
NUCLEAR ENERGY RESEARCH INITIATIVE

Development of Advanced Methods for Pebble-Bed Reactor Neutronics: Design, Analysis, and Fuel Cycle Optimization

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The goal of this project is to develop a comprehensive suite of computer codes for the design of pebble-bed reactors (PBRs) and the management of their fuel cycles. The PBR concept is a leading candidate for near-term deployment and for further development as a Generation IV reactor, yet the neutronics methods available to design and analyze PBRs are several generations behind the state of the art. Existing PBR analysis codes use finite-difference or statistical methods, which are slow and thus unsuitable for the repetitive simulations needed for optimization. Thus, an efficient deterministic method is needed for design and optimization of the PBR fuel cycle.

The INEEL has developed a new deterministic method for the neutronics analysis of PBRs. The method accounts for the pebble flow explicitly and couples the flow to the neutronics. It can model once-through cycles and cycles that allow recirculation of pebbles through the core. The method is implemented in the INEEL code PEBBED. At present, PEBBED uses a finite-difference neutronics solver and simplistic depletion and cross-section computation techniques; these methods were applied to prove the viability of the basic algorithm in the code, but they should be replaced by modern techniques that fully complement the advance achieved by that algorithm.

The project will incorporate the needed modern techniques; beyond that, it will extend the state of the art in computational neutronics. A new method will be developed to carry out long depletion steps while maintaining high fidelity in the model nuclear data. The method will be an essential tool for the reliable design of a PBR or any reactor core of cylindrical geometry. No method or code exists that contains the capabilities proposed here.

The new method and tools will greatly enhance the scientific and computing infrastructure in the United States. The resulting codes will be essential to cost-effective PBR design, and they will give unprecedented fidelity to PBR modeling. Thus, the project will directly support two areas of the NERI work scope: F-1, Advanced nuclear energy systems, and F-3, Nuclear fuels/fuel systems. The project conforms to the NERAC Long-Term Nuclear Technology R&D Plan in advancing reactor physics technology for a Generation IV reactor concept, and it will enable assessment of the proliferation potential of PBRs as advocated by the NERAC TOPS report. It is also consistent with the National Energy Policy of 2001, which specifically mentions the PBR as a promising advanced reactor concept.

The following paragraphs explain the specific needs addressed in this project.

Implementation of a 3-D (r- θ -z) nodal/coarse mesh multigroup neutron diffusion solver: A way has been found to circumvent the mathematical impasse that has frustrated all previous efforts to find a mathematically rigorous formulation of an analytical nodal method in 3-D cylindrical geometry. In real PBRs, the presence of control rods or control elements, uneven burn-up, and uneven build-up of poisons will impose azimuthal asymmetry (i.e., θ -dependence). To perform core physics analyses efficiently in most reactor systems, nodal methods are generally applied. However, current nodal methods in cylindrical geometry do not include the θ -dependence rigorously because the transverse integration procedure (from which nodal method developments start) in r leads to a mathematical impasse. In this project, a new mathematically rigorous approach will be implemented into a nodal code for r - θ - z geometry.

Development of an advanced, spatially detailed depletion capability: A new nodal depletion method will be developed in this work, extending to cylindrical geometry the techniques in the NOMAD-BC code developed by one of the PIs,. The current standard methods used for PBR design and analysis rely on finite-difference neutronics solvers. Consequently, they are limited either to very low-fidelity modeling (by a very coarse computational grid) or to very long computational times (if the computational mesh is refined). Such methods in detailed design and safety studies would impose an unacceptable bottleneck by modern standards. The nodal/coarse-mesh-based depletion capability proposed in this project would eliminate this difficulty, because nodal methods have the potential to increase fidelity while greatly reducing computational times. With the new method, complete design analyses could be completed in a matter of seconds. Optimization studies would also be commensurately rapid.

Development of a new method for generation of diffusion-theory parameters: The nodal diffusion solver and nodal depletion method will be complemented by a cross-section perturbation method that will be developed in collaboration with Prof. Farzad Rahnama and his students at the Georgia Institute of Technology. This method will be an extension to cylindrical geometry of prior work at Georgia Tech. The method will be supported by the EVENT code developed by Prof. Cassiano de Oliveira at the Imperial College of London; Prof. Oliveira will collaborate as an unfunded participant. The new method extends modern equivalence theory past the present state of its art. Besides homogenized diffusion constants, the method will produce perturbation parameters, used to update nuclear data during changes in the reactor core that develop during long time steps, without resort to data-intensive, pre-computed tables or rehomogenization. This capability is unique and extremely well-suited to first-of-a-kind reactor design and analyses; it is also ideal for efficiency and fidelity in the analysis of existing reactor types.

Development of a method of feedback parametrization for temperature and depletion: In order to account correctly for the effects of temperature on diffusion-theory parameters, a feedback model must be included among the methods. Prof. Kostadin Ivanov at the Pennsylvania State University (PSU) has developed and validated a new adaptive high-order table look-up model for cross-section parametrization. PSU will modify their model to be compatible with PEBBED and with the methods developed

at Georgia Tech for generating diffusion-theory data.

Development of an automatic optimization routine for efficient and accurate sensitivity studies, design, and fuel management: An automatic optimization routine, based upon a genetic algorithm, will be developed and integrated with PEBBED to perform core design optimization. The algorithm will generate core size and flow parameters for PEBBED input and evaluate user-specified objective functions based upon the resulting PEBBED output.

Exploration of the implications of inhomogeneities in pebble packing: Packing in a cavity filled with identical spheres is not uniform, but varies according to a function that resembles a damped oscillation from zero at the walls to an asymptotic value several sphere diameters away. In small PBRs, where the oscillations may extend over a large fraction of the core diameter, the effects of the oscillations may be significant. Calculations will be performed to assess these effects, and an empirical model will be developed for inclusion in the homogenization codes.

Incorporation of code components into PEBBED: The neutronics analysis of PBRs differs from that of light water reactors because PBR fuel moves and the neutronics and depletion equations are coupled to this motion. The PEBBED code solves this coupled problem. All the new methods and codes developed in the tasks described above will be coupled to or implemented within PEBBED. The resulting code suite will be benchmarked by Prof. Barry Ganapol of the University of Arizona. Verification and validation will be performed using data supplied by the South African company, PBMR (Pty), Ltd., who will be participating as unfunded collaborators.

The team assembled for this project has a unique ability to perform the proposed work. The PIs have developed the PEBBED code and derived the θ -dependent analytical nodal formulation of the diffusion equation. The collaborators at Georgia Tech, with the support of Prof. deOliveira, have a unique and ideally suited approach to homogenization. The collaborators at PSU have a unique and ideally suited approach to data parametrization. Prof. Ganapol is known worldwide as an expert in all kinds of benchmarking problems. PBMR (Pty) Ltd. will provide relevant data from the world's foremost PBR design project.

The project will produce a set of interrelated codes to perform neutronics design and in-core fuel cycle optimization for a PBR quickly and efficiently. In addition, the project will lead to publications for conferences and