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Current Status of NuStar's PWR Core Analysis Code System

Shaohong Zhang
Shanghai NuStar Nuclear Power Technology Co., Ltd,
Room 508, 81 South Qin Zhou Road, Shanghai 200235, China
shzhang@nustarnuclear.com

1. Introduction

For years, NuStar has been developing its own PWR core analysis code system for production use. It is composed of a 2D lattice physics code ROBIN [1], a 3D nodal code EGRET [2] for steady state core analysis and a kinetic code EGRET-K [3] for 3D neutron kinetics applications. So far, after extensive code verifications and validations, especially validations against the measurement data for all the types of operating PWR units in China, the code system has been adopted for various purposes by Chinese utilities, design institutes and the regulator technical center as well. Very recently, after repeated on-site validation tests at different units, the code system has been licensed by the National Nuclear Safety Administration of China for its application for Dynamic Rod Worth Measurement (DRWM) [4].

2. Methodology

The system is developed within the framework of today's two-step method, it is an integration of proven technology, newly-emerged technology and also NuStar's proprietary technology.

2.1 Lattice code

For the lattice physics code ROBIN, the conventional equivalence theory is adopted for resonance treatment for infinite lattice, and the MOC-based enhanced neutron current method [5] is used for generating the position-dependent Dancoff factors. A correction factor table is pre-generated to consider the resonance interference effect between different resonant nuclides.

For neutron spectrum calculation, like most of today's lattice physics codes, a CMFD-accelerated MOC method is adopted. To improve the performance of both computational time and machine memory usage, a series of techniques, such as cyclic ray tracing and optimization of azimuthal angle discretization are implemented in the code.

While for fuel depletion, the linear rate (LR) method [6] and the log linear rate (LLR) method [7] are adopted for normal UO_2 fuel pin and Gd-bearing fuel pin respectively to perform transport-depletion calculation. The depletion of Gd-bearing fuel assembly can be performed with satisfactory results by adopting the same size of time step as that for the Gd-free fuel assembly.

The code has the necessary geometry modeling capability for its applications to most of today's PWR fuel assembly designs. In addition to its basic capability of unit assembly calculation with reflective boundary condition, the code is also capable to do 2x2 or 3x3 multiple fuel assemblies calculation with non-reflective boundary condition. The 2D baffle/reflector homogenization effect can be explicitly modeled by the code and it adopts the same 1D transversely-integrated neutron diffusion problem solver as that for the downstream core calculation to generate discontinuity factors for baffle/reflector nodes.

2.2 Core code

For the 3D core code EGRET, it is characterized by the following features:

- using both local instantaneous parameters and historical parameters to generate nodal homogenized cross sections from pre-generated cross section tables.
- adopting NuStar's innovative CIAMA nodal method [8] as the kernel to solve the multigroup neutron diffusion problems. It enables EGRET to explicitly consider the axial intra-nodal heterogeneities caused by fuel grid and/or partially-inserted control rod without the need to do any 3D/1D coupled iterations and the on-line nodal re-homogenization.
- adopting a group-decoupled direct fitting method for multigroup Pin Power Reconstruction (PPR) [9]. The unique feature of the method is that in addition to nodal volume and surface average fluxes and corner fluxes, transversely-integrated 1D nodal solution flux profiles are also used as the condition to determine the 2D intra-nodal flux distribution. It is demonstrated that the PPR model can not only produce satisfactory results for reactor core with UO_2 fuel, it can also give accurate results for the challenging core with UO_2/MOX fuel mixed loading [9].

While for EGRET-K, it adopts the conventional fully-implicit difference method and the time integration method to discretize the time derivative terms appearing in the neutron flux equation and the delayed neutron precursor equation respectively. The CIAMA nodal method is also adopted to solve the time-discretized equation. Due to the unique advantage of its nodal kernel, EGRET-K is able to basically eliminate the control rod cusping effect for kinetic problems involving control rod movement [3].

3. Verification and Validation (V&V) status

In order to qualify the system for practical applications, extensive verification and validation tests have been performed. For the verification purpose, both unit test and integral test are performed for each one of the constituting code. The obtained results are verified against either critical experiment data or well-defined benchmark problems. Table 1 to 3 gives the V&V matrix for ROBIN, EGRET and EGRET-K respectively.

While for the validation purpose, the ROBIN/EGRET code system has been systematically applied to analyze all the operation histories of 7 PWR units at the Qin Shan site. Other operation histories available to NuStar are also used to validate the code system. So far, totally 62 cycles have been evaluated, where besides the basic difference in the fuel and reactor designs, the validated cases cover a good variety in feed enrichment, burnable poison type, reactor core power density, fuel management strategy and fuel loading pattern. Calculations are compared against the measurement data, both for low power physics test (LPPT) conditions and for normal power operation conditions. Large amount of comparison results are obtained and statistical analyses are performed for deviations between calculation results and the measurement data. Since it is impossible to present the results exhaustively, Fig.1 and 2 give the statistic for control rod worth and assembly power as examples.

Besides code validations performed against LPPT data and the routine operation data, the whole code system, including EGRET-K, has also been validated by on-site DRWM validation tests. So far, four times of such validation tests have been performed at Qin Shan site for two types of units, and the results are quite satisfying [10].

Table 1. V&V matrix for ROBIN

V&V problem	Reference	# of cases	Coverage
2D C5G7 benchmark	*OECD NEA/NSC/DOC(2001)4, 2001*	1	MOC module
Neutronic depletion benchmark	*ANL-7416 Supplement 2,1977*	2	Depletion equation solver
Criticality experiments	*NSE, v23, p58~73, 1965* *IAEA STI/PUB/1264, 2007*	79	Library/Resonance/MOC/Leakage correction
Doppler coefficient of reactivity	*NSE, v107, p265~271, 1991*	5	Library/Resonance/MOC
JAEA LWR next generation fuel benchmark	*JNST, v39, p900-912, 2002* *NET, v44, p161-176,2012*	5	Library/Resonance/MOC/Leakage correction/Depletion
Burnup credit criticality benchmark	*NEA/NSC/DOC(92)10, 1992*	3	Ditto
Depletion calculation benchmark	*NEA/NSC/DOC(2013)1, 2013*	2	Ditto
Plutonium recycling benchmark		2	Ditto
Self-defined PWR assembly problems		7	Library/Resonance/MOC

Table 2. V&V matrix for EGRET

Verification problem	Reference	# of cases	Coverage
IAEA PWR benchmark	*ANL-7416,1977*	2	Two-group nodal solver
LRA BWR benchmark	*ANL-7416,1977*	2	Two-group nodal solver
2D BIBLIS problem	*ANE, 18(9), 1991*	1	Two-group nodal solver
3D LMW problem	*LA-UR-95-4488, 1996*	1	Two-group nodal solver
2D CISE problem		1	Two-group nodal solver
Self-defined C5G7 problem	*ANE, 72, pp.173-181, 2014*	1	Multi-group PPR
Self-defined BWR mini-core problem	*ANE, 72, pp.173-181, 2014*	1	Multi-group PPR
KAIST mini-core problem	*A-50, PHYSOR 1996*	1	Multi-group nodal solver and PPR
PWR MOX/UO2 core transient benchmark	*NEA No. 6048, 2008* *NUREG/IA-0416, 2012*	1	Multi-group nodal solver and PPR
Self-defined 3D IAEA problem	*ANE, 79, pp.152-157, 2015*	1	CIAMA
Self-defined two-loop reactor problem	*ANE, 79, pp.152-157, 2015*	1	CIAMA

Table 3. V&V matrix for EGRET-K

Verification problem	Reference	# of cases	Coverage
2D TWIGL Seed-Blanket Problem	*NSE, v38, p8, 1969*	2	Two-group kinetics solver
3D LMW benchmark Problem	*NSE, v63, p437, 1977*	1	Two-group kinetics solver CIAMA

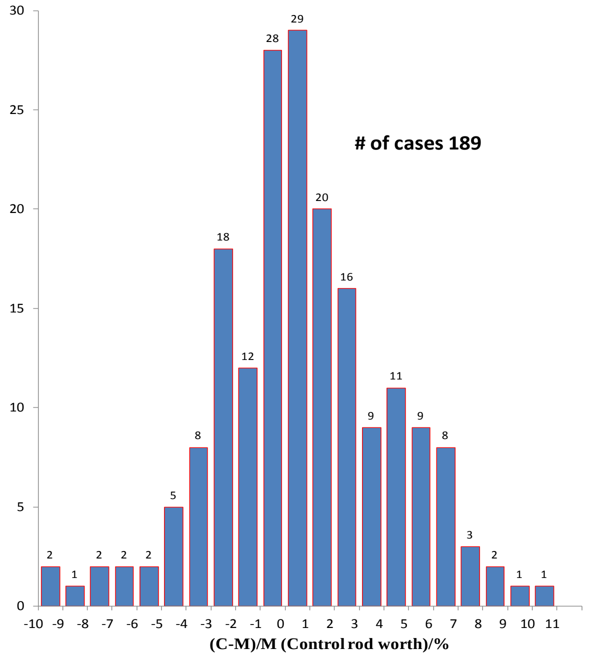

Fig.1 Statistics of relative control rod bank worth error.

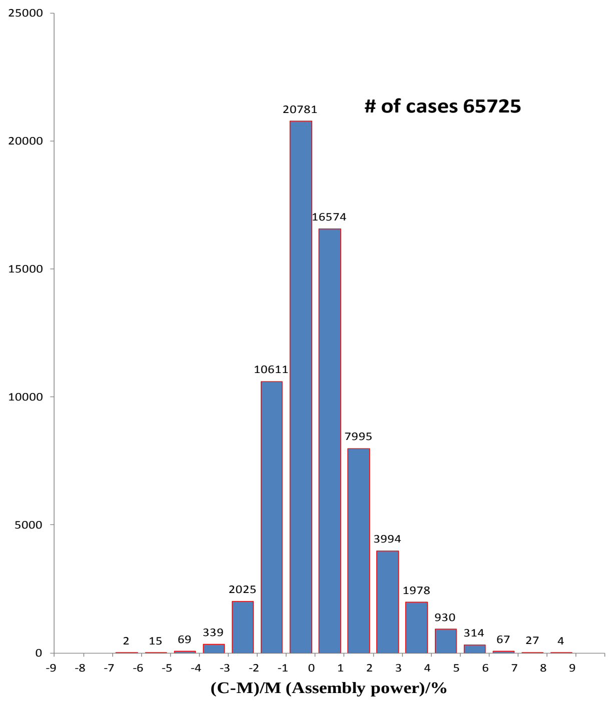

Fig.2 Statistics of relative assembly power error.

4. Application status

Gradually, NuStar's PWR core analysis code system is absorbing code users in Chinese domestic nuclear power industry. Currently, CNNC Nuclear Power Operation Management Co., Ltd (CNNO), which is one of the major nuclear power operation companies in mainland China, is using the code system as a routine tool for reactor core reload design independent check and for DRWM physical test and operation support as well. So far, the code system has been used for checking 11 reload cycle designs, and when compared against the LPPT measurement data, the accuracy of NuStar's code system is either comparable with or slightly superior to that of the foreign nuclear design code that the design institutes are currently using.

Besides CNNO, the Nuclear and Radiation Safety Center, which is the technical center of National Nuclear Safety Administration, China Institute of Atomic Energy and China Nuclear Power Technology Research Institute are also NuStar's code users. They are using either the whole system or just part of it for various purposes.

6. Conclusions

After years of intensive research and development, verification and validation, NuStar's PWR core analysis code system, for both steady-state and kinetic applications, is ready for engineering application. As China's first domestically developed and licensed code system, it is expected to play an important role in the fast growing Chinese nuclear power industry.

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