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Fuel Cycle Research and Development Overview

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Outline

- The NE Roadmap and Objectives
- Changes: AFCI/GNEP to FCR&D – science-based approach, grand challenges, shifting resources
- Fuel Cycle Options
- FCR&D Technical Areas

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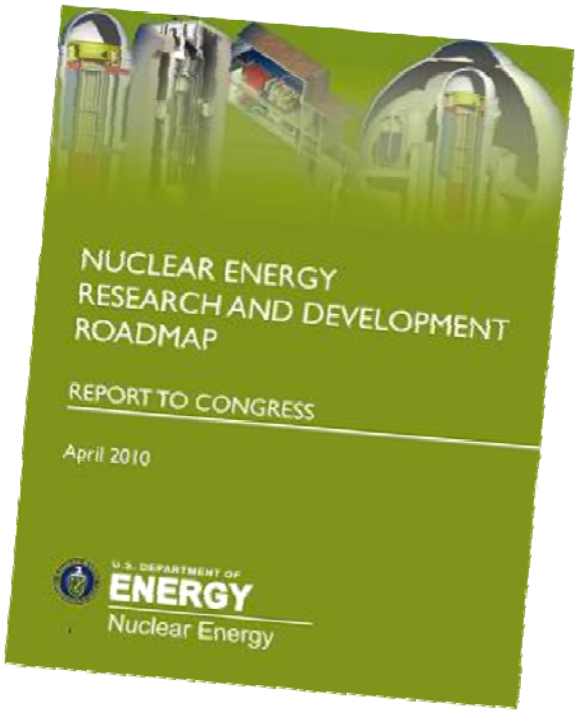
Nuclear Energy Roadmap

- **Nuclear energy objectives:**
  - were developed to focus resources on national imperatives for clean energy, economic prosperity, and national security.
- **Nuclear power will play:**
  - an important role in helping to meet the nation's goals of energy security and GHG reductions.
  - — Studies have projected potential growth on the order of 50 to 100 GWe by 2030.



- **Roadmap addresses transformation of NE programs to a more science-based approach.**

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Four Main NE R&D Roadmap Objectives

- **R&D Objective 1:**
  - Develop technologies and other solutions that can **improve the reliability, sustain the safety, and extend the life of current reactors.**
- **R&D Objective 2:**
  - Develop **improvements in the affordability of new reactors** to enable nuclear energy to help the Administration's energy security and climate change goals.
- **R&D Objective 3:**
  - **Develop Sustainable Nuclear Fuel Cycles**
- **R&D Objective 4:**
  - **Understand and minimize the risk of nuclear proliferation and terrorism.**

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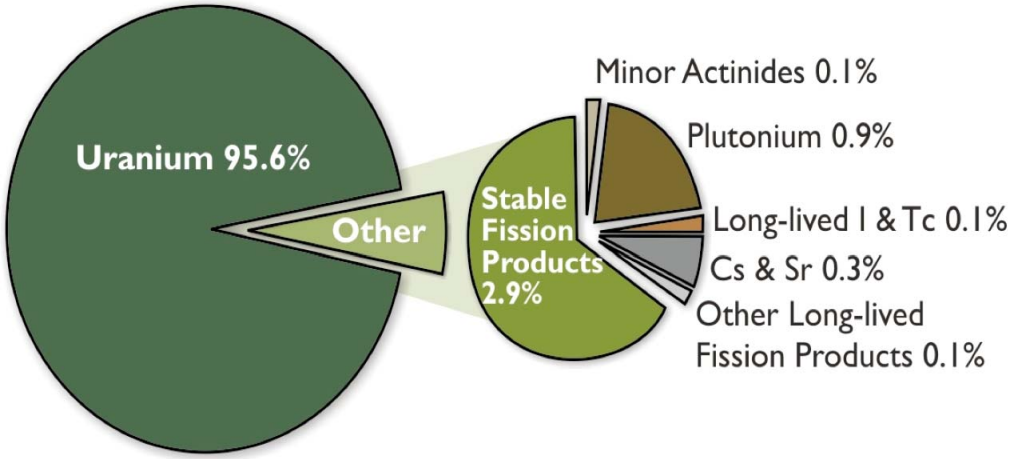
Objective 3: Sustainable Fuel Cycles

- **Goals**
  - In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
  - In the medium term, select preferred fuel cycle option for further development
  - By 2050, deploy preferred fuel cycle

- **Challenges**
  - Develop high burnup fuel and structural materials to withstand irradiation for longer periods of time
  - Develop simplified separations, waste management, and proliferation risk reduction methods
  - Develop optimized systems to maximize energy production while minimizing waste



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Setting the Stage for Changes

- **Domestic GNEP terminated by FY 2009 budget process in advance of DOE decision to formally end program**
- **Appointment of Secretary Chu provided clear new direction**
  - **Long-term, science-based, and transformational**
- **Program began taking steps in January 2009 to redefine the program to meet the new direction**
  - Initial emphasis was **no fuel cycle facility construction; refocus on long-term, high-risk, high-reward R&D**
- **Arrival of ASNE Miller modified program direction to re-incorporate the requirement for demonstration (goal-oriented approach)**
  - **Develop options for decision-makers to select fuel cycle technologies for commercialization in the 2050 time frame**

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Changes: Advanced Fuel Cycle Initiative (w/GNEP) to Fuel Cycle Research and Development

Advanced Fuel Cycle Initiative With GNEP	Fuel Cycle Research and Development
■Incremental improvement of existing technologies	■Transformational breakthroughs
■Driven by better utilization of Yucca Mountain repository	■Unconstrained range of storage and disposal options
■Focused on near-term technology deployment	■Long-term, goal-oriented, science-based approach

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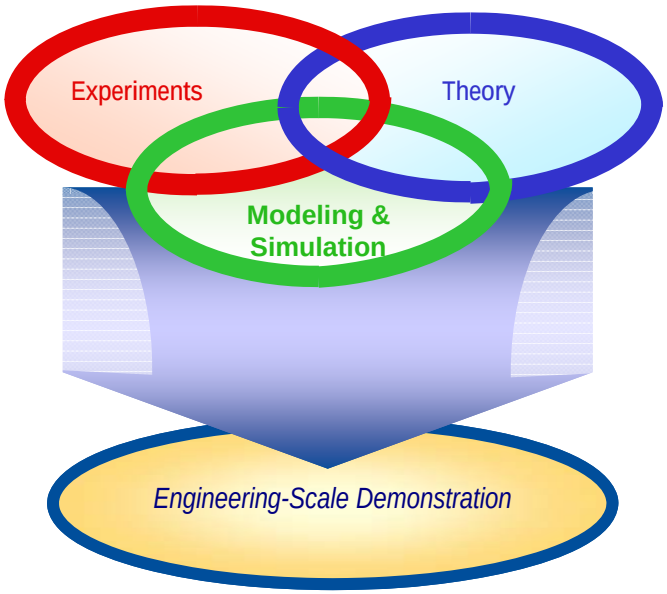
Science Based Approach to Nuclear Energy Development

- ***Experiments*** **– Physical tests done to develop understanding of single effects or integrated system behaviors.**

- ***Theory*** **– Creation of models (i.e., theories) of physical behaviors based on understanding of fundamental scientific principals and/or experimental observations.**

- ***Modeling and Simulation*** **– Use of computational models to develop scientific understanding of the physical behaviors of systems. Also used to apply scientific understanding to predict the behavior of complex physical systems.**

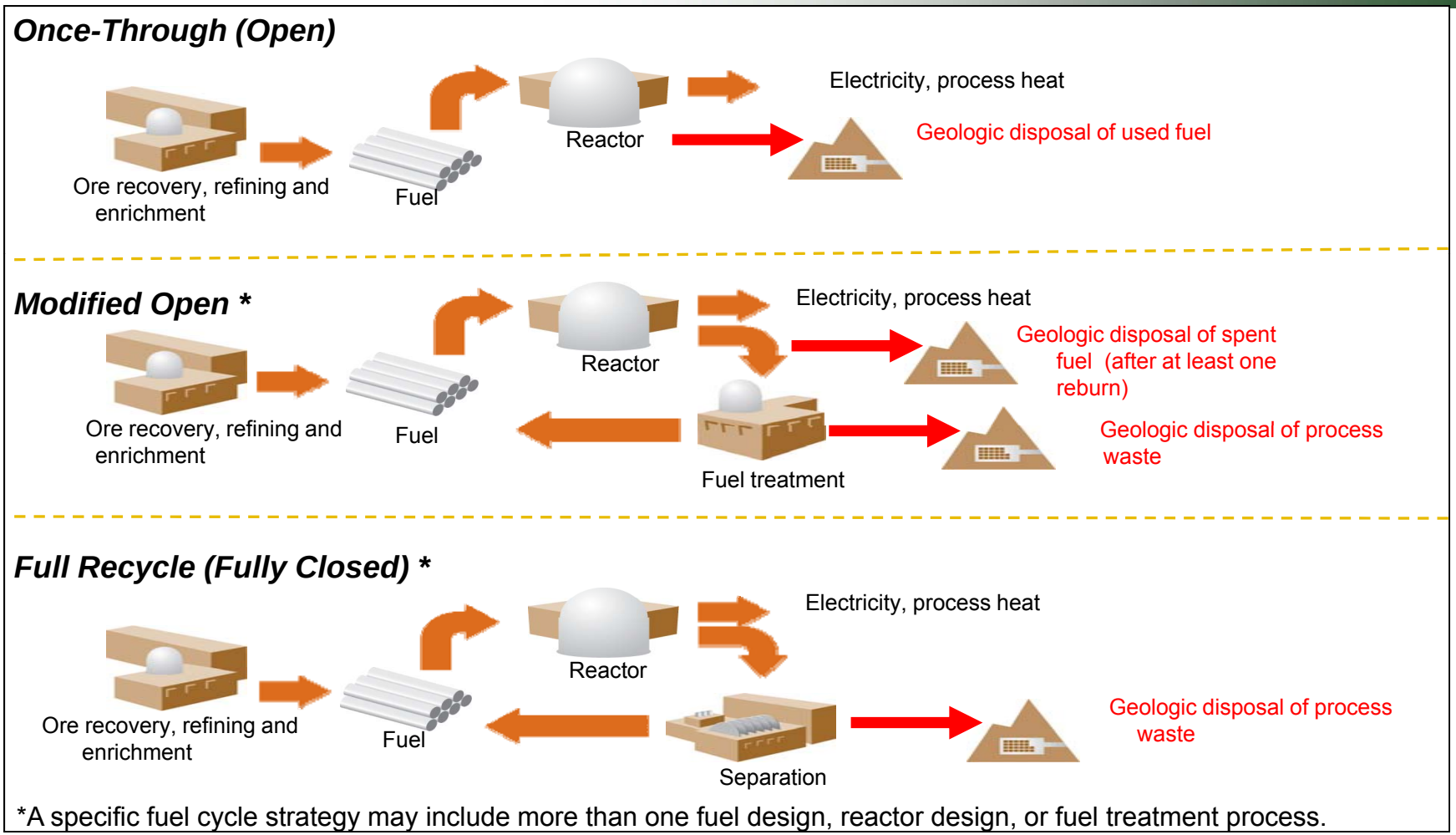
- ***Demonstrations*** **– New technologies, regulatory frameworks, and business models integrated into first-of-a-kind system demonstrations that provide top-level validation of integrated system technical and financial performance.**



Fuel Cycle Options

- **Once-Through Fuel Cycle (OTC) –** One pass through reactor, used fuel directly disposed in a geologic repository
- **Modified Open Cycle (MOC) –** No or limited separations and processing applied to used fuel to extract more energy
- **Full Recycle (FR) –** All actinides important for waste management are recycled in thermal and/or fast spectrum systems to reduce radiotoxicity and more fully utilize uranium resources

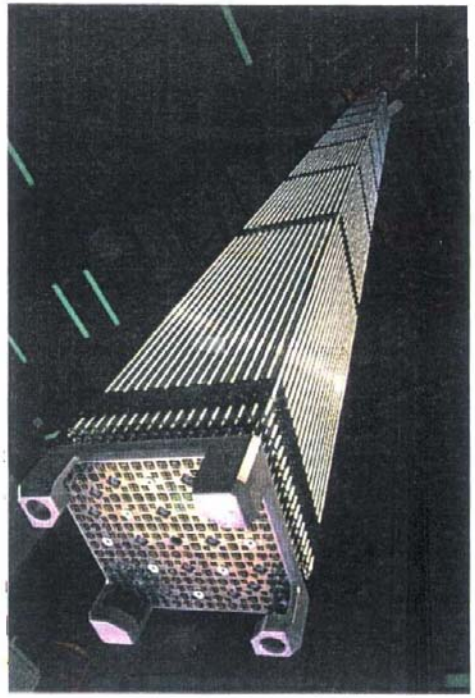
Three Potential Fuel Cycle Options



*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

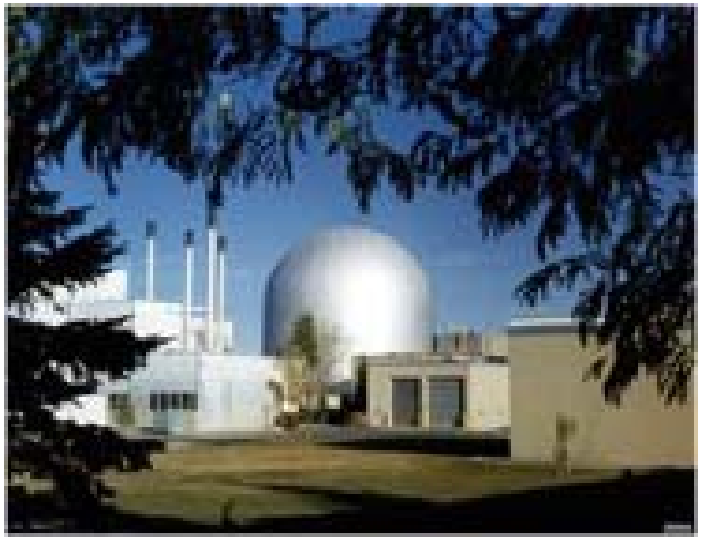
Once-Through Fuel Cycle

- **With once-through, used nuclear fuel is disposed in a repository.**
- **Uranium utilization is less than 1%.**
- **Fuel burnups have increased through the years.**
- **Higher burnups result in less spent fuel disposed but do not increase uranium utilization.**
- **Programs are pursuing advanced fuel designs that may double fuel burnups (100 GW/MTHM).**
  - **<u>Fuels may required enrichments higher than 5%.</u>**
- **Higher burnups results in less spent fuel disposed but similar amounts of actual waste (transuranics and fission products).**



Full Recycle

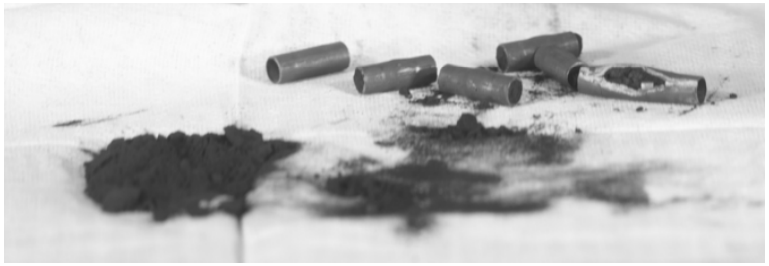
- **With completely closed fuel cycles, high-level waste forms are disposed in a repository.**
- **Recycle of plutonium to LWRs as MOX increases uranium utilization, but it is still very low.**
- **Recycle all transuranics into fast reactors combined with breeding in depleted uranium can enable uranium utilization to approach 99%.**



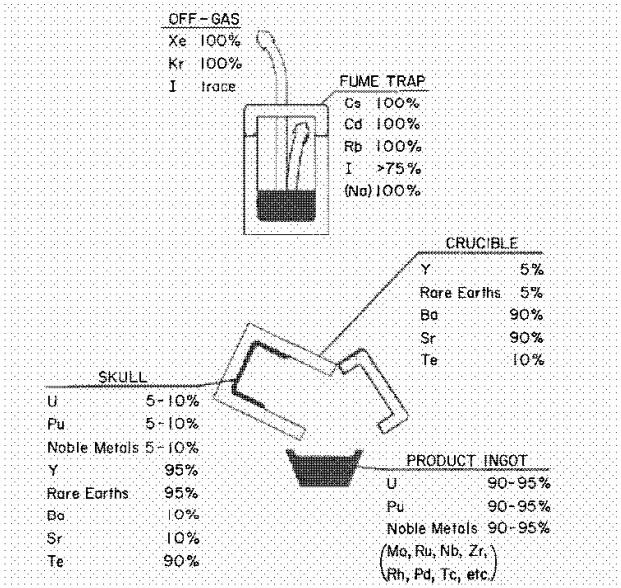
- **Both aqueous and dry technologies are being considered for fuel processing.**
- **Both metal and oxide fuels are being considered for fast reactors.**
- **As part of FCRD new technologies are also being assessed.**
  - Alkaline dissolution and separation, ionic liquid extraction and electrochemical separation, super critical fluid extraction, uranium crystallization, volatility approaches (airox, deox, fluoride volatility, etc), and zone refining

Modified Open Cycle

- **Modified open cycles <u>involve reuse of fuel which may require some form of treatment.</u>**
- **Treatment means modification of the used fuel.**
- **This could be as simple as heat treating the used fuel cladding or as complex as chemical processing and recladding the fuel.**
- **Some separations processes employed for full recycle may be used for the modified open cycle.**



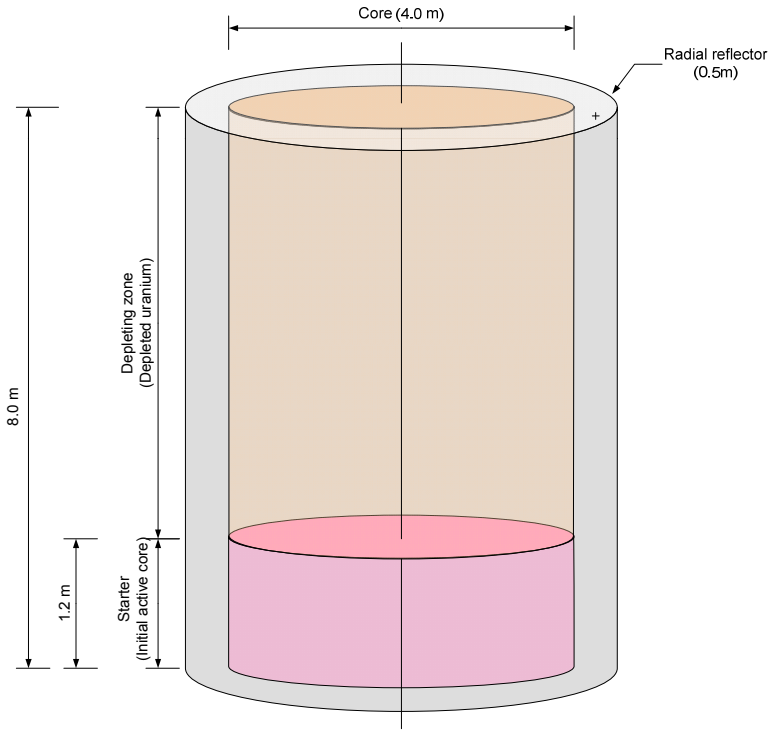
Oxide fuel after Voloxidation



Melt Refining

Modified Open Cycle Examples

- **Breed and burn concepts (including the traveling waves designs) both with and without fuel conditioning**
- **Deep burn of transuranics in high-temperature gas reactors (requires fuel processing)**
- **Deep burn of transuranics in inert matrix fuels**
- **DUPIC process for recycle of LWR fuel into CANDU reactors with thermal treatment of fuel**
- **Fission-fusion systems**
- **Accelerator driven systems**



Reactor Core Design with Axial Propagation

Technical Areas

- **Separations and Waste Forms**
- **Advanced Fuels**
- **Materials Protection, Accounting, and Control for Transmutation**
- **Used Nuclear Fuel Disposition**
- **Transmutation R&D**
- **Modeling and Simulation**
- **Systems Analysis**
  - FCRD also has a Systems Engineering activity used to evaluate and assess various fuel cycle options and issues.

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Separations and Waste Forms

Today's Technology Challenges

- Meeting **current air emission requirements**
- **Economical recovery** of transuranic elements for recycle/transmutation
- **Minimal waste generation**

Grand Challenges

- **Near-zero radioactive off-gas emissions**
- **Simplified, single-step recovery of transuranic elements**
- **Significantly less process wastes**

Development Path

- **Develop fundamental understanding** of separation process and waste form thermodynamics
- Understand **underlying separation driving forces**
- Exploit thermodynamic properties to effect separations
- Elucidate microstructural waste form corrosion mechanisms

Transformational Result

- Predictive capability for separation and waste form performance over a broad range of operational conditions
- Novel separations technologies

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Advanced Fuels

Today's Technology Challenges

- Fuels with variable compositions
- Understanding and **predicting fuel behavior and performance**
- **Reliably fabricating fuel with zero defects and with minimal process losses**

Grand Challenge

Fast reactor fuels with multi-fold increases in performance over previous generation fuels, with very low fabrication losses, and that permit high transmutation of radiotoxic elements

Development Path

- **Develop a μ-structural understanding of fuels and materials**
- Closure of combined transport and phase-field equations
- **Separate effect testing and properties measurement at sub-grain scale**
- **Effect of nano-scale implantations**
- Innovative clean and reliable fabrication techniques with tightly controlled microstructures tailored to desired performance

Transformational Result

- Predictive capability for fuel process and in-pile behavior for a variety of initial and boundary conditions
- Novel fuel forms

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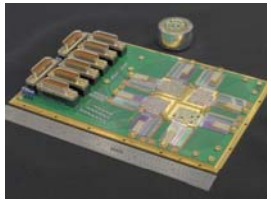
Materials Protection, Accounting, and Control for Transmutation

Today's Technology Challenges

- Large throughput facilities require shutdown for periodic inventory
- New reactor designs require new nuclear material management approach
- Move from reactive to preventive systems approach



Grand Challenge

Develop online, real-time, continuous, accountability instruments and techniques that permit an order of magnitude improvement in the ability to inventory fissile materials in domestic fuel cycle systems, in order to detect diversion and prevent misuse

Development Path

- **Next generation instrumentation**
  - High sensitivity and specificity
  - Enabled by new physics data
  - New sensor materials
- **Integration of disparate data in quantitative manner**
  - Real time assessments
  - Probability basis with uncertainties
- **Predictive modeling and simulation at atomistic and plant level**

Transformational Result

Real time nuclear materials management with continuous inventory

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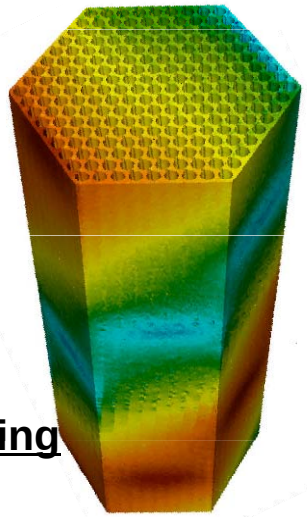
Modeling and Simulation

Today's Technology Challenges

- Current generation of nuclear modeling and simulation tools are empirically based
- Limited to use only for conditions very close to those experiments



Grand Challenge

Rapidly create and deploy "science" (1st principles) verified and validated modeling and simulation capabilities essential for the design, implementation, and operation of future nuclear energy systems with the goal of improving U.S. energy security.

Development Path

- Create teams focused on developing Integrated Performance and Safety Codes
- Support smaller projects developing atomistic scale models and methods for upscaling to integrated codes
- Develop and implement methodologies for verification, validation and uncertainty quantification
- Ensure capability transfer pathways to users of modeling and simulation capabilities (labs, industry and regulatory agencies
- Provide supporting computational technologies

Transformational Result

Develop modeling and simulation that is on par with theory and experiment to implement a modern science based approach for fuel cycle technologies.

Summary

- **DOE's Fuel Cycle Research and Development Program is an integrated, goal-oriented, science-based program to provide fuel cycle and used fuel management options to future decision makers.**
- **Program is focused on development and assessment of technical options.**
- **Research is focused on improvements to direct disposal, modified open cycle, and full recycle.**
- **The following breakout sessions are directly related to FCRD:**
  - Separations, Waste Forms and Disposition
  - Safeguards and Nonproliferation
  - Materials
  - Nuclear Instrumentation and Control
  - Systems Analysis
  - Nuclear Fuels
  - Nuclear Physics