Heat Pipe Cooled Micro-reactor

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Hyoung Kyu Cho
**Micro Nuclear Reactors**

*MICROREACTORS: Small reactors BIG potential*

Plug-and-play reactors able to produce 1-20 megawatts of thermal energy used directly as heat or converted to electric power.

*eVinci™ Micro Reactor*

Ultimate Energy Solution for the Off-grid Customer

- Eliminates fuel supply
- Affordable energy
- Enables Economic Development
- Clean energy
- Scalable power

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*Megapower*

1MW serves 1,000 houses

(Source: https://www.energy.gov)
Heat Pipe

❖ Heat pipe configuration and applications

History
- 1839: Perkins tube
- 1960s: Erickson at LANL, wick heat pipe, to cook turkey
- 1963: Grover at LANL, first modern heat pipe test, for space reactor
- 1980s: lithium heat pipe
- 1996: space test

<Source: Zohuri, B., Heat pipe design and technology: a practical approach>


<Source: http://blog.lenovo.com/>

<Source: https://celsiainc.com/heat-pipe-and-vapor-chamber-technology-overview/>
Heat Pipe

Heat pipe wick structure and operational limits

- Screen wick
- Open channels
- Channels covered with screen
- Annulus behind screen
- Artery
- Heat pipe wall
- Corrugated screen

Performance limits

- Failure limit/non-failure limit
- Viscous
- Sonic
- Entrainment
- Capillary
- Boiling
- Condenser limit


Heat Pipe

- Fast heat transfer
Heat Pipe

❖ Fluids of heat pipe

<table>
<thead>
<tr>
<th>Medium</th>
<th>Melting Point (°C)</th>
<th>Boiling Point at Atmospheric Pressure (°C)</th>
<th>Useful Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>−271</td>
<td>−261</td>
<td>−271 to −269</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>−210</td>
<td>−196</td>
<td>−203 to −160</td>
</tr>
<tr>
<td>Ammonia</td>
<td>−78</td>
<td>−33</td>
<td>−60 to 100</td>
</tr>
<tr>
<td>Pentane</td>
<td>−130</td>
<td>28</td>
<td>−20 to 120</td>
</tr>
<tr>
<td>Acetone</td>
<td>−95</td>
<td>57</td>
<td>0 to 120</td>
</tr>
<tr>
<td>Methanol</td>
<td>−98</td>
<td>64</td>
<td>10 to 130</td>
</tr>
<tr>
<td>Flutec PP2(^1)</td>
<td>50</td>
<td>76</td>
<td>10 to 160</td>
</tr>
<tr>
<td>Ethanol</td>
<td>−112</td>
<td>78</td>
<td>0 to 130</td>
</tr>
<tr>
<td>Heptane</td>
<td>−90</td>
<td>98</td>
<td>0 to 150</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>100</td>
<td>30 to 200</td>
</tr>
<tr>
<td>Toluene</td>
<td>−95</td>
<td>110</td>
<td>50 to 200</td>
</tr>
<tr>
<td>Flutec PP9(^1)</td>
<td>70</td>
<td>160</td>
<td>0 to 225</td>
</tr>
<tr>
<td>Thermex(^2)</td>
<td>12</td>
<td>257</td>
<td>150 to 350</td>
</tr>
<tr>
<td>Mercury</td>
<td>−39</td>
<td>361</td>
<td>250 to 650</td>
</tr>
<tr>
<td>Caesium</td>
<td>29</td>
<td>670</td>
<td>450 to 900</td>
</tr>
<tr>
<td>Potassium</td>
<td>62</td>
<td>774</td>
<td>500 to 1000</td>
</tr>
<tr>
<td>Sodium</td>
<td>98</td>
<td>892</td>
<td>600 to 1200</td>
</tr>
<tr>
<td>Lithium</td>
<td>179</td>
<td>1340</td>
<td>1000 to 1800</td>
</tr>
<tr>
<td>Silver</td>
<td>960</td>
<td>2212</td>
<td>1800 to 2300</td>
</tr>
</tbody>
</table>
Motivation

❖ NASA

✓ A return to the Moon for long-term exploration
✓ Crewed missions to MARS
✓ Kilopower reactor (heat pipe cooled nuclear reactor)

<Source: https://www.nasa.gov/sites/default/files/atoms/files/kilopower_media_event_charts_16x9_final.pdf>
Motivation

❖ CANADA: remote areas

✓ Seasonal fuel delivery challenges
✓ Remote communities, oilsands producers, remote mines
✓ U-BATTERY, NUSCALE (heat pipe reactor), GFP, etc.

<table>
<thead>
<tr>
<th>Oil sands</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Steam for SAGD and electricity for upgrading at 96 facilities</td>
</tr>
<tr>
<td>• 210 MWe average size for both heat and power demands</td>
</tr>
<tr>
<td>• 5% replacement by SMRs between 2030 and 2040 could provide $350-450M annually</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Remote communities and mines</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 79 remote communities in Canada with energy needs &gt; 1 MWe</td>
</tr>
<tr>
<td>• SMRs replacing costly diesel and heating oil could reduce energy costs to the territorial government</td>
</tr>
<tr>
<td>• The high cost of energy from diesel is a barrier. SMRs could facilitate and enable new mining developments</td>
</tr>
<tr>
<td>• 24 current and potential off-grid mines</td>
</tr>
</tbody>
</table>

High-temperature steam for heavy industry

• 85 heavy industry locations (e.g. chemicals, petroleum refining)
• 25-50 MWe average size
• 5% replacement by SMRs between 2030 and 2040 could provide $46M annually

Replacing conventional coal-fired power:

• 29 units in Canada at 17 facilities
• 343 MWe average size
• 10% replacement by SMRs between 2030 and 2040 could provide $469M in value annually

Motivation

❖ US: Vulnerability in military force

✓ Supply of liquid fuel and water
  – Majority of the mass transported to deployed military forces

✓ Casualties during land transport missions
  – Mainly associated with resupplying fuel and water
  – 18,700 causalities (52% of total US casualties over a nine-year period)
    – Iraqi Freedom and Enduring Freedom

“Unleash us from the tether of fuel”

(Source: https://www.forbes.com/sites/jamesconc/a/2019/03/12/our-military-wants-small-nukes-to-reduce-convoy-casualties/amp/)
Growing energy demand

✓ The Army of the future will require far more power even than today’s Army.

- Directed-energy weapons, electromagnetic rail guns, electric vehicles, drones
- Soldiers connected into a secure communications network
- Ground attack jets
- Army’s tanks battery-electric powered

Energy and technology = “force multipliers”
vSMR (very Small Modular nuclear Reactor)

✓ 1~10 MWe, several years without refueling
✓ Transportable by the existing defense infrastructure (trucks and planes)
✓ Fully autonomous, load-following, cooled passively by the environment and meltdown-proof
✓ Useful for Humanitarian Assistance Disaster Relief (HADR) missions

(Source: DOD, Task Force on Energy Systems for Forward/Remote Operating Bases)
Key required characteristics of vSMR (1)

❖ Outputs
  ✓ Modular and scalable units capable of producing 2–10 MWe
  ✓ Potentially useful heat (which could facilitate water or fuel production)

❖ Size and transportability
  ✓ 25–40 tons; transportable by truck or C-17 aircraft

❖ Ultimate heat sink
  ✓ Ambient air; capable of passive cooling

❖ Refueling
  ✓ Refueling should not be required more than annually
  ✓ fresh and used fuel should be transportable by air, sea, and ground

❖ Operation
  ✓ Autonomous/ semiautonomous operations with minimal manning

❖ Time to install: 12–72 hours

❖ Time for planned shutdown, cool down, disconnect, and removal: 6 hours to 7 days
Key required characteristics of vSMR (2)

❖ Response to emergency
  ✓ Capable of immediate shutdown and passive cooling

❖ Health and safety risks
  ✓ No net increase in risk to public, military personnel, environment
  ✓ No net increase in consequences of adversary attack

❖ Proliferation risk
  ✓ No net significant increase in proliferation risk

❖ Roadmap for the Deployment of Micro-Reactors for DOD
  ✓ General Atomics, NuScale, Oklo, Westinghouse, X-energy
  ✓ HolosGen, LeadCold Nuclear, NuGen,
    Starcore Nuclear, Urenco, and Ultra Safe Nuclear

Heat Pipe Cooled Nuclear Reactor Development at LANL

❖ KRUSTY (Kilopower Reactor Using Stirling Technology)

✓ Testbed for Kilopower reactor

<Source: KRUSTY Design and Modeling, LA-UR-16-28377>
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Heat Pipe Cooled Nuclear Reactor Development at LANL

❖ KRUSTY (Kilopower Reactor Using Stirling Technology)

✓ Specification

<table>
<thead>
<tr>
<th>Material/Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>Heat pipe material</td>
</tr>
<tr>
<td>UMo</td>
<td>Fuel Material</td>
</tr>
<tr>
<td>Haynes-230</td>
<td>Heat Pipe and Core Structure</td>
</tr>
<tr>
<td>BeO</td>
<td>Neutron Reflector Material</td>
</tr>
<tr>
<td>B4C</td>
<td>Internal Neutron Poison Rod</td>
</tr>
<tr>
<td>B4C/SS316</td>
<td>Neutron/Gamma Shielding</td>
</tr>
<tr>
<td>5</td>
<td>KRUSTY “Rated” Power (kWt)</td>
</tr>
<tr>
<td>3</td>
<td>Nominal Test Power (kWt)</td>
</tr>
<tr>
<td>28</td>
<td>Proposed Full-Power Test Hours (hr)</td>
</tr>
<tr>
<td>1073</td>
<td>Core Ave Fuel Temperature (K)</td>
</tr>
<tr>
<td>~1023</td>
<td>Heat Pipe Condenser Temperature (K)</td>
</tr>
<tr>
<td>1.6</td>
<td>Ave Test Fuel Power density (W/cc)</td>
</tr>
<tr>
<td>~1.77</td>
<td>Peak Test Fuel Power density (W/cc)</td>
</tr>
<tr>
<td>93.10%</td>
<td>U235 Enrichment %</td>
</tr>
</tbody>
</table>

<Source: KRUSTY Design and Modeling, LA-UR-16-28377>
Heat Pipe Cooled Nuclear Reactor Development at LANL

❖ KRUSTY (Kilopower Reactor Using Stirling Technology)

✓ Nuclear test

<Source: KRUSTY Design and Modeling, LA-UR-16-28377>
Heat Pipe Cooled Nuclear Reactor Development at LANL

- **KRUSTY (Kilopower Reactor Using Stirling Technology)**
  - Nuclear test (March 20, 2018)

<Source: The Kilopower Reactor Using Stirling Technology (KRUSTY) Nuclear Ground Test Results and Lessons Learned, LA-UR-19-23192>
KRUSTY (Kilopower Reactor Using Stirling Technology)

- Achieved a Technology Readiness Level (TRL) of 5
- The first space reactor test completed in over 50 years
- Took 3-1/2 years to complete from concept to test
  - Affordable project (~$ 15 M)

<Source : Dionne Hernandez-Lugo, Special Topic for Nuclear CLT: Kilopower Project 1, 2018>
Heat Pipe Cooled Nuclear Reactor Development at LANL

- **MegaPower** (TRL: 6 or better)

![Diagram showing power levels and reactor types]

- 0.5 to 10 kW Non-LWR
- 10 to 100's kW Non-LWR
- 0.1 to 10 MW Non-LWR
- 10 to 50 MW Non-LWR
- 50 to 300 MW LWR Focus
- 1000 MW LWR Focus

- **Factor built, assembled. Licensing based on prototype.**

- **Deep space Power**
  - Space propulsion & planetary surface power; Med Isotopes Military Ops

- **Military Ops**
  - Distributed Hybrid Power; Disaster Relief; Mining; CHP -- Fuels

- **Power to Grid**
  - Large Military Bases; Process Heat
  - Power to Grid; Small Cities, Burning of actinides
  - Power to Grid 5 units under construction in US

- **Power Level in Kilo-Watts Electric**
  - Micro Reactors
  - Small Modular
  - Large
MegaPower (Megawatt Power Mobile Reactor, TRL: 6 or better)

- Developed by Los Alamos National Lab. with funding from NASA
- Specification
  - UO2 fuel, 19.5% enriched
  - Fuel → solid steel monolith → heat pipe → open-air Brayton or supercritical CO2 Stirling engines
  - 2 MW of electricity + 2 MW of process heat for 12 years
  - 35 tons → transportable by air and highway
  - 72 hours for operation upon arrival
  - 7 days for shut down, cooled, disconnected and “wheeled out”
  - Special armor for beyond the design basis attack
Heat Pipe Cooled Nuclear Reactor Development at LANL

❖ MegaPower (Megawatt Power Mobile Reactor, TRL : 6 or better)

https://www.energy.gov/ne/articles/big-potential-nuclear-micro-reactors

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LANL MegaPower Reactor

Nominal 2 MWe (5 MWth) Mobile Reactor Package

- Proven U02 fuel (19% enriched)
- Solid steel monolith core
- Passive heat pipe coupling with no moving parts in the core
- Housed in armored and shielded cask during operation and transport

Proven materials and nuclear design

Core monolith has openings for the nuclear fuel and the heat pipes. It also conducts heat from the fuel to the heat pipes.

He-Over Gas & Fission Gas Plenum

Dime-size nuclear pellets are stacked in the monolith.
Westinghouse eVinci Micro Reactor

❖ eVinci
✓ Transportable energy generator
✓ Fully factory built, fueled and assembled
✓ Combined heat and power – 200 kWe to 5 MWe
✓ Up to 600°C process heat
✓ 5- to 10-year life with walkaway inherent safety
✓ Target less than 30 days onsite installation
✓ Autonomous load management capability
✓ Unparalleled proliferation resistance
✓ High reliability and minimal moving parts
✓ Green field decommissioning and remediation

❖ DeVinci
✓ eVinci for defense

<Source: http://www.westinghousenuclear.com/new-plants/evinci-micro-reactor>
Westinghouse eVinci Micro Reactor

❖ eVinci

Resilient  Secure  Flexible  Sustainable energy

Active shutdown system
Passive shutdown system

<Source: http://www.westinghousenuclear.com/new-plants/evinci-micro-reactor>
Westinghouse eVinci Micro Reactor

- eVinci

Decay heat pathway from reactor to outside of canister via conduction & radiative heat transfer.

Air is typically the ultimate heat sink for decay heat removal in micro reactors.
Westinghouse eVinci Micro Reactor

❖ eVinci

<Source: Nuclear Energy Institute, Cost Competitiveness of Micro-Reactors for Remote Markets, 2019>
Westinghouse eVinci Micro Reactor

- **Development timeline**
  - The eVinci™ Micro Reactor Nuclear Demonstration Unit Readiness Project
    - By 2022, Operational electrical demo unit
    - To prepare for construction of the Nuclear Demonstration Unit (NDU)
    - Design, analysis, testing and licensing to fabricate, assemble and install it
    - Testing outcomes
      - Accelerated qualification of materials and manufacturing processes
      - Data for V&V of detailed microreactor TH models under startup, shutdown, steady-state, off-normal transient behavior
  - 2023: Nuclear Demonstration Unit
  - 2025: First Commercial Deployment
Aurora (OKLO)

- Compact fast reactor, heat pipe cooled reactor, site: INL
  - Power: $4 \text{ MW}_{th} (~1.5 \text{ MW}_{e})$, supercritical CO$_2$ Power Conversion System
  - Containment Type: underground, reactor contained in several layers, including a robust cask-like module
  - Metallic uranium-zirconium. High Assay Low Enriched Uranium (HALEU)
  - FSAR submitted
Aurora (OKLO)

- Fast spectrum (1 keV~1 MeV) (very similar to the SFR)
- Fuel: metal alloy, U with 10% zirconium (U-10Zr)
- Operation limit: 720°C of peak fuel temperature
  - Eutectic penetration between fuel and steel
  - Steady-state maximum fuel temperature: 640 °C
- Net negative power coefficient of reactivity
- Strong neutron leakage characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Reactivity coefficient (pcm/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel thermal expansion</td>
<td>-0.50</td>
</tr>
<tr>
<td>Fuel doppler</td>
<td>-0.15</td>
</tr>
<tr>
<td>Reactor cell thermal expansion</td>
<td>-0.07</td>
</tr>
<tr>
<td>Baseplate thermal expansion</td>
<td>-1.40</td>
</tr>
<tr>
<td><strong>Net</strong></td>
<td><strong>-2.12</strong></td>
</tr>
</tbody>
</table>
Aurora (OKLO)

- **Aurora (OKLO)**
  - Decay heat: 153 kW (30 sec. after shutdown) in 29 tons of core
    - PWR: 4 times larger in 0.5 tons of core
    - Reactor vessel auxiliary cooling system (RVACS): air natural circulation
  - Safety criteria

<table>
<thead>
<tr>
<th>Type</th>
<th>Goal</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Control release of radionuclides by maintaining fuel integrity</td>
<td>$T_{\text{fuel}} &lt; 1200 , ^\circ\text{C}$ (Melting point)</td>
</tr>
<tr>
<td>Operational</td>
<td>Maintain reactor cell can integrity by keeping fuel-steel temperatures within time-temperature limits</td>
<td>$T_{\text{fuel}} &lt; 720\times C$</td>
</tr>
</tbody>
</table>

*Onset of eutectic formation is conservatively defined to begin at 720, but is very slow if it occurs at all at these temperatures, and no cliff-edge effects occur.*

- Safety analysis using
  - ANSYS Mechanical + Serpent, in-house Oklo point kinetics solver
Nuclear Reimagined with Microreactors

Remote Arctic Community

Clean Transit Hub

Catalyst for Clean Growth

<Source: https://www.thirdway.org/blog/nuclear-reimagined, 2017>
Nuclear Reimagined with Microreactors

<Source: https://www.thirdway.org/blog/nuclear-reimagined, 2017>
Design Issues in Heat Pipe Cooled Reactor Core

❖ **Defense in depth**
  ✓ A tear or fraction in monolith → release of fission products
  ✓ Direct pathways between the fuel and environment

❖ **Monolith thermal stress**
  ✓ Monolith webbing: 1.75 mm

❖ **Single heat pipe failure**
  ✓ Localized steel monolith temperature and thermal stress exceeding the limits

❖ **Machining**

❖ **Inspection and qualification**

❖ **Monolith structure**
  ✓ Structural integrity following a seismic event

*Source: Sterbentz, INL/EXT-16-40741, 2017*
Design Issues in Heat Pipe Cooled Reactor Core

❖ Core criticality
  ✓ Very small lattice pitch increase causes the core excess reactivity to drop
  ✓ Web thickness cannot be easily increased
  ✓ Sensitive with geometry of web, cladding, heat pipes

❖ Monolith structure
  ✓ High operation temperature → time dependent property regime
    – Material properties are not sufficient.
  ✓ Thermal gradients, thermal expansion, thermal creep with elevated temp.
  ✓ Creep behavior of heat pipe welds

❖ Heat pipe
  ✓ Thermal gradients → localized loss of a heat pipe
  ✓ Cumulative stress and strain in the monolith
  ✓ Radioactivity release via breach → release of activated potassium
  ✓ Long-term irradiation

<Source: Sterbentz, INL/EXT-16-40741, 2017>
HW-5