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Challenges and Approaches to Coupled Monte Carlo Neutronic/Fluid Flow Analysis of Commercial Nuclear Reactors

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Despite the great advancements in Monte Carlo neutral particle transport methods and their implementation on advanced computing platforms, Monte Carlo methods have achieved decidedly little impact on either the design or licensing of commercial light water reactors (LWRs). There are numerous reasons that contribute to this lack of penetration:

Conventional Monte Carlo analysis requires 10s to 100s of billions of neutron histories to resolve local spatial details in high dominance ratio reactor cores (e.g. source convergence is extremely difficult, even without multi-physics effects).

Traditional Monte Carlo statistical treatments lead to non-conservative estimates of spatial parameter uncertainties because of inter-cycle correlation effects in high dominance ratio cores (e.g., central limit theorem can not be applied directly).

Reactor core depletion requires tracking several hundred nuclides in each radial ring of 100,000 fuel pins at each of several hundred axial levels (e.g., 100s of billions of tallies are required).

Each fuel depletion region and each feedback region has unique physical properties (e.g., nuclear data in each region must be treated as functions of local temperatures).

Accurate analysis requires dynamic coupling of Monte Carlo neutronics to nuclear fuel/fluid flow models (e.g. coupled physics is crucial to accuracy).

Steady-state core analysis cannot answer safety questions that require dynamic multi-physics analysis (e.g., Monte Carlo methods must be extended to the time domain for both rapid and long-duration transient applications).

The authors will present a formal LWR cycle depletion benchmark that can be used to test coupled neutronic/fluid flow models in pseudo steady-state (reactor cycle depletion) applications. This benchmark will be based on two cycles of operation of a commercial LWR, and measured reactor data will be provided to assess computational model uncertainties in core reactivity and 3D fission rate distributions. The inherent challenges and difficulties in developing methods to solve this challenge problem will be outlined and discussed in detail. In particular, limitations of parallelization of Monte Carlo by replication and challenges arising from massive storage requirements (for temperature-dependent nuclear data and detailed spatial tallies) will be discussed. A summary of recent algorithmic testing of alternative parallelization strategies to overcome these limitations will be presented.

The authors experiences in applying one class of non-linear operators to the acceleration of deterministic multi-physics methods will be summarized, and computational results from recent extensions of these methods to steady-state Monte Carlo analysis will be presented. Authors will present results from recent parallel algorithm computational tests and a proposed strategy for using non-linear operators to solve coupled Monte Carlo neutronics and nuclear fuel/flow problems.

The authors will also present their proposed approach for extending these non-linear operators to the development of transient Monte Carlo coupled multi-physics reactor analysis methods. Key developments needed for success will be outlined, and prospects for future success will be discussed.