pu isotopes should be precisely evaluated in epi-thermal and thermal ranges for MOX fuels. Thereby an ultra fine group resonance reaction calculation module, PEACO, is utilized throughout for the effective cross section calculation. The thermal cut-off energy was carefully chosen and determined to be 1.855eV through a sensitivity study. After generating 16-group cell cross sections (fast range - 8 groups and thermal range - 8 groups) , core calculations in 1/4 symmetry configuration were performed using the CITATION and/or TWOTRAN modules of the SRAC system. In two-dimensional calculation model, axial leakage is implicitly taken into account using the measured axial buckling.

6. Calculation results and discussion

Varieties of comparisons between the calculations and the measurements have been carried out for MH1.2 (which is devoted to study on basic characteristics of a 30% MOX core in the EPICURE program), MISTRAL-1, -2 -3 and -4. The critical keff for 4 core reference configurations is shown in Table 1. The calculation results of MVP with

JENDL-3.2 overestimated all the critical keff both for the UO_2 core and the MOX cores. For MISTRAL-1, the overestimation is about 0.5%. On the other hand, the calculation results of SRAC for MISTRAL-1 underestimated the critical keff because of the calculation errors for such a very small core. Among the MOX cores, a small trend of increasing of the critical keff with the experiment date is observed. This increase is considered to be related with the change of the atomic number densities of the materials in MOX pins (the Pu aging effect). After the additional study, the underestimation of the neutron capture cross section of ^{241}Am of JENDL-3.2 would be a main reason. Among the 7 core configurations of MISTRAL-4 experiments, the partial UO_2 configurations are of much interest because they provide the UO_2 and MOX combined critical mass and complicated radial power distributions. The critical keff for the 7 configurations of MISTRAL-4 is shown in Table 2. For the full-MOX core configuration, the calculation results of MVP agree very well each other and the overestimation of the critical keff is always about 0.9%. Compared with this, the calculation result for the UO_2-Reference configuration is smaller. Because the UO_2-zone is installed at the center of the core hence the overestimation was little reduced by the features of the UO_2 core with JENDL-3.2. In the UO_2-B_4C configuration, the ratio of the outer MOX-zone was increased and the character of a UO_2 core was diminished. Thereby it showed almost the same critical keff of MOX cores in MISTRAL-4. The root-mean-square (R.M.S) differences of the radial power distribution is shown in Table 3. The differences are as much as the uncertainty of measurement. Further studies both for the critical keff and the power distribution are required and still ongoing.

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Table.1 Critical keff for 4 Core Reference Configurations

PROGRAM	EPICURE	MISTRAL			
CORE NAME	MH 1.2	CORE 1	CORE 2	CORE 3	CORE 4 (MOX-Ref)
FEATURE	Partial MOX	Uranium CORE	Full MOX	Full MOX	PWR Mock-up
FUEL PIN	3.7%UO2 + 7% MOX	3.7% UO2	7% MOX (Mainly)	7% MOX	7% MOX
LATTICE PITCH	1.26 cm	1.32 cm	1.32 cm	1.39 cm	1.32 cm
H/HM	3.7	5.1	5.1	6.2	5.8
CORE DIAMETER	69 cm	41 cm	60 cm	59 cm	62 cm
EXPERIMENT DATE	June 1996	---	April 1997	August 1998	August 1999
MVP	1.0027 ±0.02 % (1σ)	1.0048 ±0.03 % (1σ)	1.0070 ±0.02 % (1σ)	1.0077 ±0.02 % (1σ)	1.0093 ±0.02 % (1σ)
SRAC (Pij + TWOTRAN)	1.0013	0.9981	1.0041	1.0042	1.0074

Table. 2 Critical keff of 7 Core Configurations in MISTRAL-4

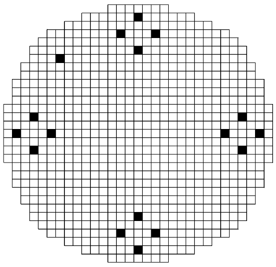
Core Configuration		Calculation Method		
		SRAC (Pij + CITATION)	SRAC (Pij + TWOTRAN)	MVP
Full-MOX	MOX - Reference	1.0074	1.0074	1.0093 ± 0.02 % (1σ)
	MOX - SUS	1.0074	1.0072	1.0093 ± 0.02 % (1σ)
	MOX - Hf *	1.0054	1.0072	1.0091 ± 0.02 % (1σ)
	MOX-AIC *	1.0054	1.0073	1.0094 ± 0.02 % (1σ)
	MOX -B_4C *	1.0049	1.0092	1.0098 ± 0.02 % (1σ)
Partial UO_2 (UO_2 + MOX)	UO_2 - Reference	0.9990	1.0024	1.0060 ± 0.02 % (1σ)
	UO_2 - B_4C	1.0017	1.0071	1.0089 ± 0.02 % (1σ)

* UO_2 pins were put in the outer part of the core

Table. 3 R.M.S Differences of Radial Power Distribution between Calculation and Measurement for each Experimental Core

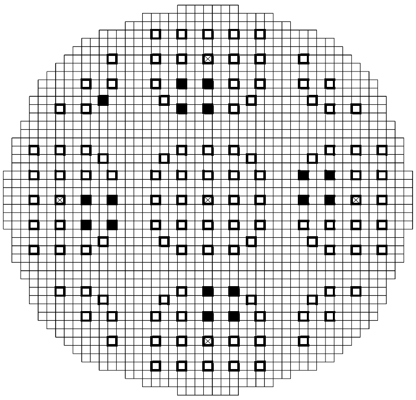
PROGRAM	EPICURE	MISTRAL			
CORE NAME	MH 1.2	CORE 1	CORE 2	CORE 3	CORE 4
FEATURE	Partial MOX	Uranium CORE	Full MOX	Full MOX	PWR Mock-up
MVP	1.2 %	1.7 %	1.7 %	1.4 %	1.3 %
SRAC (Pij + CITATION)	0.9 %	2.0 %	1.1 %	1.3 %	1.0 %

Measurement uncertainty UO$_2$ rod ～1.0 % : MOX rod ～ 1.5 % （1σ）



☐ MOX(7.0%) fuel rod

■ Guide tube for safty and control rod



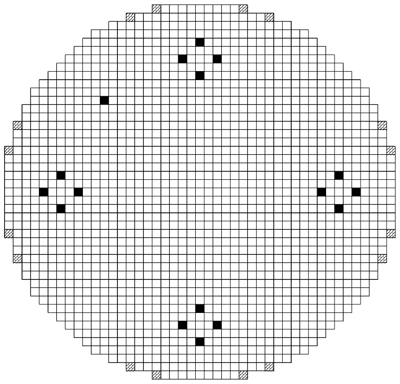
☐ MOX(7.0%) fuel rod

☐ Mock-up thimble tube

☒ Instrumentation tube

■ Guide tube for safty and control rod

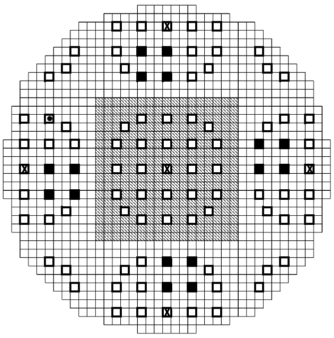
Fig.3 Core Configuration of MISTRAL-4
MOX-Reference configuration



☐ MOX(7.0%) fuel rod

▨ MOX(8.7%) fuel rod

■ Guide tube for safty and control rod



☐ MOX(7.0%) fuel rod

▨ UO_2(3.7%) fuel rod

☒ Instrumentation tube

■ Guide tube for safety and control rod

Fig.4 Core Configuration of MISTRAL-4
UO_2-Reference configuration