Nuclear Mathematical and Computational Sciences: A Century in Review, A Century Anew
Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2003)

SAPHYR: A CODE SYSTEM FROM REACTOR DESIGN TO REFERENCE CALCULATIONS

B. Akherraz, A.M. Baudron, L Buiron, M. Coste-Delclaux, C. Fedon-Magnaud, J.J. Lautard, F. Moreau, A. Nicolas, R. Sanchez, I. Zmijarevic
Direction de l'Energie Nucléaire
Département de Modélisation des Systèmes et Structures
Service d'Etudes des Réacteurs et de Modélisation Avancée
Commissariat à l'Energie Atomique
Saclay (France)
bruno.akherraz@cea.fr anne-marie.baudron@cea.fr laurent.buiron@cea.fr mireille.coste@cea.fr
christine.magnaud@cea.fr jean-jacques.lautard@cea.fr frederic.moreau@cea.fr
anne.nicolas@cea.fr richard.sanchez@cea.fr igor.zmijarevic@cea.fr

A. Bergeron, D. Caruge, P. Fillion, D. Gallo, E. Royer
Direction de l'Energie Nucléaire
Département de Modélisation des Systèmes et Structures
Service Fluides numériques, Modélisations et Etudes
Commissariat à l'Energie Atomique
Saclay (France)
andre.bergeron@cea.fr, daniel.caruge@cea.fr, philippe.fillion@cea.fr, danielle.gallo@cea.fr,
eric.royer@cea.fr

S. Loubière
Direction de l'Energie Nucléaire
Direction de la Simulation et des Outils Expérimentaux
Commissariat à l'Energie Atomique
Saclay (France)
stephane.loubiere@cea.fr

ABSTRACT

In this paper we briefly present the package SAPHYR [1] (in French, Advanced System for Reactor Physics) which is devoted to reactor calculations, safety analysis and design. This package is composed of three main codes: APOLLO2 [2] for lattice calculations, CRONOS2 [3] for whole core neutronic calculations and FLICA4 [4] for thermalhydraulics.
A brief presentation of each of those components is done in the full paper.
The code system is presented in the poster session and a demonstration is provided on a personal computer, for interesting situations (Reactivity Insertion Accident…).

Key Words: lattice calculation code, core calculation code, APOLLO2, CRONOS2, FLICA4

1. INTRODUCTION

The package SAPHYR [1] (in French, Advanced System for Reactor Physics) is devoted to reactor calculations, safety analysis and design. It is composed of three main codes, APOLLO2 [2] for lattice calculations, CRONOS2 [3] for whole core neutronics calculations and FLICA4 [4] for thermalhydraulics.

The SAPHYR code system is used to model various types of reactors, from PWRs and BWRs to experimental reactors, from spatial power reactor designs to VVERs, from RBMKs to gas cooled reactors.

SAPHYR is based on a modular structure that allows a great flexibility of use. A specific user oriented language, and a shared numerical toolbox have been developed to chain the various computation modules.

The code system is presented in the poster session and a demonstration is provided on a personal computer, for interesting situations (Reactivity Insertion Accident…).

2. APOLLO2

The neutron and gamma multigroup transport lattice code APOLLO2 was previously presented [2]. Since this presentation, a method of characteristics has been added [5] [6] [7] [8] and the performances of the code have been improved.

APOLLO2 works with an arbitrary number of regions, groups, isotopes and burn up zones. The operators and data structures have been designed for optimal calculation performances in the 100-group range, but reference calculations using a very fine energy mesh can be performed [9]. The main functions are shortly described hereafter.

The CEA93 multigroup isotopic library is based on the JEF2 evaluation. Transfer cross-sections for some specific 'isotopes,' such as lead or light water, have been developed up to P_5 order of anisotropy. Various depletion chains are associated with the CEA93 library. The CEA93 does not require any cross-section adjustments. Recently, gamma cross-sections have been introduced in order to treat coupled neutron-gamma problems. APOLLO2 and its library are widely qualified [10].

In order to provide better stability and enhanced accuracy, a continuous effort has been put into the improvement and development of self-shielding methods [11]. The main directions of research are improvement of the existing methodology (especially for mutual shielding effects), development of new models and elaboration of fine-multigroup reference calculations.

Cross-section collapsing and homogenization is done either by direct flux weighting or via equivalence theory (SPH formalism) [12].

APOLLO2 allows the use of various leakages models, the B1 homogeneous one and a P1-corrected heterogeneous model called TIBERE [13].

Transport solvers based on the classical collision probability method have been, for many years, implemented in APOLLO2. The transport solver (TDT) introduced in the APOLLO2 code [6], provides an interface-current method with the ability of treating unstructured 2D meshes and the 3D geometries axially generated from these meshes. Recently, the method of characteristics has been implemented in TDT allowing, thus, for consistent collision probability (CP) and characteristics (MOC) solution that use the same set of trajectories for unstructured geometries. Several acceleration techniques [15] have been developed for the MOC as well as generalized quadrature formulas adjusted on the integration of Bickley-Naylor functions for a wide range of optical thicknesses [14]. Finally, both the CP and the MOC can treat several types of periodic lattices with the use of cyclic trajectories [14]. The discrete ordinates IDT solver [8] allows to treat 2D and 3D Cartesian regular geometries with nodal and characteristics approximations. Powerful DSA acceleration techniques have been introduced in IDT [16].
A user-friendly interface is provided with the code [17].

3. CRONOS2

The CRONOS2 code has been designed to provide all the computational means needed for core calculations, including design, fuel management, operation and accidents.

It allows steady state, burn up and kinetic multigroup calculations of power distribution taking into account the thermal-hydraulic feedback effects. All these calculations can be done without any limitation on any parameter (energy groups, meshes...).

The CRONOS2 code is able to solve the diffusion and the transport equations. Both eigenvalue and source calculations can be performed. The two main flux solvers in CRONOS2 are the PRIAM solver and the MINOS solver.

- The PRIAM solver is based on an even parity formulation using a finite element approximation (FEM) in space and a SN discrete ordinate in angle. This approach offers a high degree of flexibility when defining the geometry: rectangular, hexagonal or cylindrical, and more recently geometry based on triangular and curvilinear triangle elements [20]. Various boundary conditions (reflection, symmetry, periodicity, translation, albedos) are available. Thanks to this method, CRONOS2 was one of the first codes to solve the 3D pin-by-pin transport equation [21].
- The MINOS solver uses a powerful nodal method [22] for dealing with structured geometries. It differs from conventional nodal methods in that it has a rigorous FEM mathematical background using SPN approximation of transport equation. The main advantage of this method is that it preserves the continuity of the current and that it is able to take into account the discontinuities factors at the mesh interfaces. MINOS provides very fast solution using SPN approximation that allows its use for routine calculation. [23] [24].

The resolution method for kinetic calculations is based on a scheme with an implicit time step (θ method). The delayed neutron equations are integrated exactly. The method was extended to SPN transport equations, taking into account the time dependence of all harmonics. The Improved Quasi-Static method (IQS) is also available in CRONOS2 [18]. General perturbation

calculation tools have been implemented and generalized to treat any order [19]. Either isotopic and macroscopic depletion calculations are available.

The thermal hydraulics of the core can be dealt with by the FLICA4 code coupled with CRONOS2 via the ISAS application (PVM). This coupling has a part to play in the study of accidental situations such as main steam line break or control rod ejection.

There is a large range of processing possibilities regarding both cross-sections and geometry modifications. The code also includes a number of graphical tools for pre and post processing.

4. FLICA4

The FLICA4 code [4] has been designed to provide all the computational means needed for steady state and transient thermalhydraulic calculations, particularly two-phase reactor core analysis.

FLICA4 is a 3D two-phase compressible flow code, specially devoted to reactor core analysis. The fluid is modeled by a set of four equations: mass, momentum, and energy conservation for the two-phase mixture, and mass conservation for the vapor. The velocity disequilibrium is taken into account by a drift flux correlation. The vapor is set at saturation conditions. This four equations model is well suited to describe two-phase flow conditions from PWR nominal operating conditions up to boiling crisis.

A specific finite volume numerical method has been developed for FLICA4 [25,30,31]. This method is based on an extension of Roe's approximate Riemann solver to define convective fluxes versus mean cell quantities. To go forward in time, a linearized conservative implicit integrating step is used, together with a Newton iterative method. This kind of numerical method has proved to be very accurate (low numerical diffusion) and efficient for the numerical solution of the two-phase flow problem.

FLICA4 also features a 1D thermal module to solve the heat conduction in solids (fuel plates or fuel rods) and the coupling with CRONOS2 when 3D neutronics is needed to compute the thermal power [27,28,29].

A complete set of closure laws is qualified for PWR [26], but due to its large flexibility (modular design of SAPHYR), FLICA4 provides numerous correlations for wall friction, drift flux, heat transfer and critical heat flux, and many fluids can be calculated: liquids like lead or freons, or gas like hydrogen or carbon dioxide.

FLICA4 includes an object-oriented pre-processor to define the geometry and the boundary conditions. Radial unstructured mesh is available, without any limitation on the number of cells. Zooming on a specific radial zone can be performed either with a non-conform radial mesh or by a second calculation using a finer mesh coupled with the coarse one (for instance a sub-channel calculation on the hot assembly).

5. CONCLUSION

Thanks to a continuous developmental effort, the SAPHYR system is an outstanding tool covering a large domain of applications, from sophisticated R&D studies that need state-of-the-art methodology to routine industrial calculations for reactor and criticality analysis. SAPHYR is powerful enough to carry out calculations for all types of reactors and is invaluable to understand complex phenomena. SAPHYR components are in use in various nuclear companies such as Electricité de France, Framatome-ANP, Cogema, SGN, Transnucléaire and Technicatome.

Waiting for the next generation tools (DESCARTES for neutronics and NEPTUNE for thermalhydraulics) to be available for such a variety of use, with a better level of flexibility and at least equivalent validation and qualification level, the improvement of SAPHYR is going on, to acquire new functions constantly required by users and to improve current performance levels.

ACKNOWLEDGEMENTS

Here we would like to thank everyone that has contributed, through his work, suggestions and criticisms, to the improvement of the SAPHYR system. We extend our thanks to the large pool of users that have patiently waited for requested developments and that had helped with their criticism and support to make SAPHYR a better system. Thanks are due, in particular, to the entire SAPHYR project team. Last, we thank Framatome-ANP and Electricité de France that financially and through constant cooperation have backed CEA's effort to elaborate the successive versions of SAPHYR codes.

REFERENCES

1. C. Fedon-Magnaud "SAPHYR, an overview," *International Conference PHYSOR 2002*, Seoul, South Korea, October 2002.
2. S. Loubière, R. Sanchez, M. Coste, A. Hébert, Z. Stankovski, C. Van Der Gucht, I. Zmijarevic, "APOLLO2 twelve years later," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.
3. J-J. Lautard, S. Loubière, C. Fedon-Magnaud, "CRONOS: a modular computational system for neutronic core calculations," *IAEA Specialists Meeting on Advanced Calculational Methods for Power Reactors, Cadarache*, France, September 10-14, 1990.
4. I. Toumi, A. Bergeron, D. Gallo, E. Royer, D. Caruge, "FLICA4: a three-dimensional two-phase flow computer code with advanced numerical methods for nuclear applications," *Nuclear Engineering and Design*, **200**, pp 139-155 (2000).
5. F. Moreau, R. Sanchez, S. Santandrea, "Contribution to the NEA C5G7 MOX benchmark," *International Conference PHYSOR 2002*, Seoul, South Korea, October 2002.
6. S. Santandrea, R. Sanchez, "Positive Linear and Nonlinear Surface Characteristic Schemes for the Neutron Transport Equation in Unstructured Geometries," *International Conference PHYSOR 2002*, Seoul, South Korea, October 2002.
7. R. Sanchez and A. Chetaine, "Synthetic acceleration for a 2D characteristics method in non regular meshes," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999

8. I. Zmijarevic, " Multidimensional discrete ordinates nodal and characteristics methods for the APOLLO2 code," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.

9. A. Aggery, M. Coste, "Reference calculations with APOLLO2 code working with a very fine energy mesh," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.

10. A. Santamarina et al. "Qualification of the APOLLO2.5/CEA93 V6 code for UOX and MOX fuelled PWRs," *International Conference PHYSOR 2002*, Seoul, South Korea, October 2002.

11. M. Coste, S. Perruchot-Triboulet, C. Van der Gucht, "Self-shielding calculations by APOLLO2 code for fuel pins with a temperature distribution," *Saratoga Springs*, New York USA, October 6-10, 1997.

12. A. Hébert, G. Mathonnière, "Development of a third generation SPH method for the homogenization of a pressurized water reactor assembly," *Nucl. Sci. Eng.*, **115**, p129 (1993).

13. P. Benoist, I. Petrovic, Z. Stankovski, "Improvements in leakage calculation of nuclear reactor assemblies and consistent definition of cell leakage coefficients by an equivalence procedure," *Int. Top. Mtg on Advances in Mathematics, Computations and Reactor Physics*, Pittsburgh, Pennsylvania, April 28 - May 1,1991.

14. R. Sanchez, L. Mao and S. Santandrea, 'Treatement of Boundary Conditions in Trajectory-Based Detreministic Transport Methods,' *Nucl. Sci. Eng.*, **140**, pp23-50 (2002).

15. S. Santandrea and R. Sanchez, "Acceleration Technique for the Characteristic Method in Unstructured Meshess," *Ann. Nucl. Energy.*, **29**, pp323-352 (2002).

16. I. Zmijarevic, R. Sanchez and D. Lamponi, "Diffusion Synthetic Acceleration of Linear Nodal Schemes in Weighted Difference Form," ANS *International Meeting on Mathematical Methods for Nuclear Applications*, Slat Lake City, Utah, USA, September 2001.

17. Z. Stankovski, "La Java de Silène: A graphical user interface for 3D pre & post processing," *Joint Int. Conf. on Mathematical Methods and Supercomputing for Nuclear Applications*, Saratoga Springs, New York USA, October 6-10, 1997.

18. M. Dahmani, A. M. Baudron, J. J. Lautard and L. Erradi, "Application of The Nodal Mixed Dual Technique of Spatial Reactor Kinetics Using the Improved Quasi-Static Method," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.

19. A.M. Baudron, G.B. Bruna, A. Gandini, J.J. Lautard, S. Monti, G. Pizzigati, "Application of the HGPT methodology of reactor operation problems with a nodal mixed method," *Ann. Nucl. Energy*, **25**, p1383 (1998).

20. F. Damian, X. Raepsaet, F. Moreau, "Code and Methods Improvement in HTGR Modelling at CEA," *International Conference PHYSOR 2002*, Seoul, South Korea, October 2002.

21. C. Fedon-Magnaud, "Pin-by-pin Transport Calculation with CRONOS Reactor Code", *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.

22. J.J. Lautard, D. Schneider, A.M. Baudron, "Mixed Dual Methods for Neutronic Reactor Core Calculations in the CRONOS System," *International Conference on Mathematical and*

Computation, Reactor Physics and Environmental Analysis in Nuclear Applications, Madrid, Spain, September 1999.

23. S. Mengelle, A. Nicolas, E. Richebois, "A new Power Reactor 3D Transport Calculation Scheme using the CRONOS2 and APOLLO2 codes," *International Conference on Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 1999.
24. E. Richebois, C. Fedon-Magnaud, Ph. Magat, G. Mathonnière, S. Mengelle, A. Nicolas, "Determination of multigroup and multi-operator reflector constants. Application to a power reactor transport calculation," *International Conference on the Physics of Nuclear Science and Technology*, Long Island, New York, USA, 1998.
25. I. Toumi, D. Caruge, "An implicit second order numerical method for three dimensional two-phase flow calculations," *Nucl. Sci. Eng.*, **130**, p213 (1998).
26. A. Bergeron, D. Caruge, P. Clément, "Assessment of the 3D thermalhydraulic nuclear computer code FLICA4 on rod bundle experiments," *NURETH-9*, San Francisco, 3-8 October 1999.
27. E. Royer, D. Caruge, D. Gallo, "Computation of main steam line break with the SAPHYR codes," *American Nuclear Society: 1999 Annual Meeting* Boston, Massachusetts, June 1999.
28. P. Ferraresi, S. Aniel, E. Royer, "Calculation of a reactivity initiated accident with a 3D cell-by-cell method: application of the SAPHYR system to the TMI1-REA benchmark," CSNI *workshop Barcelone*, April 2000.
29. E. Royer, E. Raimond, D. Caruge, "CEA-IPSN participation in the MSLB benchmark," *Nuclear Technology*, to be published
30. P. Fillion, D. Caruge, S. Clerc, "FLICA4: An advanced code for two-phase flow parallel computing," *NURETH-9*, San Francisco, 3-8 October 1999.
31. M. Grandotto, P. Goldbronn, I. Toumi, P. Fillion, "Comparison of finite element and finite volume algorithms for thermohydraulic studies of steam generators and nuclear reactor cores," *10th International Conference on Finite Elements in Fluids*, Tucson, AZ, USA, 5-8 January 1998.