Small Modular Reactors (SMRs)
What are they? Why are they cool?

Alex Harkness
SMR Design Lead/Fellow Engineer

ANS Meeting Rocky Hill, CT
January 19, 2012
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What are they? Why are they cool?

Creed Taylor  
SMR Steam Generator Lead/Senior Engineer  
ANS Meeting Chattanooga, TN  
January 24, 2012
Energy Demand is Growing

- World population will increase **25 percent in the next 20 years** with most of that growth in countries with emerging economies.
- Additionally, rising energy demand from economic output and improved standards of living will strain energy supplies.
- In China alone, increasingly prosperous citizens are projected to purchase more than 100 million new vehicles before 2020.
- As a result energy consumption by 2030 is expected to **nearly double** (IEA).
Critical Decisions Must Be Made

• World must address growing energy needs with CO₂ friendly energy solutions
• At the same time, the U.S. must reduce our reliance on imports and move toward energy independence
• There are multiple ways to achieve these goals:
  – Conservation
  – Implement a balanced portfolio of “clean” energy technologies
  – Increase the deployment of vehicles powered from clean energy sources (clean electricity, cleanly produced hydrogen)

...secure nuclear as a foundation in providing environmentally sustainable, economic power
Utility investment trends have been moving towards “cleaner” energy sources
Average Baseload - Recent U.S. Trends

The recent increase in average unit size is due to temporarily high coal plant additions.
Load Growth in the Energy Market

Utilities with 10-Year Growth >200 MW
- Utilities facing load growth of 1000 MW or more over the next ten years: 13 Utilities

Utilities facing load growth of between 200 and 1000 MW over the next ten years: 72 Utilities
Base Load Energy - Aging Fossil Facilities

Coal-Fired Power Plants by First Year in Service
(626 reporting in-service date out of 636 total)

<table>
<thead>
<tr>
<th>Year First in Service</th>
<th>Number of Power Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920-1929</td>
<td>8</td>
</tr>
<tr>
<td>1930-1939</td>
<td>10</td>
</tr>
<tr>
<td>1940-1949</td>
<td>67</td>
</tr>
<tr>
<td>1950-1959</td>
<td>171</td>
</tr>
<tr>
<td>1960-1969</td>
<td>112</td>
</tr>
<tr>
<td>1970-1979</td>
<td>93</td>
</tr>
<tr>
<td>1980-1989</td>
<td>98</td>
</tr>
<tr>
<td>1990-1999</td>
<td>58</td>
</tr>
<tr>
<td>2000 - 2007</td>
<td>9</td>
</tr>
</tbody>
</table>

Base Load Energy – U.S. Coal Example

West
Number of Units: 88
Average Nameplate Capacity: 187 MW
Average Age of Units: 40 years

Midwest
Number of Units: 583
Average Nameplate Capacity: 195 MW
Average Age of Units: 44 years

Southwest
Number of Units: 95
Average Nameplate Capacity: 365 MW
Average Age of Units: 44 years

Northeast
Number of Units: 131
Average Nameplate Capacity: 216 MW
Average Age of Units: 43 years

Southeast
Number of Units: 458
Average Nameplate Capacity: 267 MW
Average Age of Units: 44 years

Base Load Energy – Investment Cost Options

Market Capitalization of U.S. Electric Utility and Merchant Entities
($-Millions as of 1/11)

Large Nuclear Economics:
$8 to $10B Investment
Only the largest utilities can finance

SMR Economics:
~ $1B Investments
Opens practically the whole U.S. utility market to this solution

Target for SMR Overnight Costs
Small Modular Reactors
The Next Phase of Nuclear Energy

• SMRs provide an affordable, reliable, carbon-free, energy source to meet the world’s growing energy demand
  – Nuclear for users who do not need a large MWe with lower financial commitment
  – Replacement capacity for 40-70GW of coal at-risk
  – Stable base load to hedge against natural gas price volatility

• Broadening application for nuclear
  – Clean, safe and affordable solution for industrial applications (process heat)
  – Remote installations / small grid markets
  – Desalination
  – District heating

• Offering clean energy
  – Generation portfolio diversity
  – Operational flexibility such as load following
The SMR provides a compelling portfolio fit from many points of view

Coal Perspective
Coal plant closures as a result of EPA air and water emission rules will likely be significant across the country and future new coal plant development is not likely, including advanced and IGCC

Renewable Perspective
While renewable resources are more costly, continued subsidization and renewable portfolio standards will force wind into portfolio mixes. Rapid cost reductions in solar will lead to more rapid portfolio penetration

Natural Gas Perspective
Shale gas has transformed today’s energy markets in North America, but price and volatility is still very uncertain when making 40 year resource decisions

The SMR provides a credible base load replacement technology for coal
Built to load follow, the SMR provides a base load renewable integration option
The SMR provides the low cost and price certainty of nuclear fuel vs. the uncertainty of natural gas
Price-Anderson Nuclear Industry Indemnity Act

• Congress introduced the Price-Anderson Act in 1957
  – Act required companies to obtain the maximum possible insurance cover against accidents
  – Does not apply to small reactors < 300 MWe
• Has effectively set the upper bound for small reactors
NRC/Licensing

• Issues being evaluated
  – Risk informed licensing
  – Mechanistic source term
  – Liability & property insurance
  – Manufacturing licenses
  – Staffing, security and emergency planning
NRC/Licensing

- Control room staffing
  - Assessing staff-related exemptions (NUREG 1791)
- Security
  - Opportunity for “security by design”
- Emergency planning
  - Exploring alternatives for SMRs
- Design specific review plans to replace SRP
- Revised fee structure based on net power output
Many are Developing Small Reactors
Light Water Reactors

- Small light water reactors are designed to capitalize on the benefits of North American modular construction, ease of transportation and reduced financing, making them a good option for areas where large nuclear reactors are not needed. These designs typically are smaller than 300 megawatts electric and could replace older fossil-fired power stations of similar size.
Light Water Reactors

- Babcock & Wilcox Co. mPower Reactor
  - 160*-megawatt electric advanced light water reactor design that uses natural phenomena such as gravity, convection and conduction to cool the reactor in an emergency with a belowground containment.

- Holtec Inherently Safe Modular Underground Reactor (HI-SMUR) 140
  - The HI-SMUR is a 145*-megawatt electric reactor with an underground core. That feature, Holtec says, means there is no need for a reactor coolant pump or off-site power to cool the reactor core.

- NuScale Power Inc. NuScale Reactor
  - The NuScale is a 45-megawatt electric advanced light water reactor. NuScale’s passive cooling systems uses natural circulation to maximize safe operation.

- The Westinghouse SMR
  - The Westinghouse SMR is a 225-megawatt integral pressurized water reactor with all primary components located inside the reactor vessel. It is based on the AP1000® reactor design, which is being built in several locations around the world.

* Updated
mPower

- “Twin-pack” configuration
  - 160 MWe/Unit
- Underground construction
- Forced convection
Tennessee Valley Authority

- TVA Clinch River Site

- Letter of intent between Generation mPower and TVA to build 6 units at the Clinch River Site in Tennessee

- Plan to use both Part 50 and Part 52 licensing to achieve completion in 2020
NuScale

- 6-12 pack modular deployment
- 45 MWe/Unit (270-540 MWe)
- Natural convection
- Submerged containment
Hi-SMUR

- Single unit deployment
- 145 MWe/Unit
- Natural convection
- Core underground
Westinghouse SMR

- Standalone unit
- > 225 MWe
- Safety systems below grade
- Submerged containment vessel

Leveraging AP1000 Technology
# Westinghouse SMR

## Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Output</strong></td>
<td>800 MWt</td>
</tr>
<tr>
<td><strong>Electrical Output</strong></td>
<td>&gt; 225 MWe</td>
</tr>
<tr>
<td><strong>Passive Safety Systems</strong></td>
<td>No operator intervention required for 7 days</td>
</tr>
<tr>
<td><strong>Core Design</strong></td>
<td>17 x 17 Robust Fuel Assembly</td>
</tr>
<tr>
<td></td>
<td>8.0 ft Active Length</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% Enriched U235</td>
</tr>
<tr>
<td></td>
<td>89 Assemblies</td>
</tr>
<tr>
<td></td>
<td>Soluble Boron and 37 Internal CRDMs</td>
</tr>
<tr>
<td></td>
<td>24 Month Refueling Interval</td>
</tr>
<tr>
<td><strong>Reactor Vessel Size</strong></td>
<td>Outer Diameter: 11.5 ft</td>
</tr>
<tr>
<td></td>
<td>Height: 81 ft</td>
</tr>
<tr>
<td><strong>Upper Vessel Package</strong></td>
<td>280 Tons</td>
</tr>
<tr>
<td><strong>Containment Vessel Size</strong></td>
<td>Outer Diameter: 32 ft</td>
</tr>
<tr>
<td></td>
<td>Height: 89 ft</td>
</tr>
<tr>
<td></td>
<td>Fully Modular Construction</td>
</tr>
<tr>
<td><strong>Reactor Coolant Pumps</strong></td>
<td>8 External, Horizontally-Mounted Pumps</td>
</tr>
<tr>
<td></td>
<td>Sealless Configuration</td>
</tr>
<tr>
<td><strong>Steam Generator</strong></td>
<td>Recirculating, Once-Through, Straight-Tube</td>
</tr>
<tr>
<td><strong>Pressurizer</strong></td>
<td>Integral to Vessel</td>
</tr>
<tr>
<td><strong>Instrumentation and Control</strong></td>
<td>OVATION®-based Digital Control System</td>
</tr>
</tbody>
</table>
High-Temperature Gas-Cooled Reactors

• High-temperature gas-cooled reactors could be used for electricity generation, but they would be especially well-suited to providing process heat for industrial purposes, including hydrogen production. These reactors also could be used in the development of tar sands, oil shale and coal-to-liquids applications. The small nuclear reactors would reduce the life-cycle carbon footprint of all these activities.
High-Temperature Gas-Cooled Reactors

- **AREVA Antares**
  - AREVA based the design for the Antares on the concept of a gas-cooled (helium) reactor. The company is developing the design in the context of the Generation IV International Forum.

- **General Atomics Gas Turbine Modular Helium Reactor (GT-MHR)**
  - The GT-MHR is a high-temperature reactor with advanced gas turbine technology.

- **Pebble Bed Modular Reactor Ltd. (PBMR)**
  - The PBMR is a high-temperature reactor that uses a gas or steam turbine for power conversion. Substantial design, component testing and fuel development have been undertaken in South Africa.

Source: NEI
Liquid Metal and Gas-Cooled Fast Reactors

- Liquid metal or gas-cooled fast reactor technologies hold the promise of distributed nuclear applications for electricity, water purification and district heating in remote communities. Fast reactors also could provide sustainable nuclear fuel cycle services, such as breeding new fuel and consuming recycled nuclear waste as fuel, and could support nonproliferation efforts by consuming material from former nuclear weapons, thus eliminating them as a threat.
Liquid Metal and Gas-Cooled Fast Reactors

- **GE Hitachi Nuclear Energy Power Reactor Innovative Small Module (PRISM)**
  - The PRISM is an advanced reactor cooled by liquid sodium. As with some other small reactor designs, the plant will be built underground on seismic isolators to dampen the effects of earthquake motion.

- **General Atomics Energy Multiplier Module (EM2)**
  - The EM2 is a modified version of General Atomics’ high-temperature, helium-cooled reactor. The 240-megawatt reactor is capable of converting used nuclear fuel into electricity and industrial process heat without conventional reprocessing.

- **Hyperion Power Generation Hyperion Power Module (HPG)**
  - The HPG is a 25-megawatt reactor. Company officials say the module's initial application is likely to be in oil shale fields.

- **Toshiba 4S (Super-Safe, Small and Simple)**
  - The 4S is a 10-megawatt reactor cooled by liquid sodium for use in remote locations.

Source:
Development Landscape

• DOE Funding of $452M – *Delayed*
  – Funding Opportunity Announcement (FOA) for a 50/50 cost share program originally expected in March of 2011
• Congress appropriated $67M for GFY-12
  – Expected to be a $452M program over 5 years
• Revised FOA expected end of March 2012
• Expected to respond to the FOA
  – Westinghouse, mPower, NuScale and Holtec
• FOA expected to emphasize U.S. Jobs/Manufactioning and Technology Leadership
Westinghouse’s Global Vision

Westinghouse will develop and deploy a safe, economic SMR that meet the many needs of “existing” and “new to nuclear” customers around the world

- Working within constraints
  - Land, grid, cooling water, transportation, financing, distributed service territory

- Offering clean energy
  - Offset owner costs for infrastructure development: land, cooling, T&D
  - Generation diversity
  - Operational flexibility

- Providing project certainty
  - Reduced licensing risk
  - Short-construction durations
  - Cost predictability and certainty

A brighter future for nuclear...

- Aging Fossil Plants
- District Heating
- Remote Markets
- Small Grid Markets
- Desalinization
- Process Heat
Overcoming the Economies of Scale

Flattening economies of scale:
Overcome with cost-driven design, supply chain competition, manufacturing economies, innovative business model, compressed construction schedule

Our Goal
Modular Construction by Design

- SMR’s size accommodates increased use of modules beyond AP1000
  - Remember this graphic? We need to turn it up a notch (or two)

Shop-Build → Predictable Schedule → Reduced Risk → Competitive capital costs
How Small is Small?

25 Westinghouse SMR Containment Vessels fit in a single AP1000 Containment Vessel
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