Liquid-salt cooled Advanced High Temperature Reactors (AHTR)

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Overview

• Overview of liquid-salt cooled high-temperature reactors

• Modular PB-AHTR design
  – 900 MWth / 410 MWe
  – Core power density 20 - 30 MW/m³
  – Core inlet/outlet temps 600°C/704°C
  – Uses available ASME Section III materials

• Modular PB-AHTR development
AHTR Technology Overview
Advanced High-Temperature Reactors (AHTRs) combines two older technologies

Coated particle fuel

Liquid fluoride salt coolants
- Excellent heat transfer
- Transparent, clean fluoride salt
- Boiling point ~1400°C
- Reacts very slowly in air
- No energy source to pressurize containment

Fuel performance chart (Source: PBMR [Py] Ltd.)

Fuel failure fraction vs. temperature
Liquid fluoride salts have fundamentally different properties than other reactor coolants

Thermophysical Properties* of S-PRISM, GT-MHR, and AHTR Reactor Coolants and Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{\text{melt}}$ (°C)</th>
<th>$T_{\text{boil}}$ (°C)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$C_p$ (kJ/kg°C)</th>
<th>$\rho C_p$ (kJ/m$^3$°C)</th>
<th>$k$ (W/m°C)</th>
<th>$\nu \cdot 10^6$ (m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li}_3\text{BeF}_4$ (Flibe)</td>
<td>459</td>
<td>1430</td>
<td>1940</td>
<td>2.34</td>
<td>4540</td>
<td>1.0</td>
<td>2.9</td>
</tr>
<tr>
<td>0.58NaF-0.42ZrF$_4$</td>
<td>500</td>
<td>1290</td>
<td>3140</td>
<td>1.17</td>
<td>5670</td>
<td>~1</td>
<td>0.53</td>
</tr>
<tr>
<td>Sodium</td>
<td>97.8</td>
<td>883</td>
<td>790</td>
<td>1.27</td>
<td>1000</td>
<td>62</td>
<td>0.25</td>
</tr>
<tr>
<td>Lead</td>
<td>328</td>
<td>1750</td>
<td>10540</td>
<td>0.16</td>
<td>1700</td>
<td>16</td>
<td>0.13</td>
</tr>
<tr>
<td>Helium (7.5 MPa)</td>
<td>0</td>
<td>100</td>
<td>3.8</td>
<td>5.2</td>
<td>20</td>
<td>0.29</td>
<td>11.0</td>
</tr>
<tr>
<td>Water (7.5 MPa)</td>
<td>~1350</td>
<td>100</td>
<td>732</td>
<td>5.5</td>
<td>4040</td>
<td>0.56</td>
<td>0.13</td>
</tr>
<tr>
<td>Hastalloy C-276</td>
<td>8890</td>
<td>1700</td>
<td>0.43</td>
<td>3820</td>
<td>9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>1700</td>
<td>1.90</td>
<td>3230</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Approximate physical properties 700°C except the pressurized water data shown at 290°C for comparison; $\rho = $ density, $C_p = $ specific heat, $k = $ thermal conductivity, $\nu = $ viscosity.

- **High volumetric heat capacity provides high thermal inertia**
  - High power density, low pressure operation possible compared to helium cooled reactors
  - High efficiency, compact primary loop equipment compared to water cooled reactors
  - Transparent coolant, low thermal shock, low chemical reactivity compared to sodium cooled reactors

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Fluoride salts are of interest for multiple applications

Liquid-Salt-Cooled VHTR
(Advanced High-Temperature Reactor; Coated-Particle Fuel; Salt Coolant)

Molten Salt Reactor

Liquid-Salt Fast Reactor
(Metal-Clad Fuel; Salt Coolant)

Fusion

Heat-Transport Systems
For H₂ Production

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The Modular PB-AHTR is a compact pool-type reactor with passive decay heat removal.
The PB-AHTR uses well understood materials and fuel

• TRISO based fuel is well understood
  – Peak temperature during normal operation and accidents < 1000°C
  – Capability to manufacture being reestablished
  – Uses special pebble design (see later slide), requires confirmatory testing

• Metallic components are Alloy 800H clad with Hastelloy N for corrosion resistance
  – The baseline design has a conservatively low 704°C core outlet temperature to assure high corrosion resistance (extensive test data available)
  – Alloy 800H provides structural strength and is ASME Section III code qualified for use up to 760°C; ORNL now extending code case to 900°C
  – Hastelloy N has well understood corrosion resistance with fluoride salts

• Reflectors are graphite
  – Capability to manufacture nuclear-grade graphite has been reestablished

The baseline PB-AHTR fuel and materials have moderate development risk
In September 2007 UCB published 3 key papers on the Pebble Bed AHTR

- Neutronics analysis, verifying that the PB-AHTR
  - can be designed with negative void reactivity
  - can achieve high discharge burn up, comparable to MHRs
- Thermal hydraulic analysis, using RELAP5-3D to verify that the PB-ATHR
  - has very gentle response to Loss of Forced Cooling Transient
  - can be designed to have acceptable response to Anticipated Transient Without Scram
  - Power levels up to 4800 MWth possible
- Results from the Pebble Recirculation Experiment (PREX-1), verifying
  - pebble injection into the reactor cold leg
  - lower plenum pebble landing dynamics
  - pebble defueling from the top of the reactor core

PREX-1 with 8300 pebbles

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Modular 410-MWe PB-AHTR Design Overview
The PB-AHTR power conversion system design is derived from the PBMR/Mitsubishi design.

168-MWe PBMR/Mitsubishi helium cooled HTR

To scale

410-MWe PB-AHTR liquid cooled HTR
The Modular PB-AHTR uses seismic base isolation

- Structure isolated with resonant period of 3.6 seconds
- Isolators filter out higher frequency seismic energy
GT-MHR and PB-AHTR reactor buildings (to scale)

GT-MHR reactor building (287MWe)

AHTR reactor/turbine building (410 MWe)

Typical LWR and SFR buildings are ~75m high
The current Modular PB-AHTR plant design is compact compared to LWRs and MHRs

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Reactor Power (MWe)</th>
<th>Reactor and Auxiliaries Volume (m³/MWe)</th>
<th>Turbine Building Volume (m³/MWe)</th>
<th>Ancillary Structures Volume (m³/MWe)</th>
<th>Total Building Volume (m³/MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970’s PWR</td>
<td>1000</td>
<td>129</td>
<td>161</td>
<td>46</td>
<td>336</td>
</tr>
<tr>
<td>ABWR</td>
<td>1380</td>
<td>211</td>
<td>252</td>
<td>23</td>
<td>486</td>
</tr>
<tr>
<td>ESBWR</td>
<td>1550†</td>
<td>132†</td>
<td>166</td>
<td>45</td>
<td>343</td>
</tr>
<tr>
<td>EPR</td>
<td>1600</td>
<td>228</td>
<td>107</td>
<td>87</td>
<td>422</td>
</tr>
<tr>
<td>GT-MHR</td>
<td>286</td>
<td>388</td>
<td>0</td>
<td>24</td>
<td>412</td>
</tr>
<tr>
<td>PBMR</td>
<td>170</td>
<td>1015</td>
<td>0</td>
<td>270</td>
<td>1285</td>
</tr>
<tr>
<td><strong>Modular PB-AHTR</strong></td>
<td><strong>410</strong></td>
<td><strong>105</strong></td>
<td><strong>115</strong></td>
<td><strong>40</strong></td>
<td><strong>260</strong></td>
</tr>
</tbody>
</table>

† The ESBWR power and reactor building volume are updated values based on the Design Certification application arrangement drawings.
The new Modular PB-AHTR is designed to maintain superior economics with a modular HTR design

- Comparison of PB-AHTR with the PBMR:
  - 2 x power output per reactor
  - ~30 MWth/m³ core power density versus 4.8 MWth/m³
  - large reduction in vessel size
  - atmospheric pressure operation
  - 4 x reduction in spent fuel volume per unit of electricity/process steam produced
  - maximum fuel temperature during transients/accidents reduced from 1600°C to 1000°C

The smaller size and low mass of major components (reactor vessel weight < 180 tons) has implications for the construction schedule.
The Modular PB-AHTR uses pebble channel assemblies
Viability phase R&D includes construction of PREX-2 to verify pebble recirculation in a PCA

Baseline design for lower half of PCA showing configuration of pebble channels
Modularity enables simple scaling from Pilot to Modular to Central-Station power levels

- **Pilot PB-AHTR**
  - 125 MWth
- **Modular PB-AHTR**
  - 900 MWth
- **Central Station PB-AHTR**
  - 2400 MWth
The Modular PB-AHTR primary and intermediate loops facilitate natural circulation shutdown cooling.

Configured to operate with natural circulation to shut down cooling heat exchanger in intermediate loop (not yet designed).
Equipment hallways and turbine hall act as an external events shell for the PB-AHTR reactor citadel.

**PB-AHTR HVAC Zones**

1. Reactor cell (Low-Leakage Inerted Containment)
2. Reactor citadel (Filtered Confinement)
3. Reactor equipment hallways (Ambient air)
4. Turbine hall (Ambient air)
RELAP5-3D Modeling of 900 MWth PB-AHTR transient response to LOFC and LOHS transients, with and without scram
RELAP5-3D model for 900 MWth Modular PB-AHTR
Transient response of 900 MWth PB-AHTR to LOFC

PB-AHTR thermal response (annular pebbles)

• Response is gentle even with 30 MW/m³ power density
Development Approach for the Pilot and Modular PB-AHTR Designs
A PB-AHTR Development Program has four phases

- **Viability Phase**
  - Major end product is a NRC Pre-Application Submittal

- **Performance Phase**
  - Major end product is a NRC Design Certification Submittal

- **Licensing Phase**
  - Major end product is NRC Design Certification and a NRC Combined Construction and Operating License for a Pilot PB-AHTR Plant

- **Construction and Testing Phase**
  - Major end product is operational experience to support commercial deployment of Modular PB-AHTR plants
PB-AHTR Experimental Program

Viability phase --> Performance phase --> Demonstration phase
The Modular PB-AHTR Experimental Program

• Integral Effects Tests
  – Compact Integral Effects Test (CIET) facility (Viability phase)
    » Scaled simulant fluid IET to study system response to LOFC, ATWS, and other transients
  – Pebble Recirculation Experiment (Viability phase)
    » Scaled simulant fluid IET to study pebble recirculation hydrodynamics
  – EROS zero power critical tests (w/ salt) (Viability phase)

• Separate Effects Tests
  – Scaled High Temperature Heat Transfer (S-HT²) facility (Viability phase)
    » Heat transfer coefficient measurements using simulant fluids
  – Other SET experiments (Viability/Performance phases)
    » Pebble confirmatory irradiation experiments, etc.
    » Materials corrosion test loop experiments
The Modular PB-AHTR Experimental Program (con’t)

• Component Tests
  – Various scaled component tests with simulant fluids (water) (Viability phase)
  – Component Test Facility (CTF) (Performance phase)
    » Major non-nuclear facility to test primary, intermediate and DRACS loop components under prototypical liquid salt conditions

• Pilot Plant Tests (Demonstration phase)
  – nuclear fuel loading and pre-critical (zero power) testing
  – low-power (<5%) testing and operation
  – power ascension testing and operation not in excess of 100%
  – interim operation
  – maintenance and in-service inspection procedures
The current UCB test program has 3 facilities

**PREX**
Pebble recirculation IET
Match Re, Fr, pebble/salt density ratio w/ water

**S-HT²**
Salt heat transfer SET
Match Re, Fr, Pr, Gr w/ Dowtherm A

**PRISM**
Passive shutdown rod IET
Match Re, Fr, rod/salt density ratio w/ sugar water

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*UC Berkeley*
Collaboration with Czech Republic NRI to validate AHTR neutronics models in the LR-0 Zero Power Critical Test facility
EROS Test Assembly

The design of the test assembly is a hexagonal block with a pitch of 23.6cm with 19 channels drilled for uranium pins surrounded by salt.

Fuel pins are .753 cm diameter (without cladding) 3.6% enriched and clad with zirconium alloy.

Initial design uses 60% natural LiF and 40% NaF salt.
Thermal hydraulics integral test program

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The Compact Integral Effects Test
Dowtherm heat transfer oil will be used as the principal simulant fluid for PB-AHTR IET/SET experiments

Scaling parameters to match Pr, Re, Gr, and Fr for flibe and Dowtherm A

<table>
<thead>
<tr>
<th>Flibe Temperature [°C]</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>800</th>
<th>850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowtherm A Temperature [°C]</td>
<td>63</td>
<td>82</td>
<td>104</td>
<td>129</td>
<td>157</td>
<td>191</td>
</tr>
<tr>
<td>Length scale</td>
<td>$l_m/l$</td>
<td>0.52</td>
<td>0.51</td>
<td>0.49</td>
<td>0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>Velocity scale</td>
<td>$u_m/u$</td>
<td>0.72</td>
<td>0.72</td>
<td>0.70</td>
<td>0.68</td>
<td>0.66</td>
</tr>
<tr>
<td>ΔT scale</td>
<td>$ΔT_m/ΔT$</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>Heat conductivity</td>
<td>$λ_m/λ$</td>
<td>0.14</td>
<td>0.13</td>
<td>0.13</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Ther. diffusivity</td>
<td>$α_m/α$</td>
<td>0.37</td>
<td>0.35</td>
<td>0.33</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>$βΔT$</td>
<td>$(βΔT)_m/βΔT$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$γΔT$</td>
<td>$(γΔT)_m/γΔT$</td>
<td>0.81</td>
<td>0.94</td>
<td>1.06</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>$κΔT$</td>
<td>$(κΔT)_m/κΔT$</td>
<td>-0.84</td>
<td>-0.86</td>
<td>-0.89</td>
<td>-0.92</td>
<td>-0.95</td>
</tr>
<tr>
<td>Pumping power</td>
<td>$P_{p,m}/P_p$</td>
<td>5.2%</td>
<td>5.0%</td>
<td>4.2%</td>
<td>3.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Heating power</td>
<td>$P_{q,m}/P_q$</td>
<td>2.1%</td>
<td>2.1%</td>
<td>1.9%</td>
<td>1.7%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

• Note that Pr, Re, Gr and Fr can be matched at < 2% of prototypical heater power
• Water can be used for hydrodynamics experiments
The Compact Integral Effects Test (CIET) facility will validate the PB-AHTR transient thermal hydraulics code during Viability Phase R&D

• The Compact Integral Effect Test (CIET) facility (located at UC Berkeley) will be a reduced height, reduced area, reduced power scaled 100 kW (70 V DC) IET that will:
  – provide low-distortion IET data for transient code validation
  – exceed the quality of data produced by earlier IET’s for light water reactors (e.g. Semiscale) (100 kW in CIET is equivalent to 4.7 MW with the prototypical coolant)

• Additional SET experiments will be performed to study specific phenomena
  – e.g. pebble bed heat transfer coefficients, pebble friction coefficients, etc.

• A primary purpose of the NRC Pre-Application Review will be to review and approve use of the IET/SET test program data for safety code validation
CIET can be compared to the INL Semiscale facility

- **Semiscale simulation of PWR LOCA**
  - 1:1 height
  - 1:1705 flow area
  - 1:1705 power (2 MW)
  - 1:1 time
  - prototype temperature / pressure
- **CIET simulation of the PB-AHTR LOFC/ATWS**
  - 1:1 effective height (1:2 actual)
  - 1:190 effective flow area (1:756 actual)
  - 1:190 effective power (1:9000 actual, 100 kW)
  - 1:(2)\(\frac{1}{2}\) time
  - reduced temperature / pressure
  - reduced heat loss
  - small distortion from thermal radiation

See [http://users.owt.com/smsrpm/nksafe/testfac.html](http://users.owt.com/smsrpm/nksafe/testfac.html) for a list of other LWR IET’s
Conclusions

• Work at UC Berkeley and elsewhere has identified attractive features of liquid-salt cooled high temperature reactors
  – Potential for high power density (20-30 MWt/m³)
  – Low pressure operation, chemically inert coolant
  – Use of available ASME Section III code qualified materials
  – Safety code validation using integral effects tests with simulant fluid
  – Capability to operate on both LEU and TRU fuels
  – Reduced spent fuel volume
  – Likely attractive economics compare to LWRs and MHRs