Objective is to Provide Overview of Advanced Reactor Technologies, Applications, and Issues

<table>
<thead>
<tr>
<th>Background</th>
<th>Advanced Reactor Types</th>
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<tbody>
<tr>
<td></td>
<td>Evolution of Reactor Technology</td>
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<tr>
<td></td>
<td>Why Advanced Reactors?</td>
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<tr>
<th>Advanced Reactor Development - US</th>
<th>Government R&amp;D</th>
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<td>Public-Private Partnerships</td>
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<td>Profile of Concepts</td>
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<tr>
<th>Advanced Reactor Development - Internationally</th>
<th>Nuclear Now &amp; Future Plans</th>
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<td>Advanced Reactor Concepts</td>
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<td>Cooperative Efforts</td>
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**Issues and Challenges**
Advanced Reactors Today Principally Means Non-Light Water Reactor Coolants

- Reactors typically differentiated by
  - Coolants used => light water, heavy water, gas, liquid metal, salts
  - Application => commercial power, test, research, isotope production, special purpose => power level
  - Neutron spectrum => thermal and fast
  - Loop and pool

- Integral reactor designs
  - Include pumps, steam generators, piping, etc., within the pressure vessel
  - Characteristic of new small reactors, particularly those based on pressurized-water reactor technology (iPWR)

- US NRC’s terminology for “advanced reactors” includes iPWRS

- Safety – active vs. passive (typical of advanced concepts)

- Siting for small modular reactors (SMRs) typically underground
  - Enhanced security
  - Enhanced safeguards
Typical Classification of Reactor Technology
Generation I thru IV => Gen IV Advanced Reactors

Source: Generation IV International Forum (GIF)
For Reactor Coolant Properties Think Temperature and Pressure

Source: Andrew Sowder, EPRI
For Reactor Coolant Properties Think Temperature and Pressure - Quadrant View

- HI T - Lo P
- HI T - HI P
- Lo T - Lo P
- Lo T - Hi P

Graph showing primary coolant outlet temperature vs. primary coolant pressure for different reactor types.
## Key Physical Parameters for Selected Coolants and Potential Reactor Applications

<table>
<thead>
<tr>
<th>Reactor Coolant</th>
<th>T – melt (°C)</th>
<th>T – boil (°C)</th>
<th>pC&lt;sub&gt;p&lt;/sub&gt; (kJ/kg °C)</th>
<th>Neutron Spectrum</th>
<th>Reactor Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized Water, 7.5 MPa</td>
<td>0</td>
<td>290</td>
<td>4040</td>
<td>Thermal</td>
<td>1, 2</td>
</tr>
<tr>
<td>Helium</td>
<td>NA</td>
<td>NA</td>
<td>20</td>
<td>Thermal Fast</td>
<td>1, 2, 3, 1, 2, 4, 6</td>
</tr>
<tr>
<td>Sodium</td>
<td>97.8</td>
<td>883</td>
<td>1040</td>
<td>Fast</td>
<td>1, 4, 5, 6</td>
</tr>
<tr>
<td>Lead</td>
<td>328</td>
<td>1750</td>
<td>1700</td>
<td>Fast</td>
<td>1, 4, 5, 6</td>
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<tr>
<td>Salts</td>
<td>400-500</td>
<td>1750 – 3140</td>
<td>2640-4670</td>
<td>Thermal Fast</td>
<td>1, 2, 3, 6, 1, 3, 4, 6</td>
</tr>
</tbody>
</table>

1. Electricity Production
2. Possible integration with hybrid power system
3. Co-generation
4. Transmutation of wastes (actinide burner)
5. Fuel recycling / breeder
# Why Consider Advanced Reactors Now?

## Enhanced Business Case
- Higher operating temperatures
  - Higher thermal efficiencies => more electricity
  - Product diversity such as process heat => co-generation
  - Potential for use w/ hybrid energy systems
  - Modular fab and construction
- => Reduced capital costs

## Enhanced Safety-Passive Systems
- No need for emergency power for removal of decay heat
- No / reduced requirements for operator action under accident conditions
- Long-term cooling options
  - => Laws of nature highly reliable

## Deployment Options
- Coupling hi-temp concepts with advanced power conversion systems => can site plants - limited water resources
- Small advanced reactors – reduced footprint and source terms
- Actinide burning for waste mgmt.
- Option – replacing retiring fossil and LWR capacity in 2030 time frame

## US National Interests
- Meet clean energy goals
- International market opportunity
- Maintain nuclear technology leadership => energy security and international influence

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GNI Workshop
02232016
Several Factors Offer Opportunities to Deploy Advanced Reactors in Future

- **Importance of LWR fleet**
  - 19.5% of US electricity*
  - 91.7% avg capacity factor*
  - 64% carbon free energy
  - Grid stability – base load
  - Retirement of coal plants
  
  *2014 data from NEI

- **Issues facing LWR fleet**
  - Economics
    - Natural gas - cheaper
    - Distorted market pricing
  - Looming retirement cliff in 2030-2040 time frame

---

**Projected Electric Capacity Dependent on License Renewals**

**U.S. Commercial Nuclear Power Reactor Operating Licenses—Expiration by Year**

**Source:** NRC Information Digest, 2014-2015 (NUREG-1350)

Includes approved licensed extensions to 60 years
iPWR SMRs Offer Simplified Design and Passive Safety Features

- Simplifies design by eliminating loop piping & external components
- Enhances safety—eliminates major classes of accidents
  - No large pipes in primary circuit means no large break LOCAs
  - Increased water inventory means slower response to transients
  - Internal CRDMs means no rod-ejection accidents
- Reduced source term
- Improved decay heat removal
- Compact containment enhances siting and security
- Countries with viable design
  - US, NuScale / Argentina, CAREM
  - South Korea, SMART / China, ACR-100
Advanced Reactor R&D is Supported Via DOE-NE’s Office of Advanced Reactor Tech.

- Mission of DOE-NE Office of Advanced Reactor Technologies (ART) is to develop future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts
  - Nuclear Energy University Program
  - Congressionally directed R&D
    - Advanced Test / Demonstration Reactor (AT/DR)
    - Recent Funding Opportunity Announcement Awards
- ART supports
  - Reactor concept and technology development (recent focus on SFRs and HTGRs)
  - Advanced reactor licensing framework development in collaboration with the NRC
- ART employs international collaboration to leverage and expand R&D investments
- ART R&D Budgets
  - FY2016 enacted: $101,718,000
  - FY2017 request: $ 73,500,000
  - Other programmatic elements on advanced fuels, mod-sim, cross-cutting technologies support advance reactor technology
DOE Announces 2 New Investments in Advanced Reactors – Major Public-Private Initiative

• Southern Company leads team to develop fast spectrum molten chloride salt-cooled reactor
  – Team includes TerraPower, ORNL, EPRI, & Vanderbilt University
  – Fast / chloride salt cooled
  – Integrated effects tests
  – Materials compatibility

• X-energy formed team to develop high temperature pebble bed gas-cooled reactor
  – Team includes BWXT, ORNL, Oregon State Univ., Teledyne-Brown Engr, SGL Group, & INL
  – Small pebble-bed gas-cooled reactor
  – Address design and fuel developments issues

DOE selects two companies to develop new advanced reactors - $40 M each
FY15 Funding from Congress - Advanced Test/Demonstration Reactor Planning Study

• Study to evaluate advanced reactor technology options, capabilities, and requirements to support innovation in nuclear energy to meet national needs
  – FY15 - $ 7 M / FY16 funds included (?)
  – Principal labs: ANL (fast reactors), INL (HTGRs), ORNL (FHRs)

• Principal barriers to advanced reactor deployment are uncertainty in reactor performance, cost, and schedule
  – Uncertainty in plant economic and safety performance
  – Uncertainty in licensing cost and schedule
  – Uncertainty in construction cost and schedule

• Developing point designs to meet following objectives:
  – High temperature process heat application and electricity production
  – Actinide management to extends natural resource utilization / reduce waste
  – Small-scale demonstration reactor to advance TRL
  – Irradiation test bed to support development/qualification of fuels and materials
Significant Growth in Private Sector Development of Advanced Reactor Concepts

- $1.3 B in private capital invested in US and Canada
- Some 40 companies engaged
  - Traditional reactor vendors (GE, Westinghouse, GA)
  - Startup companies (Transatomic, Oklo [UPOWER], Terrestrial)
  - National labs (ANL, INL, ORNL)
  - iPWRs (NuScale, Westinghouse, Holtec, m-Power)
  - Adv SMRs (EM², GenIV Energy, X-energy)
  - Universities (UCB, MIT, Univ. of Missouri)
  - $$ Investors (TerraPower)
- Spans wide power ranges: 1-2 MWe to 1000 MWe with several at 100 MWe and in the 300-400 MWe
  - Modular designs
  - Variety of coolants
  - Wide range of applications

NuScale iPWR – 12 modules 50 MWe each

General Electric-Hitachi (GEH) PRISM Sodium-cooled Fast Reactor – 2 reactors form power block of 622 MWe
New Nuclear Capacity Needed to Maintain ~ Nuclear 20% Share of Electricity Production as Current Generation LWRs Retire

Projected U.S. electrical demand overall increase from 2015-2040 at ~22% total. Source DOE Energy Information Administration
What is Happening Internationally Regarding Strategies for Nuclear Power?

Nuclear Power Worldwide
* 440 commercial reactors in 31 countries
* 380 GWe installed capacity
* 65 reactors under construction
* 16 countries where nuclear produces at least 25% of electricity

World Electricity Generation By Fuel

Source: IAEA's Key World Energy Statistics – Updated: 4/15

9th annual IAEA Technical Meeting on Topical Issues in the Development of a Nuclear Power Infrastructure
February 3-6, 2015
Number of Operating Reactors by Type and Net Electrical Power (Dec 2014)-Worldwide

Source: IAEA Nuclear Power Reactors in the World - 2015
Reactor Under Construction by Type and Net Electrical Power (Dec 2014)-Worldwide

Source: IAEA Nuclear Power Reactors in the World - 2015
China and India proposing aggressive plans for new nuclear capacity

Source: IAEA Nuclear Power Reactors in the World - 2015
Note: Nuclear share of electricity supplied in Taiwan, China was 18.9% of total.
New Nuclear Capacity for Selected Countries

- **China**
  - 30 operating / 24 under construction / 7 new plants in 2015 including AP1000’s
  - Double its capacity by 2020 to ~58 GWe / 150 GWe by 2030
  - Policy is to market globally / adapting western designs / developing Chinese designs
  - Developing Chinese design of PWR – CAP1400 based on AP1000
  - Demonstration HTGR (HTR-10) critical 2000 – full power 2003 / HTR-PM 2017
  - Demonstration SFR (CEFR) – 65 MWt / Critical 2010 / Grid 2011 / Full power 2014

- **India**
  - 21 operating (5.3 GWe) / 6 under construction including 2 PHWRs
  - Fast breeder reactor (470 MWe) under construction – utilize thorium fuel cycle
  - “XII Plan”: 8 indigenous 700 MWe PHWRs / 2 500 MWe FBRs / 1 300 MWe AHWR / 8 LWRs
  - 14.6 GWe by 2024 / 63 GWe by 2032 / 25% electricity from nuclear by 2050

- **UK**
  - 15 operating / 18% electricity / 50% to be retired y 2025
  - Planned new capacity 19 GWe starting 2025
  - Planned new reactors
    - 4 EPRs (1670 MWe each)
    - 4 ABWRs (1380 MWe each)
    - 3 AP-1000s (1135 MWe each)
    - 2 Hualong One’s (1150 MWe)

- **UAE**
  - $20 B contract to South Korean consortium for 4 1400 MWe PWRs by 2020
  - Construction started on all 4
  - First unit nearing completion – 2017 planned operation
China to Developing Molten Salt-Cooled Reactors for Interior Areas – Lack of Water
Generation IV International Forum (GIF) Is Cooperative R&D Effort

- Founded in 2001
- Technology Roadmap 2002
- Research Projects defined

**Generation IV System Development**

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<th></th>
<th>Canada</th>
<th>China</th>
<th>France</th>
<th>Japan</th>
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<th>South Africa</th>
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- ● Participating member, a signatory of System Arrangements (SA)
- ○ Participating member, a signatory of Memoranda of Understanding (MOU)
Examples of Advanced Concepts Show Innovative Design and Applications

Russian Floating Nuclear Plant
KLT-40S - PWR

Traveling Wave Reactor
Sodium-Cooled - TerraPower

Next Generation Nuclear Plant
HTGR - DOE


4S Toshiba-West. Sodium Cooled – 10/50 MWe

<table>
<thead>
<tr>
<th>SIZE</th>
<th>600 MWe (Prototype Plant) 1150 MWe (Commercial Plant)</th>
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<tbody>
<tr>
<td>TEMPERATURE</td>
<td>510°C</td>
</tr>
<tr>
<td>PRESSURE</td>
<td>Low (Atmospheric)</td>
</tr>
<tr>
<td>PRIMARY FUEL</td>
<td>Depleted Uranium</td>
</tr>
<tr>
<td>COOLANT</td>
<td>Sodium</td>
</tr>
<tr>
<td>ENERGY CONVERSION</td>
<td>Steam (Rankine Cycle)</td>
</tr>
<tr>
<td>WASTE REPROCESSING</td>
<td>Not Required</td>
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</table>
ORNL is Supporting the Development of an Advanced Reactor Licensing Framework

**Driving Force:**
- 2012 - DOE Advanced Reactor Concepts Technical Review Panel noted the need for a regulatory framework for non-light water advanced reactors
- 2012 – NRC, in response to Congressional direction, noted the need for regulatory guidance for non-light water reactors

**Challenge:**
- General Design Criteria (GDC) in Appendix A of 10CFR50 specific to light-water reactors
- Path forward for non-LWR designs?

**Objective:**
- Derive/develop principal general design criteria for non-LWRs from existing GDCs

**Benefit:**
- Reduced regulatory uncertainty for advanced reactor designers and developers

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**Appendix A GDCs**

**Advanced Reactor Design Criteria (ARDCs)**

**Sodium Fast Reactor Design Criteria (SFR-DC)**

**Modular High Temperature Reactor Design Criteria (mHTR-DC)**
Projecting Costs for Advanced Reactors is Difficult – Tradeoffs Vs. LWRs

- High temperature
  - Increases thermal efficiency
  - Increases capital cost
- High burnup/closed fuel cycle
  - Decreases natural resource requirement
  - Increases fuel fabrication (and maybe reprocessing) cost
- Low pressure coolant
  - Decreases capital cost (subject to regulatory approval)
  - Increases O&M cost for metal coolant
  - Increases materials cost for salt coolant
- FOAK vs NOAK projections

Current Projected Costs for US AP-1000: $3400-5600/kWe
Challenges and Issues Advanced Reactors Face to Realize Potential Advantages

• Customer (utility) interest – “market pull”

• Costs => must offer economic advantage over LWRs (e.g. construction, M&O, process heat, increased efficiencies)

• Price of natural gas

• Licensing framework => reduce uncertainty / phased approach to provide information for sustained investments

• Roles of government and industry
  – RD&D
  – Infrastructure => test reactors => demonstration reactors
  – First movers

• US=> electricity market policies => value nuclear power as baseload, 24/7, dispatchable power, renewable subsidies

• Ensure viability of existing fleet to transition to advanced reactors

• International collaboration / standards / licensing
Useful References

- December 2014 Issue of *Nuclear News* – Advanced Reactors
- [http://www.thirdway.org/issue/energy](http://www.thirdway.org/issue/energy)  Advanced Nuclear Summit and Topical Summaries
Backup Slides
Material Challenges

US and China Are Cooperating on FHR Research and Development

- Collaboration supports the US-China memorandum of understanding on cooperation in civilian nuclear energy science and technology
- ORNL and the Shanghai Institute of Applied Physics (SINAP) of the Chinese Academy of Sciences (CAS) are the lead organizations
  - ORNL will call on expertise throughout the US to support CRADA tasks
- Project is intended to benefit both countries through more efficiently and rapidly advancing a reactor class of common interest
- FHR remain at a pre-commercial level of maturity
  - All of the results are intended to be openly available
  - Project is scheduled to end after SINAP’s higher-power test reactor has completed its operational testing program
- Collaboration includes research and development to support the evaluation, design, and licensing of a new reactor class
  - Does not include fuel development or fissile material separation technology
ORNL Staff* Conducts Training Program for Chinese Regulators on Fluoride Salt-Cooled High Temperature Reactors

• Conducted at Shanghai Institute of Applied Physics from Dec 7-9
  – In support of SINAP/ORNL $49 M CRADA
  – Focus of training for China’s National Nuclear Safety Administration (NNSA)

• Attendance from NNSA and SINAP staffs and support organizations: 270
  – 50: NNSA staff and 20 support organizations
  – 200: staff from SINAP and other institutes from Chinese Academy of Sciences
  – 10 modules: FHR reactor technology, systems, and safety

*George Flanagan and David Holcomb