The United States Advanced Reactor Technologies Research and Development Program

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Presentation Will Address Several Aspects of Advanced Reactor Development

- Nuclear energy mission
- Reactor research development and deployment (RD&D) programs:
  - Light Water Reactor Sustainability Program
  - Small Modular Reactor Licensing Technical Support
  - Advanced Reactor Technologies (ART)
United States Committed to “All of the Above” Clean Energy Strategy

“By 2035, 80% of America’s electricity will come from clean energy sources. Some folks want wind and solar. Others want nuclear, clean coal and natural gas. To meet this goal we will need them all.”

~2011 State of the Union

“All-of-the-above is not merely a slogan, but a clear-cut pathway to creating jobs and at the same time reducing carbon emissions, which recently stood at their lowest level in 20 years... President Obama has made clear that he sees nuclear energy as part of America’s low carbon energy portfolio. And nuclear power is already an important part of the clean energy solution here in the United States.”

~Secretary of Energy, Dr. Ernest Moniz at National Press Club, February 19, 2014
Estimated U.S. Energy Use in 2012: ~95.1 Quads
Nuclear Energy Could Significantly Reduce Other CO₂ Emissions

Estimated U.S. Energy-Related Carbon Dioxide Emissions in 2012: ~5,290 Million Metric Tons
High-Temperature Reactors Can Provide Process Heat for Multiple Industries

Industrial Application

Reactor Outlet Temperature (°C)

District Heating
Seawater Desalination

Petroleum Refining

Oil Shale and Oil Sand Processing

Cogeneration of Electricity and Steam

Steam Reforming of Natural Gas

Hydrogen Production

800‐1000°C

LWRs

80‐200°C

VHTR

NGNP/HTGR

SFR
Role of U.S. Department of Energy for Sustainable and Innovative Nuclear Energy

Conduct Research, Development, and Demonstration to:

- Reduce technical risk
- Reduce financial risk and improve economics
- Reduce regulatory risk
- Used fuel management
- Minimize the risks of nuclear proliferation and terrorism
- Foster international and industry collaboration
Nuclear Reactor Technology Programs

- Light Water Reactor Sustainability Program (LWRS)
- Small Modular Reactor Licensing Technical Support
- Advanced Reactor Technologies (ART)
Light Water Reactor Sustainability (LWRS) Program

**LWRS Program Goal**
- Develop fundamental scientific basis to allow continued long-term safe operation of existing LWRs (beyond 60 years) and their long-term economic viability

**LWRS program is developing technologies and other solutions to:**
- Enable long term operation of the existing nuclear power plants
- Improve reliability
- Sustain safety

**LWRS focus areas:**
- Materials Aging and Degradation
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Reactor Safety Technology
**Accident Tolerant Fuel Behavior**

- **Improved Reaction Kinetics with Steam**
  - Heat of oxidation
  - Oxidation rate

- **Improved Fuel Properties**
  - Lower operating temperatures
  - Clad internal oxidation
  - Fuel relocation / dispersion
  - Fuel melting

- **High temperature during loss of active cooling**

- **Slower Hydrogen Generation Rate**
  - Hydrogen bubble
  - Hydrogen explosion
  - Hydrogen embrittlement of the clad

- **Improved Cladding Properties**
  - Clad fracture
  - Geometric stability
  - Thermal shock resistance
  - Melting of the cladding

- **Enhanced Retention of Fission Products**
  - Gaseous fission products
  - Solid/liquid fission products
SMRs: reactor units with less than 300 MWe and are able to have large components or modules fabricated remotely and transported to the site for assembly.

Potential Benefits

- Enhanced safety and security
- Reduced capital cost makes nuclear power feasible for more utilities
- Shorter construction schedules due to modular construction
- Improved quality due to replication in factory-setting
- Meets electric demand growth incrementally
- Regain technical leadership and advance innovative reactor technologies and concepts

Potential Markets

- Domestic and international utility markets
- Non-electrical (process heat/desalination) customers
SMR Licensing Technical Support

- Major challenge for commercialization is completing the NRC licensing process
- In 2012, DOE initiated the SMR Licensing Technical Support program – Currently a 6 year/$452 M program
- Accelerate commercial SMR development through public/private arrangements
  - Deployment as early as 2022

- Exploring additional mechanisms for SMR fleet deployment

“I believe small modular reactors could represent the next generation of nuclear energy technology, providing a strong opportunity for America to lead this emerging global industry.”

-- Secretary of Energy, Dr. Ernest Moniz
Generations of Nuclear Power Plants Leading to Gen IV

**Generation I**
- **Early prototypes**
  - Calder Hall (GCR)
  - Douglas Point (PHWR/CANDU)
  - Dresden-1 (BWR)
  - Fermi-1 (SFR)
  - Kola 1-2 (PWR/VER)
  - Peach Bottom 1 (HTGR)
  - Shippingport (PWR)

**Generation II**
- **Large-scale power stations**
  - Bruce (PHWR/CANDU)
  - Calvert Cliffs (PWR)
  - Flamanville 1-2 (PWR)
  - Fukushima II 1-4 (BWR)
  - Grand Gulf (BWR)
  - Kalkar (PWR/VER)
  - Kursk 1-4 (LWGR/RBMK)
  - Palo Verde (PWR)

**Generation III / III+**
- **Evolutionary designs**
  - ABWR (GE-Hitachi; Toshiba)
  - ACR 1000 (AECL CANDU PHWR)
  - AP1000 (Westinghouse-Toshiba PWR)
  - APR-1400 (KHNP PWR)
  - APWR (Mitsubishi PWR)
  - Atmea-1 (Areva NP - Mitsubishi PWR)
  - CANDU 6 (AECL PHWR)
  - EPR (AREVA NP PWR)
  - ESBWR (GE-Hitachi BWR)
  - Small Modular Reactors
    - Atomenergoiproekt PWR
    - B&W mPower PWR
    - Holtec SMR-160 PWR
    - India DAE AHWR
    - KAERI SMART PWR
    - NuScale PWR
    - Westinghouse SMR PWR
  - VVER-1200 (Gidropress PWR)

**Generation IV**
- **Revolutionary designs**
  - GCR gas-cooled fast reactor
  - LFR lead-cooled fast reactor
  - MSR molten salt reactor
  - SFR sodium-cooled fast reactor
  - SCWR supercritical water-cooled reactor
  - VHTR very high temperature reactor
President’s Climate Action Plan (June 2013): Supports the deployment of clean energy, which includes continuing to drive American leadership in clean energy technologies, including nuclear technology.

NE R&D Objective 2: Meet the Administration’s energy security and climate change goals by developing technologies to support the deployment of affordable advanced nuclear reactors.

NE R&D Objective 3: Optimize energy generation, waste generation, safety, and nonproliferation attributes by developing sustainable nuclear fuel cycles.

- ART conducts activities focused on improvements in the affordability of advanced reactors
- ART is also focused on longer term improvements in safety and economics that will expand options for production of electricity and process heat, and actinide management
Advanced Reactor Technologies

- **Fast Reactor Technologies**
  - For actinide management and electricity production
  - Current focus on sodium coolant

- **High Temperature Reactor Technologies**
  - For electricity and process heat production
  - Current focus on gas- and liquid salt-cooled systems

- **Advanced Reactor Generic Technologies**
  - Common design needs for advanced materials, energy conversion, decay heat removal systems and modeling methods

- **Advanced Reactor Regulatory Framework**
  - Development of licensing requirements for advanced reactors

- **Advanced Reactor System Studies**
  - Analyses of capital, operations and fuel costs for advanced reactor types

High Temperature Test Facility Oregon State University
## Advanced Reactor Technologies

<table>
<thead>
<tr>
<th>Area</th>
<th>FY 2014 Current</th>
<th>FY 2015 Request</th>
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<tbody>
<tr>
<td>Fast Reactor Technologies</td>
<td>11,770</td>
<td>13,250</td>
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<tr>
<td>High Temperature Reactor Technologies</td>
<td>32,554</td>
<td>25,900</td>
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<td>Advanced Reactor Generic Technologies</td>
<td>14,880</td>
<td>19,062</td>
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<td>Advanced Reactor Regulatory Framework</td>
<td>6,324</td>
<td>5,500</td>
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<td>Advanced Reactor System Studies</td>
<td>432</td>
<td>4,180</td>
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<td>Industry Awards</td>
<td>11,607</td>
<td></td>
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<tr>
<td>SBIR/STTR</td>
<td>2,650</td>
<td>2,348</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>80,217</strong></td>
<td><strong>70,240</strong></td>
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</table>
Sodium Fast Reactor

- Integral part of a closed fuel cycle
- Detailed design of ASTRID (France), JSFR (Japan), PGSFR (Korea) are proceeding, BN-1200 is under development (Russia)
- Planned start-up of BN-800 (Russia)
- R&D focus
  - Analyses and experiments to demonstrate safety approaches
  - High burn-up actinide bearing fuels
  - Develop advanced components and energy conversion systems

550°C
Elevation View of METL Facility

- Storage Tank (~3,000 liters)
- Intermediate Vessels
- EM Pump
- Large Vessels
- Catch Pan
- East
- Sodium Reaction/Passivation vessel
- Expansion Tank
- Economizer
Identify areas where information is at risk of being lost or destroyed
  – Example – FFTF document preservation

Collect and organize FR-related information
  – EBR-II SHRT database
  – FFTF Passive Safety Testing database
  – TREAT Database
  – EBR-II Fuels Irradiation Database
  – Fast Reactor Reliability Database

Recover lost computer codes
  – NUBOW-3D code recovery – supports core restraint design
  – SWAAM (sodium-water interaction) code recovery
    • Upgraded to include sodium-\(\text{CO}_2\) interactions
  – SOFIRE – a sodium pool fire code

Make information accessible to U.S. and other Fast Reactor technology development countries
  – DOE’s Office of Scientific and Technical Information
  – IAEA CRP on EBR-II Passive Testing Benchmark
High temperature enables non-electric applications

Goal - reach outlet temperature of 1000°C, with near term focus on 700-950°C

Reference configurations are the prismatic and the pebble bed
  - Designed to be “walk away safe”

R&D focus on materials and fuels
  - Develop a worldwide materials handbook
  - Benchmarking of computer models
  - Shared irradiations
    - confirmed excellent performance TRISO fuel
Development and Qualification Needs

Graphite Characterization, Irradiation Testing, Modeling and Codification

High Temperature Materials Characterization, Testing and Codification

Fuel Fabrication, Irradiation, and Safety Testing

Design and Safety Methods Development and Validation
**TRISO Fuel Accomplishments**

- **UCO TRISO fuel is being fabricated at industrial scale (B&W) to the high quality low defect level required by designer to support the HTGR safety case**
  - This contributes substantially to the very low source term under normal operation

- **The irradiation performance of UCO TRISO is excellent up to 20% FIMA and 1250°C**
  - The failure rate is 20x below the designer requirement (substantial margin)
  - Releases of key safety-relevant fission products (e.g. Cs and Sr) are very low (high degree of fission product retention)

- **The safety performance of UCO TRISO fuel is excellent**
  - Fuel is robust after 300 hours at 1600, 1700 and 1800°C
  - Failure rate at 1600°C is 8-10x below designer requirement (substantial margin)
  - Releases of key safety-relevant fission products are very low (high degree of fission product retention)
High Temperature Test Facility (HTTF) at Oregon State University

- Provide data for system code validation.
  - Primarily designed to model depressurized conduction cooldown transient.
  - Other scenarios examined for applicability of facility

- Facility Scaling
  - 1/4 length scale.
  - 1/4 diameter scale.
  - Reduced pressure.
  - Prototypical temperature.

- MHTGR Reference Design
Large-scale integral test facility

- Argonne National Laboratory
- 1/2 scale axial height
- 19° sector slice
- Confirm performance of reactor cavity cooling systems (RCCS) and similar passive confinement or containment decay heat removal systems.
- Will be reconfigured to test water-cooled passive systems.
Development of Material Properties and Design Rules and ASME Codification

Materials:
- Pressure vessel steels
- Alloys for heat exchangers (up to 800°C)
- Control rod sleeves and other core internals

Material Characterization

Environmental Testing

Mechanical Testing

Program Participants INL, ORNL, ANL

Ni from Watts bath plating
Cr Oxide surface layer
Al Oxide intergrowth

High Temperature Materials Program
## Advanced Reactor Materials

### Primary Circuit Materials* (classic future)

<table>
<thead>
<tr>
<th>Reactor</th>
<th>ROT °C</th>
<th>Dose-dpa</th>
<th>RPV</th>
<th>Piping</th>
<th>Internals</th>
<th>HX</th>
<th>SG</th>
<th>Cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWR cooled</td>
<td>288</td>
<td>&lt;1</td>
<td>508/533 (clad w/ss)</td>
<td>low alloy or stainless steel</td>
<td>304/316/ NF-709</td>
<td>N/A</td>
<td>508/533/ 600/690</td>
<td>Zirc/ SiC-SiC</td>
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<tr>
<td>Helium cooled thermal</td>
<td>750-800/ 850-900</td>
<td>&lt;1</td>
<td>1-5</td>
<td>508/533/ Gr 91</td>
<td>508/533/ Gr 91</td>
<td>graphite/ 304/316/ 800H/ SiC-91</td>
<td>800H/ 617</td>
<td>2.25Cr-1Mo/ 800H/ 617</td>
</tr>
<tr>
<td>Sodium cooled fast</td>
<td>500-550</td>
<td>&lt;1</td>
<td>10-20/ 80-150</td>
<td>304/316/ NF-709</td>
<td>2.25Cr-1Mo/ 316/ Gr 91 /Gr 92</td>
<td>304/316/ NF-709</td>
<td>304/316/ NF-709</td>
<td>2.25Cr-1Mo/ 800H/ Gr 91 /Gr 92</td>
</tr>
<tr>
<td>Molten/Liquid Salt cooled thermal</td>
<td>700/ 750-900</td>
<td>&lt;1</td>
<td>1-25</td>
<td>Hast N/ 316SS or 800H-clad/ insulated steel/ new Ni alloy</td>
<td>Hast N/ 316SS or 800H-clad/ insulated steel/ new Ni alloy</td>
<td>graphite/ Hast N/ C-C or SiC-91/ new Ni alloy</td>
<td>Hast N/ 316SS, 800H or 617 w 2-side Ni clad/ new Ni alloy / SiC-91</td>
<td>Hast N/ 316SS, 800H or 617 w 2-side Ni clad/ new Ni alloy / SiC-91</td>
</tr>
<tr>
<td>Lead/Lead-Bismuth cooled fast</td>
<td>500-550</td>
<td>&lt;30</td>
<td>100-200</td>
<td>HT-9/Gr 91/ Si mod steel</td>
<td>HT-9/Gr 91/ Si mod steel</td>
<td>HT-9/Gr 91/ Si mod steel</td>
<td>HT-9/Gr 91/ Si mod steel</td>
<td>HT-9/Gr 91/ Si mod steel</td>
</tr>
</tbody>
</table>

*Structural materials underlined are currently included in ART R&D Program with Hast N, HT-9 & the new Ni alloy being examined within NEUP.
New Developments in HTGRs Have Revitalized ASME Nuclear Code Activities for Inelastic Matls & Designs

- ASME Roadmaps for sodium- and gas-cooled reactor materials and design code needs have been developed and ISI needs for advanced reactors are being actively evaluated

- High-temperature design methodology being updated
  - Creep-fatigue, relaxation, elastic follow-up, etc.
  - Simplified design rules, including elastic-perfectly plastic methodology

- Sec III Div 5 Construction Rules for HTRs issued

- Sec XI Div 2 (for SMR and Advanced Reactors) being developed
  - More advanced techniques (volumetric UT, AE for crack or leak monitoring, phased arrays for micro-cracking, etc.)
  - Creep-crack growth evaluation procedures
  - Rules for compact heat exchangers (joint with Sec III)

*High-temperature advanced reactors all still have materials, design, and ISI issues that need updated ASME Code rules*
Overall purpose of this initiative is to establish “guidance” for developing the principal design criteria that advanced reactor designers will be required to include in their NRC license applications

Benefits

- Clearer direction to reactor designers submitting applications
- Clearer direction to NRC personnel reviewing applications
- Reduced regulatory uncertainty for advanced reactor developers
- Improved timeliness of licensing activities for both applicants and NRC staff
Annual NEUP solicitation reflects programmatic needs.

Cover multiple reactor concepts and programmatic R&D areas:
- Various coolants (Sodium, liquid salt, helium)
- Energy conversion (SCO$_2$, heat exchangers, heat transport systems)
- Materials
- Thermohydraulic modeling and experimental validation

Reactor Technologies Integrated Research Projects (IRP)
- High Fidelity Ion Beam Simulation of High Dose Neutron Irradiation. Awarded to more than eight collaborators led by University of Michigan in FY 2013.

Awards
- FY 12: $17.2 million available for NEUP
- FY 13: $16.2 million available for NEUP
- FY 14: $19.2 million available for NEUP