*Proceedings of the Reactor Physics Asia 2015 (RPHA15) Conference*
*Jeju, Korea, Sept. 16-18, 2015*

# Reactor Physics Education and Research at Nuclear Engineering Department of Seoul National University

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## 1. Introduction

The nuclear engineering department of Seoul National University (SNUNED) was established in 1959. The department offers a curriculum leading to a Barchelor of Science (B.S.) degree, a Master of Science (M.S.) degree, and a Doctor of Philosophy (Ph.D.) degree. The enrollment of in the department is approximately 30 undergraduate and 30 graduate students. As of 2015, the department has produced 219 Ph.D.'s, 536 M.S.'s, and 1,476 B.S.'s who play vital roles in the Korean nuclear industry, research and education areas.

The reactor physics education and research programs of SNUNED led by the two authors focus on high fidelity analyses, efficient designs, and sensitivity and uncertainty (S/U) analyses of various types of nuclear reactor cores. We have different specialties on numerical methods of the neutron transport analysis, namely, deterministic methods for Prof. Joo the Monte Carlo (MC) method for Prof. Shim. In order to foster the students to have proper knowledge and experience in both deterministic and Monte Carlo (MC) reactor analysis methods with clear understanding of the physical behaviors of nuclear reactors, the undergraduate and graduate courses cover various mathematical and numerical methods as well as principles of nuclear characteristics and physical behaviors. The reactor experiment education is done by sending the graduate students to Kyoto University Research Reactor Institute (KURRI) to conduct various experiments at the KUCA (Kyoto University Critical Assembly) facility during the summer of the first graduate year.

Reactor Physics Laboratory (SNURPL) directed by Prof. Joo has been developing advanced numerical methods and computer codes covering direct whole core (DWC) calculation, cross section generation, resonance treatment, depletion, advanced nodal methods, space-time kinetics method, et cetera. Computer codes developed by SNURPL are as the followings.

- nTRACER [1]: DWC calculations by the method of characteristics
- RENUS (Reactor Numerical Simulator) [2]: nodal kinetics code
- FREK (Fast Reactor Kinetics) [3]
- EXUS (Effective Xsec generator with Ultrafine-group Slowingdown calculation) [4]
- FEDONA (Finite Element Discrete Ordinate Neutronic Analysis) [5]
- SHAFE (Simplified spherical Harmonics based Analysis employing Finite Elements)
- PRIDE (Probabilistic Reactor Investigation with Discretized Energy) [6]

Monte Carlo Laboratory (SNUMCL) directed by Prof. Shim is mainly developing advanced MC neutronics analysis methods for the DWC calculation [7], the few-group diffusion theory constant generation [8,9] and the S/U analysis [10,11], which are implemented in a continuous-energy MC code, McCARD [12,13]. Reactor physics experiments and the related MC simulations are highly encouraged to deepen understandings of reactor physics. Experiments of the isothermal temperature reactivity coefficient at the KUCA C-core [14] were carried out with helps of KURRI and their sensitivity analyses were performed by the MC perturbation techniques. [15] A joint research program with Belarus JIPNR-Sosny is currently ongoing for the modeling and simulation of its critical assembly experiments by McCARD.

This paper provides a summary of "Reactor Physics Education at Seoul National University" [16] presented in PHYSOR 2014. The reactor physics curriculum and contents of the relevant courses are described in Section 2. Research topics and relevant achievements of SNURPL and SNUMCL are introduced in Section 3.

## 2. Reactor Physics Curriculum

Undergraduate students of SNUNED take the course of "Introduction to Nuclear Engineering" during the sophomore year. The fundamental concept of cross sections, flux, neutron attenuation and diffusion are covered in that course but a real start of reactor physics curriculum is via "Nuclear Reactor Theory" at the first semester of the junior year. The course of "Nuclear Reactor Dynamics and Control" is then taught in the following semester. Elementary numerical methods are also given in the second semester of juniors to provide the fundamental understanding and programming practice that are essential to reactor physics methods and code developments. In the second semester of seniors, a course named "Reactor Numerical Analysis and Design" is offered to provide basic knowledge required for the neutronic and thermal analyses of nuclear reactors.To the first year graduate students, a core course named "Analysis of Reactor Static Characteristics" covering the basic transport and resonance methods is given. It is followed then by "Advanced Reactor Dynamics" and "Monte Carlo Reactor Analysis" courses. The curriculum is summarized in Table I with the primary course contents and textbooks.

Table I. Reactor Physics Courses at SNUNED

| Course Title | Year-Sem.-(Type) | Contents |
|---|---|---|
| Computer Concepts & Practice | 1-S (M) | Computer structure and data types (2Wks), C (8 Wks), Assembly language (1Wk), FORTRAN (3Wks), etc. |
| Nuclear Reactor Theory | 3-S (M) | Nuclear reactions, Neutron slowing down, diffusion equation solution, thermal feedback, point kinetics, etc. |
| Reactor Dynamics & Control | 3-F (S) | Control analysis, adjoint, kinetics equations and parameters, reactivity feedback, stability analysis, etc. |
| Elementary Numerical Analysis | 3-F (S) | Interpolation and approximation, differentiation and integration, linear system solutions, eigenvalue problems, BVP, ODE, root finding, etc. |
| Reactor Numerical Analysis & Design | 4-F (S) | Multigroup neutron diffusion equation, iterative methods for linear systems, eigenvalue acceleration, heat conduction solution, fuel loading pattern design, etc. |
| Analysis of Reactor Static Charactertics | G-S (M) | Collision probability method, resonance methods, $P_L$, $S_n$, $B_1$ methods, method of characteristics, depletion methods, nodal methods, etc. |
| Advanced Reactor Dynamics | G-F (S) | Multigroup spatial kinetics method, Krylov subspace methods, system coupled spatial kinetics, rod ejection and MSLB analysis, etc. |
| Monte Carlo Reactor Analysis | G-F (S) | Collision density equation, random numbers, MC eigenvalue calculation, scoring, fission source convergence, MC Wielandt method, real variance, MC adjoint and uncertainty analysis |

*Abbreviations: S=Spring, F=Fall, G=Graduate, (M)=Mandatory, (S)=Selective

## 3. Computational Reactor Physics Researches

The reactor physics research of SNUNED is primarily on the computational side balanced by the deterministic and the Monte Carlo approaches. The deterministic approaches are driven by SNURPL whereas the Monte Carlo approaches by SNUMCL. The two approaches are mutually supporting each other to render synergetic enhancement. The typical example of the synergetic enhancement is the BEAVRS benchmark analyses [17] that were performed by using the nTRACER DWC code [1] and the McCARD MC code [12]. The accuracy of the two codes can be mutually verified by solving the common problems for which measured data are not available. In the following, the current research activities of the two laboratories are briefly described.

### *3.1 Researches on Advanced Deterministic Methods*

At SNURPL, the development of the top-notch DWC MOC code nTRACER is being continued. Other transport codes such as FEDONA and SHAFE are also being developed for general geometry applications employing finite element methods (FEM). In addition, the efforts for enhancing the diffusion or SP3 equation based nodal codes such as RENUS and FREK are also continued to provide fast running core simulator employing the conventional two-step core analysis procedure. Researches on multigroup cross generation through proper resonance self shielding treatment through ultrafine group slowing down solution through the EXUS code and by the subgroup method are also going on. In the following, current research themes on the deterministic methods are listed.

- Method of Characteristics:
  - ✓ Ray tracing considering the sub-pin level heterogeneity
  - ✓ Linear source approximation
  - ✓ $P_1$ anisotropy treatment
  - ✓ Parallel computation

- Linear System and Eigenvalue Solution Methods:
  - ✓ SOR, Krylov subspace method
  - ✓ Chevyshev and Wieland methods

- Nodal Methods for Diffusion and SPn Equations:
  - ✓ Source expansion nodal method (SENM) [18] incorporated in nTRACER
  - ✓ SP3 equation solver for nTRACER and RENUS
  - ✓ Advanced pin power reconstruction [19]

- Transient Solution Methods:
  - ✓ Stiffness confinement method [20]
  - ✓ Backward Differentiation Formula [2]

- Cross Section Generation and Resonance Treatment Methods:
  - ✓ Ultrafine group slowing down calculation
  - ✓ Subgroup method [21]

- Advanced Depletion Methods [1]

- Group Constant Generation and Functionalization for Two-Step Procedure

- FEM Based Sn and SP3 Transport Calculation [5]

- Multi-Objective Multi-Cycle Fuel Loading Pattern Optimization Methods [22,23]

### *3.2 Researches on Advanced Monte Carlo Methods*

With increasing computer power, the MC particle transport analysis method is raising its competitiveness in the neutronics analyses. Yet it is still in evolutionary process for the completeness of the MC DWC calculations for commercial reactor cores. SNUMCL and SNURPL are developing advanced MC methods as well as hybrid methods of the MC and the deterministic approaches by implementing them into McCARD and PRIDE. Current research themes on the MC methods are listed as the followings.

- MC DWC calculation:
  - ✓ On-the-fly Doppler broadening [7]
  - ✓ Thermal-hydraulics coupling scheme [24]
  - ✓ Real variance estimation [25]

- MC Few-Group Constant Generation:
  - ✓ B1 theory-augmented MC method [8]
  - ✓ Incremental cross section generation for the CANDU-PHWR analysis [9]
  - ✓ Uncertainty quantification of the McCARD/MASTER code system [26]

- MC Perturbation methods:
  - ✓ MC Adjoint-weighted perturbation method [10]
  - ✓ Fuel temperature coefficient calculation by the MC perturbation method [27]

- Sensitivity and Uncertainty Analysis:
  - ✓ MC Adjoint-weighted Perturbation method [10]
  - ✓ Adjoint S/U Analysis by the MC Wielandt method [11]
  - ✓ S/U analysis with continuous-energy covariance data [28]

- Hybrid Methods:
  - ✓ MC coarse mesh finite difference method [29]
  - ✓ MC Wielandt method [30]

- Time-dependent MC simulation:
  - ✓ MC alpha iteration algorithm [31]
  - ✓ MC dynamic simulation algorithm

- Research Reactor Analysis [13]

- CAD-based Geometry Processing [13,32]

## 4. Conclusions

The course curriculum and the research activities of the SNUNED reactor physics program support students to be properly trained to become a competent computational reactor physics engineer. Continued efforts will be made to make the program stronger and more complete.

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