Portable Special Purpose Nuclear Reactor (2 MW) for Remote Operating Bases and Microgrids

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Outline

- The Need for Small Reactors as a Reliable Power Source
- Defense Science Board (DSB) Recognition of Need and Recommendation
- The 2MW Nuclear Reactor and Thermal Conversion System
- Reactor Design Options in Evaluation
- Status of Development To Date
The Need for Small Reactors

• Nearly 50% of DoD bases require electric power levels <10 MWe, many need 2MWe or less
  – Critical remote bases number about 25 (e.g., Space Command)
  – New DoD sensor/communication technologies call for more power requirements
  – High costs including human casualty rates associated with fuel transport to remote bases
  – Increasing concerns over cyber vulnerability of the power grids

• Many civilian communities and remote mining operations also need reliable power (e.g., Alaska, Canada)

• Hybrid energy systems with PV/solar also need a stable generation source to address variability and provide reliability

• In recognition of need, The National Defense Authorization Act of 2014 directed DoD to address the feasibility of small nuclear reactors for FOB as a source of reliable power

• In August 2016, DSB recommends that DoD evaluate the use of small nuclear reactors (< 10 MWe for remote bases; e.g., Fort Greeley, AK; Sundance, WY; Camp Century, Greenland); the LANL Heat Pipe Reactor and the Holos Reactor are identified as more technically mature concepts. Also noted that DoD, NNSA, and DOE-NE, through the Gateway for Accelerating Innovation in Nuclear Energy (GAIN), could potentially work together to advance technology to deployment through public/private partnerships; INL and LANL collaboration recognized by DSB.
**Nuclear Reactors come in all sizes**

Existing DOE **NUCLEAR** design, prototyping and testing infrastructure can be leveraged to accelerate innovation, development and demonstration of wide range of reactors.

<table>
<thead>
<tr>
<th>Power Level in Kilo-Watts Electric</th>
<th>Micro Reactors</th>
<th>Small Modular</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 to 10 kW</td>
<td>0.1 to 10 MW</td>
<td>10 to 50 MW</td>
<td>50 to 300 MW</td>
</tr>
<tr>
<td>Deep space Power</td>
<td>Space propulsion &amp; planetary surface power; Med Isotopes Military Ops</td>
<td>Military Bases; Distributed Hybrid Power; Disaster Relief; Mining; CHP -- Fuels</td>
<td>Power to Grid; Small Cities, Burning of actinides</td>
</tr>
<tr>
<td>Military Ops</td>
<td>Military Bases; Large Military Bases; Process Heat</td>
<td>Power to Grid; Large Military Bases; Process Heat</td>
<td>Power to Grid 5 units under construction in US</td>
</tr>
<tr>
<td>Factor built, assembled. Licensing based on prototype.</td>
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<tr>
<td>10 to 100’s kW</td>
<td>10 to 50 MW</td>
<td>50 to 300 MW</td>
<td>1000 MW</td>
</tr>
<tr>
<td>Non-LWR</td>
<td>Non-LWR</td>
<td>LWR Focus</td>
<td>LWR Focus</td>
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<tr>
<td>16 to 10 kW</td>
<td>15 to 100 kW</td>
<td>16 to 1000 kW</td>
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<tr>
<td>10 to 100 kW</td>
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The Special Purpose Reactor – LANL Concept
Characteristics of the Heat Pipe Reactor

• Heat pipe cooled
  – An array of heat pipes are used to remove heat from the core using simple, reliable and well-characterized physics
  – Eliminates complicated pumps and loops
  – Allows for power conversion using open air system with no activation of the air since it does not pass through the reactor core

• Self regulation
  – Use of small highly reflected reactor cores provides simple well characterized physics
    • Large negative temperature coefficient
    • Solid, robust, monolith core eliminates concern related to positive void coefficients
    • Load following (reactor self adjusts to power demand)
  – Ease of operations – passive cooling system, 5-years sustained operation, and ease of transportability make reactor well suited for remote operations
Proven Materials and Good Performance go with Heat Pipe Design

6 Passive Components

1. 316 Stainless Steel
2. LEU-UO₂ commercial grade fuel pellets
3. Potassium Heat Pipes
4. Al₂O₃ (or BeO) reflector
5. B4C Control rod drums
6. Bio-shield cask (e.g., Holtec)
7. Heat-pipe to open air heat exchanger
8. Liquid salt heat sink for emergency/shutdown cooling
9. Open-Air Brayton Convertor

Performance Specs:

- 10+ year design life
- <1% fuel burnup
- 10¹¹ neutrons/cm² or 100krad (16yr) @ 100 M dose plane

MegaPower Reactor Nuclear Core
Schematic of the LANL Heat Pipe Reactor

Weighs about 35-45 tons loaded
Holds 3 tons of fuel in 5 tons of steel monolith
About 12 ft. long; 6 ft. diameter
Metallic grill about 10-12 ft. diameter

Potassium Heat Pipes (steel)
Primary Heat Exchanger
Decay Heat Exchanger
Al₂O₃ - Reflector
Monolith Core

Openings for shield cooling flow (also for air flow through core in case of emergency)

Impact absorber
Cask
Impact absorber

Personnel barrier
Prevents radiation workers from high dose. Could be stuffed with locally fabricated shielding (ALARA)

Cradle
Attaches cask to skid, skid with rollers/tires

Cask wall
Stainless steel outer wall, 1/4 in.
Lead gamma shield, 4 in.
Air gap for shield cooling, 1-2 in.
B4C neutron shield, 6 in.
Stainless steel containment vessel, 1-2 in.

Steel shell filled with soft wood, ridged foam, honeycombed material
Initial LANL Reactor Core Design

The core is ~1m across and 1.5m tall. The reactor can produce 5 MWt operating at 930 K with a SS/UO2 reactor.
**INL Analyses of LANL Design – Positive Attributes**

- Use of the heat pipes in a reactor system addresses one of the most difficult reactor safety issues present in current Generation II and III commercial nuclear reactors—in particular, loss of primary coolant.
- The unique core design is built around a solid steel monolith with channels for both heat pipes and fuel pellets.
- The fuel is commercial uranium oxide (UO₂).
- Each fuel pin in the core is adjacent to three heat pipes for efficiency and redundancy. Overall there is a 1-to-2 heat pipe-to-fuel ratio throughout the core.
- The reactor has a strong negative temperature coefficient with negative feedback contributions from UO₂ Doppler broadening, UO₂ axial elongation due to thermal expansion, and thermal expansion of the steel monolith.
- Any transient power excursions would be mitigated quickly by the negative temperature feedback.
- The strong negative reactivity feedback (−0.2¢/C), the small beginning-of-life excess core reactivity ($2.88), the use of control drums, and the relatively high U-235 beta effective (0.0073) will allow for easy control of the reactor power under both normal and accident conditions.
INL Analyses of LANL Design – Concerns

• **Approach to Defense in Depth** – Adequacy of fuel cladding or barriers to the environment.

• **Monolith thermal stress** – The maximum calculated thermal stresses (37.1 MPa at 696° C) in the thin 1.75 mm steel monolith webbing between some fuel pin channels exceed the maximum 29 MPa ASME pressure vessel code allowable limits at 700° C. Web failure may be problematic.

• **Single heat pipe failure** – Failure of a single heat pipe results in localized steel monolith temperature and thermal stresses that far exceed the maximum allowable ASME pressure vessel code limits.

• **Machining** – Drilling holes in the monolith block to the specified tight tolerances (1 mm) is not possible using current technologies for a 1.5-m length solid monolith block. The manufacturers may have to increase the web thickness to 2 mm or have larger tolerances than what is specified by the current design. These larger webs and tolerances impose a severe core reactivity penalty (sub-criticality). A solution is a larger core and higher uranium loading which translates into a significantly larger system footprint.

• **Inspection and qualification** – The monolith and heat pipes are integral to the design and will be required to meet and pass 100% inspection and validation requirements. The ability to perform inspection techniques needed regarding the verification of welds and the performance of the heat pipe to meet design specification is unknown.

• **Monolith Structure** – Survivability of the monolith to maintain structural integrity following a seismic event is of concern.

• **Heat Pipe** – Performance of the heat pipes under long-term irradiation and its ability to operate when exposed to fission products or contamination is of concern. Operating regimes, conditions, or properties leading to cascading heat pipe failures need to be understood.

An alternate design to the Monolith is being pursued, using a HIP structure and containment, to overcome these concerns.
**Design Alternative A**

- Pre-fab HPs
- Pre-fab Fuel Pins (cladded)
- Liquid metal Na or K or NaK fill for thermal bonding between fuel clads
- Stainless steel tank to hold HPs, fuel pins, and liquid metal
- Second stainless steel tank formed with upper reflector and lower reflector

**LANL MegaPower**
- Pitch = 2.77128 cm
- UO2 core mass = 5.22 MT

**Design A**
- Pitch = 2.7858 cm
- UO2 core mass = 5.62 MT
Configuration of Design Alternative A

Stainless steel rounded hex tube

Stainless steel HP tube
### Design A: Heat Pipe / Fuel Unit Cell

<table>
<thead>
<tr>
<th>Dimensions (cm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K vapor radius</td>
<td>0.71</td>
</tr>
<tr>
<td>K liquid radius</td>
<td>0.7875</td>
</tr>
<tr>
<td>HP SS clad radius</td>
<td>0.8875</td>
</tr>
<tr>
<td>Gap radius</td>
<td>0.8939</td>
</tr>
<tr>
<td>Inner Fuel SS radius</td>
<td>0.9339</td>
</tr>
<tr>
<td>Gap radius</td>
<td>0.9403</td>
</tr>
<tr>
<td>Fuel hex apothem (center-to-flat)</td>
<td>1.2802</td>
</tr>
<tr>
<td>Gap hex apothem</td>
<td>1.2866</td>
</tr>
<tr>
<td>SS clad hex apothem</td>
<td>1.3866</td>
</tr>
<tr>
<td>Outer gap apothem (unit cell)</td>
<td>1.3930</td>
</tr>
<tr>
<td>Inner cylinder area (cm$^2$)</td>
<td>2.777683</td>
</tr>
<tr>
<td>Inner fuel hex area (cm$^2$)</td>
<td>5.677358</td>
</tr>
<tr>
<td>Fuel area (cm$^2$)</td>
<td>2.899674</td>
</tr>
<tr>
<td>Fuel pin volume (cc)</td>
<td>435</td>
</tr>
</tbody>
</table>
Advantages of Design Alternative A

- No stainless steel monolith
- Pre-fab HPs
- Pre-fab fuel elements (hex tube) and cladded
- Significantly reduced thermal strain
- HP cascade failures reduced or eliminated
- Double tank containment
- Liquid metal Na or K fill thermal bonding between fuel clads
- Stainless steel tank to hold HPs, fuel pins, and liquid metal
- Second stainless steel tank formed with upper and lower reflectors
- Reactor core already contains hot liquid metal K in HPs (17 liters per sector)
- Fuel elements pushed together
- Same lattice pitch
- Reduced number of HPs in core
- Expect higher k-effective
- Can accommodate more UO₂
- Could increase HP diameter (higher core power)
Design Alternative B

- Pre-fab HPs
- Pre-fab Fuel Pins (cladded)
- **Spacer grid plates**
- Significantly reduced thermal strain
- Liquid metal Na or K fill for thermal bonding
- Liquid metal relatively small volume (53 liters per sector)
- Stainless steel tank to hold HPs, fuel pins, spacer grid plates, and liquid metal
- Second stainless steel tank formed with upper reflector and lower reflector
**Alternative B Inner Tank**

- 60-degree sector
- SS316 structure
- Plates (2 cm thickness) welded together to form inner tank
- Contains HPs, fuel pins, grid spacer plates, and Na
- Na fills interstitial lattice space
- HP bottom rests on bottom plate
- Fuel pin bottom rests on bottom plate
- Top plate has holes for HPs to penetrate
- HPs are seal-welded to top plate
Alternative B
Outer Tank

- Provides a double containment for the Na liquid
- Both containment tanks could be sealed
- Goal to prevent Na leakage
- Probability of Na loss greatly reduced
- Na loss (negative feedback)
Advantages of Design Alternative B

- Pre-fab fuel pins (clad)
- Pre-fab HPs
- Double tank containment
- Spacer grid plates can be easily drilled
- Liquid metal Na relatively small volume (53 liters per sector)
- Liquid metal Na forms thermal bond with HPs and fuel pins
- HP cascade failures reduced or eliminated
- Reactor core already contains hot liquid metal K in HPs (17 liters per sector)
- Liquid metal Na compatible with liquid metal K and SS
- Liquid metal Na boils at 880° C (maximum monolith temperature ~700° C)
- Liquid metal Na melts at 97-98° C
- Liquid metal K melts at 63.5° C
- Liquid metal NaK melts at -12.6° C
- Core BOL excess positive reactivity increases by factor of ~3 with Na !!!
- Reduction in total core mass by 2.32 MT (SS monolith essentially eliminated)
- Loss of Na is negative reactivity feedback
- Six individual core sectors with six separate double core tanks
  - Core tanks could be sealed
  - Probability of Na loss small and isolated to individual tanks
System Schematic of the Reactor Concept with Air Power Conversion
Simple Air Brayton Cycle

- Relative humidity of inlet air is 50%
- Isentropic efficiency of compressor is 90%
- Isentropic efficiency of turbine is 90%
- Air temperature into turbine is 675°C
- Best Efficiency is 29.4%
- Power produced for 5 MWt is 1.47 MWe
- Optimal pressure ratio for assumptions made is 11.1
Recuperated Air Brayton Cycle

- Relative humidity of inlet air is 50%
- Isentropic efficiency of compressor is 90%
- Isentropic efficiency of turbine is 90%
- Air temperature into turbine is 675°C
- Temperature of air into turbine is 675°C
- Best Efficiency is 40.3%
- Power produced for 5 MWt is 2.016 MWe
- Optimal pressure ratio for assumptions made 2.5
Thermal Efficiency & Power Out

Air Temperature into Turbine:
- 600°C
- 625°C
- 650°C
- 675°C
- 700°C
- 725°C
- 872°C

Graph showing the relationship between Pressure Ratio of Compressor and Thermal Efficiency at different air temperatures.
# Available Natural Gas Commercial Units

<table>
<thead>
<tr>
<th>Available Natural Gas Commercial Units</th>
<th>Power Output (MWe)</th>
<th>Thermal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens Industrial 501-K</td>
<td>5.1</td>
<td>30.2%</td>
</tr>
<tr>
<td>GE LM2500</td>
<td>23-34</td>
<td>38%</td>
</tr>
<tr>
<td>Kawasaki M1A-13A</td>
<td>1.45</td>
<td>23.8%</td>
</tr>
</tbody>
</table>
Summary

• Three design options of a “first-of-a-kind” (FOAK) Heat Pipe Reactor are being pursued by INL and LANL, in collaboration.
• Ongoing discussions occurring with experts in the field to identify potential improvements and concerns to chart best path for rapid prototyping and deployment.
• In parallel, contacting commercial vendors to evaluate available capabilities for ease of manufacturability.
• All aspects of reactor design, fuels and materials used, and operation are attentive to potential NRC requirements.
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