Small Modular Reactor and Advanced Reactor RD&D: Implications for Electrical Grid and Plant Scale Integrated Energy Systems

Michael Hagood, Advisor
WSU Office of Research

Energy Systems Innovation Center Seminar Series
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A Northwest Energy Leadership Opportunity

In October 2020 two teams were awarded multi-billion demonstration projects as part of U.S. DOE’s Advanced Reactor Demonstration Program (ARDP)

• TerraPower Natrium Sodium Fast Reactor Demonstration
• Xe-100 Advanced Reactor Demonstration

The goal is to have at completion (within seven years) NRC licensed operating commercial plants, HALEU fuel production, qualified reactor equipment fabrication and other key components and tools in place.

The reactor demonstrations will potentially be conducted at Energy Northwest (EN) sites in Eastern Washington State

Select Advantages for Siting on EN Property

• The advanced reactor operations can leverage previously NRC licensed sites on land leased to EN on the DOE Hanford Site
• Advanced reactors would be located adjacent to EN’s Columbia Generating Station, have access to existing key infrastructure, and to experienced and licensed nuclear operators and other qualified workforce
• Local community acceptance of nuclear power; potential for financial de-risking through supplying power to meet local demand
Energy Northwest (EN) Columbia Generating Station and Proposed ARDP Demonstration Locations
**TerraPower Natrium™ Sodium Fast Reactor Demonstration**

- **Team:** TerraPower, GE-Hitachi NE, Bechtel, PacifiCorp, EN, Duke Energy

- 345 MWe reactor, employing molten sodium as fuel (HALEU) and coolant in unpressurized system

- Delivers electricity or heat, with high output temperature (500-550 degC?)

- Combined with molten salt storage (capacity 500 MWe of power for 5.5+ hours)

- Reactor passively safe; decouples the reactor and electricity generation

- Includes one-year scope to start the design and licensing of HALEU enrichment facility

- Below ground reactor, considering EN WNP-4 site, but also evaluating other U.S. sites.

- Cooperative agreement with DOE (co-funded) not yet announced.
X-energy: Xe-100 Advanced Reactor Demonstration

- Team: X-energy, EN, Grant PUD
- High temp. pressurized helium gas-cooled reactor, with graphite core structure
- 4 x 80 MWe modules, uses graphite pebbles with Tri-structural ISOtropic (TRISO) particle fuel (HALEU).
- Delivers electricity or heat, with 565 degC steam
- Encapsulated fuel, passive safe meltdown-proof, online refueling (will deliver a commercial scale TRISO fuel fabrication facility)
- Below ground reactor, to be placed at EN WNP-1 site
- Cooperative agreement with DOE signed and TRISO fuel fabrication facility (co-funded)

Source X-Energy: https://x-energy.com/reactors/xe-100 & Bowers, 2018
X-energy: Xe-100 Advanced Reactor Demonstration

Xe-100 reactor TRISO Fuel Pebble
Source X-Energy: https://x-energy.com/reactors/xe-100
Bowers, 2018
Selected Advantages of Advanced Reactors Relevant to an Energy Systems Perspective*

• More flexible operations and integration into large, regional electricity systems as base and load-following source of low-carbon power

• Complements renewable energy resources such as wind, solar, and hydropower which produce fluctuating power levels that need to be evened out (grid resiliency)

• Ideal for project sites and other power applications with high temperature output supporting industrial processes

• Can include novel storage configurations to enhance flexibility and applications; online refueling

• Concept separates nuclear reactor from "energy island"

• Licensing/Safety footprint is lessened, expediting licensing, decreasing costs and enhancing conduct of offsite activities

• Can add modules over time in response to demand and capitalization

*Also has advantages in sustainability, economics, reliability, reduced waste, applied manufacturing, & safety
**NATRiUM**

*Single Unit Site*

- Demin Water
- Firewater
- Standby Diesels
- Warehouse & Admin
- Rx Aux. Building
- Shutdown Cooling
- Control Building
- NI Power Distribution Center & Controls
- Steam Generation
- Salt Piping
- Rx Building
- Fuel Building
- Fuel Aux. Building
- Turbine Building
- TI Power Distribution Center
- Inert Gas
- Energy Storage Tanks

**Energy Island**

**Nuclear Island**

Nuclear and Energy Island Concept

TerraPower:

https://www.terrapower.com/our-work/natriumpower/
NuScale SMR Power Module™ &
the Carbon Free Power Project (CFPP)

- **Team:** Utah Associated Municipal Power Systems (UAMPS), NuScale Power, Fluor, INL
- Water cooled reactor w/ standard LWR fuel (5 percent $^{235}$U), with 24-month refueling cycle (alternating modules)
- Steam generators and turbines, no pumps required to circulate
- NRC approved design is for 12 x 50 MWe module (*new design has uprate of 77 MWe per module*); to be located at the INL Site, first module by 2029.
- Output temperature 300 degC
- INL engaged in planning hybrid applications beyond electricity
- CFPP has been in development since 2015, is cost shared with DOE, modules to be ordered in 2022

Source: [https://www.nuscalepower.com/technology/technology-overview](https://www.nuscalepower.com/technology/technology-overview)
Integrated Nuclear Energy Systems will be dynamic and flexible

- Advanced Reactors
- New Chemical Processes
- Hydrogen and Transport Fuel
- Clean Water
- Renewables
  - Electric Grid
  - Industry
Conceptual H2@Scale Energy System

Source: H2@Scale
https://www.energy.gov/eere/fuelcells/h2scale
Flexible Plant Operations & Generation Timeline to Bolster U.S. Nuclear Reactors (Richard Boardman, 2020)

1. Techno/Economic Assessments Holistic Systems Evaluations
   - Case Specific TEAs for Additional LWRS

2. PRA: H₂ & Thermal Systems
   - PRA: Chemical Plants & Fuels Synthesis
   - Licensing Considerations with Engineering Measures

3. Interface Development & Verification
   - Engineering and case-specific thermal integration

4. 2-3 MWe LTE Demos
   - 100 - 200 MWe Plants
   - 250 kWe HTE Demos
   - 5 – 10 MWe Plants
   - 50 - 200 MWe Plants

5. NuScale Light Water Reactor
   - Molten Salt and High Temperature Gas Reactors
   - Micro-Reactors / Cartridge Reactors
   - 10-100 MWe Adv Reactors H₂ Demonstrations
Selected U.S. Nuclear-RDD&D
Integrated Energy System Developments

DOE co-funding LWR-hydrogen projects with Exelon, Energy Harbor, Xcel Energy, and Arizona Public Service over next few years

Advanced reactor technology developers advertising electricity AND heat applications, AND storage potential

FuelCell Energy/INL engaging on developing and demonstrating hi-temp electrolysis system for nuclear power, w/ emulating grid dynamics, thermal energy transport from the reactor and nuclear reactor control simulator

PNNL/INL team working with TerraPower on high temp. steam electrolysis for H2 & storage; & also conducting economics study

DoD pursuing demonstrations for mobile (2-5 MWe) and stationary (5-10 MWe) microreactors (integrated systems?)

Demonstration at the Davis-Besse plant will consume 2 MWe of power at plant output, and use a PEM electrolyzer and 2,400 gallons of water per day to produce 800-1000 Kg of H2
Selected Hydrogen Developments in Washington State

- In 2020, The governor signed SB5588 authorizing public utility districts to manufacture and sell renewable hydrogen.

- Douglas PUD broke ground in March 2021 on hydrogen production facility (integrated with hydropower).

- Tacoma Power is implementing pilot rate, designed for industrial production of e-fuels such as hydrogen or hydrogen-rich compounds.

- Bellevue’s Paccar building hydrogen fuel cell-powered vehicles for long-haul trucking.

- PNNL and PNNL-WSU Bioproducts Institute developing analytical framework for optimal sizing of hydrogen fueling stations at the Port of Seattle.

- Tri-Cities Community exploring deploying H2 ecosystem initiative.

Douglas PUD to operate a Cummins 5-MW PEM electrolyzer to convert surplus hydropower to hydrogen.

Paccar’s Kenworth H2 fuel cell electric powertrain train T680.
The Northwest (and the world) will experience major energy transitions to decarbonize electrical generation, transportation and manufacturing.

Nuclear reactors can play an important role in this energy transition, beyond just supplying low carbon electricity.

Such transitions are accompanied by complex interdependency and scaling challenges.

Lots of R&D opportunities! including from energy systems perspective to address the associated challenges and opportunities* (on many levels).

WSU and PNNL (and other regional players) have geographic presence, deep capabilities, partnerships and DOE program engagement that complement integrated nuclear energy systems development.

APS Mgr: “It’s really one thing to do a 1-MW (electrolyzer) skid in the parking lot. It’s a whole other challenge if you’re talking about 100 MW, 200 MW."
Integrated grid system that leverages contributions from nuclear fission beyond electricity sector

- Large Light Water Reactors
- Small Modular Reactors
- Micro Reactors
- Advanced Reactors
- New Chemical Processes
- Clean Water
- Heat
- Hydrogen for Vehicles and Industry
- Industry

Source: Bragg-Sitton and Boardman, 2020
Backup Slides
ADVANCED REACTORS

Benefits:

- Enhanced safety
- Versatile applications
- Reduced waste
- Apply advanced manufacturing to reduce costs

Source: S. Bragg-Sitton and R. Boardman, 2020
# ARDP
**Demonstration Awards (Oct, 2020)**
*5-7 year timeframe*

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<thead>
<tr>
<th>Project</th>
<th>Players</th>
<th>Reactors</th>
<th>Information</th>
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</table>
| Advanced Reactor Demo. Program – Proj. #1 | DOE TerraPower GE-Hitachi PacificCorp Energy NW | 1 x 345 MWe Natrium sodium fast reactor with 500 MWe molten salt storage HALEU fuel | - Total $4 (50% DOE co-funded) over 7 years  
- Undergoing negotiations with DOE  
- Anticipated ~2-3 years for siting/licensing  
- To be constructed by 2027  
- Considering former WNP 4 for demo |
| Advanced Reactor Demo. Program – Proj. #2 | DOE X-energy, Energy NW NC State U. | 4 x 80 MWe high temperature gas-cooled reactors HALEU Fuel               | - Total $2.4B (50% DOE co-funded) over 7 years  
- Cooperative agreement signed, $80M funding  
- Anticipated ~2-3 years for siting/licensing  
- Public Power Offtake  
- Grant Co. interests, seeking Hanford Ops., Vit Plant, PNNL for derisking  
- Considering former WNP-1 for demo |
## ARDP
### Risk Reduction Awards (Dec 2020)
#### 7-10 year time frame (version: }

<table>
<thead>
<tr>
<th>Project</th>
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<th>Project Focus</th>
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<tbody>
<tr>
<td>Hermes Reduced-Scale Test Reactor</td>
<td>Kairos Power</td>
<td>Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)</td>
<td>Leverages TRISO fuel in pebble form combined with a low-pressure fluoride salt coolant</td>
</tr>
<tr>
<td>SMR-160 Reactor</td>
<td>Holtec Gov. Services</td>
<td>Water-cooled SMR</td>
<td>Engineering and licensing</td>
</tr>
<tr>
<td>Molten Chloride Reactor Experiment</td>
<td>Southern Company Services, Inc w/PNNL</td>
<td>First critical fast-spectrum salt reactor relevant to TerraPower’s Molten Chloride Fast Reactor</td>
<td>Design, construct, and operate the MCRE</td>
</tr>
<tr>
<td>BWXT Advanced Nuclear Reactor</td>
<td>BWXT</td>
<td>Transportable microreactor with the design focused on using TRISO fuel particles</td>
<td>to achieve higher uranium loading, core design using silicon carbide matrix</td>
</tr>
<tr>
<td>eVinci™ Microreactor</td>
<td>Westinghouse Electric Co.</td>
<td>High Temp Heat pipe-cooled microreactor</td>
<td>Addressing tech risks canister design, improve heat pipe wick manufacture, refueling process and licensing</td>
</tr>
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## ARDP
### Concepts 2020 Awards (Jan 2021)
#### 3+ years timeframe

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<tr>
<td>Inherently Safe Advanced SMR for American Nuclear Leadership</td>
<td>Advanced Reactor Concepts, LLC</td>
<td>Conceptual design of a seismically isolated advanced sodium-cooled reactor facility, 100 MWe</td>
<td>$34.4 million over 3.5 years (DOE cost share: $27.5 million)</td>
</tr>
<tr>
<td>Fast Modular Reactor Conceptual Design</td>
<td>General Atomics w/ Framatome</td>
<td>Develop the helium-cooled fast modular concept, 50 MWe</td>
<td>$31.1 million over 3 years (DOE cost share: 24.8 million)</td>
</tr>
<tr>
<td>Horizontal Compact High Temperature Gas Reactor</td>
<td>MIT</td>
<td>Maturing its Modular integrated Gas-Cooled High Temperature reactor (MNIGHTR) from pre-conceptual state to conceptual state to support commercialization</td>
<td>$4.9 million over three years (DOE cost share: $3.9 million)</td>
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## LWR and Hydrogen (Sep 2020)
### 3+ years timeframe

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<tr>
<td><strong>H2@Scale</strong> Exelon w INL, Argonne and NREL</td>
<td>Installation of a Nel Hydrogen 1-MW PEM electrolyzer at one of Exelon Nuclears 14 boiling water reactors.</td>
<td>“By March 31, 2021, will select a site, complete 30% , 3-year project budget of $7.2 million, with the utility and DOE splitting the cost, operational by 2023. Unlikely to make a decision by April 1 2021 whether to proceed</td>
</tr>
<tr>
<td><strong>ARDP/ Energy Harbor w/ Labs</strong></td>
<td>Develop a light water reactor hybrid energy system at the 925-MWe Davis-Besse Nuclear plant in Oak Harbor, Ohio</td>
<td>Will receive $9 million in federal funding for a $11.4-million project to develop , two year project to begin in 2020. a 2-MWe low-temperature electrolysis (LTE) polymer electrolyte membrane (PEM) technology that will be integrated with Energy Harbor’s 925-MWe 2-year project</td>
</tr>
<tr>
<td><strong>ARDP/ Xcel Energy w/ Labs</strong></td>
<td>To be conducted at one of two of its Minnesota plants</td>
<td>Could being in 2021</td>
</tr>
<tr>
<td><strong>ARDP/ Arizona Public Service (APS) w/ Labs</strong></td>
<td>Palo Verde Generating Station, near phoenix, AZ. May be used as energy storage, reverse-operable electrolysis or peaking gas turbines</td>
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## DoD

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| Project Pele Design       | • BWXT, Inc                                  | Safe, mobile and advanced prototype nuclear microreactor (1-5 MWe)   | DoD Strategic Capabilities Office  
| Competition 2-year        | • X-energy, LLC                              | to support a variety of DoD missions such as generating power for     | $13.5M  
| engineering study         | • Westinghouse Government Services           | remote operating bases                                                | $14.3M  
|                           |                                              |                                                                      | $11.9M  |
|                           |                                              |                                                                      | Indoor Testing of prototype by 2023  
|                           |                                              |                                                                      | Outdoor testing by 2024  
|                           |                                              |                                                                      | Forward Operations  
|                           |                                              |                                                                      | TRISO fuel |
| Pilot program demonstration|                                              | Demonstrate efficacy of a SMR in the 2-10 MWe range by ~2023; followed | Office of the undersecretary of acquisition and sustainment  
|                           |                                              | by demo at permanent military installation by 2027                   | Initial testing at DOE site |

- BWXT, Inc
- X-energy, LLC
- Westinghouse Government Services