Argonne NATIONAL LABORATORY

... for a brighter future

Sustainable Nuclear Energy Production and Nuclear Waste Management

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A Sustainable Energy System

- **There is no single solution to the complex set of issues facing the energy system.**

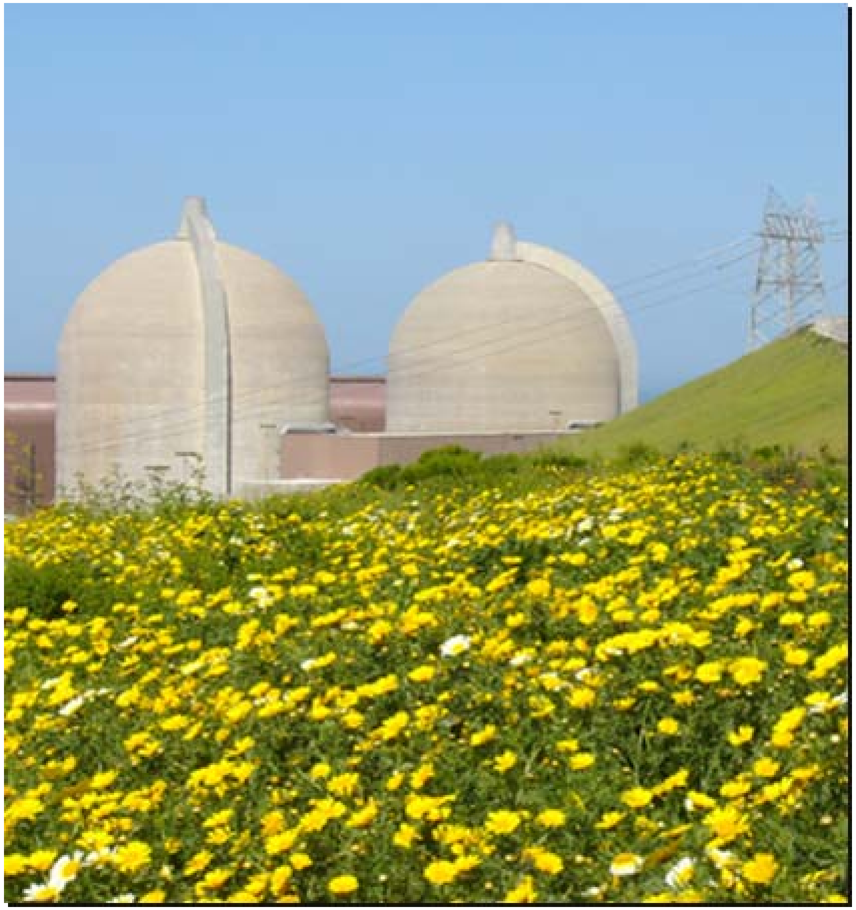
- **The serious issues we face require attention from everyone – policymakers, scientists and engineers, energy industry, and the public.**

- **The requirements are a diverse set of energy sources, more efficient homes, buildings, and vehicles, energy conservation, and robust energy infrastructure and environmental control systems.**

These solutions must be developed in parallel and require S&T solutions.

U.S. Nuclear Power Economics Reflect Solid Performance

- Strong safety record
- High average capacity factor
  - 90% in 2005
- Decreasing production costs
  - 30 percent in the last ten years
  - 1.72 cents/KWH
- Performance excellence through power uprates
  - Gain of 4,183 MWe
- Minimal greenhouse gas emissions
- Renewals continue
  - 48 complete
  - 38 filed or announced



Building a new generation of nuclear power plants

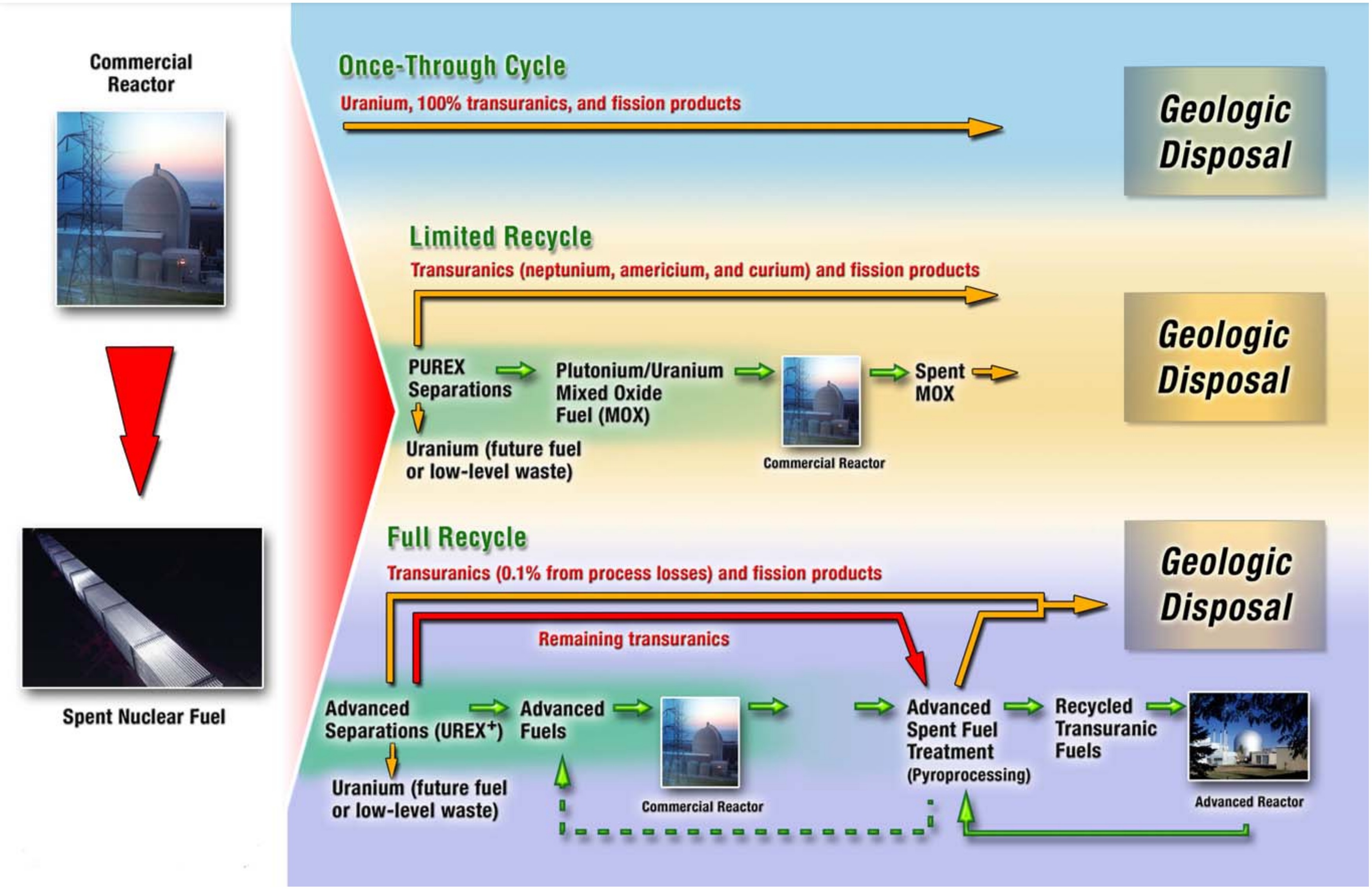
- Nuclear Regulatory Commission is accepting applications for design certifications and operating licenses
- Gen III+ designs
- Nuclear Power 2010 launched by Department of Energy in 2002
  - Reduces technical, regulatory, and institutional barriers to building new plants
- EPACT 2005 enacted federal risk insurance, production tax credits and loan guarantees for low emission technologies
- More than 30 notifications to NRC of potential new builds in the U.S.

Sustainable Nuclear Energy and Nuclear Fuel Cycle

- **The essential, sustainable future for nuclear energy warrants a more comprehensive approach to nuclear waste management in which fuel fabrication, reactor design and performance, separations, transmutation, and geologic disposal work in an integrated manner to provide abundant, sustainable nuclear energy.**

- **The closed fuel cycle provide a comprehensive vision for expanded, sustainable nuclear energy.**
  - Secure and proliferation-resistant fuel cycle technology
  - Recycle useable material, minimize waste, and resource management

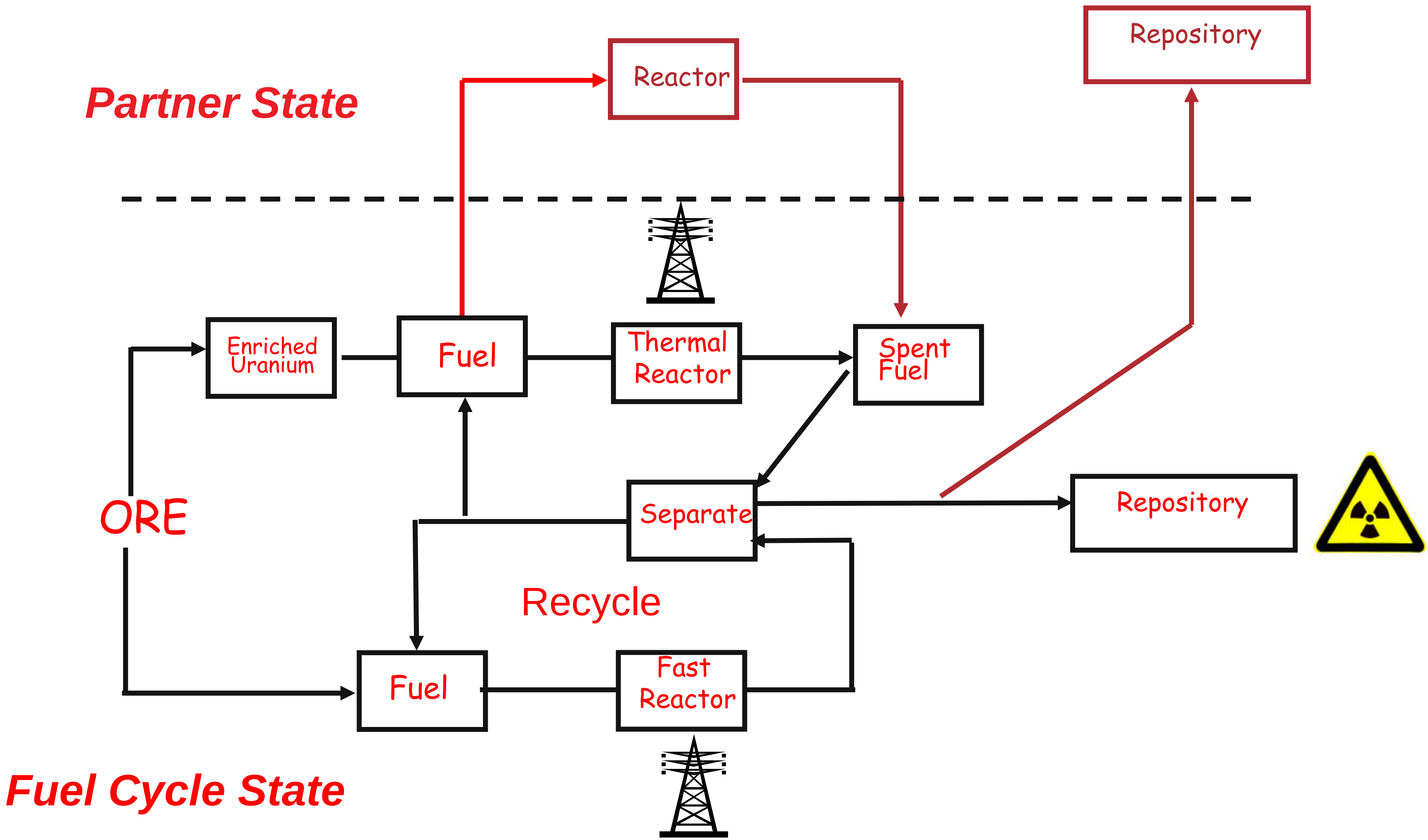
Spent Nuclear Fuel Management Options



Potential Benefits of Closed Fuel Cycle: Uranium Supply and Economics

- **A closed fuel cycle can effectively multiply uranium resources by a factor of ~100**
- **Current known uranium resources are sufficient for nuclear energy production for several decades, but there are other considerations**
  - Energy independence is a factor because much of the uranium resources are non-U.S.
  - The additional costs of a closed fuel cycle are high enough that uranium supply and demand cannot be the sole economic driver for a closed fuel cycle.
  - This will be the case for several decades – the tipping point could be as soon as 2050.

Potential Benefits of Closed Fuel Cycle: Nonproliferation

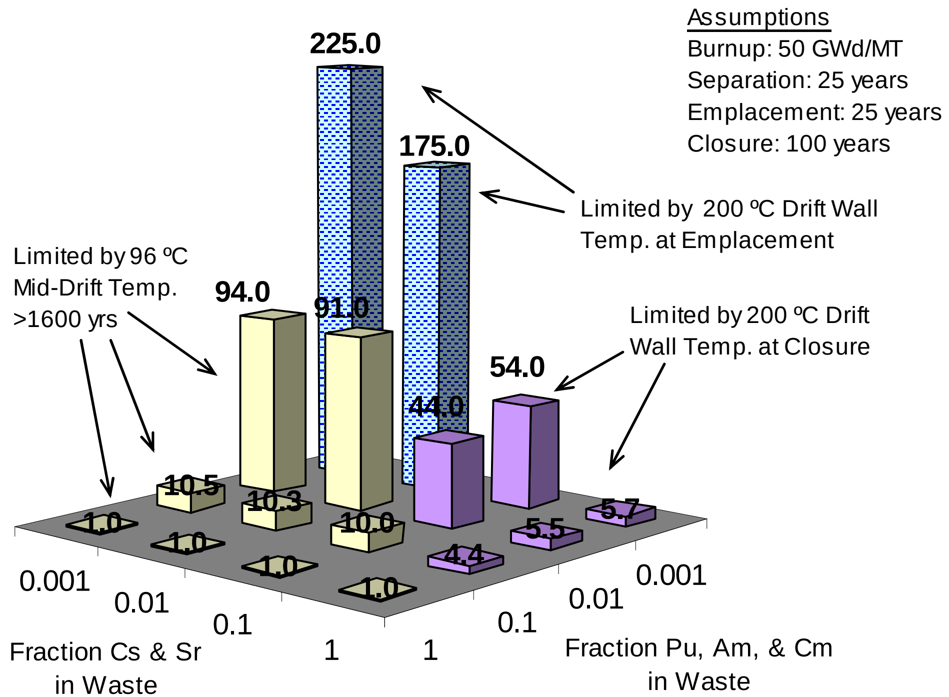


Potential Benefits of Closed Fuel Cycle: Waste Management

- **With the processing of spent nuclear fuel to remove the elements responsible for the decay heat that cause temperature limits to be reached, large gains in utilization of repository space are possible**
  - Only considers thermal performance, not dose rate

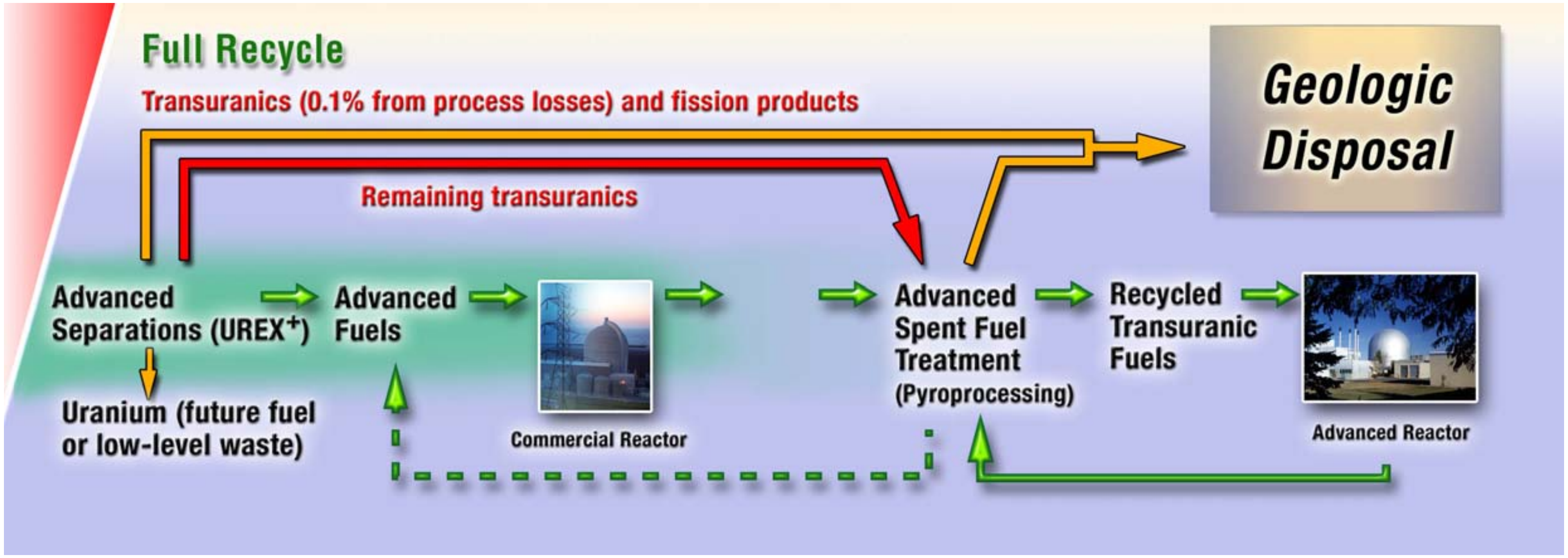
- **Pu, Am, Cs, Sr, & Cm are the dominant elements**
  - The recovered elements must be treated
    - *Separate storage of Cs & Sr for 200-300 years*

- **Recycling of Pu, Am, & Cm for transmutation and/or fission**
  - Irradiation in reactors

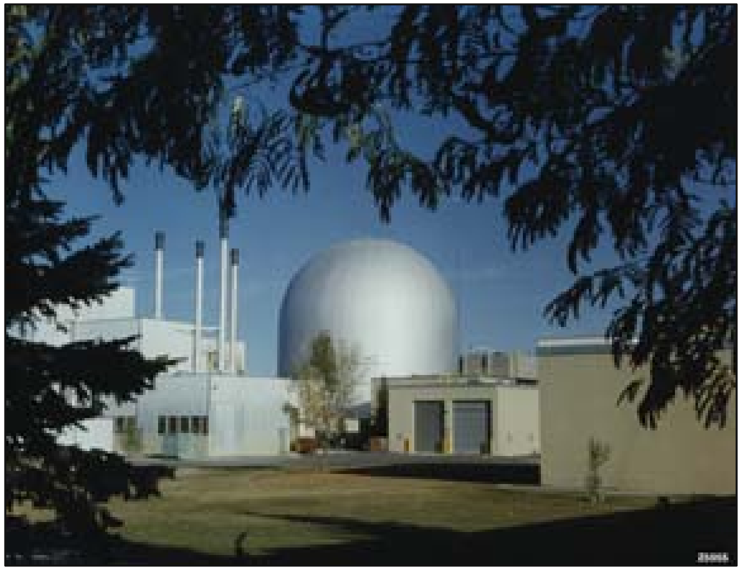


Current Developments for Closed Fuel Cycle Technologies

- **Several nations are proposing a closed fuel cycle that effectively manages spent nuclear fuel to support continued and/or expanding nuclear energy production.**
- **The selection of technologies needed to meet this objective include**
  - Advanced separations for spent nuclear fuel (UREX+ and others)
  - Advanced spent fuel treatment (e.g., pyrochemical processing)
  - Advanced reactors to burn the recycled transuranics (burner reactors)



Fast Reactor Experience



U.S. Experience

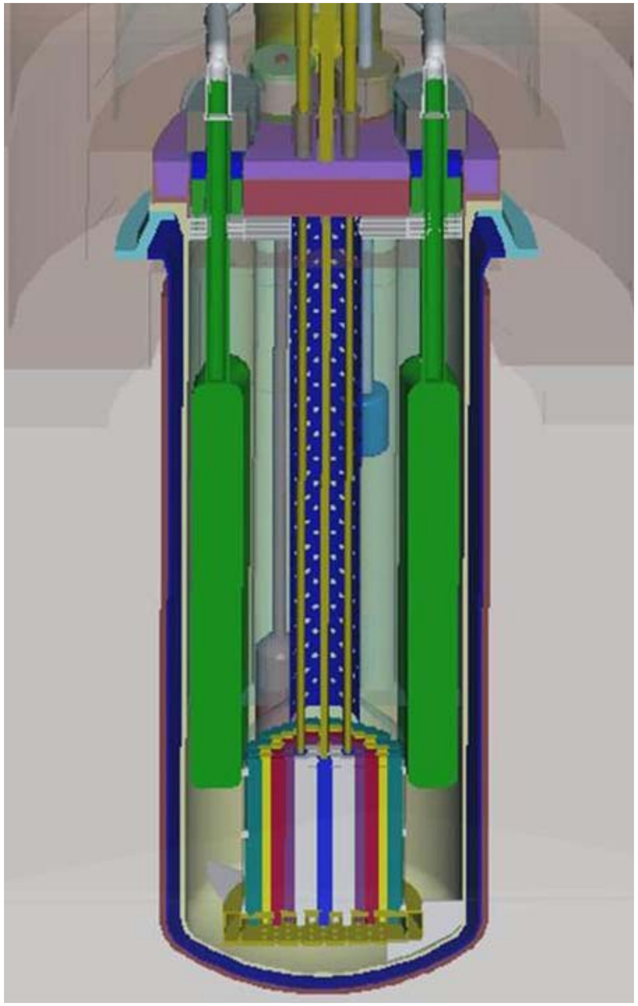
- First usable nuclear electricity generated by a fast reactor – EBR-I in 1951
- EBR-II (20 MWe) operated at Idaho site from 1963 to 1994
  - *Closed fuel cycle demonstration*
  - *Passive safety tests*
- Fast Flux Test Facility (400 MWt) operated 1980–1992

International Experience

- BN-600 power reactor since 1980 at 75% capacity factor
- Operating test reactors: PHENIX (France), BOR-60 (Russia), JOYO (Japan)
- Most recent construction was MONJU (280 MWe) in 1990

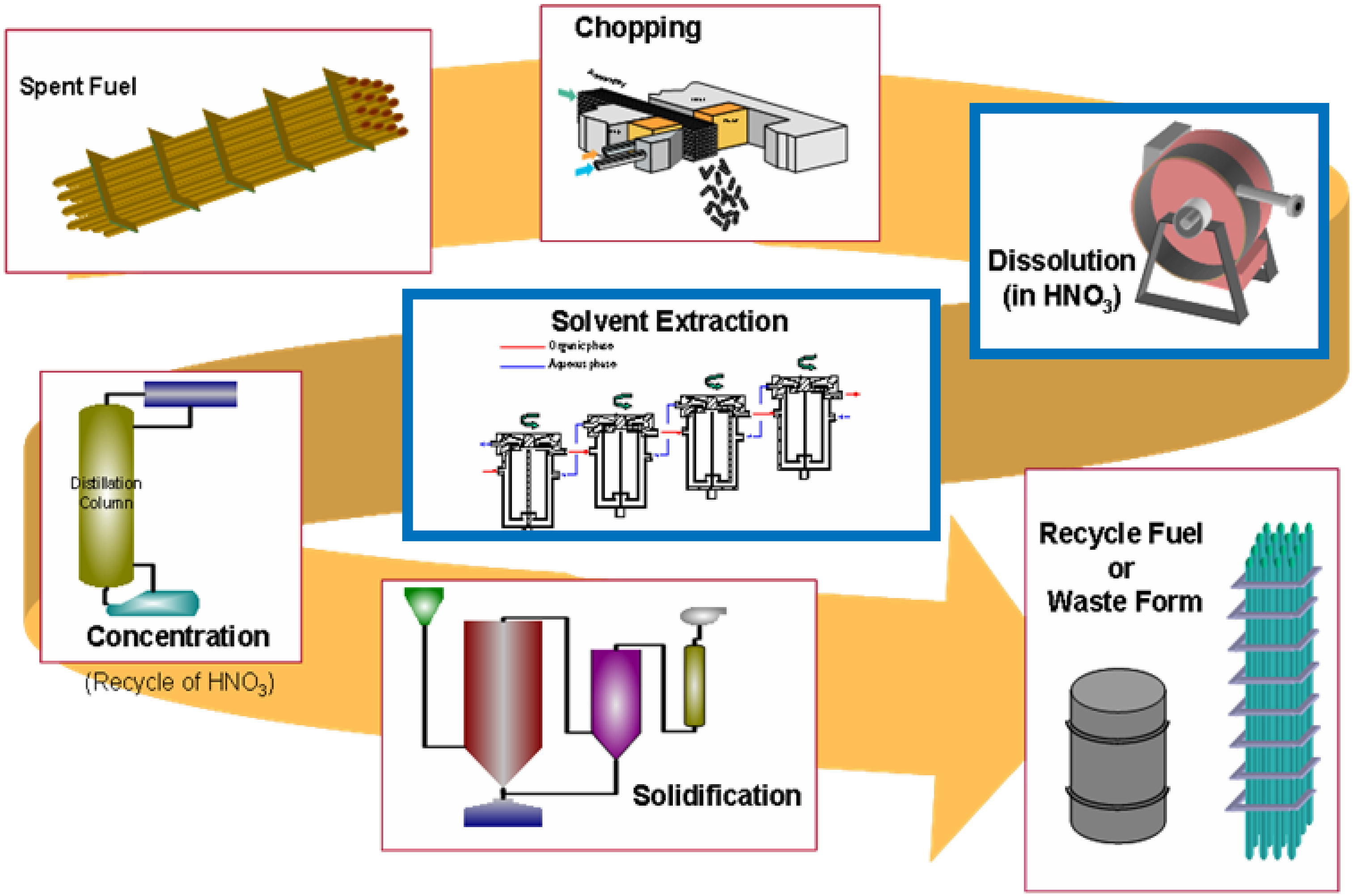
Sodium-cooled fast reactor technology has been demonstrated

Advanced Reactor: Sodium-cooled Fast Burner

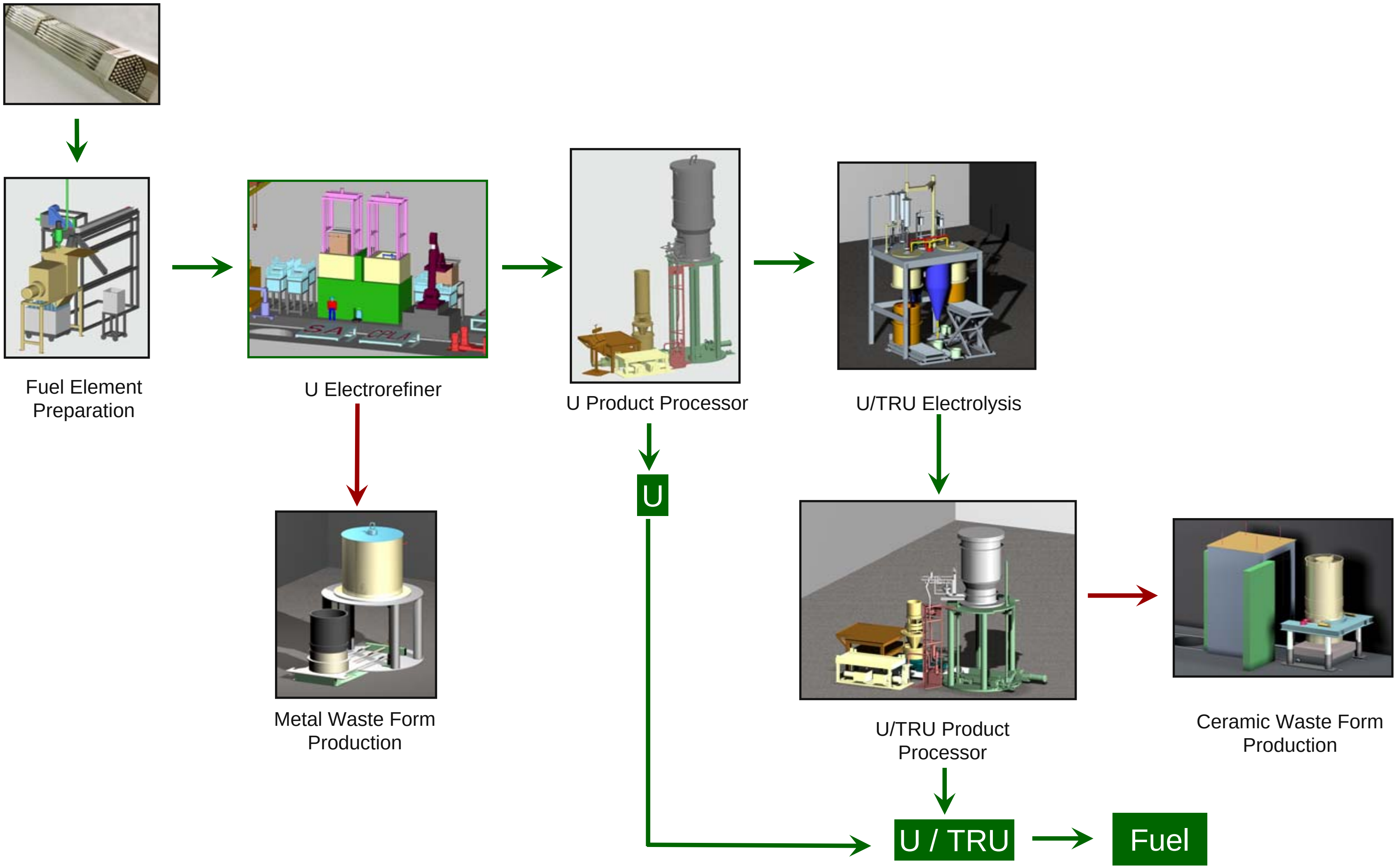


- Basic viability of sodium-cooled fast reactor technology has been demonstrated
- Low pressure primary coolant
  - Outlet temperature of 500-550ºC
- Pool configuration
  - Pumps and heat exchangers contained
  - Loop configurations favored by Japan
- Heat exchanged to secondary coolant for energy conversion system
  - Rankine steam generator or supercritical CO_2 Brayton
- High power density core
  - 250 kW/l (vs. 75 kW/l for LWR)
  - High fuel enrichment (>20% fissile)
- Passive decay heat removal
  - Either from pool heat exchangers or air cooling of reactor vessel
- Favorable inherent safety behavior

Aqueous Spent Fuel Treatment (UREX+) for Waste Management and Proliferation Resistance



Fast Reactor Fuel Fabrication and Recycle: Pyroprocessing



Major Technical Challenges

- **The challenges in developing the technologies include:**
  - **Separations**
    - ***Process losses, waste forms, and cost reduction***
  - **Advanced spent fuel treatment**
    - ***Process losses, fuel fabrication, fuel performance, and waste forms***
  - **Burner reactors**
    - ***Cost reduction***
  - **Scale-up is needed to discover and solve industrial issues**

- **A robust basic and applied R&D program is required to improve performance and develop next-generation technologies**

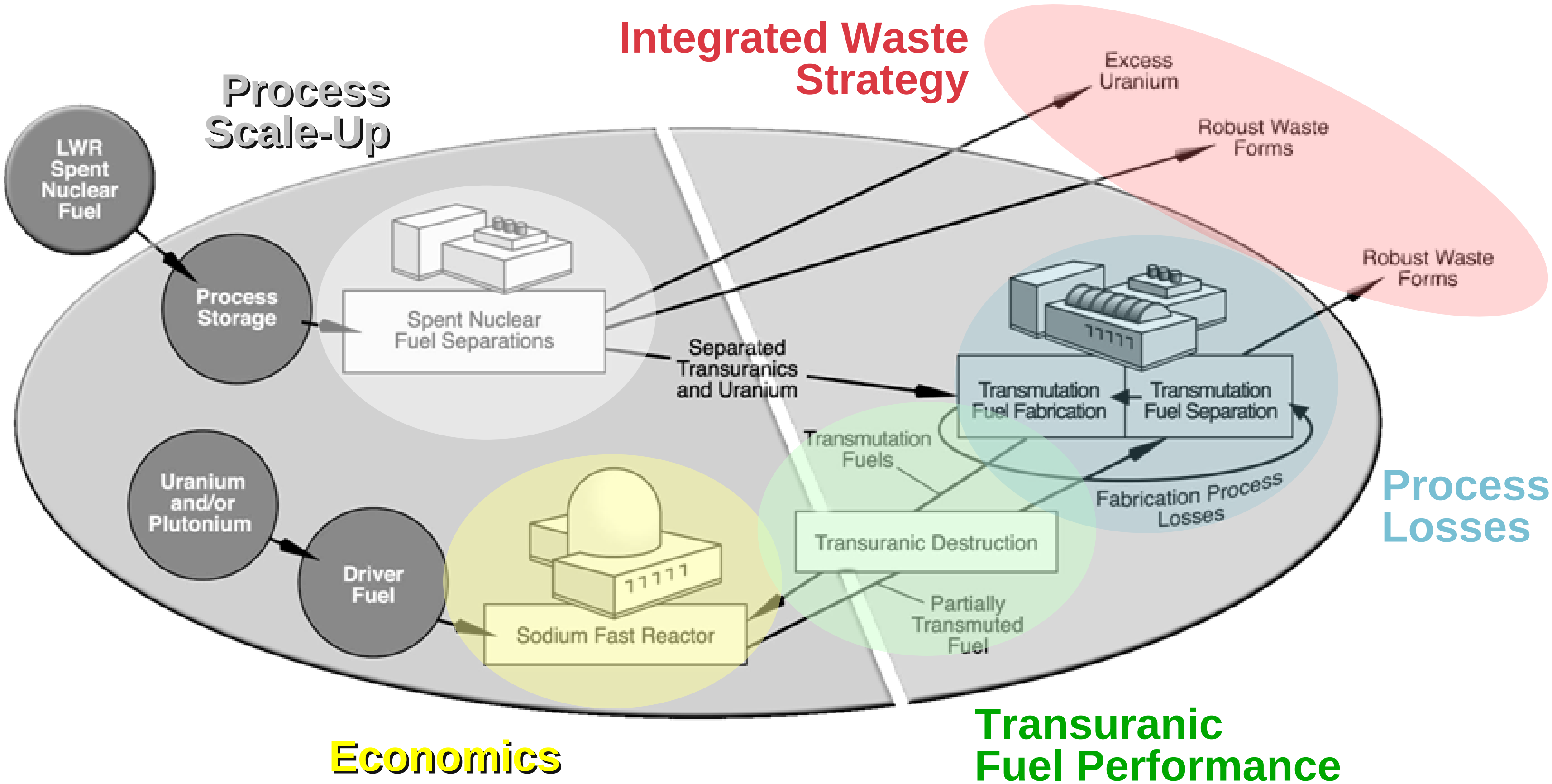
- **Advanced modeling and simulation can transform the design process for advanced nuclear energy systems**

Science-Based Engineering

- **We must continue to address the challenges of public perception and acceptance and economics to enable sustainable nuclear energy. Again, these challenges include:**
  - Reactor safety
  - Domestic nuclear waste disposal
  - International nonproliferation
  - The role of nuclear energy in addressing global warming

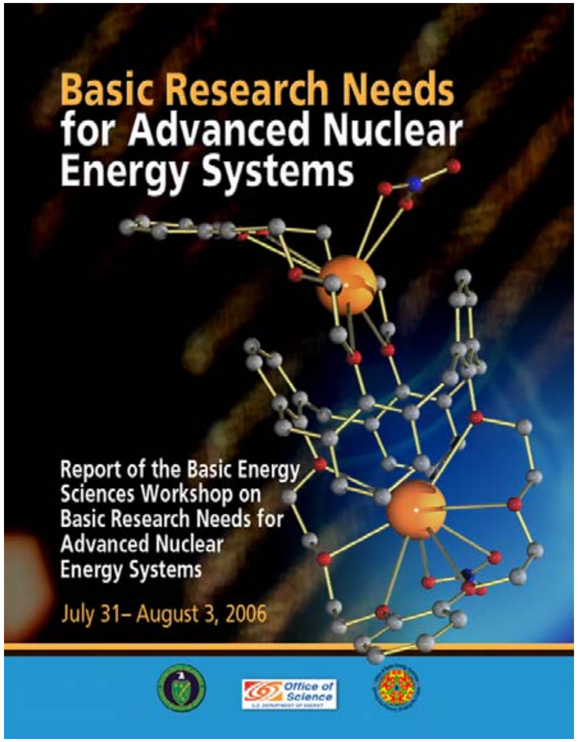
- **We should be adopting a modern science and simulation-based engineering approach**
  - High fidelity simulations must be integrated with the design process and validated by experiment
  - Science-based, validated modeling at both the detailed (small-scale) and systems-level must be part of the core capabilities
  - The field must generate internal technical excitement to attract the "best and the brightest"
  - The National Laboratories and universities must establish long-term partnerships with industry in order to translate present and future advances in science-based engineering to industrial practice

DOE Global Nuclear Energy Partnership
Applied Science and Engineering



DOE BES Workshop – "Basic Research Needs for Advanced Nuclear Energy Systems"

- **Focused on new, emerging, and scientifically challenging areas with potential for significant impact on the effective utilization of nuclear energy**
  - Materials under extreme conditions
  - Chemistry under extreme conditions
  - Separations science
  - Advanced actinide fuels, including inert matrix fuels
  - Actinide-containing waste forms
  - Predictive modeling and simulation – advanced materials, systems, and processes
  - Crosscutting and grand challenge science themes



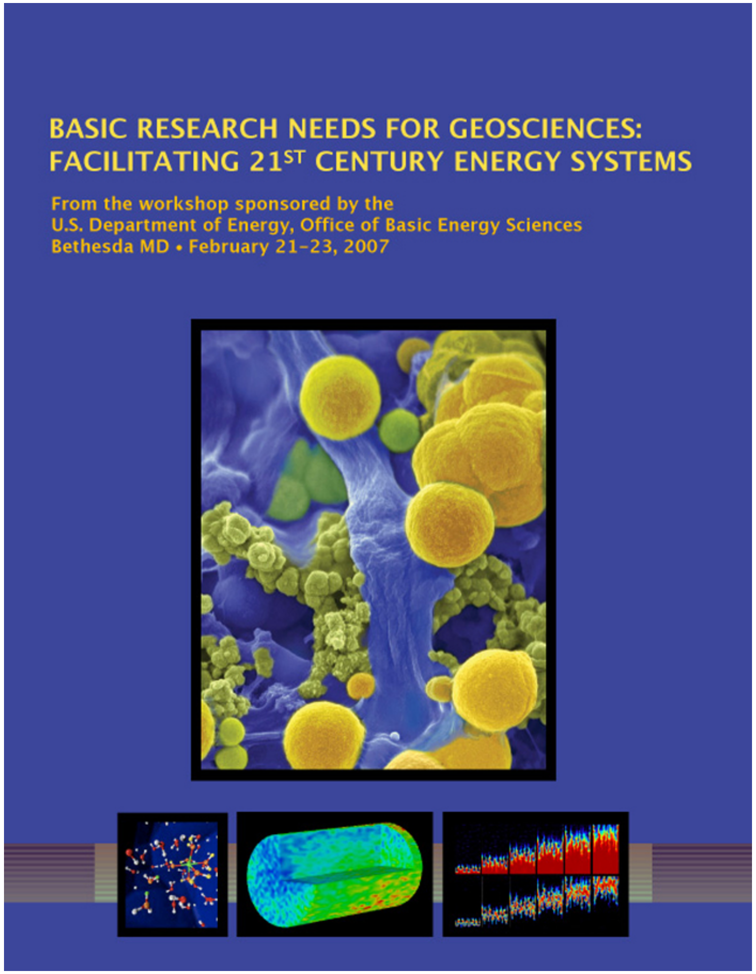
http://www.science.doe.gov/bes/reports/files/ANES_rpt.pdf

DOE NP/ASCR Workshop – "Nuclear Physics and Related Computational Science R&D for Advanced Fuel Cycles"

- **Research Priorities**
  - Nuclear data with covariances to identify priorities for cross-section measurements and improved modeling of nuclear reactions
  - Nuclear cross-section measurements using direct experiments and indirect techniques
  - Nuclear theory and computation and development of a new generation of theoretical tools and new computational codes for modern computational platforms

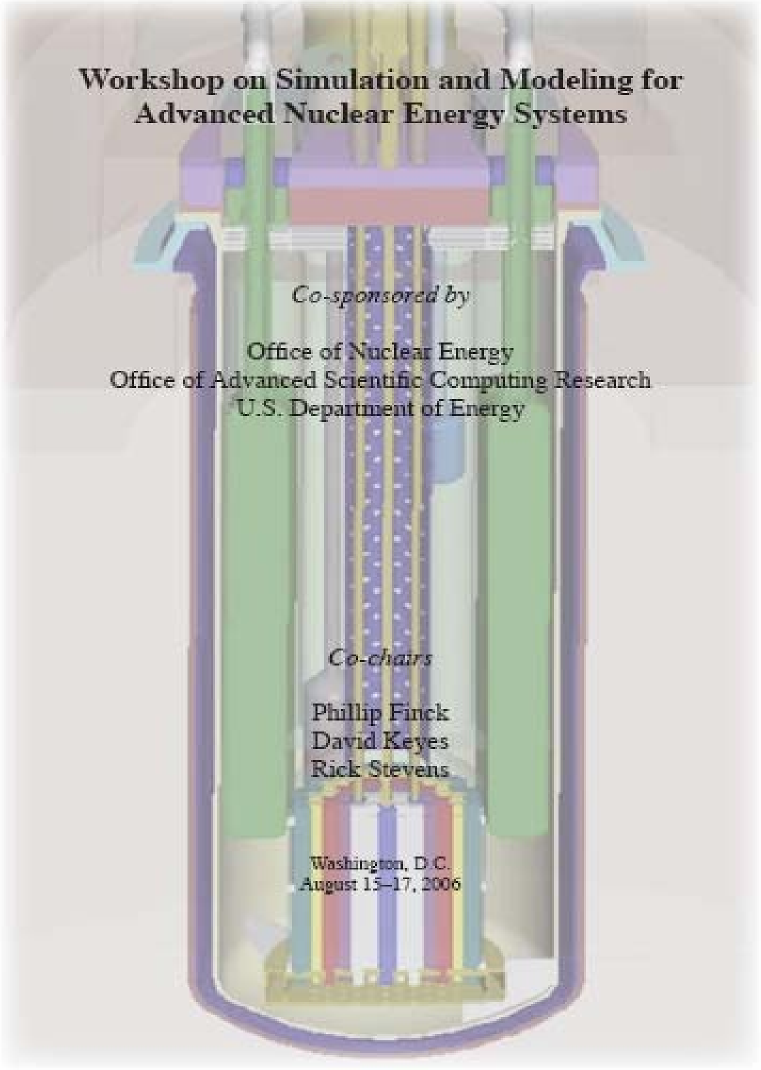
DOE BES Workshop – “Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems”

- **Priority Research Directions**
  - Chemistry of mineral surfaces, nanophases, and solutions
  - Subsurface monitoring, imaging, and characterization
  - Physics and chemistry of multiscale systems
  - Biogeochemistry



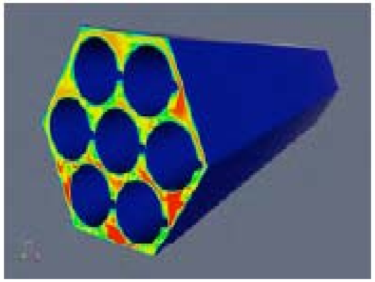
DOE ASCR/NE Workshop – “Simulation and Modeling for Advanced Nuclear Energy Systems”

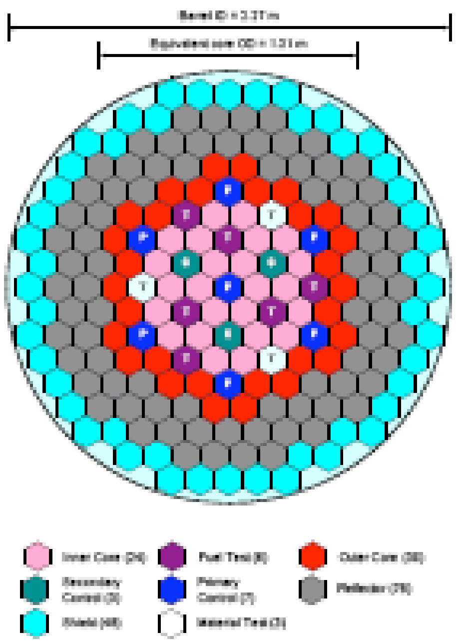
- **Explored the simulation and modeling needs for developing advanced nuclear energy systems**
  - Reactor core simulation
  - Seismic/structural mechanics/balance of plant
  - Validation
  - Repository
  - Separations chemistry
  - Materials and fuel design
  - Mathematical and geometrical modeling
  - Validation, verification, and uncertainty quantification
  - Scalable and multiscale algorithms
  - Software tools and software engineering
  - Computing facilities, data analysis and visualization, and networking

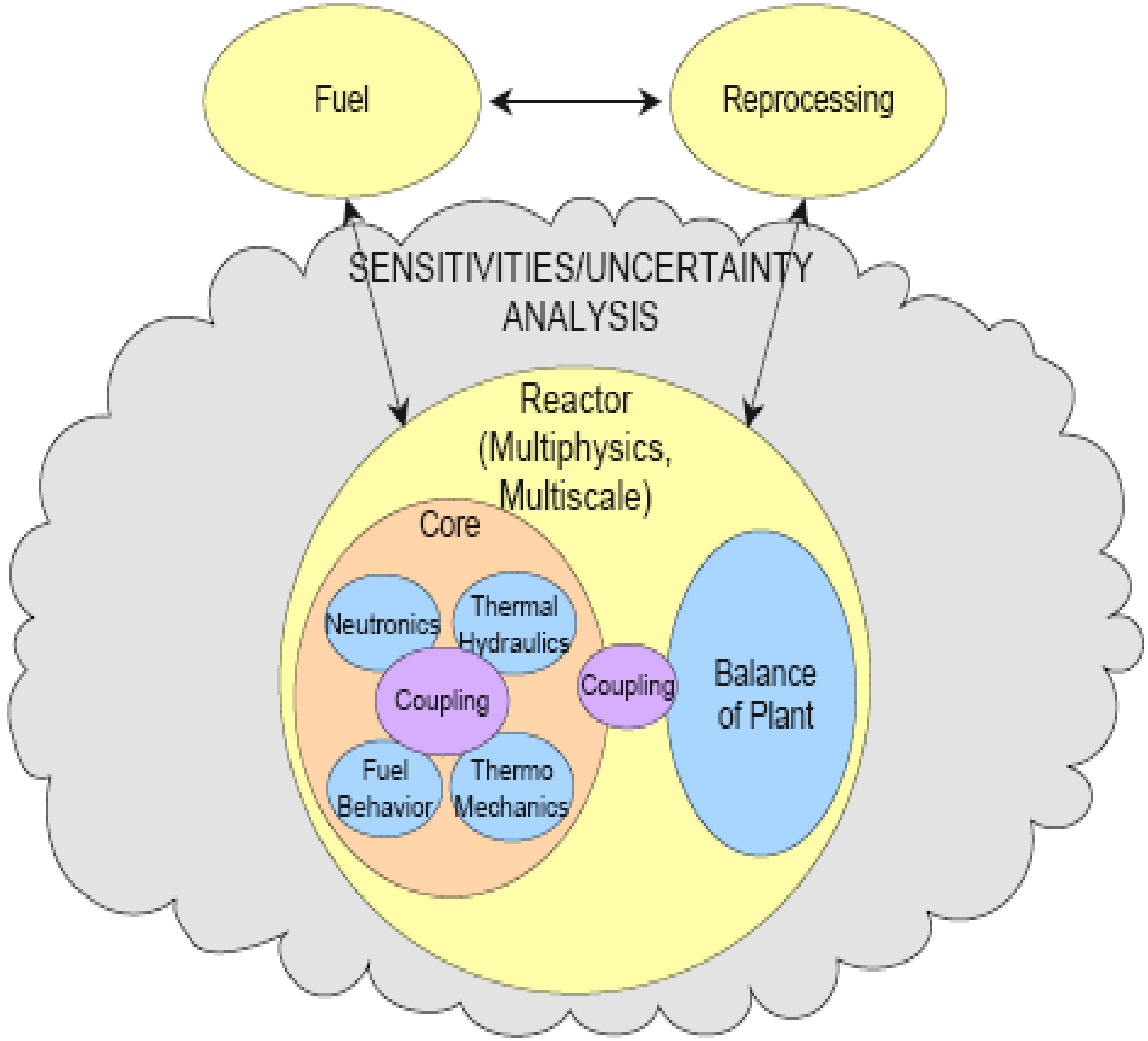


http://www-fp.mcs.anl.gov/anes/

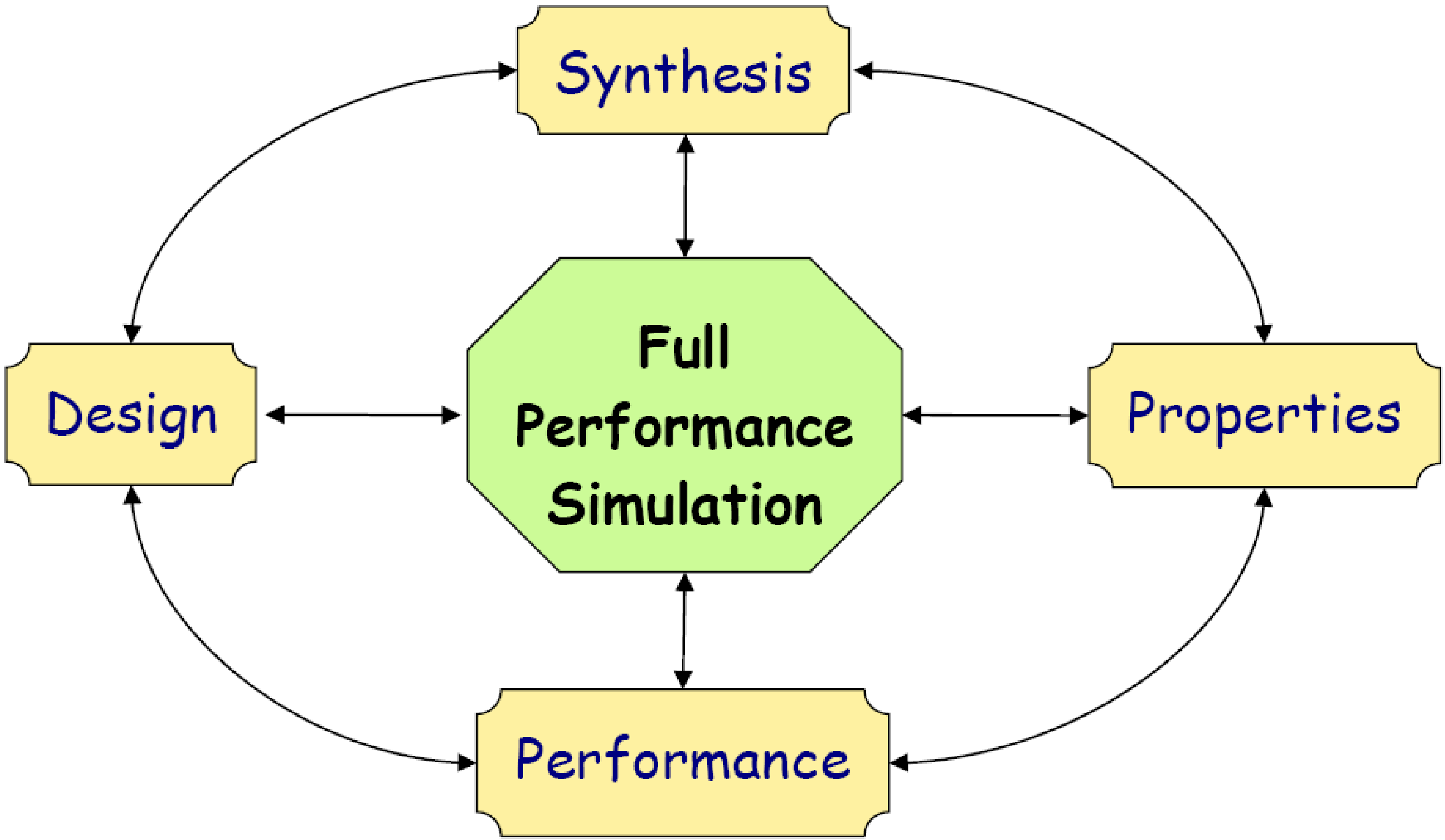
Science-Based Engineering (cont.)
Thermal-Hydraulics, Neutronics, and Coupling







Science-Based Engineering (cont.)
Full Performance Simulation –
Advanced Fuels and Waste Forms



after Tomas de la Rubia (2007) *Basic Research Needs for Materials in Extreme Environments*

Summary

- **Nuclear energy will be a critical resource for the future, especially as total energy needs increase and/or other energy sources need to be displaced.**

- **The closed fuel cycle provide a comprehensive vision for expanded, sustainable nuclear energy.**
  - Secure and proliferation-resistant fuel cycle technology
  - Recycle useable material, minimize waste, and resource management

- **Development of closed fuel cycle requires basic and applied science and engineering and nuclear R&D facilities.**

- **Basic and applied science and engineering, and the potential advances in understanding, and advanced modeling and simulation will allow for breakthroughs that will transform advanced nuclear energy systems.**