JOYO MK-II Core Characteristics Database

- Upgrade to JENDL-3.2 -

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ABSTRACT

The JOYO core characteristics database, which was published in 1998, was revised based on requests and comments from users. The revisions included changes of group constant set, addition of reactor kinetic parameters and experimental data of the MK-II core start-up test, etc..

1. Introduction

The experimental fast reactor JOYO at O-arai Engineering Center of Japan Nuclear Cycle Development Institute was operated as the MK-II irradiation core for testing fuel and material for FBR development from March 1983 to June 2000.

Through the MK-II operation, extensive data were accumulated on core management calculations and core characteristics tests. These data of thirty-one duty cycle operations and thirteen special test operations were compiled into a database which were recorded on CD-ROM and the first edition$^{1)}$ was published in 1998.

This database was widely used for the verification of nuclear calculations and analysis of post irradiation examinations. After that, there were many requests such as the renewal of the group constant set and the addition of reactor kinetic parameters, etc. from many users. The database was then revised in response to these requests.

2. Operating History of JOYO MK-II Core

The operating history of the MK-II core is shown in Fig.1. In 1982, the MK-I breeder core was replaced by the MK-II irradiation core. The MK-II core attained initial criticality on 22nd November 1982, and it achieved a power level of 100MWt in 1983. Thirty-five duty cycle operations and

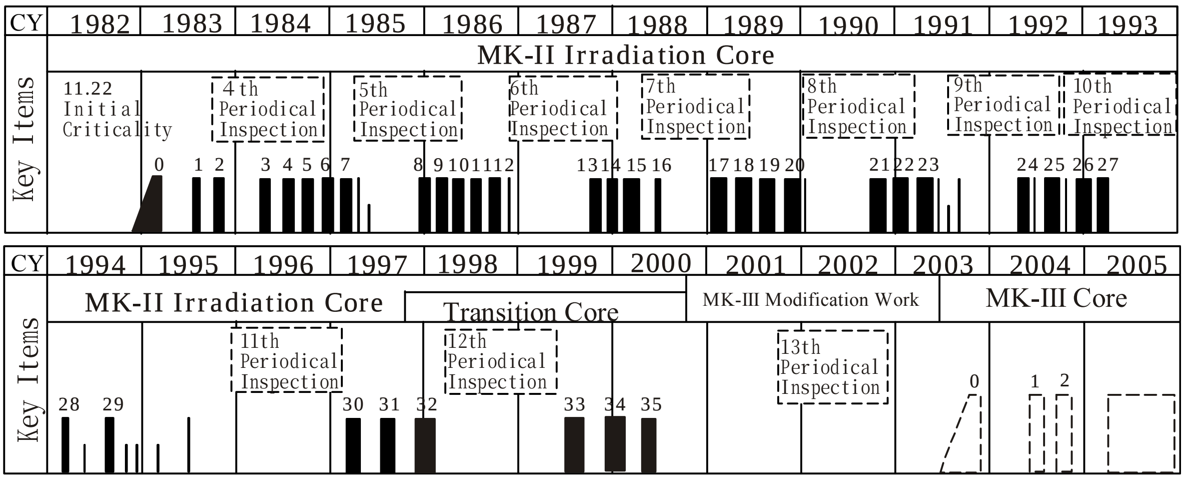

Fig.1 Operating History of JOYO MK-II Core

thirteen special tests were conducted using the MK-II core by June 2000. The thirty-second to thirty-fifth duty cycles were operated as the MK-III transition core, and the fuel region was gradually extended.

The MK-II core and the MK-III transition core were operated in total for 47,757 hours and the integrated power generation was 4,388GWh. During these operations, 362 driver fuel subassemblies and 69 irradiation test subassemblies were irradiated. A pellet peak burn-up of the driver fuel subassembly attained approximately 85GWd/t.

JOYO is currently being upgraded to the MK-III high performance irradiation core,[2), 3).4)] which will achieve its initial criticality in July 2003.

3. Specifications of MK-II Core

JOYO is a sodium cooled fast reactor with mixed oxide (MOX) fuel. The main core parameters of the MK-II core are shown in Table 1, with that of the MK-III core.

The plutonium content of the fuel subassembly was about 30wt%. At the beginning of the MK-II core operation, ^{235}U enrichment was about 12wt%(J1 fuel), and it was later increased to 18wt%(J2 fuel) to provide enough excess reactivity so that the core burn-up was increased. Consequently, the operational period was extended from 45 days to 70 days.

In the MK-III core, the number of fuel subassemblies and neutron fluence will be increased in comparison with the MK-II core. The fuel region will be divided into inner and outer regions to flatten the neutron flux distribution.

Table 1 Main Core Parameters of JOYO

		MK-II	MK-III
Reactor Power	(MWt)	100	140
Inlet / Outlet Temperature	(℃)	370/500	350/500
ore Height	(cm)	55	50
Core Volume	(liter)	230	260
Max. Number of Fuel Subassemblies		67	85
Fuel Type		MOX (UO_2-PuO_2)	
Pu Content	(wt%)	30	23/30 *
^{235}U Enrichment	(wt%)	12 (J1) 18 (J2)	18
Max. Fast Neutron Flux (E≧0.1MeV)	($\times 10^{15}$n/cm^2･s)	3.2	4.0
Max. Total Neutron Fux	($\times 10^{15}$n/cm^2･s)	4.9	5.7
Max. Excess Reactivity (at 100℃)	(%Δk/kk')	5.5	4.5
Max. Linear Heat Rate	(W/cm)	400	420
Max. Burn-up (Pin Average)	(MWd/t)	50,000(J1) 75,000(J2)	90,000
Operation Period	(days/cycle)	45 (J1) 70 (J2)	60

*:inner/outer core

4. JOYO MK-II Core Management Code System "MAGI"

The "MAGI" calculation code system was developed to predict the reactor parameters required for the core and fuel management of the MK-II core. The calculation flow of MAGI is shown in Fig.2. MAGI is a neutronic and thermo-hydraulic coupling code system that calculates the effective multiplication factor, neutron and gamma flux, power distribution, fuel burn-up, linear heat rate, coolant flow rate, coolant and fuel temperature, etc..

MAGI is based on the diffusion theory with seven neutron energy groups for the neutronic calculation. The cross section is collapsed from the 70 group JFS-3-J3.2R constant set based on JENDL-3.2[5)]. The core configuration is modeled in three-dimensional hexagonal-Z geometry for each operational cycle. The actual reactor power history, which is accumulated using the JOYO data acquisition system, is used in the burn-up calculation based on the matrix exponential method.

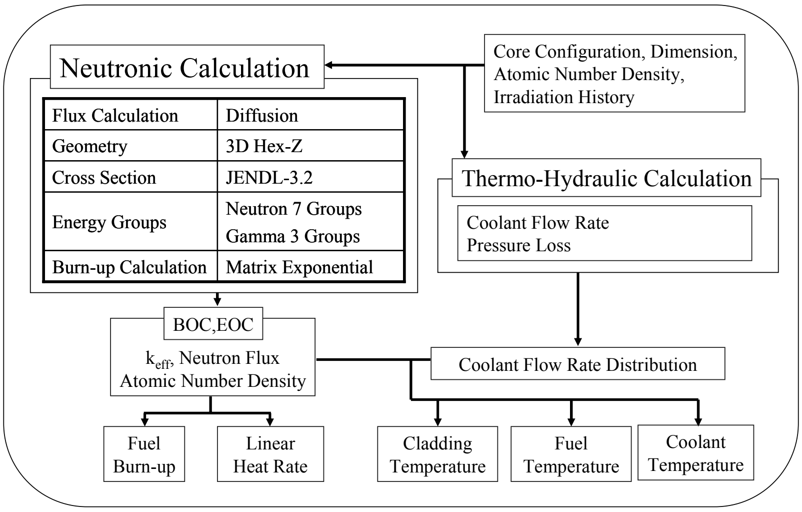

Fig. 2 JOYO MK-II Core Management Code System

In the thermo-hydraulic calculation of MAGI, the coolant flow rate distribution, and the maximum temperature of coolant, cladding and fuel are calculated. These calculation results are compiled in the CD-ROM.

5. Core Physics Tests in Each Operational Cycle

The excess reactivity in a zero power critical condition at approximately 250 °C was measured at the reactor start-up of each operational cycle.

JOYO has six control rods containing enriched B_4C. Every control rod's worth was calibrated with either the positive period method or the inverse kinetics method during the low power test of each operational cycle.

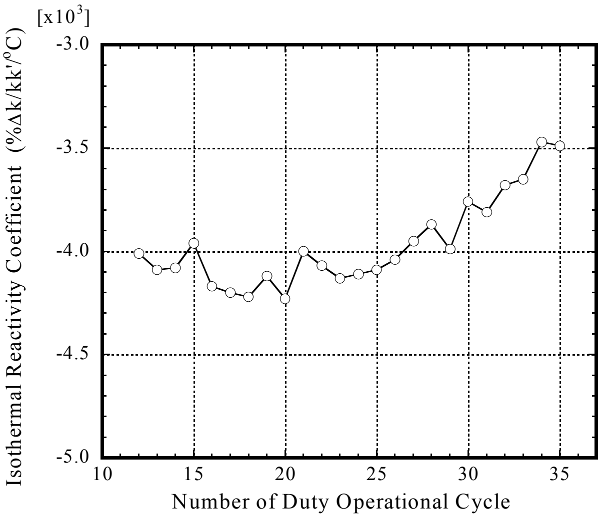

Fig.3 Measured Isothermal Reactivity Coefficient

The isothermal reactivity coefficients were measured by taking the difference of reactivity at approximately 250 °C and 370 °C in a zero power critical condition. The measured isothermal reactivity coefficients were constant through the MK-II operation because they were determined mainly by radial expansion of the core support plate, which is independent of burn-up. However, when the core region was gradually extended from the 32nd cycle, the isothermal reactivity coefficients were decreased as predicted with the mechanism of the core support plate expansion. The measured isothermal reactivity coefficient is shown in Fig.3.

The power reactivity coefficients were measured at the reactor power increasing and decreasing in each operational cycle. The measured power reactivity coefficients decreased with increasing core burn-up. It was observed that the fuel thermal expansion, which is the major component of the power reactivity coefficient of JOYO, decreases at high burn-up due to fuel restructuring during the irradiation. It was also observed that the power reactivity coefficients varied depending on the reactor power. This phenomenon appeared to be due to a combination of the core bowing effect, fuel thermal expansion and Doppler effects. These causes need further investigation.

The burn-up reactivity coefficients were determined by measuring the reactivity change during rated power operation. Measured values were compared with the MAGI burn-up calculation and both agreed within 5%. It is considered that the decrease of atomic number densities of major fissile nuclides as ^{235}U and ^{239}Pu are the dominant factor of burn-up reactivity coefficients because of JOYO's small core size, which results in a hard neutron spectrum and a small internal conversion ratio. Therefore, the burn-up reactivity coefficients can be predicted accurately even at a high burn-up.

6. Structure of Database

The MK-II core management data and core characteristics data were recorded on CD-ROM for the convenience of users. The structure of the database, which is shown in Fig.4, is the same as the first edition.

The core management data calculated using MAGI are compiled in text style. The "Configuration Data" includes the core arrangement and refueling record for each operational cycle. The "Subassembly Composition Data" includes the calculation results of MAGI, including atomic number density, neutron fluence, fuel burn-up, integral power of 362 fuel subassemblies and 69 irradiation test subassemblies. The "Irradiation Condition Data" contains the calculated neutron flux, gamma flux, power density, linear heat rate, coolant and fuel temperature distribution of all the fuel subassemblies at the beginning and end of each operational cycle(BOC,EOC). The "Reactor Kinetic Parameter Data" includes effective delayed neutron fraction, decay constant, and prompt neutron lifetime of each operational cycle.

The “Core Physics Test Data” includes the excess reactivity, control rod worth calibration curve, and reactivity coefficients of temperature, power and burn-up, which were measured in each operational cycle.

Users can edit these core management data with personal computers and analyze the core characteristics of the MK-II core, by forwarding these data to engineering workstations or super computers. By comparing the calculated core characteristics results with the measured values, users will be able to use the estimated results for the core design and the analytical development of the core characteristics.

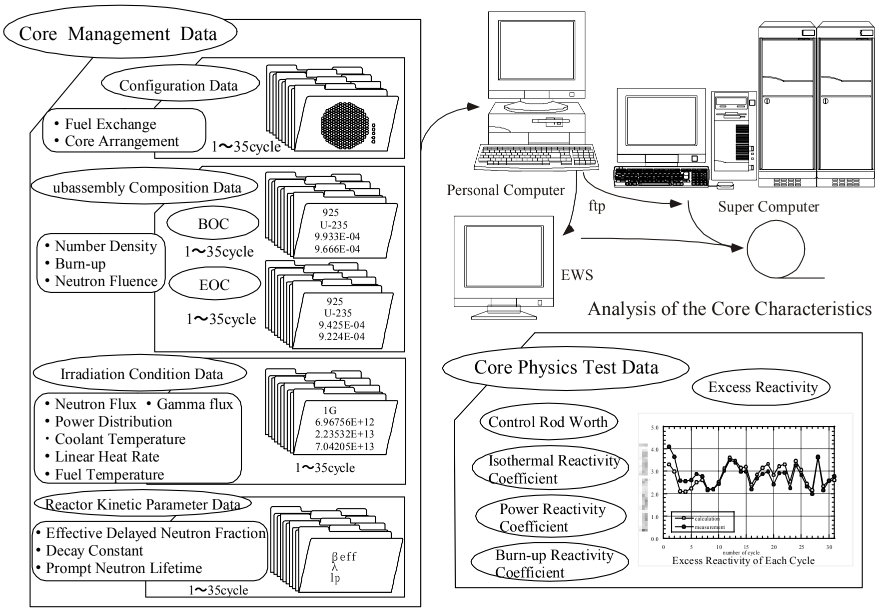

Fig. 4 Structure of JOYO MK-II Core Characteristics Database

7. Revised Point

The revisions include changes to the MAGI calculation code system to use the 70 group JFS-3-J3.2R constant set processed from the JENDL-3.2 library. The core characteristics obtained from the 32nd to 35th operational cycles, which were conducted as the MK-III transition core, were added in this revised edition. Total control rod worth, reactor kinetic parameters and the MK-II core performance test results were included according to users’ requests.

7.1 Reactor Kinetic Parameter

The effective delayed neutron fraction of each operational cycle is shown in Table 2. Each reactor kinetic parameter was calculated using equation (1) by MAGI. β and χ_d evaluated by Tomlinson[6] were used for the calculations.

$$\beta_{\mathrm{eff}}(i)=\sum_{k}\frac{\int dr\sum_{g'}\chi_d(i,k,g')\cdot\phi^*(g')\sum_{g}\nu\sigma_f(g,k)\cdot N(k)\cdot\phi(g)\cdot\beta(i,k)}{\int dr\sum_{g'}\chi_p(g')\cdot\phi^*(g')\sum_{g}\nu\sigma_f(g,k)\cdot N(k)\cdot\phi(g)} \tag{1}$$

$\beta(i,k)$: delayed neutron fraction

$\chi_d(i,k,g')$: fission spectrum of delayed neutron

$\chi_p(g')$: fission spectrum of prompt neutron

ν : number of neutrons produced per fission (n)

$\sigma_f(g,k)$: microscopic fission cross-section (cm^2)

$N(k)$: atomic number density (atoms/cm^3)

$\phi(g)$: neutron flux (n/cm^2·s)

$\phi^*(g')$: adjoint flux

i : delayed neutron precursor group

k : nuclide

g, g' : neutron energy group

Table 2 Effective Delayed Neutron Fraction of Each Operational Cycle

cycle No.	β1	β2	β3	β4	β5	β6	βeff
0	1.159E-04	8.095E-04	7.108E-04	1.399E-03	5.436E-04	1.562E-04	3.735E-03
1	1.168E-04	8.549E-04	7.477E-04	1.475E-03	5.879E-04	1.659E-04	3.948E-03
2	1.165E-04	8.535E-04	7.464E-04	1.473E-03	5.873E-04	1.658E-04	3.942E-03
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
33	1.265E-04	9.206E-04	8.037E-04	1.630E-03	6.391E-04	1.659E-04	4.286E-03
34	1.257E-04	9.165E-04	7.999E-04	1.623E-03	6.365E-04	1.650E-04	4.266E-03
35	1.253E-04	9.152E-04	7.987E-04	1.620E-03	6.365E-04	1.650E-04	4.261E-03

7.2 Upgrade to JENDL-3.2

In this revision, the group constant set was changed from JENDL-2[7)] to JENDL-3.2. The effect on the calculation results by changing of the group constant set was examined.

Table 3 Comparison of Atomic Number Density
(unit: x10^{24} atoms/cm^3)

Library	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
JENDL-3.2	9.06E-04	4.95E-03	1.29E-03	5.43E-04	1.16E-04	8.50E-05
JENDL-2	8.98E-04	4.94E-03	1.29E-03	5.49E-04	1.15E-04	8.55E-05
J3.2/J2	1.01	1.00	1.00	0.99	1.01	0.99

Table 3 shows the burn-up calculation results of a driver fuel subassembly. It was originally irradiated at the core center and it was later moved to the 2nd row and irradiation was continued until the pin averaged burn-up reached approximately 62GWd/t. The burn-up calculation was conducted using the matrix exponential method. One group cross-section, which was collapsed from the seven group cross section using the calculated neutron flux at each mesh, was used for the burn-up calculation. The calculation results of main nuclides based on JENDL-3.2 are almost the same as JENDL-2.

Figure 5 shows the calculated excess reactivity at the beginning of each cycle. By the loading of irradiation test subassemblies, the number of the replaced fuel subassemblies and operation plans, the excess reactivity changed from approximately 1.5 to 4.0%Δk/kk'. The calculated results using JENDL-3.2 are about 0.45%Δk/kk' lower than the results using JENDL-2. It is because $\nu\sigma_f$ of ^{235}U and ^{239}Pu evaluated in JENDL-3.2 are smaller than that of JENDL-2. A similar tendency was shown in the criticality analysis of JUPITER experiment.

Table 4 shows the calculation results of the total neutron flux, fuel power, radial and axial peaking factor, which were calculated using JENDL-3.2 and JENDL-2. The transport cross-sections of uranium, plutonium and sodium of JENDL-3.2 are smaller than that of JENDL-2. Therefore, diffusion coefficients for the fuel region were increased. As a result, fuel power in the core center region decreased and the radial peaking factor decreased by about 3%.

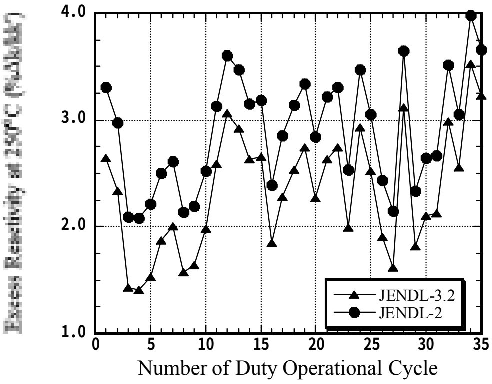

Fig. 5 Calculated Excess Reactivity of Each Operational Cycle

Table 4 Comparison of Calculated Results

Items		JENDL-2	JENDL-3.2	J3.2/J2
Total Neutron Flux($n/cm^2 \cdot s$)*	**BOC**	**4.00E+15**	**3.99E+15**	**0.999**
	EOC	**4.03E+15**	**4.03E+15**	**0.999**
Fuel Power * (MW / S/A)	**BOC**	**2.15**	**2.12**	**0.983**
	EOC	**2.13**	**2.09**	**0.983**
Radial Peaking Factor	**BOC**	**1.451**	**1.405**	**0.968**
	EOC	**1.434**	**1.396**	**0.974**
Axial Peaking Factor	**BOC**	**1.199**	**1.195**	**0.997**
	EOC	**1.190**	**1.186**	**0.997**

* Core Center

8. Conclusion

The JOYO MK-II core characteristics database was revised in response to the requests from the users. In the revised version, the group constant set was changed from JFS-3-J2 based on JENDL-2 to JFS-3-J3.2R based on JENDL-3.2, and the following data were added: reactor kinetic parameter, MK-II core start-up test results(0 cycle), core characteristics data from the 32nd to 35th cycles and total control rod worth.

The effect of updating the group constant set was observed as follows: The calculation results of excess reactivity decreased by about 0.45%Δk/kk', radial peaking factor was reduced by about 3%, and fuel composition change of the main nuclides due to burn-up was negligible.

The core characteristics data of JOYO are very valuable data. This database is anticipated to be used in the various fields for, e.g., verification of the nuclear data and nuclear calculation codes. Application of JOYO MK-II database is shown in Fig.6.

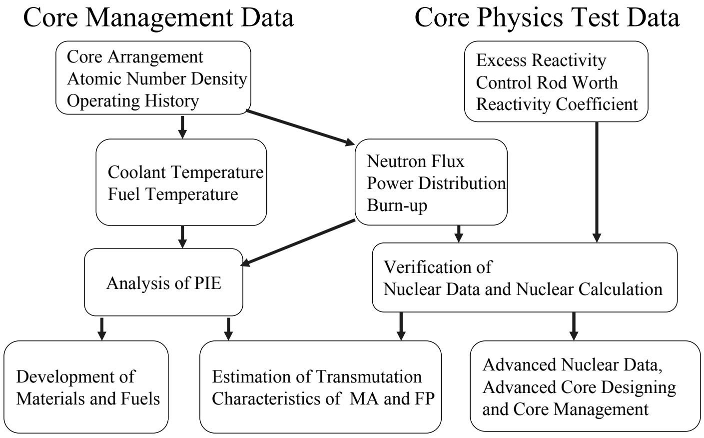

Fig. 6 Application of JOYO MK-II Core Characteristics Database

The MK-III high performance irradiation core will achieve initial criticality in July 2003. In order to confirm the core characteristics from low power to rated power, core performance tests will be conducted. The power and neutron flux distribution will be measured in detail using about 90 dosimeter sets.

To improve the neutronic calculation accuracy in the MK-III core, the upgraded core management code system "HESTIA" is applied. Three-dimensional triangle-Z model is used in HESTIA to increase the calculation points. In the horizontal cross section, one hexagonal core subassembly is divided into 24 meshes. In the vertical direction, the fuel region (50cm) is divided into 20 meshes. Eighteen neutron energy groups are adopted to improve the calculation accuracy of the neutron spectrum. Through these upgrades of the core management code system, neutron flux within the driver fuel and irradiation test subassemblies can be calculated in detail.

The calculated and measured results of the MK-III core will be published as the JOYO MK-III core characterization database.

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