Current Status of the UCB PB-FHR Mark-1 Commercial Prototype Design Effort

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Fluoride Salt-Cooled High-Temperature Reactors (FHRs) Combine Two Nuclear Technologies

Coated Particle Fuel

- Fission Product Retention > 1600° C
- FHRs have uniquely large fuel thermal margins (fuel temp < 1000° C)
- BUT need to confirm performance at higher FHR power densities

Fluoride Salt Coolants

- Excellent heat transfer properties
- Transparent, clean fluoride salt
- Boiling point ~ 1400° C
- Reacts very slowly in air
- No energy source to pressurize containment
- BUT high freezing temperature (459° C)
- AND industrial safety for Be control
FHR Design Space Allows for Coupling to Air Cycles

<table>
<thead>
<tr>
<th>Coolant Temperature</th>
<th>System Pressure</th>
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<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Light-Water</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>Sodium Fast</td>
<td>Reactor</td>
<td>Medium</td>
</tr>
<tr>
<td>High</td>
<td>FHR (High Inlet</td>
<td>Reactor</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Temperature)</td>
<td>(Low Inlet</td>
<td>Temperature)</td>
</tr>
</tbody>
</table>

Nickel-based structural materials

![Graph showing allowable stress vs. temperature for different materials]
Current FHR Development Efforts

- **DOE Integrated Research Project (IRP)**
  - Collaborative university effort with MIT, UCB, and UW
  - Includes commercialization strategy, commercial prototype and test reactor pre-conceptual design effort, and assorted technology development efforts

- **Oak Ridge National Laboratory**
  - Ongoing FHR development work on technology roadmap and reactor design (plate fuel)

- **ANS Standards Committee 20.1**
  - Currently developing FHR-specific GDCs and design standards

- **Shanghai Institute of Applied Physics (SINAP)**
  - Currently developing FHR and MSR technology
  - 10 MW FHR test reactor deployment planned for 2017
Goals for the Compelling FHR Market Case

- **ENVIRONMENT**
  - Enable a low-carbon nuclear-renewable (wind/solar) electricity grid by providing economic dispatchable electricity

- **ECONOMIC**
  - Increase revenue relative to base load nuclear power plants with natural gas co-firing

- **SAFETY**
  - No major offsite radionuclide releases even in bounding severe accident cases
PB-FHR Mk1 Design Goals

- Demonstrate a plausible, self-consistent Nuclear Air Combined Cycle (NACC) system design
  - 2 archival articles now accepted to ASME Journal of Engineering for Gas Turbines and Power
- Provide detailed design for decay heat management systems
  - Provide basis for establishing integral effects testing and TH code validation and benchmark exercises
- Develop a credible, detailed annular FHR pebble core design
  - Provide basis for future FHR code benchmarking
- Identify additional systems and develop notional reactor building arrangement
  - “Black-box” level of design for many of these systems
  - Include beryllium and tritium management strategies
- Final Design Report Expected: June 2014
  - Pre-Conceptual Level
Nominal PB-FHR Mk1 Design Parameters

- **Annular pebble bed core with center reflector**
  - Core inlet/outlet temperatures 600/700° C
  - Control elements in channels in center reflector
  - Shutdown elements cruciform blades insert into pebble bed

- **Reactor vessel 3.5-m OD, 12.0-m high**
  - Vessel power density 3 x higher than S-PRISM & PBMR

- **Power level:** 236 MWth, 100 MWe (base load), 242 MWe (peak w/ gas co-fire)
  - Base load efficiency: 42.4%
  - Natural gas conversion efficiency: 66.4%

- **GE 7FB gas turbine w/ 3-pressure HRSG**

- **Air heaters:** Two 3.5-m OD, 10.0-m high CTAHs, direct heating

- **Tritium control and recovery**
  - Recovery: Absorption in fuel and blanket pebbles
  - Control: Kanthal coating on air side of CTAHs
PB-FHR Mk1 NACC Physical Arrangement

Main exhaust stack
Air intake filter
Simple cycle vent stack
Generator
GE F7B compressor
HP/LP turbines
HP air ducts
HP CTAH
Hot well
Reactor vessel
Heat recovery steam generator
Combustor
Hot air bypass
LP air ducts
LP CTAH
Main salt drain tanks
GE 7FB Turbine Modified for External Nuclear Heating

- High pressure extraction and injection nozzles for external heating to 670°C
- High pressure expansion stage
- Turbine exit diffuser is not modified
- Low pressure expansion stage
- Low pressure extraction and injection nozzles for external heating to 670°C
- Combustor for co-firing
- Compressor is not modified, nominal exit temperature is 420°C
Unique Features of NACC

- Capability to provide peak power with auxiliary fuel
  - Increase revenue after paying for fuel
  - Natural gas today, hydrogen and bio-fuels in future
- Fast response because turbine is always hot and spinning - peak power starts from base-load NACC
- Efficient natural gas to electricity conversion
  - 66.4% heat to electricity efficiency vs. NGCC ~ 60%
- 40% cooling water required of LWR per kW(e)h
- Efficient process heat option
  - No isolation steam generator with capital cost and temperature drop penalty. No tritium concern.
  - High temperature steam

Maximize Revenue By Selling Electricity When the Price is High

Electricity Price Vs Hours Sold at that Price

Distribution of electricity prices, by duration, at Houston, Texas hub of ERCOT, 2012

Renewable Deployment Changes the Grid

Unstable Electrical Grid   Excess Electricity with Price Collapse

California Daily Spring Electricity Demand and Production with Different Levels of Photovoltaic Electricity Generation

Source: C. Forsberg, "Commercialization Strategy and Challenges for Fluoride-Salt-Cooled High-Temperature Reactors (FHRs)." 19 January 2014
Transition to a Low-Carbon Electricity Market Imply More Hours of Low / High Price Electricity

Impact of Non-Dispatchable Solar and Wind

- Large Sun and Wind Output Collapses Revenue
- No Sun and No Wind

Favors FHR with NACC Economics

Distribution of electricity prices, by duration, at Houston, Texas hub of ERCOT, 2012

PB-FHR Mk1 Reactor Vessel Cross Section

- Defueling wells (2)
- Hot leg nozzle (1)
- Vessel outer lid
- Vessel inner lid
- Support skirt
- DHX wells (3)
- Shutdown blades (8)
- Control rods (8)
- Outer radial reflector
- Center radial reflector
- Graphite blanket pebbles
- Fuel pebbles
- Downcomer
- Lower reflector support

3.50 m
The Mark-1 center reflector block geometry minimizes stresses induced by neutron irradiation.

- Control rod channel keyed to maintain block alignment
- 8 lobes reduce neutron irradiation induced stress
- 16 instrument guide tubes
- Control channel coolant injection holes
- Center coolant flow channel
- Center channel coolant injection holes and slot

Exploded View

0.70 m
Pebble Injection and Core Flow in PB-FHR Mk1

Narrow Slot Heap Structure

Scaled Pebble Flow (Dry System)
PB-FHR Mk1 Refractory Reactor Cavity Liner System

- Insulated cavity cover structure
- Upper core support internals
- Upper cavity insulation blocks
- Reactor vessel
- Hot leg pipe
- Hot leg penetration
- Reactor vessel support ring
- Water cooled steel liner plate
- Lower cavity insulation blocks
- Reactor core
- Electrical heating elements
- Thermal expansion gap
- Steel/concrete composite wall structure
- Liner cooling leak drain sump

DRAFT FIGURE

UCB Nuclear Engineering Thermal Hydraulics Lab
V.C. Summer Unit 2 Reactor Cavity Module CA04

Sept. 27, 2013

http://www.flickr.com/photos/scegnews/sets/72157629244341909/

- The Mk1 PB-FHR reactor building will use the same modular, steel-plate/concrete composite structures as AP-1000
- The Mk1 reactor cavity system will use the a similar stainless steel liner design
## Comparison to Other Reactor Designs

<table>
<thead>
<tr>
<th></th>
<th>Mk1 PB-FHR</th>
<th>ORNL 2012 AHTR</th>
<th>Westinghouse 4-loop PWR</th>
<th>PBMR</th>
<th>S-PRISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor thermal power (MWt)</td>
<td>236</td>
<td>3400</td>
<td>3411</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>Reactor electrical power (MWe)</td>
<td>100</td>
<td>1530</td>
<td>1092</td>
<td>175</td>
<td>380</td>
</tr>
<tr>
<td>Fuel enrichment †</td>
<td>19.90%</td>
<td>9.00%</td>
<td>4.50%</td>
<td>9.60%</td>
<td>8.93%</td>
</tr>
<tr>
<td>Fuel discharge burn up (MWt-d/kg)</td>
<td>180</td>
<td>71</td>
<td>48</td>
<td>92</td>
<td>106</td>
</tr>
<tr>
<td>Fuel full-power residence time in core (yr)</td>
<td>1.38</td>
<td>1.00</td>
<td>3.15</td>
<td>2.50</td>
<td>7.59</td>
</tr>
<tr>
<td>Power conversion efficiency</td>
<td>42.4%</td>
<td>45.0%</td>
<td>32.0%</td>
<td>43.8%</td>
<td>38.0%</td>
</tr>
<tr>
<td>Core power density (MWt/m3)</td>
<td>22.7</td>
<td>12.9</td>
<td>105.2</td>
<td>4.8</td>
<td>321.1</td>
</tr>
<tr>
<td>Fuel average surface heat flux (MWt/m2)</td>
<td>0.189</td>
<td>0.285</td>
<td>0.637</td>
<td>0.080</td>
<td>1.13</td>
</tr>
<tr>
<td>Reactor vessel diameter (m)</td>
<td>3.5</td>
<td>10.5</td>
<td>6.0</td>
<td>6.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Reactor vessel height (m)</td>
<td>12.0</td>
<td>19.1</td>
<td>13.6</td>
<td>24.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Reactor vessel specific power (MWe/m3)</td>
<td>0.866</td>
<td>0.925</td>
<td>2.839</td>
<td>0.242</td>
<td>0.299</td>
</tr>
<tr>
<td>Start-up fissile inventory (kg-U235/MWe) ††</td>
<td>0.79</td>
<td>0.62</td>
<td>2.02</td>
<td>1.30</td>
<td>6.15</td>
</tr>
<tr>
<td>EOC Cs-137 inventory in core (g/MWe) *</td>
<td>30.8</td>
<td>26.1</td>
<td>104.8</td>
<td>53.8</td>
<td>269.5</td>
</tr>
<tr>
<td>EOC Cs-137 inventory in core (Ci/MWe) *</td>
<td>2672</td>
<td>2260</td>
<td>9083</td>
<td>4667</td>
<td>23359</td>
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<tr>
<td>Spent fuel dry storage density (MWe-d/m3)</td>
<td>4855</td>
<td>2120</td>
<td>15413</td>
<td>1922</td>
<td>-</td>
</tr>
<tr>
<td>Natural uranium (MWe-d/kg-NU) **</td>
<td>1.56</td>
<td>1.47</td>
<td>1.46</td>
<td>1.73</td>
<td>-</td>
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<tr>
<td>Separative work (MWe-d/kg-SWU) **</td>
<td>1.98</td>
<td>2.08</td>
<td>2.43</td>
<td>2.42</td>
<td>-</td>
</tr>
</tbody>
</table>

† For S-PRISM, effective enrichment is the Beginning of Cycle weight fraction of fissile Pu in fuel

†† Assume start-up U-235 enrichment is 60% of equilibrium enrichment; for S-PRISM startup uses fissile Pu

* End of Cycle (EOC) life value (fixed fuel) or equilibrium value (pebble fuel)

** Assumes a uranium tails assay of 0.003.
FHRs Provide Robust Inherent Defense-In-Depth to Retain Radionuclides During Accidents

- Inherent characteristics of the fuel and coolant retain radionuclides:
  - TRISO Fuel
    » Demonstrated FP retention > 1600°C in NGNP Program
    » FHRs operate with 100s°C of fuel temperature margins
    » No incremental fuel failure expected during accidents
      • Need to confirm performance at higher power densities
  - Flibe Coolant
    » Demonstrated retention of solid FPs and iodine in MSRE
      • MSRE ~ FHR Test with 100% Fuel Failure
    » Low pressure coolant reduces stored energy in containment
- Low-pressure low-leakage containment reduces the release of noble gas fission products or their daughter radionuclides
  - Noble gas fission products will be removed under normal operation in the processing of the inert cover gas
Intrinsic characteristics can provide two key benefits:

1. Reduce licensing uncertainty with conservative analysis
2. Reduce development costs by using best estimate analysis

Preliminary Results for PB-FHR Cs-137 Release Bounding Case with 1% Defective Fuel

- Total release after 100 days is less than 4 Ci
- 99.998% retention in the fuel and flibe
Preliminary Thyroid Dose Analysis Bounding Case with 1% Defective Fuel

- **PB-FHR Mk1** should meet 10% of the 10 CFR 50.34 dose limits with EAB and LPZ boundaries at 100 and 300 meters
  - Provides margin for multi-module sites
- The Plume EPZ may be set at approximately 850 meters
(Partial) List of PB-FHR Opportunities and Challenges

• Opportunities
  - Simplified Safety Analysis
    » Large fuel temperature margins, low-pressure system, single phase coolant, scaled experiments
  - Flexible operation of NACC
  - Low pressure system with thin-walled components
  - Modular design and construction methods

• Challenges
  - Demonstrate tritium control strategy
  - Procurement of flibe coolant with enriched Li-7
  - Fuel fabrication and qualification
  - High temperature materials with long-term creep

• Future Potential
  - New structural alloys for increased temperature/power
  - Operational experience with salts could benefit MSR efforts