Nuclear Energy Research at US Universities and Development of a Virtual Reactor

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Outline

- Nuclear Energy R&D Roadmap
  - US Department of Energy's Nuclear Energy R&D (Fission Reactors and Fuel Cycle R&D)
- US DOE Nuclear Energy University Program
  - Information from a Workshop, July 2010
- DOE Nuclear Simulation HUB (2010-2014)
  - CASL: The Consortium for Advanced Simulation of Light Water Reactors – a **Virtual Reactor**

Information Source

- All the information obtained from presentations made by DOE staff which are publicly available

- DOE Nuclear Energy University Program presentations given at a NEUP Workshop, July 2010

  http://events.energetics.com/UnivWorkshop2011/agenda.html

- DOE Nuclear Simulation HUB (CASL) presentation given at the American Nuclear Society Meeting, June 2010 (courtesy of Dr. Doug Kothe, ORNL)

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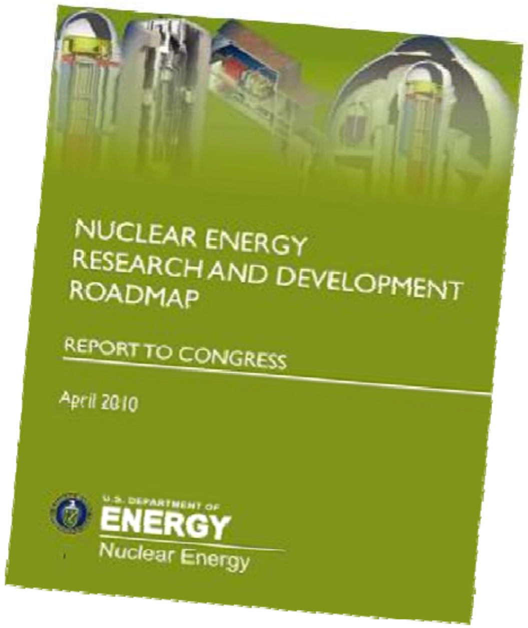
Nuclear Energy Roadmap

April, 2010

- **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. GEN-IV, SMR
- **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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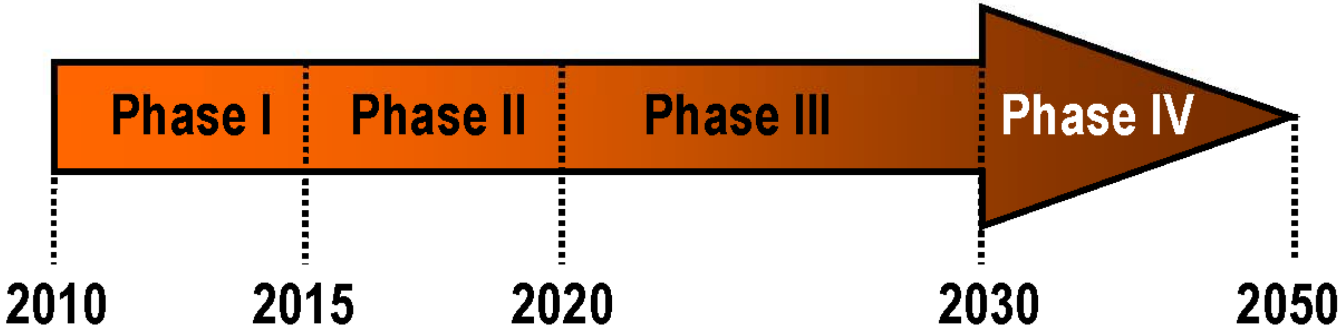
Light Water Reactor Sustainability

R&D Objective 1: Extend Life, Improve Performance, and Maintain Safety of the Current Fleet

Science-Based R&D to Extend Nuclear Plant Operation

July 2010

LWRS Program R&D Investment



Build Confidence in Life Extension with Data and Tools

Enable Industry Decision to Invest and License for License Extension

Acceptance of Advanced Tools, Methods and Technologies

Fleet Operation Beyond 60-year Life

$100M

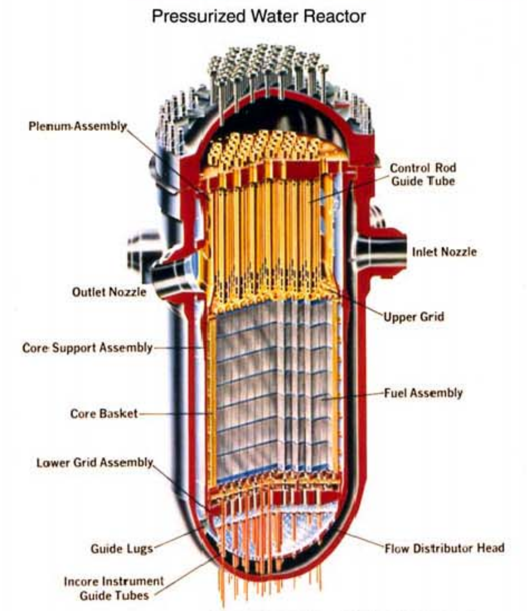
$10M

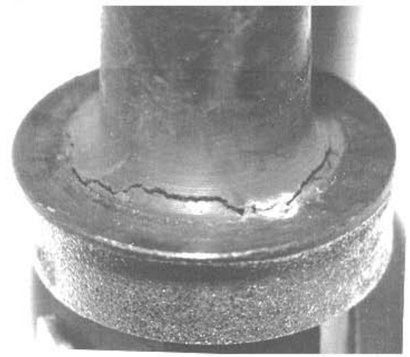
(FY 2010 university funding: $1.3M)

Large Payoff: Moderate R&D Cost Leveraging High Capital Investments

Extending the service life of today's LWR fleet may create new material challenges

- Extending reactor life to beyond 60 years will likely increase susceptibility and severity of known forms of materials degradation and potentially introduce new forms of degradation
- The LWRS R&D effort seeks to provide the scientific basis for understanding and predicting materials aging and degradation within components, systems, and structures
  - Reactor metals (RPV's, internals, steam generators, balance of plant, and weldments)
  - Concrete
  - Buried piping
  - Cabling
  - Mitigation, repair, and replacement technologies
- A new working group has been formed to integrate the materials efforts within DOE's LWRS, EPRI's LTO, and NRC's LB60 programs





Characterization of safety margin is central to decision making in plant operational performance, power uprate, and life extension

ing of Structures, Systems and Components (SSC) has potential

- to increase frequency of initiating events of certain safety transients;
- to create new and more complex transient sequences associated with previously-not-considered SSC failures; and
- to increase severity of safety transients due to cascading failures of SSCs.

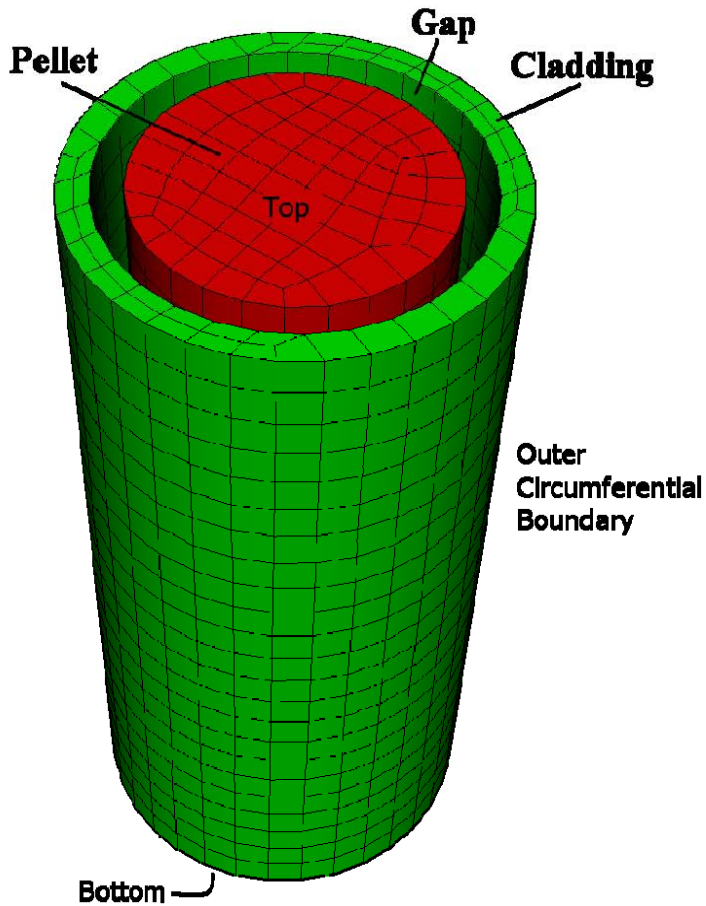
antification of the effect of SSC aging on plant safety is hindered by

- deficient data and models required to predict behaviors of the aging SSCs in a broad range of plant operating, upset and accident conditions;
- large uncertainties in using the existing M&S tools to analyze the plant system dynamics in scenarios involving aging-induced SSC failures; and
- lack of a risk assessment methodology that takes into account (reliability of) passive SSCs and passive safety features.

→ ***New Methods, Tools and Data are Needed to Meet High Demands in LWR Safety Decision Making***

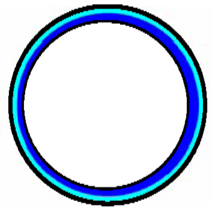
Advanced Fuel Designs & R&D Concepts

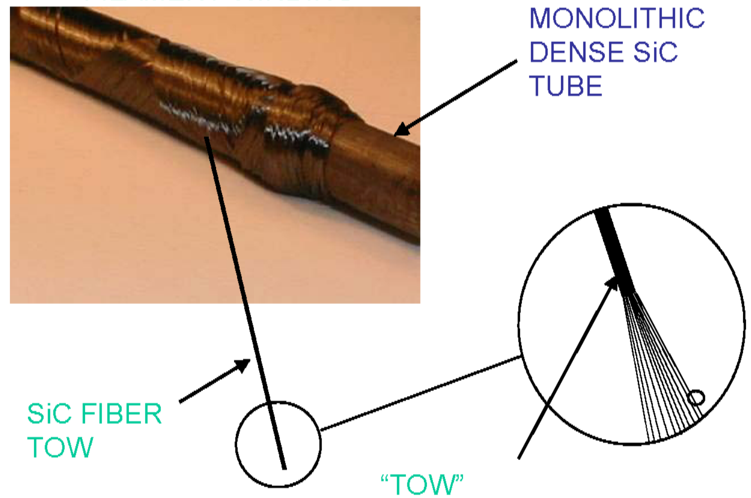
- Advanced fuels
  - UOX variants (additive fuels, >5% U-235, enriched gadolinium)
  - Alternate fuels (UN, UC, hydride)
  - Novel designs (annular fuel, innovative shapes, liquid metal bond)
  - Dopants for PCI, thermal conductivity
- Advanced Cladding
  - optimized next generation zirconium alloys
  - SiC
- Modeling and Simulation
  - Address fuel performance issues through basic scientific understanding
  - Accelerate design to implementation



SiC Cladding Development

- Develop high performance, high burnup nuclear fuels with improved safety, clad integrity, and fuel cycle economics
- Design, develop and test a multilayered SiC clad fuel that significantly increases fuel performance. Key characteristics include:
  - strength retention to at least 1500°C, appears to be DNB proof, and therefore can facilitate power uprates of 30% or more.
  - minimal exothermic water reaction or H_2 release during LOCA's,
  - fully retains fission gases – no creep and FG retention to at least 5000 psi
  - composite layer solves ceramic "brittleness" problem
  - Can operate in LWR coolant for over 10 years with no appreciable corrosion
    - Zirc alloys embrittle after 5 years operation and are therefore limited by regulation to 62 gwd/t
  - When coupled with increased U235 loading, can double the burnup to 100 gwd/t
  - Very hard, resists fretting and debris failure, further reduction in operational failures





Efficiency Improvement IP Schedule

	Phase I	Phase II	Phase III
Alternative Cooling Technology	Preserve once-through technology	Cost reduction and efficiency improvement for dry and hybrid cooling technology	Application of advanced cooling technologies
	Development of water conservation technology for wet cooling tower		
Non-electirc Applications	Technology and economics viability	Interface design	Applications
Power Uprate	Collaborate with other pathways to enable 10 GWe extra capacity addition through power uprates, with a stretch goal of 20 GWe		

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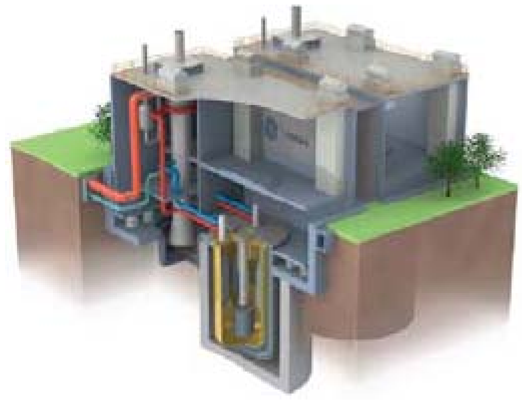
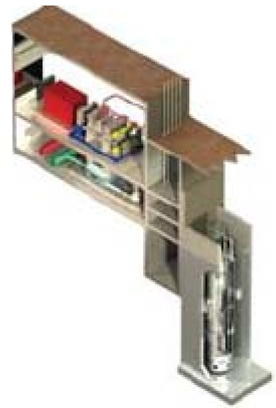
New Reactor Designs

- Small Modular Reactors
  - < 300 MWe
  - Factory-fabricated





- High Temperature Gas Reactor
  - Process heat, H_2 generation
- Fast Reactor
  - For fuel cycle

Small Modular Reactors

Challenges:

- Integrated PWR designs introduce new material, inspection, and maintenance challenges
- Performance uncertainty introduced by new designs and technologies
- Departure from traditional licensing experience
- Cost (economies of series versus economies of scale)

R&D focus areas:

- Testing systems to assess PWR concepts with steam generators located within the reactor pressure vessel
- Modeling and simulation of unique SMR characteristics and safety considerations
  - natural circulation, decay heat removal
- Instrumentation and control – measurement , diagnostics, prognostics
- Specialty components, e.g., helical coil steam generators

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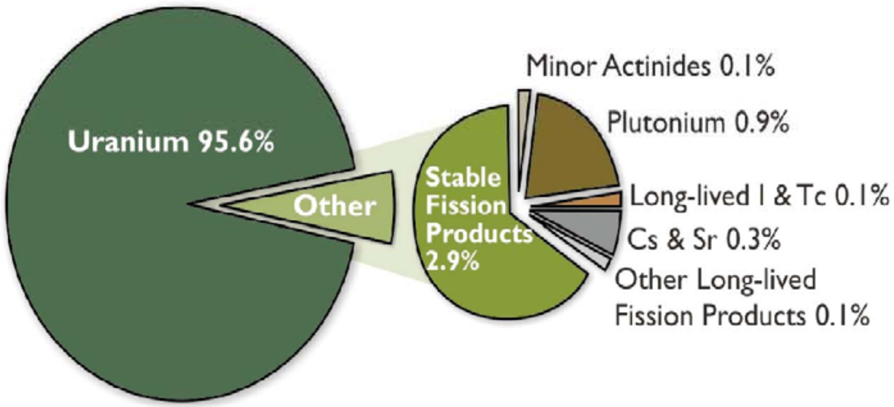
Objective 3: Sustainable Fuel Cycles

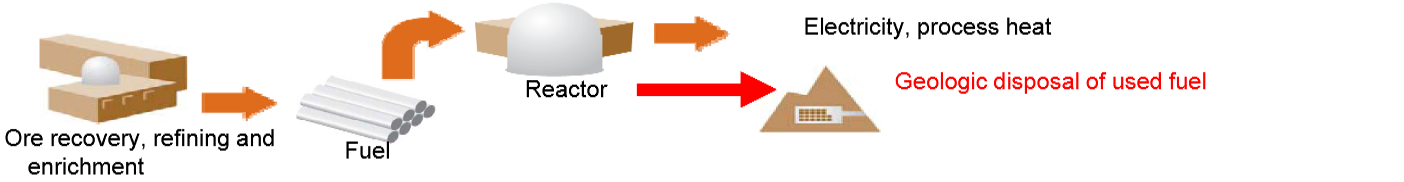
- **Goals**
  - In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
  - In the medium term, select preferred fuel cycle option for further development
  - By 2050, deploy preferred fuel cycle

- **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

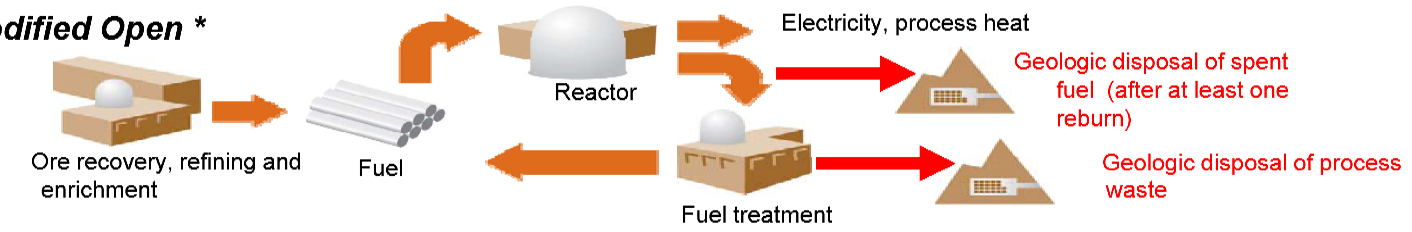


Three Potential Fuel Cycle Options

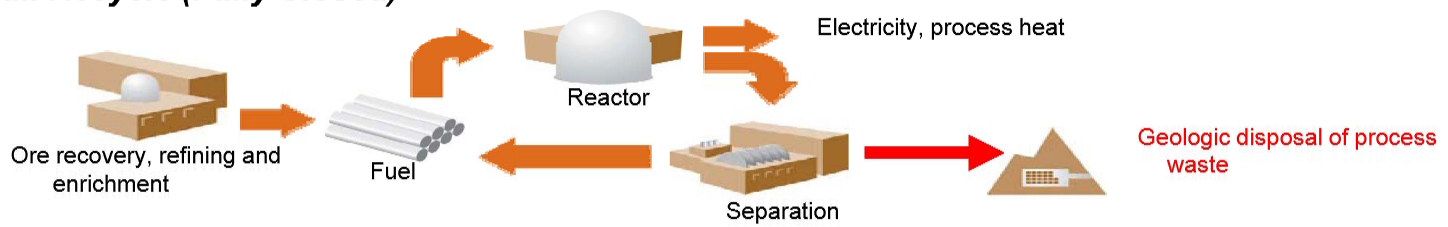
Once-Through (Open)



*Modified Open **



*Full Recycle (Fully Closed) **



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

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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

Advanced Fuels

In Fuel Cycle Perspective

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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Nuclear Energy University Program 2010

REVIEW

Three Categories for Funding:

- Research & Development
- Infrastructure, e.g. Research Reactors
- Fellowships and Scholarships

2010 Overall Competed Funding

▪ R&D:	$38,700,022
▪ Infrastructure:	$13,187,503
▪ S&F:	$5,000,000

Total Competed Funding: $56,887,525

RESEARCH AND DEVELOPMENT

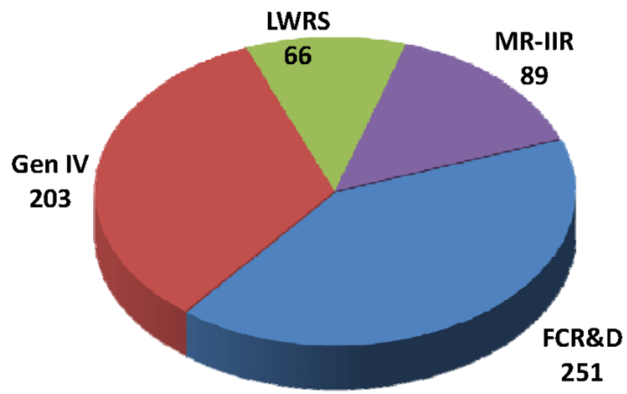
GEN-IV
- High Temperature Gas Reactor
- Fast Reactor

Fuel Cycle

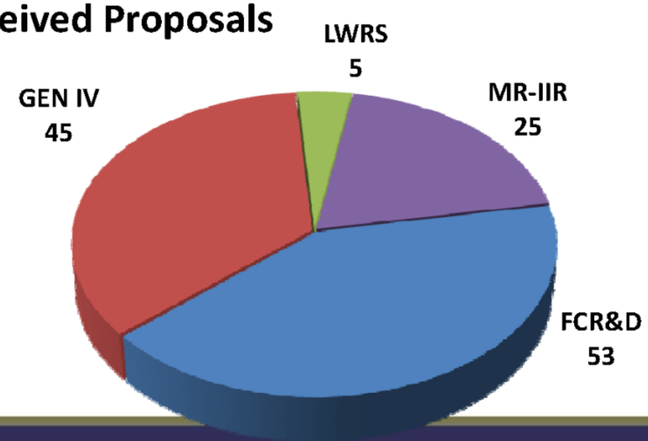
Light Water Reactor Sustainability

PROGRAM OVERVIEW

Received Pre-Applications

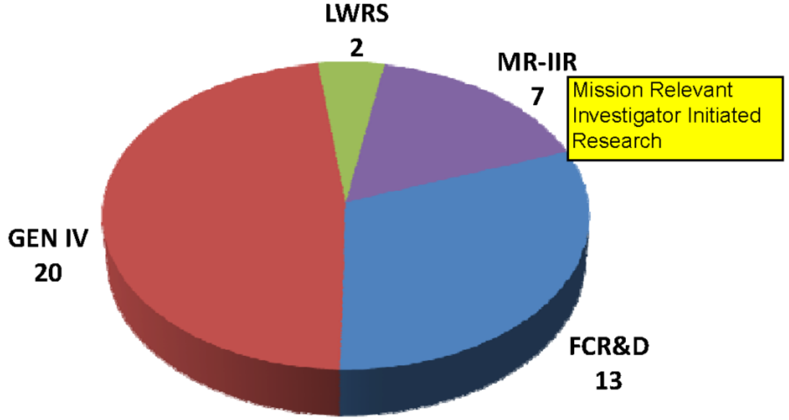


Received Proposals

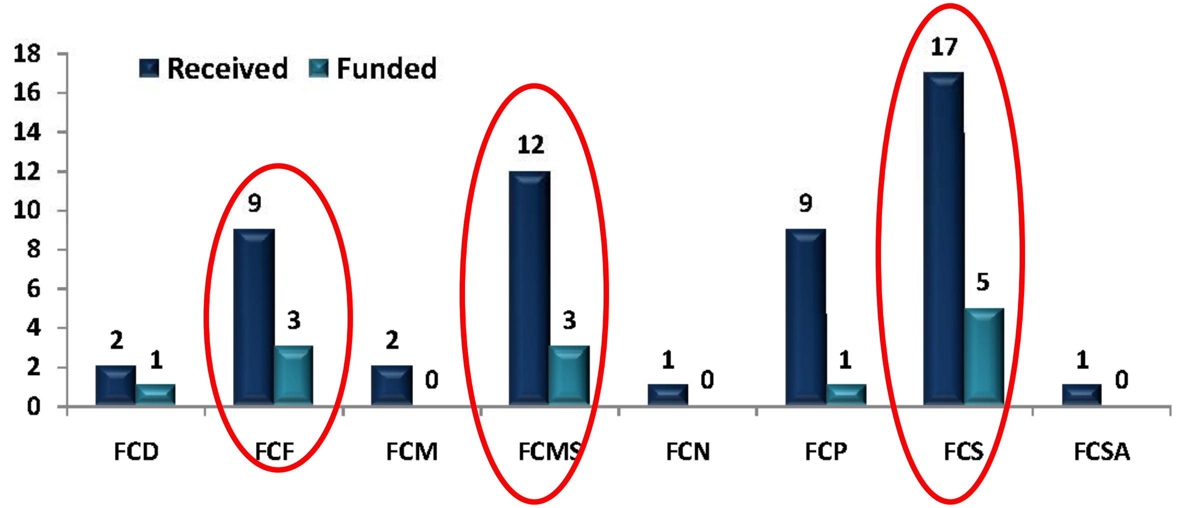


- 609 pre-applications
- 131 requested full proposals
- 128 submitted proposals
- 42 funded proposals

Funded Proposals



Fuel Cycle Research & Development (FCR&D)



FCD – FCR&D Used Nuclear Fuel Disposition

FCF – FCR&D Fuels

FCM – FCR&D Materials

FCMS – FCR&D Modeling & Simulation

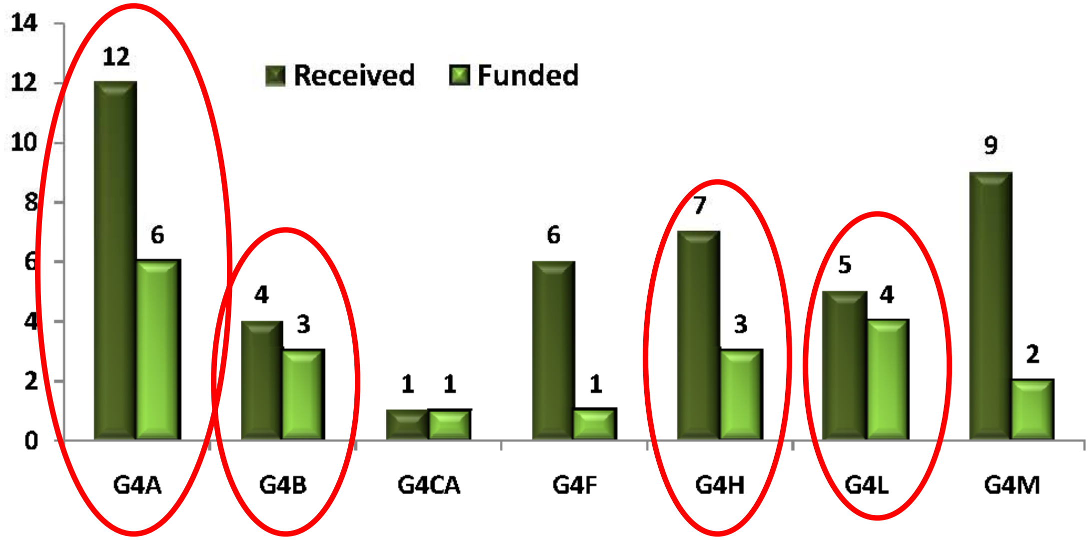
FCN – FCR&D Nuclear Physics & Theory Development

FCP – FCR&D MPACT

FCS – FCR&D Separations & Waste Forms

FCSA – FCR&D Systems Analysis

Generation IV Reactor Research & Development (Gen IV)



G4A – Gen IV High-Temperature Materials

G4B – Gen IV Advanced Reactor Concepts

G4CA – Crosscutting R&D: Structural Materials

G4F – Gen IV Fuels

G4H – Gen IV Heat Transport, Energy Conversion, Nuclear Heat Applications

G4L – Gen IV Fast Reactors

G4M – Gen IV Methods

Sample Topics selected in 2010

- **Next Generation Nuclear Plant (NGNP)/Generation IV Nuclear Systems**
  - Liquid Salt Heat Exchanger Technology for VHTR Based Applications
  - Irradiation Creep in Graphite
  - Optimizing Neutron Thermal Scattering Effects in Very High Temperature Reactors
  - Investigation of Countercurrent Helium-air Flows in Air-ingress Accidents for VHTRs
  - Investigation on the Core Bypass Flow in a Very High Temperature Reactor

Sample Topics selected in 2010

- **Advanced Fuel Cycle Initiative (AFCI)**
  - Development of Alternative Technetium Waste Forms
  - Thermodynamic Development of Corrosion Rate Modeling in Iron Phosphate Glasses
  - Adsorptive Separation and Sequestration of Krypton, I and C14 on Diamond Nanoparticles
  - Thermal Properties of LiCl-KCl Molten Salt for Nuclear Waste Separation
  - Simulations of the Thermodynamic and Diffusion Properties of Actinide Oxide Fuel Materials
  - Sharp Interface Tracking in Rotating Microflows of Solvent Extraction

Overall NEUP Program Three Program Areas

2011

Fuel Cycle R&D (FCRD)

- Separations and Waste Forms
- Advanced Fuels
- Systems Analysis and Integration
- Materials Protection, Accountancy, and Controls (MPACT)
- Used Fuel Disposition and Storage

Reactor Concepts (RC)

- Small Modular Reactors
- Next Generation Nuclear Plant
- Light Water Reactor Sustainability
- Advanced Reactor Concepts

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DOE Energy Innovation HUB

$122 million over five years for each HUB

- Nuclear Simulation HUB
  - Consortium for Advanced Simulation of Light Water Reactors (CASL) led by Oak Ridge National Lab
- The Fuels from Sunlight Energy
  - Joint Center for Artificial Photosynthesis (JCAP) led by California Institute of Technology with Lawrence Berkeley Lab
- Building Energy Efficiency

What is a DOE Energy Innovation Hub?
(as documented)

- Target problems in areas presenting the most critical barriers to achieving national climate and energy goals that have heretofore proven the most resistant to solution via the normal R&D enterprise
- Represent a new structure, modeled after research entities likes the Manhattan Project (nuclear weapons), Lincoln Lab at MIT (radar), and AT&T Bell Labs (transistor)
- Consistent with Brookings Institution's recommendations for "Energy Discovery-Innovation Institutes" (early 2009)
  - "…new research paradigms are necessary, we believe, that better leverage the unique capacity of America's research" - Dr. Jim Duderstadt, President Emeritus, University of Michigan
- Focuses on a single topic, with work spanning the gamut, from basic research through engineering development to partnering with industry in commercialization
- Large, highly integrated and collaborative creative teams working to solve priority technology challenges
- Embrace both the goals of understanding and use, without erecting barriers between basic and applied research

CASL: The Consortium for Advanced Simulation of Light Water Reactors

A DOE Energy Innovation Hub for Modeling & Simulation of Nuclear Reactors

Core partners

- Oak Ridge National Laboratory
- Electric Power Research Institute
- Idaho National Laboratory
- Los Alamos National Laboratory
- Massachusetts Institute of Technology
- North Carolina State University
- Sandia National Laboratories
- Tennessee Valley Authority
- University of Michigan
- Westinghouse Electric Company

Building on longstanding, productive relationships and collaborations to forge a close, cohesive, and interdependent team that is fully committed to a well-defined plan of action

Individual contributors

- ASCOMP GmbH
- CD-adapco, Inc.
- City University of New York
- Florida State University
- Imperial College London
- Rensselaer Polytechnic Institute
- Southern States Energy Board
- Texas A&M University
- University of Florida
- University of Tennessee
- University of Wisconsin
- Worcester Polytechnic Institute

CASL vision: Create a virtual reactor (VR) for *predictive* simulation of LWRs

Leverage

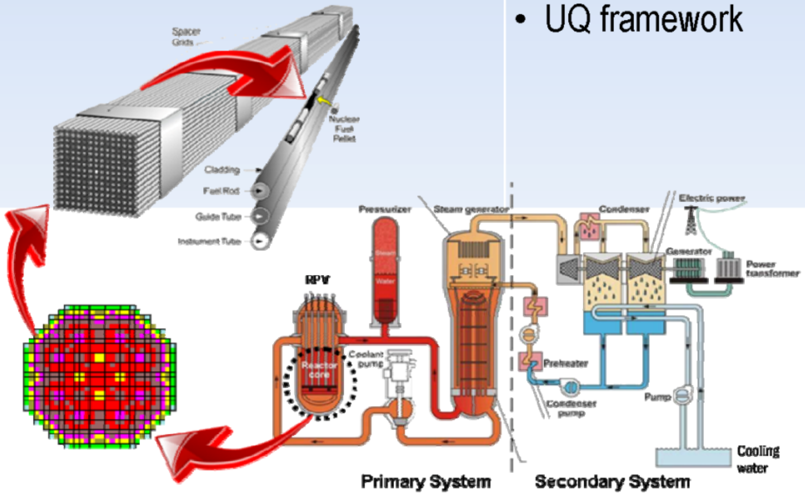
- Current state-of-the-artneutronics, thermal-fluid, structural, and fuel performance applications
- Existing systems and safety analysis simulation tools

Develop

- New requirements-driven physical models
- Efficient, tightly-coupled multi-scale/multi-physics algorithms and software with quantifiable accuracy
- Improved systems and safety analysis tools
- UQ framework

Deliver

- An unprecedented predictive simulation tool for simulation of physical reactors
- Architected for platform portability ranging from desktops to DOE's leadership-class and advanced architecture systems (large user base)
- Validation basis against 60% of existing U.S. reactor fleet (PWRs), using data from TVA reactors
- Base M&S LWR capability

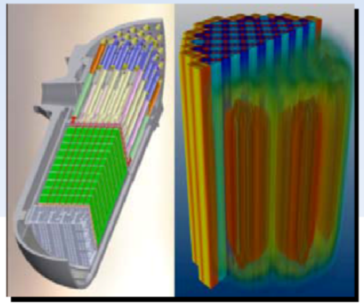


CASL mission: Develop and apply the VR to address 3 critical performance goals for nuclear power

1 **Reduce capital and operating costs** per unit energy by:
- Power uprates
- Lifetime extension

2 **Reduce nuclear waste** volume generated by enabling higher fuel burnups

3 **Enhance nuclear safety** by enabling high-fidelity predictive capability for component and system performance from beginning of life through failure



CASL evaluated safety, operating, and design aspects to develop the set of challenge problems

Safety	Operating	Design
• DNB safety limit • Reactivity coefficients • Shutdown margin • Enrichment • Internal gas pressure • PCMI • RIA fragmentation • Non-LOCA runaway oxidation • LOCA: PCT, oxidation, H release, long-term cooling • Seismic loads • Holddown force • Criticality	• DNB operating limit • LHGR limit • PCI • Coolant activity • Gap activity • Source term • Control rod drop time • RIA fuel failure limit	• Crud deposition • Stress/strain/fatigue • Oxidation • Hydride concentration • Transport loads • Fretting wear • Clad diameter increase • Cladding elongation • Radial peaking factor • 3D peaking factor • Cladding stability

Source: *Fuel Safety Criteria in NEA Member Countries,* NEA/CSNI/R(2003)10

CASL targets key limiting phenomena that are barriers to improved reactor performance

	Power uprate	High burnup	Life extension
Operational "Challenge Problems"			
CRUD-Induced Power Shift (CIPS)	✖	✖	
CRUD-Induced Localized Corrosion (CILC)	✖	✖	
Grid-to-Rod Fretting Failure (GTRF)		✖	
Pellet Clad Interaction (PCI)	✖	✖	
Fuel Assembly Distortion (FAD)	✖	✖	
Safety "Challenge Problems"			
Departure from Nucleate Boiling (DNB)	✖		
Cladding Integrity during Loss of Coolant Accidents (LOCA)	✖	✖	
Cladding Integrity during Reactivity Insertion Accidents (RIA)	✖	✖	
Reactor Vessel Integrity	✖		✖
Reactor Internals Integrity	✖		✖

CASL scope: Develop and apply the VR to assess fuel design, operation, and safety criteria

Near-term priorities (years 1–5)

- Deliver improved predictive simulation of PWR core, internals, and vessel
  - Couple VR to evolving out-of-vessel simulation capability
  - Maintain applicability to other NPP types
- Execute work in 5 technical focus areas to:
  - Equip the VR with necessary physical models and multiphysics integrators
  - Build the VR with a comprehensive, usable, and extensible software system
  - Validate and assess the VR models with self-consistent quantified uncertainties

Longer-term priorities (years 6–10)

- Expand activities to include structures, systems, and components beyond the reactor vessel
- Established a focused effort on BWRs and SMRs
- Continue focus on delivering a useful VR to:
  - Reactor designers
  - NPP operators
  - Nuclear regulators
  - New generation of nuclear energy professionals

Focus on challenge problem solutions

Three VRI projects combine to deliver the CASL VR capability

Virtual Reactor Integration

Computational Coupled Multiphysics Environment

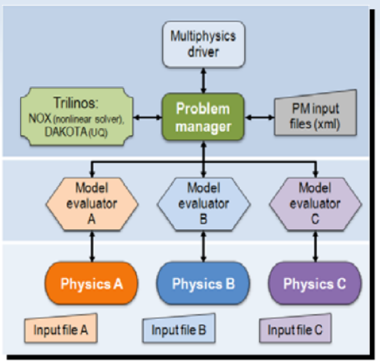
- Development of Lightweight Integrating Multiphysics Environment (LIME)
- Workflow and usability
- Meshing and mesh management
  - Leverage activities such as NEAMS ECT

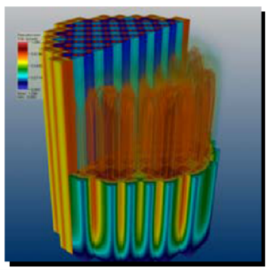
Virtual Reactor Simulation Suite

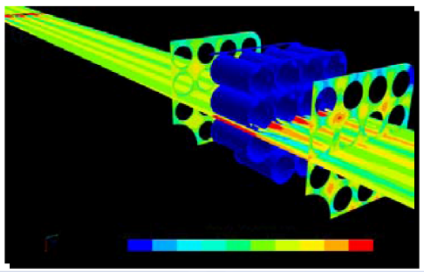
- Integrate existing and evolving capabilities:
  - Fuel performance
  - Chemistry
  - Neutronics
  - Thermal-hydraulics (T-H)
  - Structural mechanics
- Closely coordinate with VUQ
- Couple to reactor system simulation

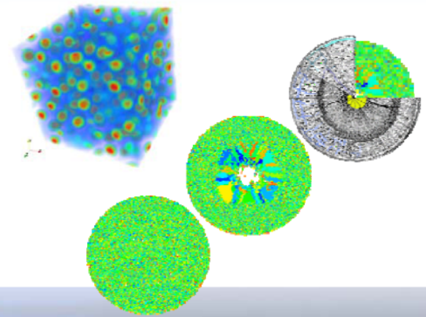
Coupled Mechanics

- Fuel performance
  - Leverage efforts such as BISON (INL) and AMP (NEAMS)
- Assembly dynamics and reactor internals
  - T-H and structural response of assembly components and reactor internals
- Chemistry and materials models









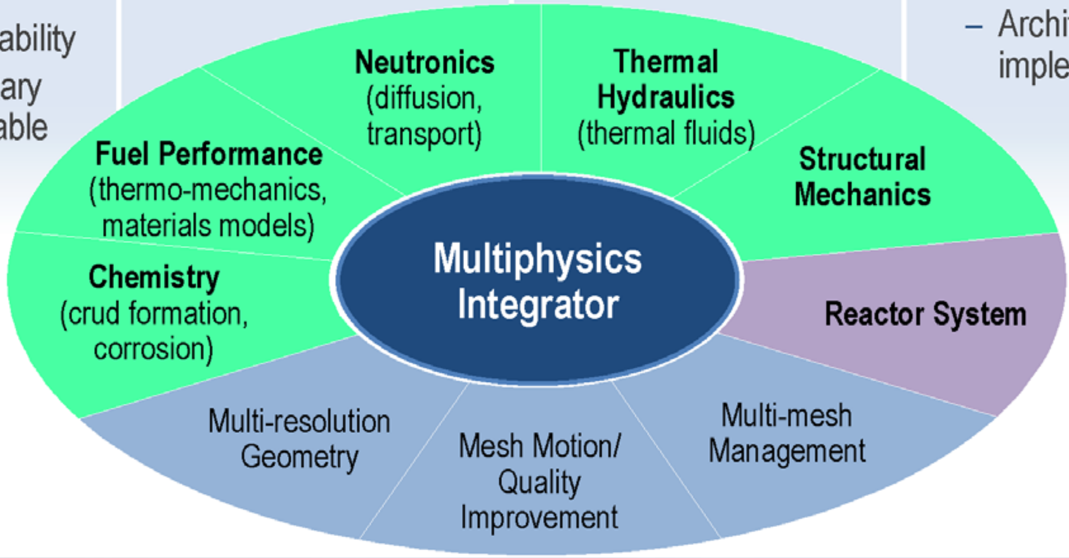
The CASL Virtual Reactor: A code system for scalable simulation of nuclear reactor core behavior

- Flexible coupling of physics components
- Toolkit of components
  - Not a single executable
  - Both legacy and new capability
  - Both proprietary and distributable

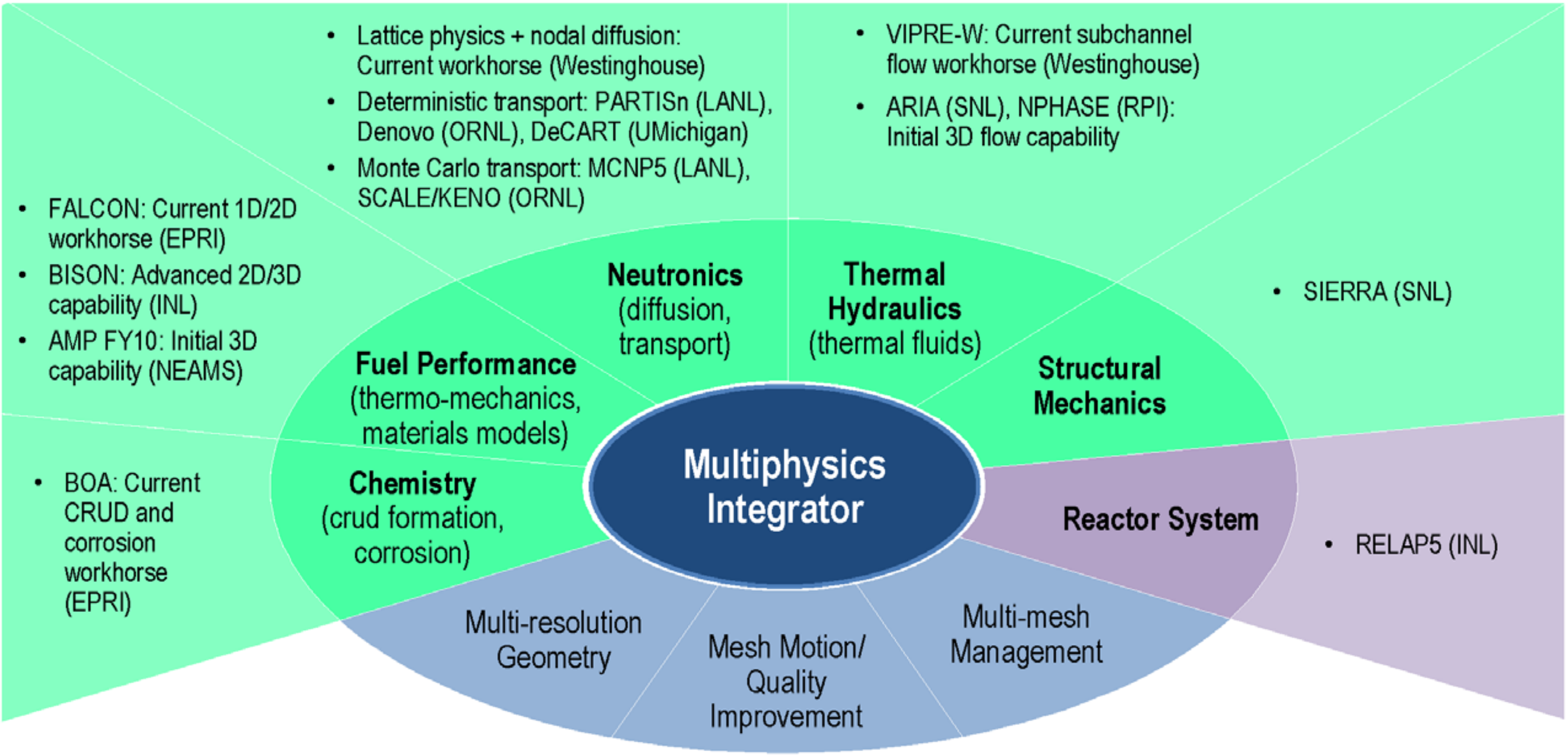
- Attention to usability
- Rigorous software processes
- Fundamental focus on V&V and UQ

- Development guided by relevant challenge problems
- Broad applicability

- Scalable from high-end workstation to existing and future HPC platforms
  - Diversity of models, approximations, algorithms
  - Architecture-aware implementations



The CASL VR builds on a foundation of mature, validated, and widely used software



- CASL developers have delivered code for production (not just research)
  - ORNL and LANL codes account for almost 80% of RSICC distributions since 2005

Thank you for your kind attention!