

Nuclear Energy: Back to the Future

Almost three decades ago, as a chemical engineering undergraduate student, I made what was for me a momentous career and life decision – to apply for entrance into the nuclear navy. My fascination with nuclear energy, the sea, and naval vessels made this one a lock for me – a lock, that is, until I took the “nuke navy” entrance exams and discovered that I was colorblind and, therefore, not qualified to be a navy officer. But, as Yogi Berra says, when I came to this fork in the road I “took it” by opting instead to enter graduate school in nuclear engineering and pursue a doctorate in reactor physics. So, when I got to graduate school that fall in 1983, eager to learn about nuclear reactors, my incoming class was informed by the graduate chairman that we should “not worry about our career choice of nuclear engineering, as the nation needs lots of people like us to help decommission and close down our nuclear reactors.”

Talk about sobering. The chairman was merely trying to be positive by pointing to career-long opportunities and challenges but his words went over like a lead balloon. It was just four years past the Three Mile Island (TMI) accident and the nation was still reeling. (In fact, around 50 post-TMI reactors had already been cancelled by that time.) Thereafter, although I took many courses on nuclear reactor physics, I chose to instead focus my dissertation research on fusion theory, guided in part by a computational science application I developed as part of my research. And so it goes for many nuclear engineers like me: we strayed from the field, pursuing other, related endeavors, not anticipating returning.

How things have changed. For me, and many others, it is “back to the future” for nuclear energy. Spiking energy prices, increased demand for clean and reliable energy, and potential anthropogenic contributors to climate change have generated renewed interest and excitement. It is arguably more exciting now for nuclear engineers than it has been in over three decades.

Young people are taking notice: an Oak Ridge Institute for Science and Education report indicates the number of nuclear engineering bachelor’s degrees granted in 2008 was the highest in 20 years, and the number of graduate degrees granted showed a 70% increase over the last 10 years. Undergraduate enrollment is almost triple what it was 10 years ago (but still below the numbers of my time). A very good sign indeed.

A “nuclear renaissance” is on the horizon as we look to solving the nation’s energy assurance challenges in an environmentally sustainable way. And why not? The benefits of nuclear energy are hard

to ignore: abundant fuel with high energy concentration (one pellet of uranium fuel is equivalent to about one ton of coal), no greenhouse or acid rain effects, a stable base load capacity with high capacity factors (typically over 90%), waste more compact than for currently significant energy sources, energy production costs competitive with coal, and proven safety and reliability.

So what role has modeling and simulation (M&S) played for nuclear energy? Huge! M&S has been key from the beginning, in all aspects: analysis, design, safety, and licensing. Many of the same methodologies and ideas fostered during the Manhattan Project carried over naturally to nuclear energy. The simulation legacy established in the 1940s and 1950s is a testament to the fact that M&S is a backbone in nuclear energy, perhaps more so than in most other science and engineering fields.

Today’s suite of nuclear energy M&S applications is frequently capable of predicting the behavior of present-day reactors. But these applications were not necessarily designed for a broad enough range of conditions as we move forward. If a new reactor design differs from its predecessors in significant ways – for example, in the use of higher temperatures or new materials, geometric configurations or safety features – the predictions from the current suite of applications need higher fidelity and predictability, either in their physical models, numerical solution techniques, or resolution of geometric features. Next-generation nuclear energy applications must encompass a host of relevant physical phenomena in operating nuclear reactors: neutron transport and depletion; thermal hydraulics and turbulent heat transport;

Biography in Brief: Dr. Douglas B. Kothe

Dr. Douglas B. Kothe currently serves as Director of Science in the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory (ORNL) National Center of Computational Sciences, where he is responsible for guiding the research teams using the Advanced Scientific Computing Research leadership systems residing at the center.

Doug has more than 25 years of experience in computational science research, with his interests and expertise centered on developing physical models and numerical algorithms for simulating physical processes in the presence of incompressible and compressible fluid flow. A leader in modeling interfacial flows, he has been the principal developer of broadly disseminated scientific simulation tools. His most notable contribution has been the development of methods for flows possessing interfaces, especially free surfaces.

Before joining ORNL in 2006, Doug was Deputy Program Director for Theoretical and

Computational Programs in the Advanced Simulation and Computing (ASC) program at Los Alamos National Laboratory (LANL). He served for several years as the leader of ASC's Telluride Project, which developed the advanced manufacturing simulation tool "Truchas" for the Department of Energy complex. He joined the technical staff at LANL in 1985 first as a member of the Inertial Fusion and Plasma Theory Group and then later in the Fluid Dynamics Group, where he helped develop the Ripple, Pagosa, and CFDLIB computational fluid dynamics codes. He subsequently worked in the Structure/Relations Group in the Materials Science and Technology Division before serving as Group Leader of the Continuum Dynamics Group in the Computer, Computational, and Statistical Sciences Division.

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multiphase and interfacial fluid flow; structural mechanics and phase change heat transfer; fuel and material performance under extreme conditions; surface chemistry and corrosion; and multi-physics coupling and interactions such as fluid-structure, thermo-mechanics, and thermal hydraulics-neutronics.

This list of functional requirements is daunting. And don't forget system and balance-of-plant M&S requirements as well as software quality assurance and validation pedigree requirements to be considered if the application is to play any sort of design or licensing and regulatory role. Nuclear energy has an established competitive, international, commercial aspect and a government organization with regulatory/safety oversight; it is affected by political decisions on issues such as waste, national energy strategy, and national security. High consequence decisions are made with the nuclear energy application suite.

Assuming these next-generation nuclear energy M&S applications will be developed and applied, many nuclear energy challenges and opportunities will come within our grasp more easily. Prime targets are the five "imperatives" cited in the recent DOE Office of Nuclear Energy roadmap: extend life, improve performance, and sustain health and safety of the current fleet; enable new builds and

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improve the affordability of nuclear power; enable a transition away from fossil fuels in the transportation and industrial sectors; enable sustainable fuel cycles; and assure proliferation risk is not an obstacle to nuclear power deployment.

The first imperative, for example, includes the aging fleet challenge: Most plants were designed to last 40 years, as guided by the adoption of a 40-year licensing regime by the Nuclear Regulatory Commission. The average U.S. plant age is about

30 years old, and more than half of these plants have already had their life extended by two decades. Extending plant life, say, to 80 years, has safety implications, however, because care and attention must be given to the many aging components. This is where M&S can play a larger role, much like it has for the aging nuclear stockpile in the Advanced Simulation and Computing Program in the DOE National Nuclear Security Agency – where a complete transformation to a M&S-based predictive science program has been completed.

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Imperative number 1 also includes “power uprates” – increases in the maximum power level at which a commercial nuclear power plant may operate – which have been quite fruitful for nuclear utilities. Since 1997, for example, power uprates at existing plants have given us an additional 5–6 Gigawatts electric (GWe). That is the equivalent to building an additional five to six nuclear power plants with a much lower (that is, five times) capital investment! Much more is possible from further increasing power, and M&S will play a leading role in making this happen.

So how can the DOE’s Office of Advanced Scientific Computing Research (ASCR) help? From my perspective, ASCR’s role here is crucial. Current nuclear energy M&S applications are way behind where they should be given the requirements for advanced nuclear energy fuel cycle and high-temperature applications. Like many other fields, nuclear energy will benefit from a fresh injection of modern computer and computational science: new, improved models, algorithms, and software implementations capable of

exploiting current and incoming hardware possessing memory and floating-point hierarchies (such as accelerators).

ASCR’s involvement will be key to advancing the field through the use of unprecedentedly large leadership systems as well as more widely available commodity systems. Most industry, design, and licensing usage still consist of many small, quick turn-around calculations. Yet given that desktop computers equivalent in power to a circa-2006 leadership-class systems will be commonplace in a mere few years (because of hybrid and floating-point acceleration hardware), modernizing these legacy applications becomes even more compelling.

This does not even take into account the challenges in building new, next-generation M&S applications for nuclear energy simulations on leadership systems. The challenge is astonishing due to the time and length scales over which physical processes occur and the complexities of the processes themselves, requiring an unprecedented breadth and depth of multiple, simultaneous, physical processes to be simulated in an operating reactor. To do it right, nuclear energy M&S high-performance computing requirements dictate exascale resources. Recent DOE town hall and exascale workshops support this view. Whether we are resolving the material microstructural evolution in a single nuclear fuel pellet or the entire neutron state (energy, location, direction) in a full reactor, exascale resources will enable new science and understanding and help to greatly reduce uncertainties.

Taking on the nuclear energy challenge will also directly benefit ASCR. Building new M&S applications for nuclear energy will require effective management and execution of large multi-institutional, multi-disciplinary projects. In fact, this effort may well serve as a prototype for future endeavors for ASCR. Nuclear energy M&S also requires working closely with industry and other government agencies. Fostering these close working relationships will be important and will require the latest virtual collaboration technologies. Licensing and high-consequence design and safety decisions driven by M&S results require stringent software quality and validation pedigrees. This culture will benefit ASCR in its other current and planned high-consequence computer and computational science projects.

It’s *game on* for nuclear energy, and ASCR will be an important player on the team. ●

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