Collaboration for Advanced Nuclear Simulation: Predictive Reactor Simulation for GNEP

Presented by

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Nuclear reactors have operated safely for decades throughout the world.

Many operating nuclear reactors worldwide

- More than 400 commercial power plants worldwide
- Approximately 200 nuclear-propulsion plants on Navy vessels worldwide
- More than 100 research reactors on every continent

Immediate response to global warming

- No CO_2, sulfur, or mercury releases to the atmosphere
- The only carbon-free, high-energy-density electricity source
- Greenpeace founder Patrick Moore supports expansion of nuclear energy

Designs static for 20 years

- Mostly water-cooled “thermal” reactors fueled by uranium from ore
- Optimized using more than 10,000 reactor-years of experience
- Not sustainable now because they use more fuel than they produce

Global Nuclear Energy Partnership (GNEP) will expand sustainable nuclear energy worldwide.

International consensus

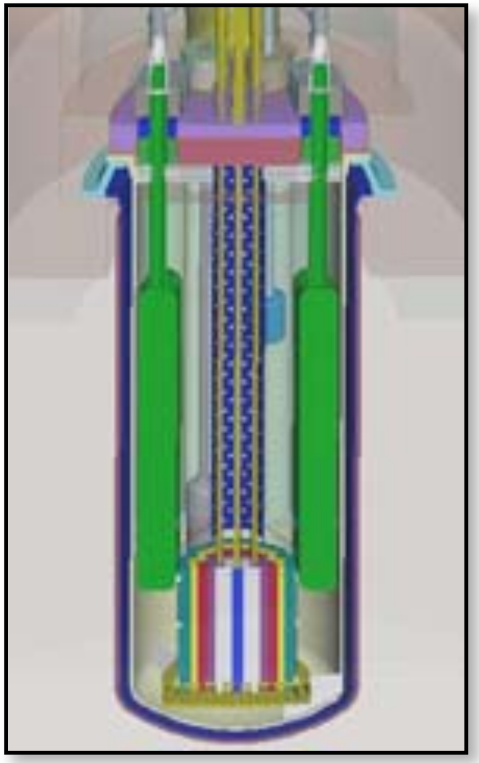
- Enables expanded use of economical, carbon-free nuclear energy
- Recycles nuclear fuel for energy security and international safety
- Establishes user-supplier nuclear fuel services strategy:
  - Supplier nations provide fresh fuel and recovery of used fuel
  - User nations receive economical reactors and fuel for power generation purposes only

Global benefits

- Provides abundant energy without generating greenhouse gases
- Recycles used nuclear fuel to minimize waste and reduce proliferation concerns
- Safely and securely allows developing nations to deploy nuclear power to meet energy needs
- Maximizes energy recovery from still-valuable used nuclear fuel
- Requires only one U.S. geologic waste repository for the rest of this century

The GNEP reactor consumes nuclear "waste" and produces power, but needs more analysis.

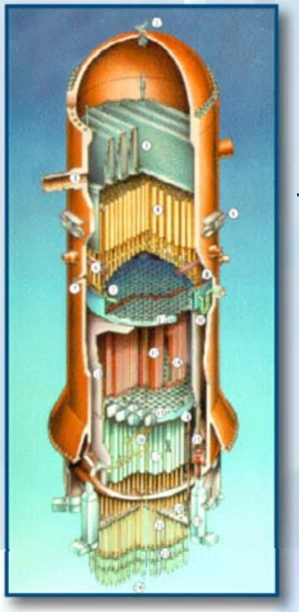
- Fast reactors are fueled by the waste from used fuel.
  - Burning the worst of the radioactive isotopes (plutonium, americium, curium, etc.) to produce heat.
  - Allowing reuse of the uranium in traditional reactors, potentially creating a sustainable energy cycle.
  - Providing electricity from traditional "waste" source.
- Fast reactors have operated safely worldwide.
  - Eighteen reactors in 9 countries, including 9 in the United States.
  - World's first nuclear electricity generated by EBR-I in Idaho.
  - Over 250 reactor-years of experience.
- Fast reactors are not (presently) competitive in an unregulated electricity market.
  - Electricity costs are 25 to 50% higher than present cost from coal.
  - Optimization for economics often counters improved safety.
  - Use is not sustainable if reliant upon subsidies for competitiveness.
  - Risk is increased for licensing of a novel reactor concept in the United States.



GNEP will not succeed without optimization of fast reactors for safety and economics.

Optimization through experience

- Thermal reactors have >10,000 years of commercial experience.
  - It took decades of poor performance to learn best practices.
- Fast reactors have very little commercial experience.
  - Test reactor experience does little to help a commercial entity optimize.



Inherent versus engineered safety

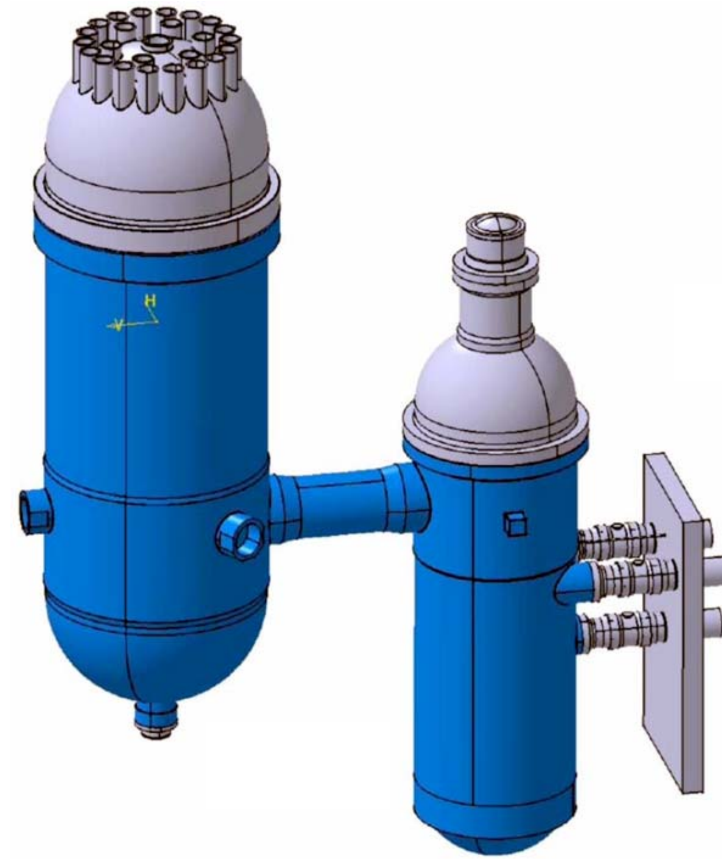
- Thermal reactors have added expensive engineered safety systems because of high-profile accidents.
  - New thermal reactor designs incorporate inexpensive systems designed to be inherently safe.
  - Fast reactors must reduce their reliance on engineered systems for additional safety and improved economics.

Predictive simulation of fast reactors to aid competitiveness

- High-fidelity simulation replicates years of operating experience.
  - Incorporate all of the physics that are integrated within the system.
  - Uses an as-built design with accurate data.
- Offers a flexible simulation tool for optimization of many concepts.
  - May require thousands of independent computations of the full system.
  - Easily scalable, but how many CPU-hours would be required to be predictive?

OAK RIDGE National Laboratory

CANS: Collaboration for Advanced Nuclear Simulation



- Explore scientific phenomena.
  - Complex interaction of nuclear, mechanical, chemical, and structural processes in fission reactors.
- Simulate severe accidents.
  - Multiphysics transients with advanced materials at high temperature and pressure in a changing radiation spectrum.
- Optimize nuclear designs.
  - Nuclear facilities are expensive in cost and time.
  - Radiation activation prevents retrofits.

Operate as a multilaboratory, multiuniversity collaboration

Argonne National Laboratory · INL Idaho National Laboratory · Los Alamos National Laboratory · Oak Ridge National Laboratory · The University of Arizona · Columbia University · Georgia Tech · UT

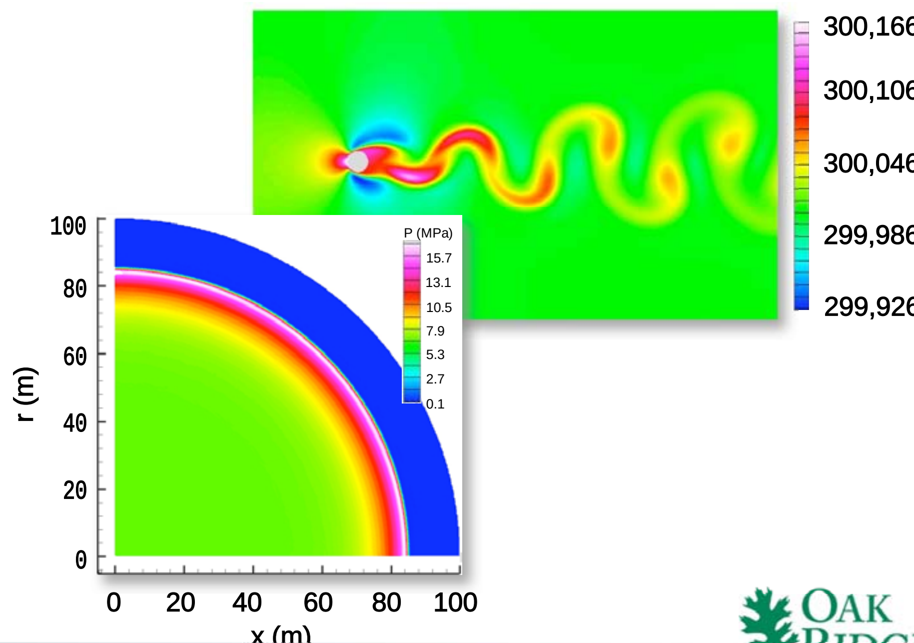
EMPRESS: All-speed CFD and conjugate heat transfer

Conjugate heat transfer

- Conduction and convection with all-speed computational fluid dynamics (CFD)
  - Three coupled, transient governing equations: conservation of mass, momentum, and energy
  - Multiscale simulation spans: 7 orders of magnitude in space, 10 orders in time
  - Solutions required for coupled equations, each with 10^{10} degrees of freedom per time-step
- Radiative heat transfer: nonlinear Boltzmann transport and Planck emission
  - Coupled through quartic temperature dependence
  - Span similar orders of magnitude as convection
  - To be coupled with CFD and heat transfer
- High-fidelity distribution of heat generation

EMPRESS: Parallel CFD and conjugate heat transfer

- Development of advanced algorithms: pressure-corrected implicit continuous Eulerian CFD
- Multilaboratory code development
  - Idaho: CFD and nonlinear coupling
  - Argonne: numerical solvers/parallelization
  - Los Alamos: radiative heat transfer



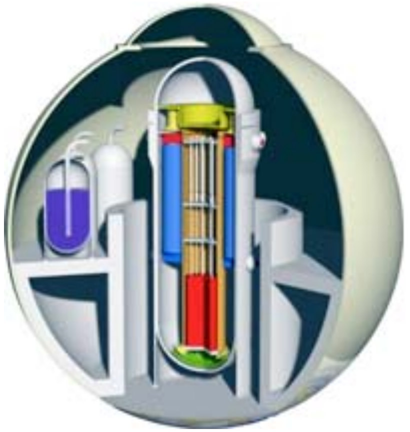
NEWTRNX: High-fidelity transport for heat generation

Heat generation

- Neutron-induced nuclear fission
  - 6-D neutron distribution (3-D space and momentum) defined by the linear Boltzmann transport equation
  - Multiscale simulation spans: 5 orders of magnitude in space, 10 orders in momentum
  - 10^{12}–10^{21} degrees of freedom required per time-step
- Radiation capture from radioactive decay
  - Coupled production/destruction of 1600 isotopes in time
  - 6-D photon distribution also defined by linear Boltzmann transport equation
  - Space scales similar to neutron distribution
- Dependency upon accurate temperature and density distribution

NEWTRNX: Parallel transport coupled to accurate nuclear data

- Initial testing
  - Up to 10^{12} degrees of freedom on more than 2000 processors
- Utilizing advanced software tools
  - ORNL’s SCALE: world-leading nuclear data processing software
  - Advanced HPC software from SciDAC: CCA, PETSc
- Developing advanced mathematical algorithms
  - Slice-balance spatial discretization
  - Nonlinear multilevel, multigrid acceleration techniques



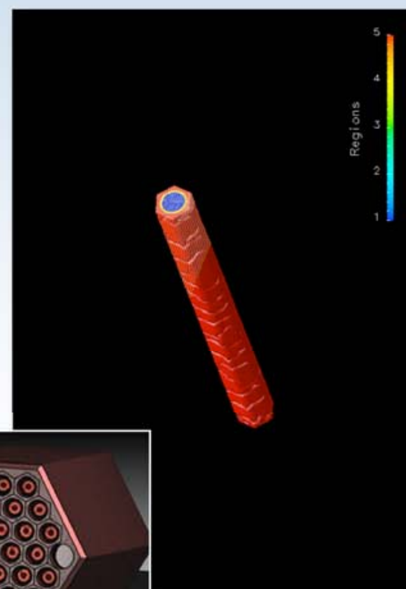
NEWTRNX: Scalable algorithms for 6-D transport

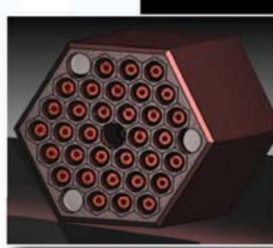
Memory and computation decomposition

- Spatial domain decomposition
  - Parallel Block-Jacobi algorithm executed on up to 2000 processors
  - 85% parallel efficiency on 512 processors with 10^{12} degrees of freedom
  - Efficient terascale scaling for full reactor simulations
- Space/momentum decomposition in the future
  - Required for petascale computing, subsets of the full reactor, or other systems
  - Collaboration with Los Alamos National Lab for additional development

Asynchronous MPI communication

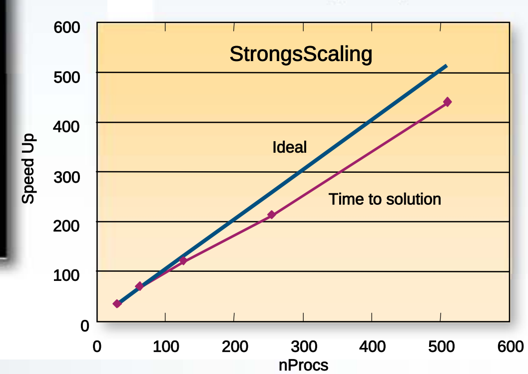
- Well suited for weakly dependent domains
- Provides a level of built-in load balancing
- Continues improvement with PEAC end station





Initial testing and verification

- Demonstration on the High-Temperature Test Reactor in Japan
- Incorporation of as-manufactured facility design with a CAD interface
- Use of fine-mesh discretization in space (10^6 elements) and momentum (10^6)
- Replication of Monte Carlo for simple problems



Collaboration for Advanced Nuclear Simulation: Predictive reactor simulation for GNEP

GNEP seeks to revolutionize the global energy market.

- Provides abundant energy without generating greenhouse gases.
- Recycles used nuclear fuel to minimize waste and reduce proliferation.
- Allows developing nations to deploy nuclear power to meet energy needs safely.
- Maximizes energy recovery from still-valuable used nuclear fuel.
- Requires only one U.S. geologic waste repository for the rest of this century.

The "fast" reactor concept must be optimized for economics and safety.

- Decades are not available to overcome shortfalls in commercial operating experience.
- The job can be done only with predictive simulation tools that require coupling high-fidelity solvers for each physics domain and using leadership-class hardware.

Global Nuclear Energy Partnership

The Collaboration for Advanced Nuclear Simulation.

- Integrate advanced tools for high-performance computing.
- Develop advanced algorithms and solvers where present tools are lacking.
- Couple all of the appropriate physics domains on relevant scales.
- Collaborate among premier institutions to use the **best in class**.

Contact

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The team

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