SCIENCE NUCLEAR CODE PACKAGE AND ITS USAGE IN RELOAD DESIGN OF DAYA BAY NUCLEAR POWER STATION

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ABSTRACT

Framatome ANP's SCIENCE nuclear code package is an integrated system combining neutron computation codes and a complete operating environment with friendly man-machine interface. It is based on two reference models, which include:

- An assembly transport computation performed with the APOLLO2-F code incorporating recent evaluations of the basic data;
- A 3D advanced nodal type core calculation performed with the SMART code incorporating pin power reconstruction capacities, a microscopic evolution of the fuel, and a feedback model based on multiple-parameter tables.

The SCIENCE system code was qualified on a square lattice, using one of the richest experimental bases, based on critical experiments, benchmark comparisons and experimental data from operating PWRs.

In this article is described how SCIENCE code package and HADES II operating system were firstly used in the reload design of Unit 1&2 Cycle 9 of Daya Bay Nuclear Power Station. Unit 1&2 Cycle 9 is the first transition cycle for both units to enter the extended long cycle fuel management – 18-month fuel cycle newly designed for Daya Bay Nuclear Power Station deviated from original yearly 1/3 core reload. With the help of the new SCIENCE code package and the new HADES II operating system, an automatic reload design could be finished in very few time to automatically generate contractual documents. Finally the design is compared with the measurement in the Start-up Physics Test and very good consistency is observed.

1. INTRODUCTION

To achieve better economic benefit under sufficient safety margin, a plan was brought forward in Daya Bay Nuclear Power Station to change from the 1/3 core yearly reload with fresh fuel enrichment 3.7% w/o U235 to 18 month fuel cycle with fresh fuel enrichment around 4.45% w/o U235. Consequently the outage to plan per unit per year would be replaced by outage per unit each 18 month, i.e. two outages during three years and one outage less.

Finally this 18-month fuel cycle project was finalized by the contractor Framatome ANP Company. To secure extended long cycle operation, Framatome proposed the usage of Advanced Fuel Assembly 3rd Generation (AFA 3G) to sustain high burnup irradiation with cladding material M5. Three Mid Span Mixing Grids (MSMG) were used to provide thermal-hydraulic margin. Gadolinium burnable

poison was chosen for two key roles: power distribution control and critical boron concentration and/or moderator temperature coefficient control. Low Leakage Loading Pattern was suggested for the fuel management in replace of the original out-in loading pattern.

After the generic fuel management study and safety analysis were finished, the reload design starting from Cycle 9 for both units was realized to start the transition from yearly reload to 18-month reload. SCIENCE nuclear code package and HADES II operating system were used for the automatic reload design.

2. SCIENCE NUCLEAR CODE PACKAGE

The SCIENCE code package is a calculation system performing neutron calculations required to design
PWR cores. It uses lattice calculations to solve the transport equation and core calculations in the diffusion approximation model. The lattice calculations are performed by the APOLLO2-F code, which uses the collision probability method. The core calculations are performed by the SMART code, which uses an advanced nodal method.

Both the APOLLO2-F and SMART codes are entirely modular, a module being a computer software entity permitting the carrying out of a basic neutronics function or a task.

The use of APOLLO2-F and SMART in the SCIENCE code package for design studies relies on the utilization of preassembled calculation schemes. SCIENCE's user-friendly graphic screens guide the engineers in the use of these calculation schemes.

2.1 APOLLO2-F CODE

APOLLO2-F solves the Boltzmann transport equation in multigroups on two-dimensional geometry. To do this, it makes use either of collision probabilities (processing the equation in its integral form) or Sn methods (processing the equation in its integral-differential form). The first of these methods is the one used for the application developed by Framatome.

The generation of self-shielded cross sections on the calculation geometry makes use of a sophisticated self-shielding model in which one can apply spatial processing based on the "dilution matrix" method and energy group processing containing "narrow resonance" and "wide resonance" approximations.

APOLLO2-F also has all the modules required to calculate fuel evolution (with a predictor/corrector method), critical buckling, heterogeneous transport/homogeneous transport equivalence, and spacial and energy condensation calculations.

The library used for the transport calculations with APOLLO2-F is CEA93 developed by the CEA based on the JEF2 evaluations.

Ninety-nine groups are used in the energy discretization for the project calculation scheme, 47 of which are in the thermal neutron range (<0.625 eV) and 52 in the fast neutron range (>0.625 eV).

2.2 SMART CODE

For the 3D flux calculation, SMART uses the nodal expansion method (NEM) characterized by the introduction of inter-nodal coupling equations containing discontinuity coefficients. The two-energy-group diffusion operator used is based on nodal equivalence according to the Koebke method.

For this, SMART solves the nodal system in three iteration levels: internal iterations, source iterations, and the calculation of the nodal coupling coefficients. These coupling coefficients are evaluated on a two-node cell problem with a quadratic approximation for transverse leakage.

The nodal expansion method is used to determine the inter-nodal currents and fluxes. Fast flux is represented by a fourth-degree polynomial. Thermal flux is represented by a similar polynomial or by a second-degree polynomial associated with hyperbolic functions.

2.3 SCIENCE'S MAN-MANCHINE INTERFACE

SCIENCE nuclear code package is designed with a user-friendly man-machine interface. Geometrical and material data are preset for normal fuel assembly type used in nuclear design. Default data could be called from the database or modified by the user as necessary. When defining a loading pattern, fuel assembly shuffle is realized with the move of mouse with shuffle option of horizontal move, 90˚-rotation etc. A typical interface is listed in Figure 1 as follows:

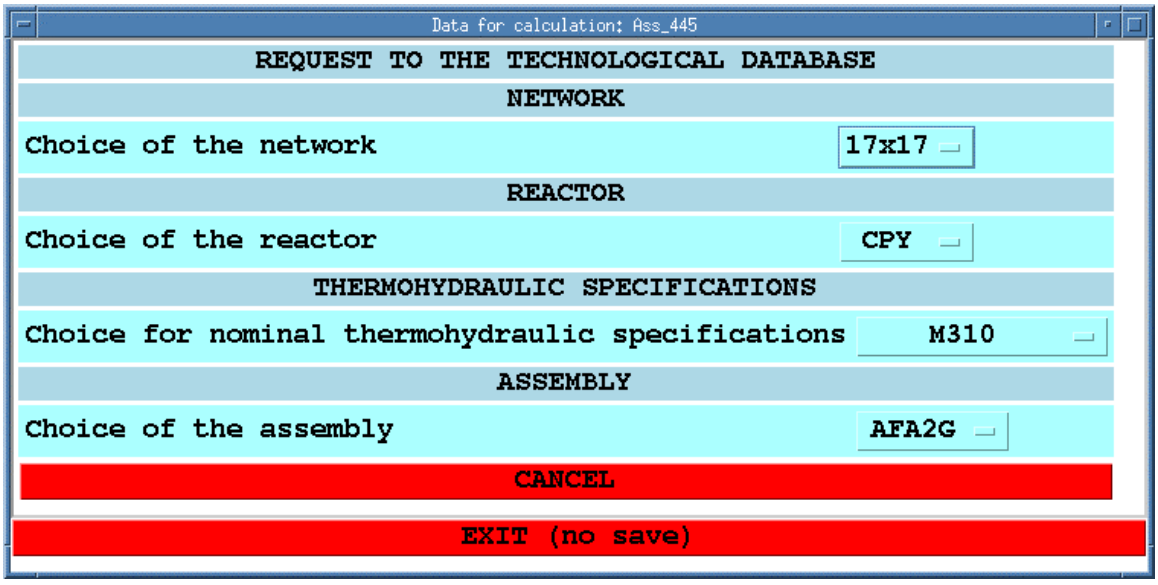

Figure 1. SCIENCE'S Man Machine Interface.

3. HADES II OPERATING SYSTEM AND RELOAD DESIGN METHOD

The reload calculations are performed partly with SCIENCE and linked to the HADES II operating system for 1D models and calculations relating to the synthesis method.

The library calculations are carried out with the assembly transport code APOLLO2-F and the core calculations with the 3D SMART code. The ESPADON 1D model created from the SMART 3D code

is used to generate all the worst-case transients for the accident and power capability studies. The maximum power axial upper bound is evaluated with the COSTAR code.

In addition to the generic structure of the SCIENCE studies controlled by COPILOTE, a number of pre-processing and post-processing utilities can be grafted onto the SCIENCE structure in order to improve design study productivity. These utility program, grouped in the HADES II operating system, are used to:

- Process the upstream and downstream data of the basic software programs to automatically generate the inputs to the 1D and synthesis codes.
- Analyze and generate reduced outputs from the SCIENCE calculations and from the 1D and synthesis calculations.
- Automatically process the results for verification of key parameters.
- Automatically generate a design book "cahier" per calculation.
- Automatically generate contractual documents.

Once a "reference study" is made with COPILOTE and HADES II operating system, during the reload design, the reload design engineer just needs to make a copy of the "reference study" to produce a specific study. Then all calculations, with little change, have to be finished almost automatically to get contractual documents expected within the scope of a contract. A complete reload study could take place in less than a week.

4. CYCLE 9 RELOAD DESIGN AND COMPARISON WITH MEASUREMENT

4.1 FUEL MANAGEMENT OBJECTIVE

The fuel management objectives and the criteria are summarized as followed:

- Alternating equilibrium cycle length: 462/502 EFPD. For cycle 9 the first transition cycle, the required cycle length:

	UNIT 1	UNIT 2
CYCLE 9	360	370

- No use of stretch-out or coast-down to reach natural cycle length
- Enrichment : ≤4.45 w/o U235
- Operation limits of burn-up for AFA 3G
  - Average batch 47 GWd/tU
  - Assembly maximum 52 GWd/tU (47 GWd/tU for AFA 2G)
  - Peak rod 57 GWd/tU
- FΔH: AFA 3G: $\leq$ 1.65 (AFA 3G: $\leq$ 1.61 in cycle 9) (AFA 2G: $\leq$ 1.55) (including uncertainties: 1.03*1.04*1.04)
- FQ: AFA 3G: $\leq$ 2.45 (AFA 2G: $\leq$ 2.25)
- Moderator temperature coefficient: $\leq$ 0 pcm/°C (including uncertainty)
- Shutdown margin ($\geq$2300 pcm) is also verified
- Low leakage loading pattern

4.2 CYCLE 9 RELOAD DESIGN AND COMPARISON WITH MEASUREMENT

To make reload design, first the loading pattern has to be chosen. Low leakage loading pattern is used for both Units 1&2. An optimized loading pattern for Unit 2 Cycle 9 is listed in Figure 2 as an example.

After the loading pattern is defined, the automatic reload design could be started. With the help of the new COPILOTE and HADES II operating system, an automatic reload design could be finished in very few time to automatically generate contractual documents. During urgent cases the reload design could be finished in less than a week. In this reload design for each unit 7 contractual documents are produced which are Loading Pattern Evaluation Report, Specific Safety Evaluation Report, Nuclear Design Report, Startup Physics Tests Report, Fuel Management Report, Incore Data Report and Boron Follow-up Report.

With the introduction of the reload, the physics test is performed to verify the design study during start-up of the unit. Key safety parameters are compared such as Critical boron concentration, Isothermal temperature coefficient, Integral bank worth and Boron differential worth etc. The comparison results are listed in Tables 1&2 for Unit 1&2 Cycle 9. It is observed that all parameters are within the corresponding criteria. Deviation for boron concentration between measurement and design value is much less than the criteria 50 ppm, while it sometimes overstepped the criteria in the original design using ARMEL-NARVAL code package. Deviation for bank integral worth between measurement and design value is much less than the criteria ±10%, while it sometimes overstepped the criteria in the original design.

CONCLUSIONS

The automatic reload design for both units is a success with new SCIENCE nuclear code package and HADES II operating system. The automatic reload design could be finished in less than a week and has been proven to save time since the original design would take about 2-3 months. Starting transition to 18-month fuel cycle, Cycle 9 reload design is verified with good consistency with the measurement in Start-up Physics Test. Consequently SCIENCE code package has been shown to provide a significant improvement in the agreement between measured and predicted results in 18-month fuel cycle in Daya Bay Nuclear Power Station.

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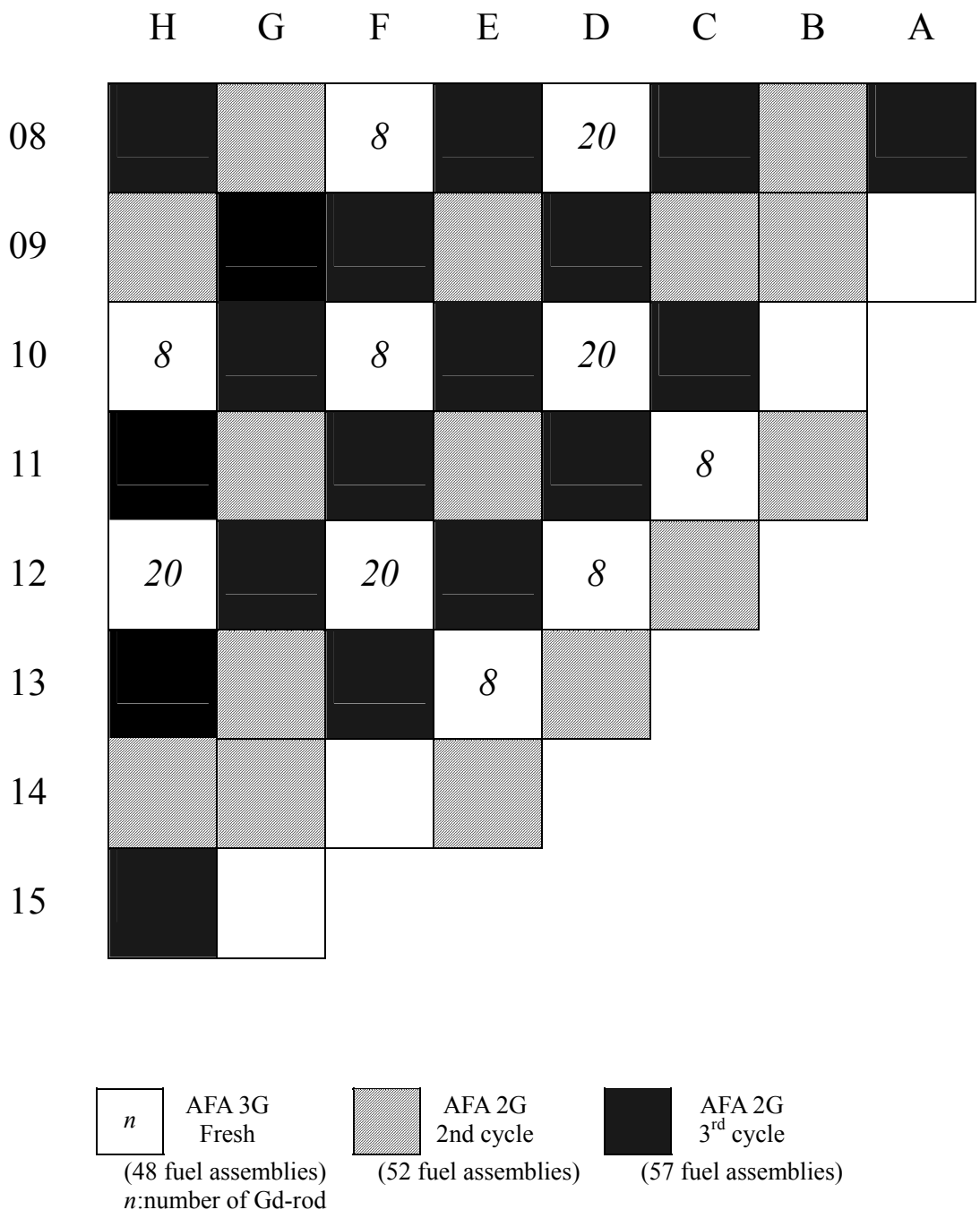

Figure 2. Core loading pattern and composition of Unit 2 Cycle 9

Table 1. Zero Power Physics Test Result Unit 2 Cycle 9

Item	Measurement	Criteria	Design value	Acceptance
1	Critical boron concentration at All Rods Out CB_{ARO}^{MES} =1775ppm	$CB_{ARO}^{MES} = CB_{ARO}^{CAL}$ ±50ppm	CB_{ARO}^{CAL} =1740ppm	ok
2	Isothermal Temperature Coefficient at All Rods Out $(\alpha iso)_{ARO}^{MES}$ = -6.65pcm/℃	$(\alpha iso)_{ARO}^{MES} = (\alpha iso)_{ARO}^{CAL}$ ±5.4pcm/℃	$(\alpha iso)_{ARO}^{CAL}$ = -7.92 pcm/℃ $\alpha_{Doppler}$= -2.9 pcm/℃	ok
3	Temperature Regulation Bank R Integral Worth $\Delta\rho_R^{MES}$ =1225.6pcm	$\Delta\rho_R^{CAL}$ ±10%(pcm)	$\Delta\rho_R^{CAL}$ =1202pcm	ok
4	Boron Differential Worth (Δρ/ΔCB) = -6.812 pcm/ppm	$(\Delta\rho/\Delta CB^{CAL})$± 1pcm/ppm	$(\Delta\rho/\Delta CB^{CAL})$ = -7.49pcm/ppm	ok

Table 2. Zero Power Physics Test Result Unit 1 Cycle 9

Item	Measurement	Criteria	Design value	Acceptance
1	Critical boron concentration at All Rods Out CB_{ARO}^{MES} =1695ppm	$CB_{ARO}^{MES} = CB_{ARO}^{CAL}$ ±50ppm	CB_{ARO}^{CAL} =1676ppm	ok
2	Isothermal Temperature Coefficient at All Rods Out $(\alpha iso)_{ARO}^{MES}$ = -8.9pcm/℃	$(\alpha iso)_{ARO}^{MES} = (\alpha iso)_{ARO}^{CAL}$ ±5.4pcm/℃	$(\alpha iso)_{ARO}^{CAL}$ = -9.5 pcm/℃ $\alpha_{Doppler}$= -3.11 pcm/℃	ok
3	Temperature Regulation Bank R Integral Worth $\Delta\rho_R^{MES}$ =992pcm	$\Delta\rho_R^{CAL}$ ±10%(pcm)	$\Delta\rho_R^{CAL}$ =977pcm	ok
4	Boron Differential Worth (Δρ/ΔCB) = -8.00 pcm/ppm	$(\Delta\rho/\Delta CB^{CAL})$± 1pcm/ppm	$(\Delta\rho/\Delta CB^{CAL})$ = -7.45pcm/ppm	ok