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

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Outline

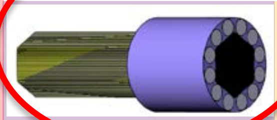
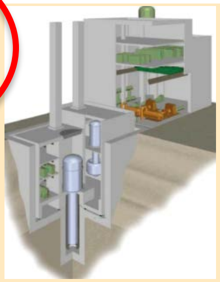
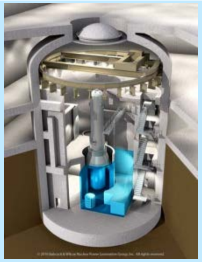
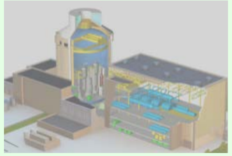
- The Need for Small Reactors as a Reliable Power Source
- Defense Science Board (DSB) Recognition of Need and Recommendation
- The 2MW Nuclear Reactor and Thermal Conversion System
- Reactor Design Options in Evaluation
- Status of Development To Date

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

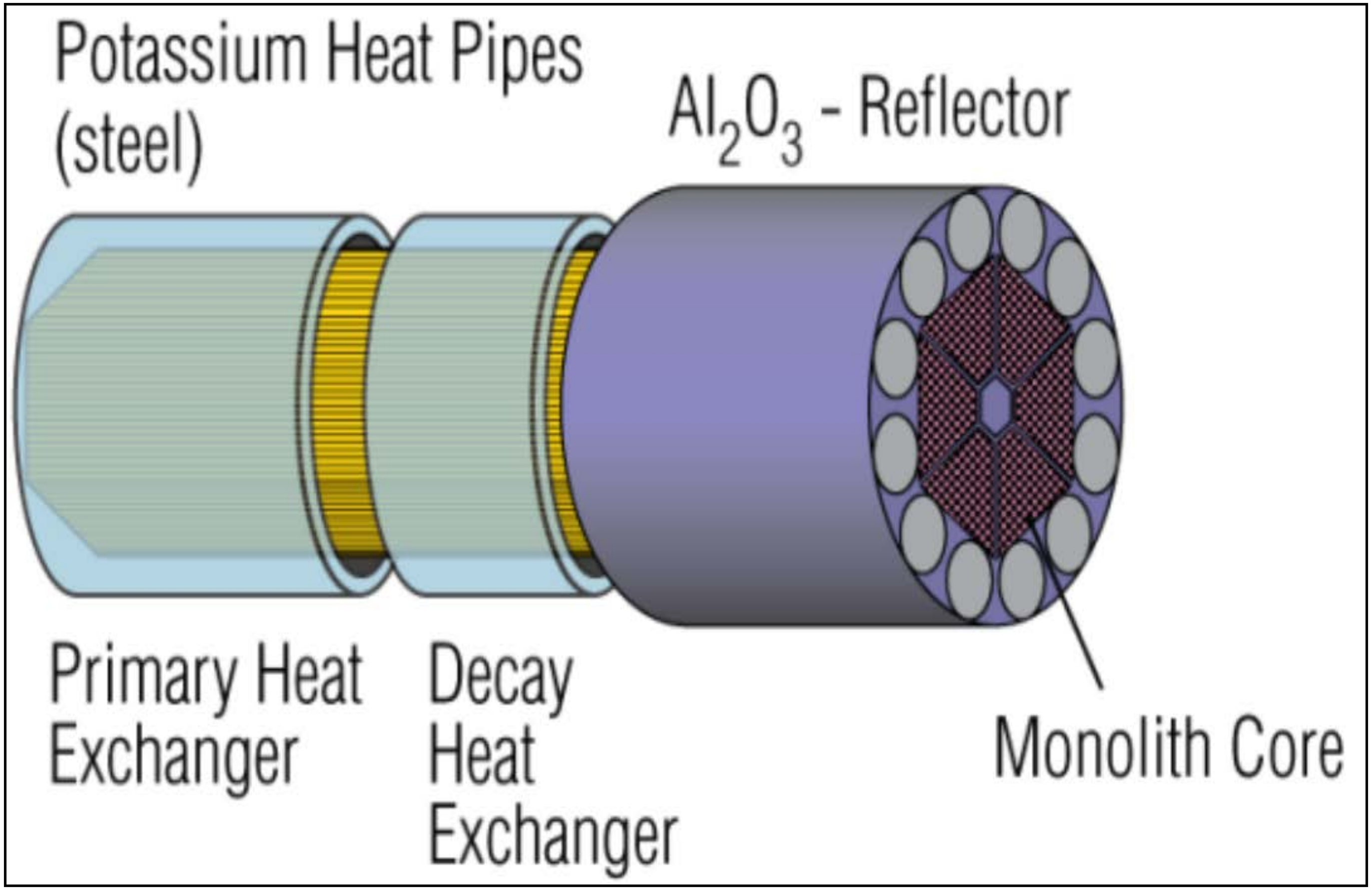
Existing DOE **NUCLEAR** design, prototyping and testing infrastructure can be leveraged to accelerate innovation, development and demonstration of wide range of reactors

Micro Reactors			Small Modular		Large
					
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 Military Ops	Space propulsion & planetary surface power; Med Isotopes Military Ops	Military Bases; 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

1^0 1^1 1^2 1^3 1^4 1^5 1^6

Power Level in Kilo-Watts Electric

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

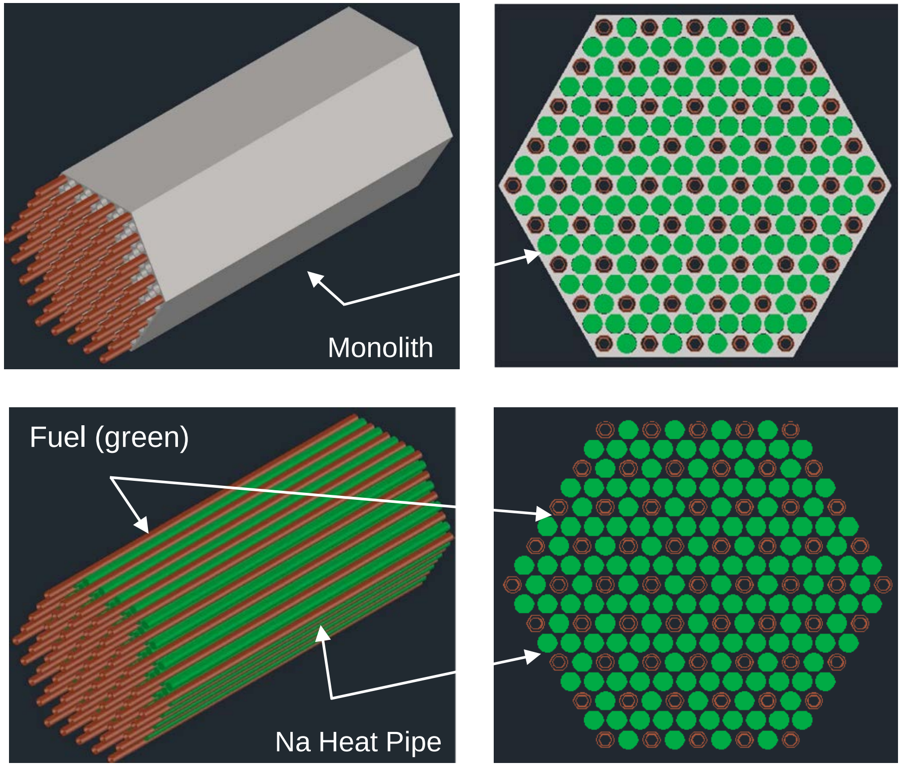
Proven Materials and Good Performance go with Heat Pipe Design

6 Passive Components

1. 316 Stainless Steel
2. LEU-UO_2 commercial grade fuel pellets
3. Potassium Heat Pipes
4. Al_2O_3 (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

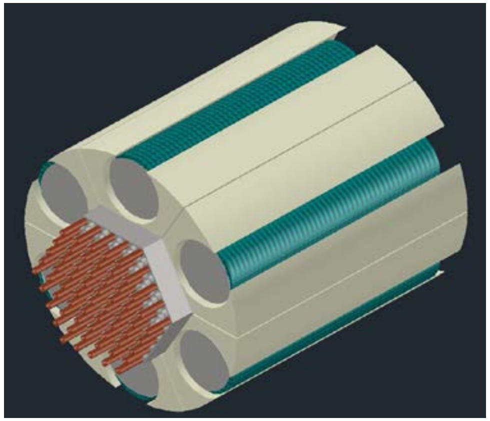
Performance Specs:

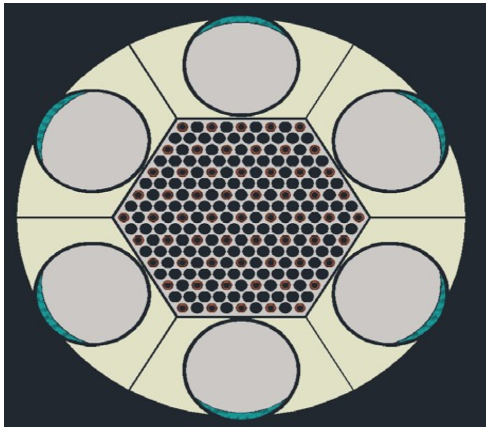
- 10+year design life
- <1% fuel burnup
- 10^{11} neutrons/cm^2 or 100krad (16yr) @ 100 M dose plane)

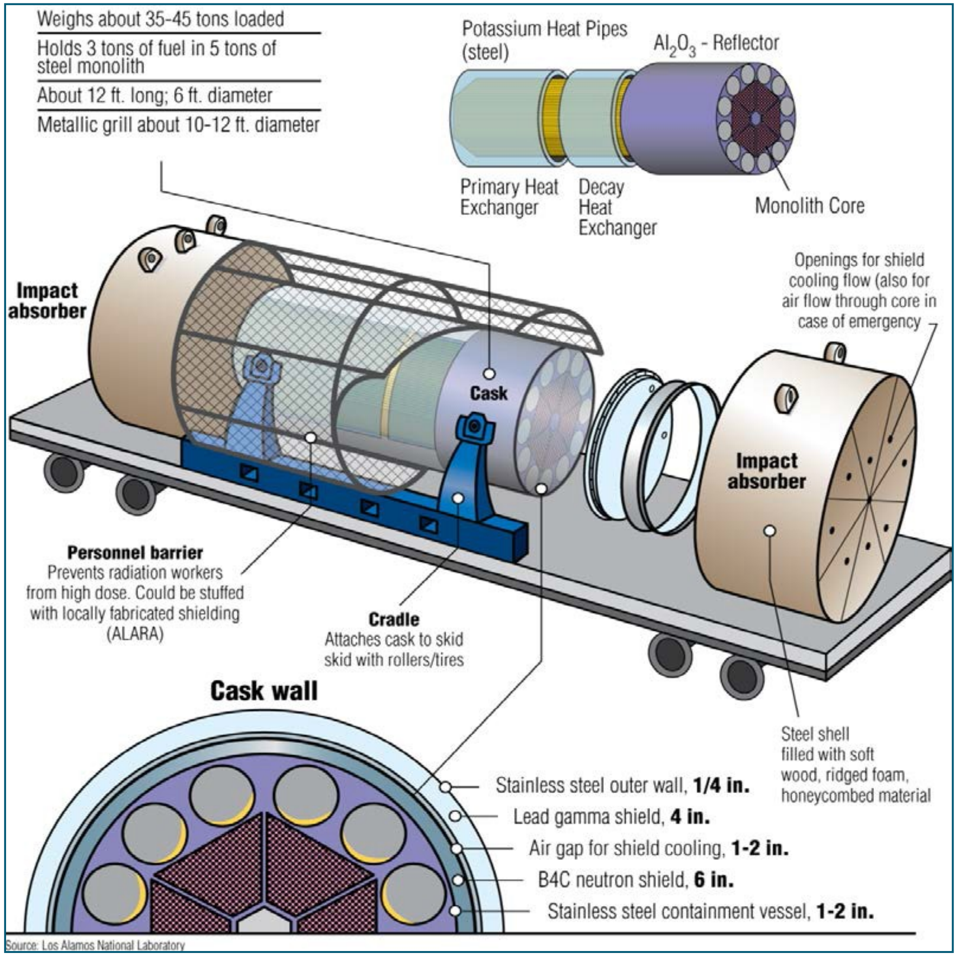


MegaPower Reactor Nuclear Core

Schematic of the LANL Heat Pipe Reactor

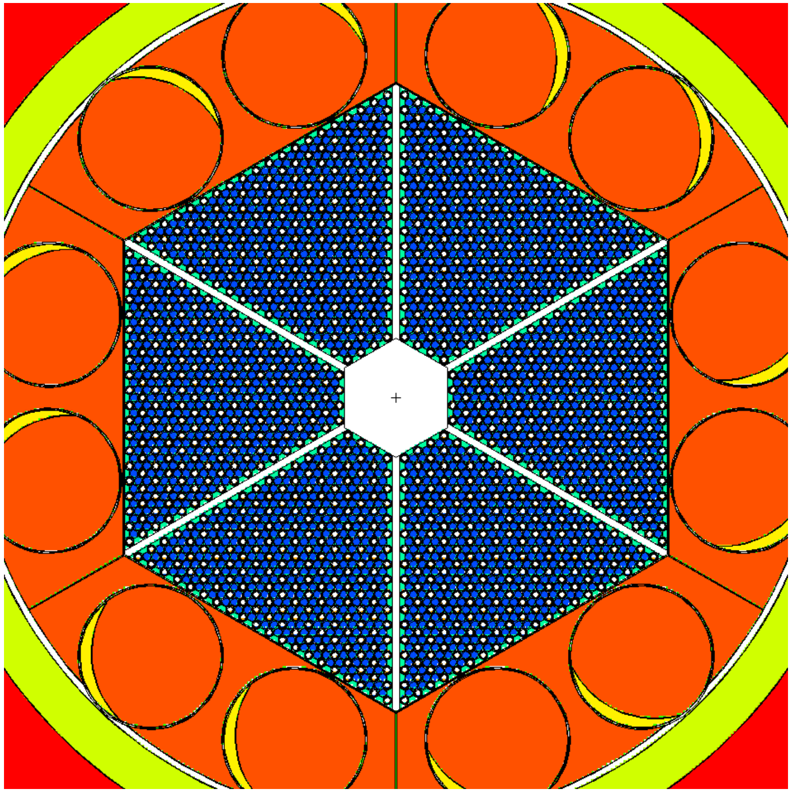


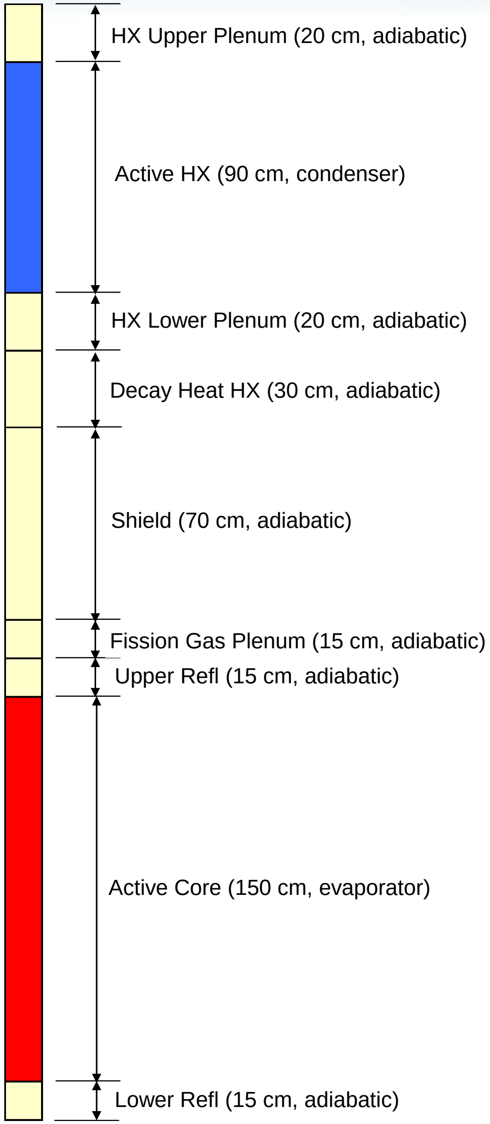




Initial LANL Reactor Core Design

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 (UO_2).
- 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 UO_2 Doppler broadening, UO_2 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.

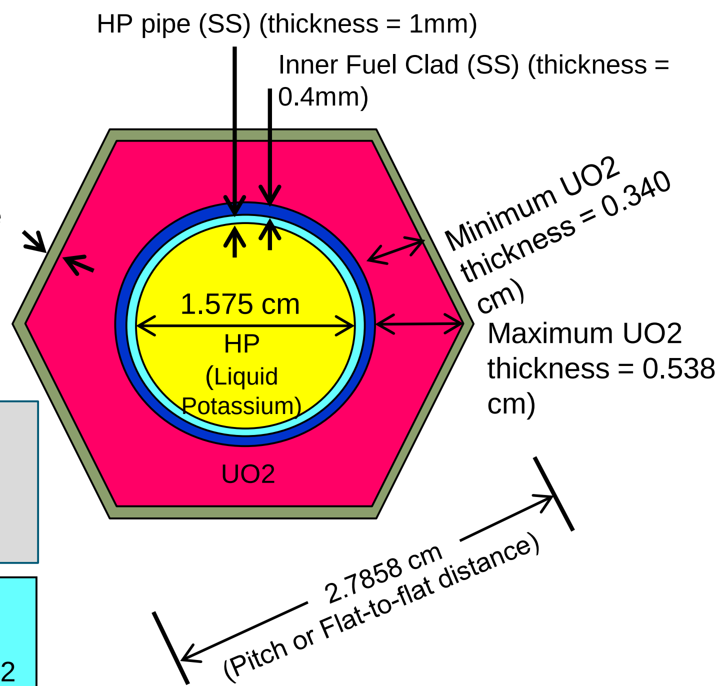
INL Analyses of LANL Design – Concerns

- **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

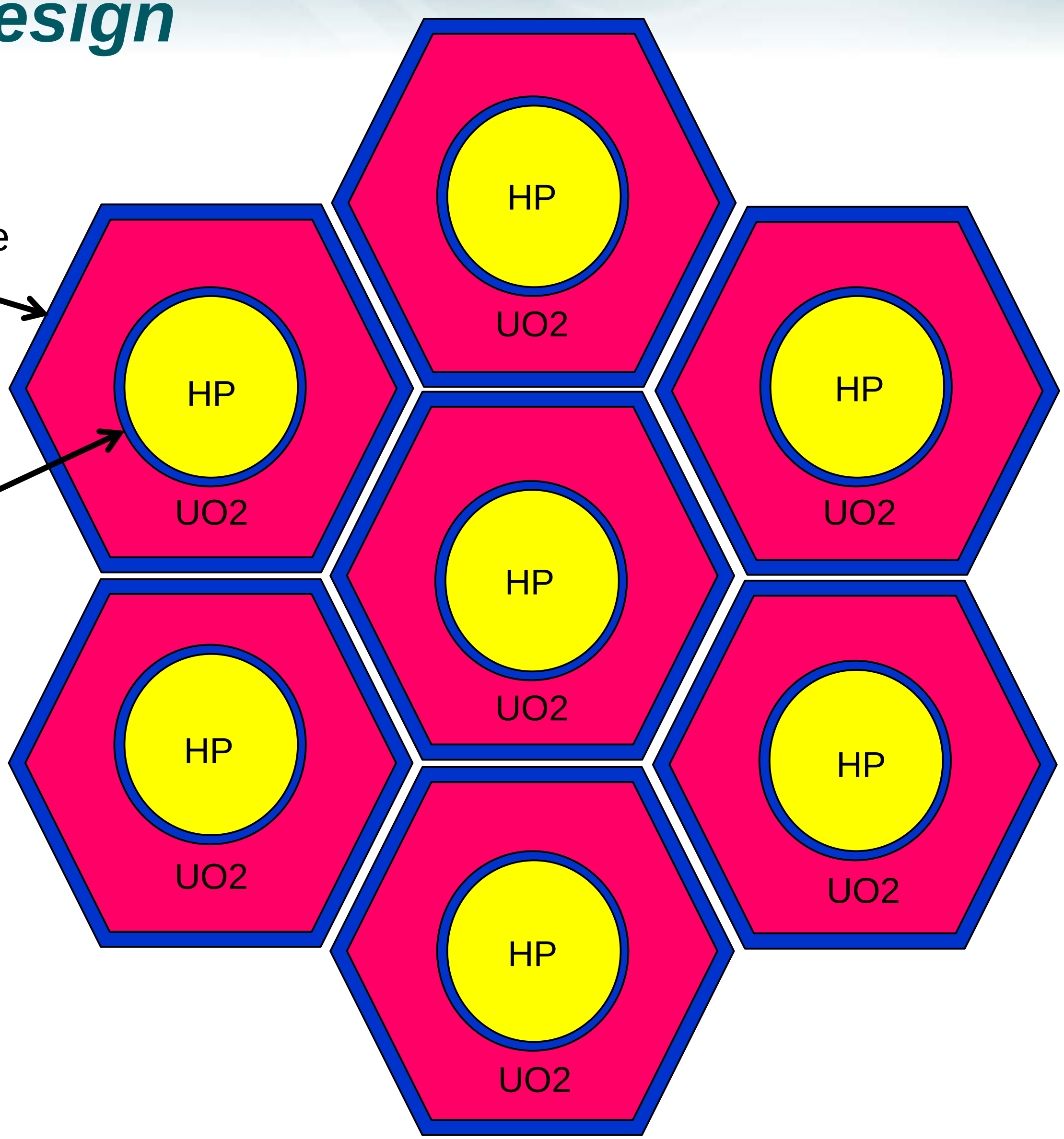
- Pre-fab HPs
- Pre-fab Fuel Pins (cladded)
- Liquid metal Na or K or NaK fill for thermal bonding between fuel clads
- Stainless steel tank to hold HPs, fuel pins, and liquid metal
- Second stainless steel tank formed with upper reflector and lower reflector

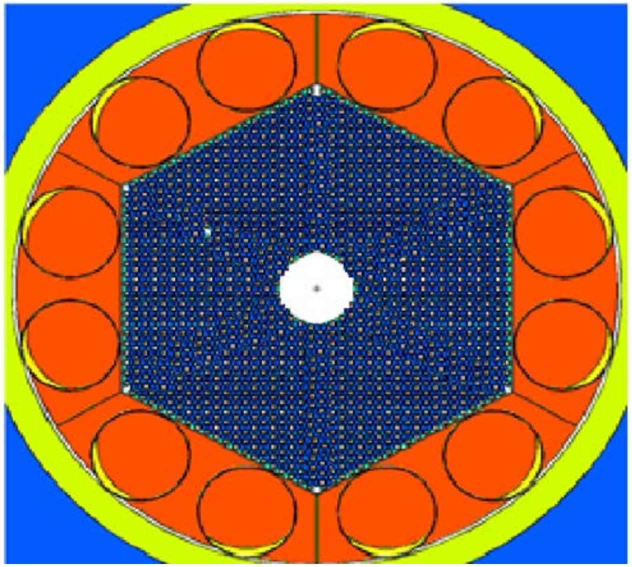


<u>Design A</u>
Pitch = 2.7858 cm
UO2 core mass = 5.62 MT

<u>LANL MegaPower</u>
Pitch = 2.77128 cm
UO2 core mass = 5.22 MT

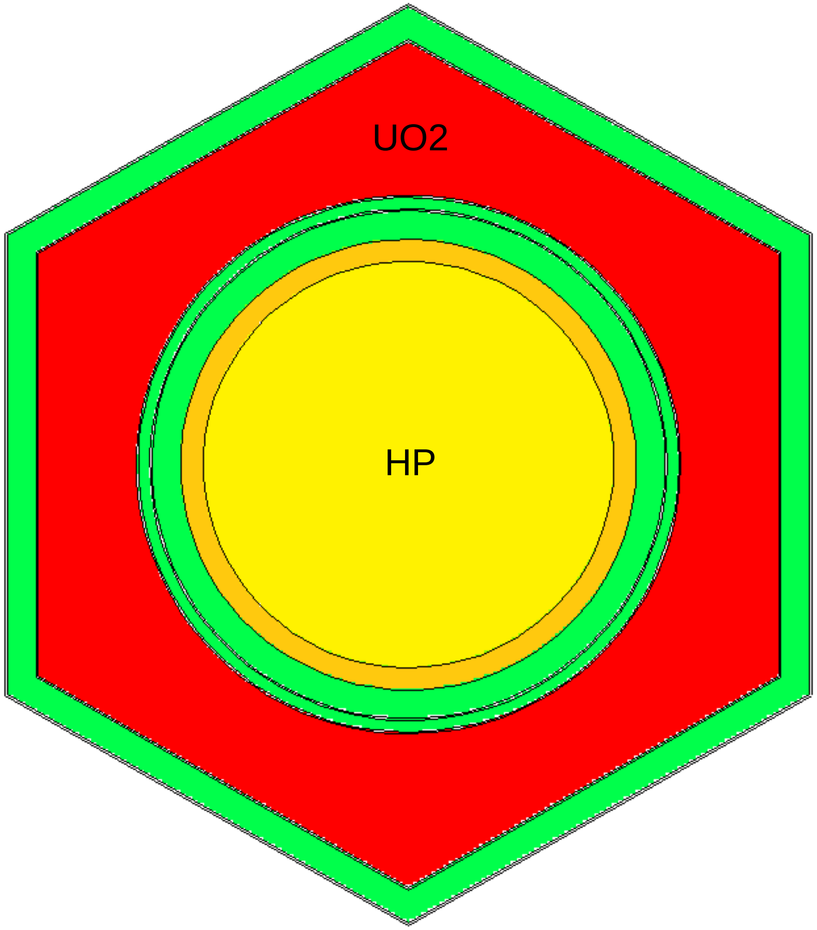
Configuration of Design Alternative A





Design A: Heat Pipe / Fuel Unit Cell

Dimensions (cm)	
K vapor radius	0.71
K liquid radius	0.7875
HP SS clad radius	0.8875
Gap radius	0.8939
Inner Fuel SS radius	0.9339
Gap radius	0.9403
Fuel hex apothem (center-to-flat)	1.2802
Gap hex apothem	1.2866
SS clad hex apothem	1.3866
Outer gap apothem (unit cell)	1.3930
Inner cylinder area (cm^2)	2.777683
Inner fuel hex area (cm^2)	5.677358
Fuel area (cm^2)	2.899674
Fuel pin volume (cc)	435



Advantages of Design Alternative A

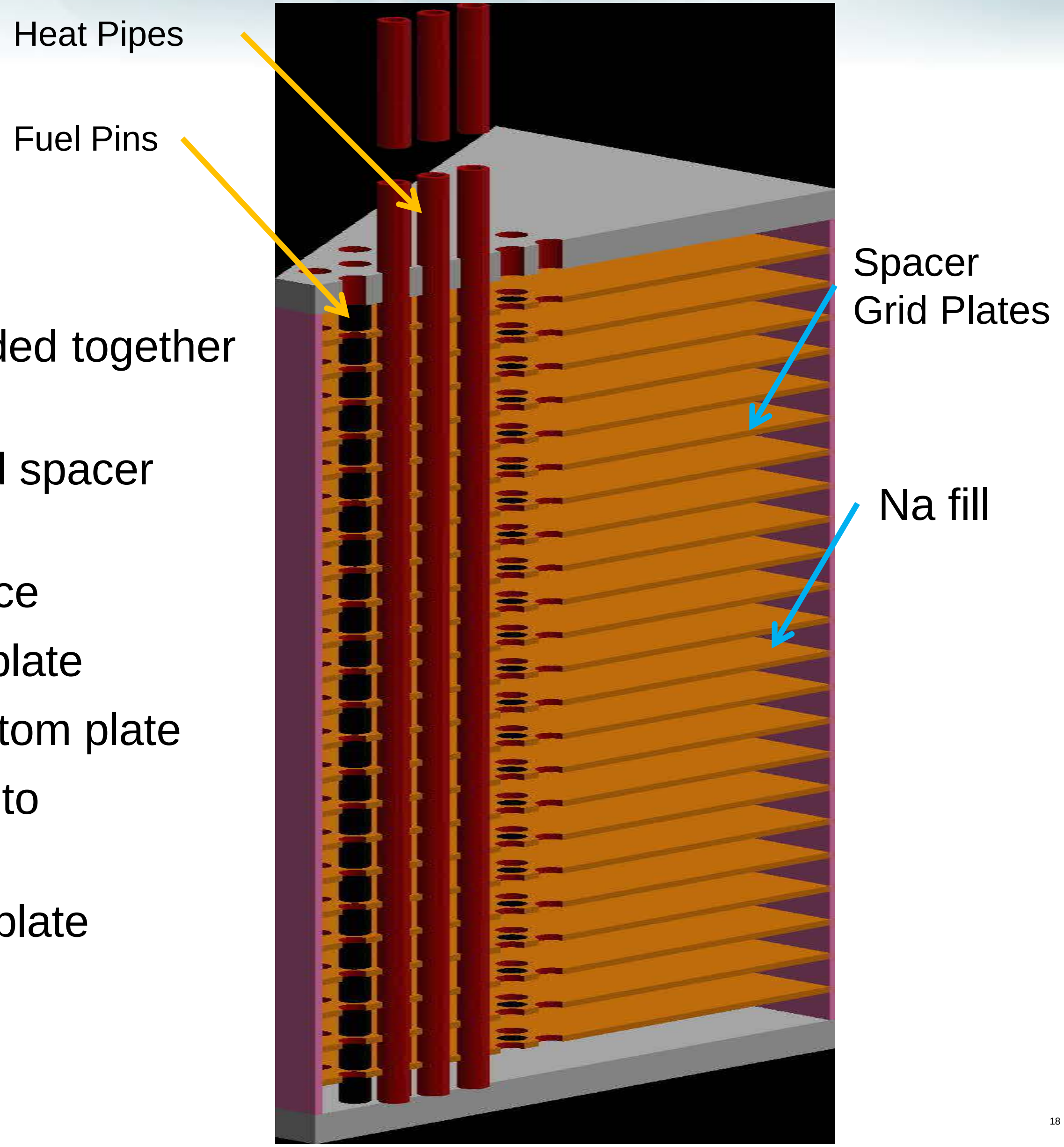
- No stainless steel monolith
- Pre-fab HPs
- Pre-fab fuel elements (hex tube) and cladded
- Significantly reduced thermal strain
- HP cascade failures reduced or eliminated
- Double tank containment
- Liquid metal Na or K fill thermal bonding between fuel clads
- Stainless steel tank to hold HPs, fuel 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 UO_2
- 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



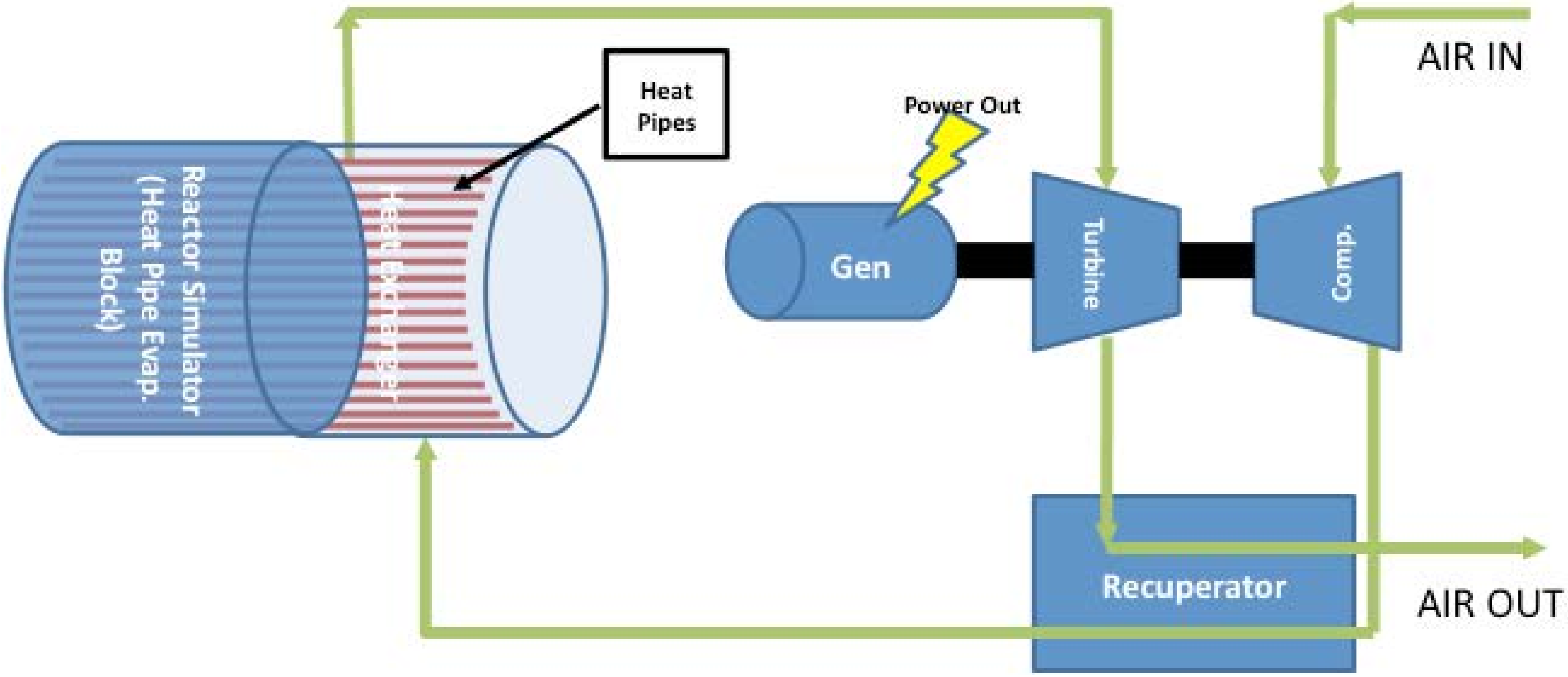
Alternative B
Outer Tank

- 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

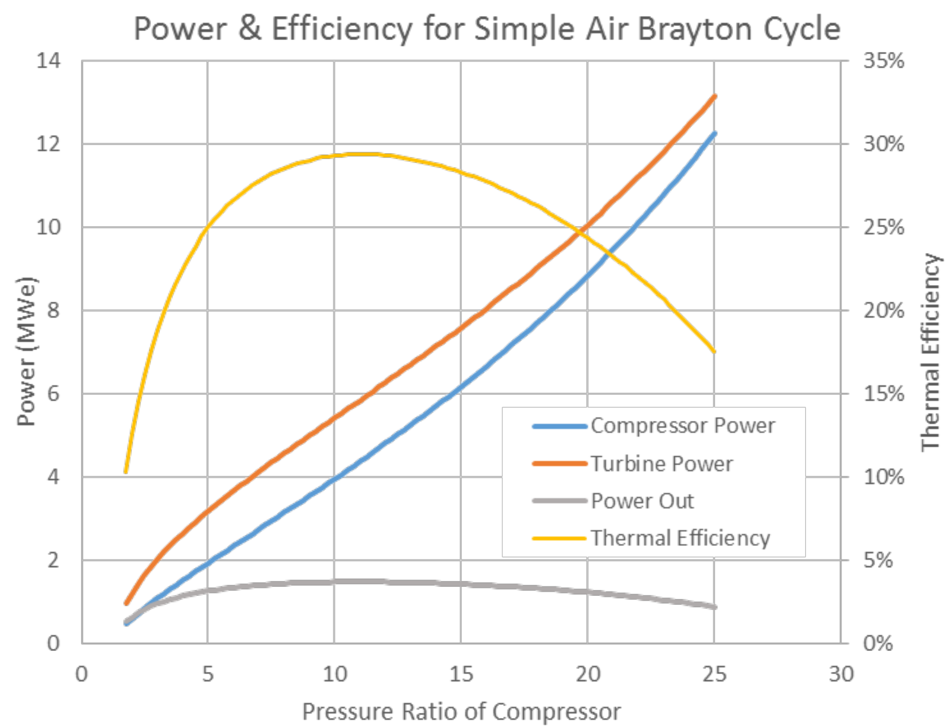
- Pre-fab fuel pins (clad)
- Pre-fab HPs
- Double tank containment
- Spacer grid plates can be easily drilled
- Liquid metal Na relatively small volume (53 liters per sector)
- Liquid metal Na forms thermal bond with HPs and fuel pins
- HP cascade failures reduced or eliminated
- Reactor core already 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

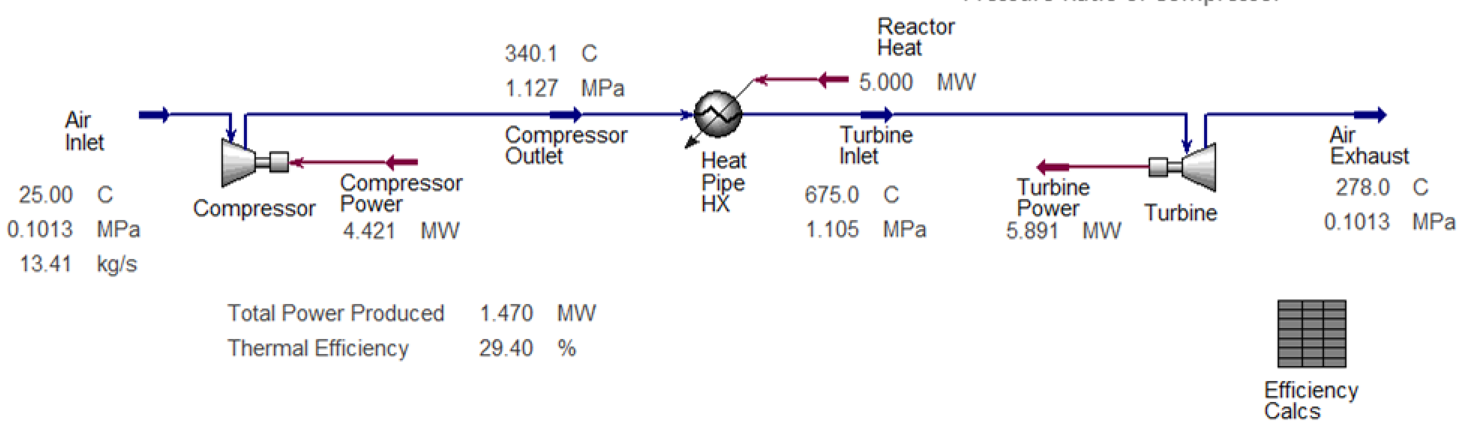
System Schematic of the Reactor Concept with Air Power Conversion



Simple Air Brayton Cycle

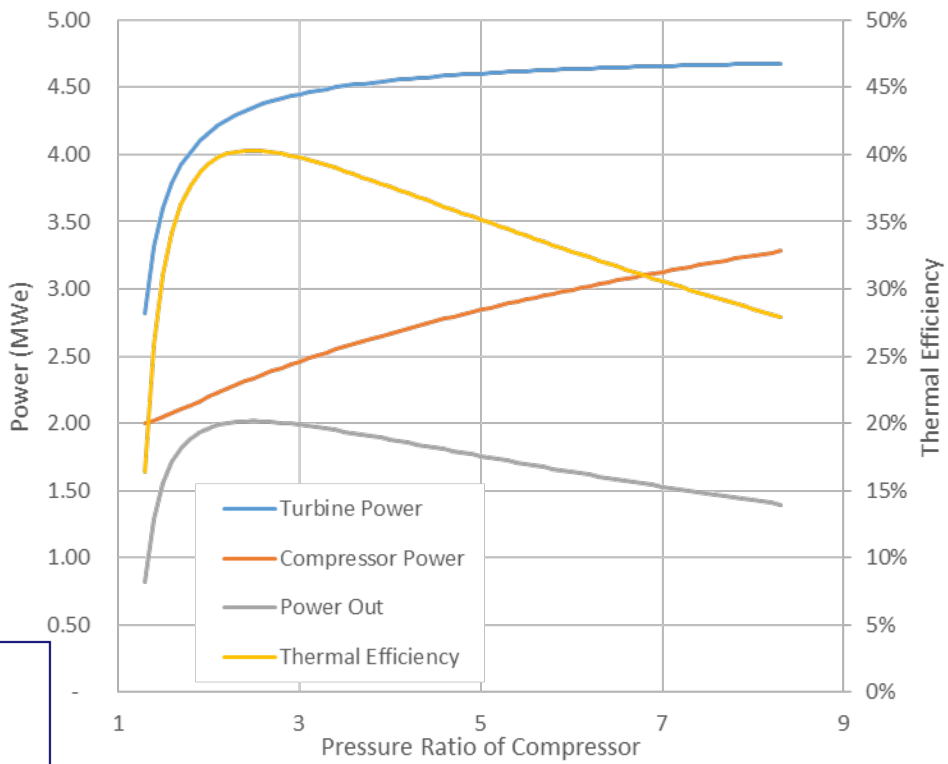
- Relative humidity of inlet air is 50%
- Isentropic efficiency of compressor is 90%
- Isentropic efficiency of turbine is 90%
- Air temperature into turbine is 675ºC
- Best Efficiency is 29.4%
- Power produced for 5 MWt is 1.47 MWe
- Optimal pressure ratio for assumptions made 11.1

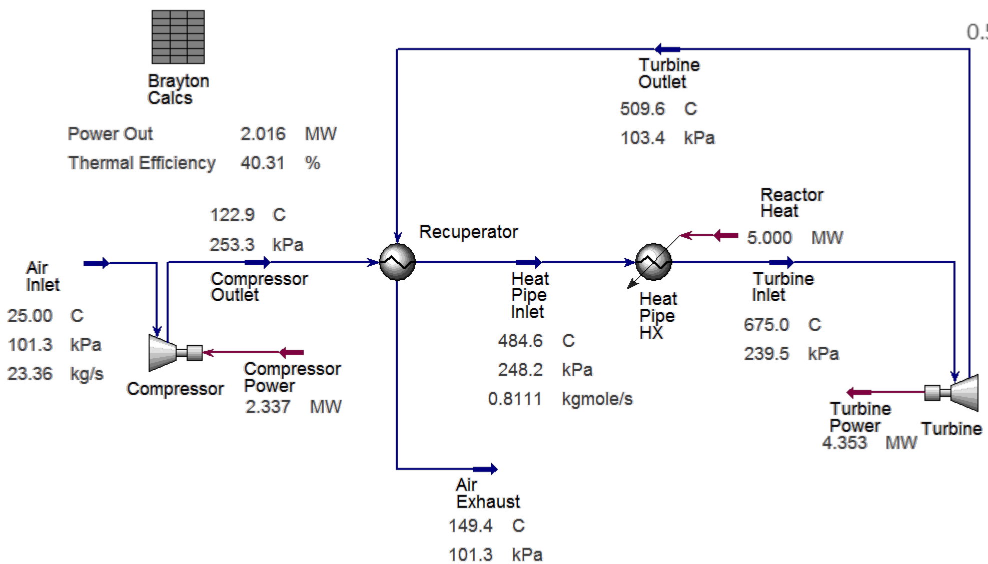




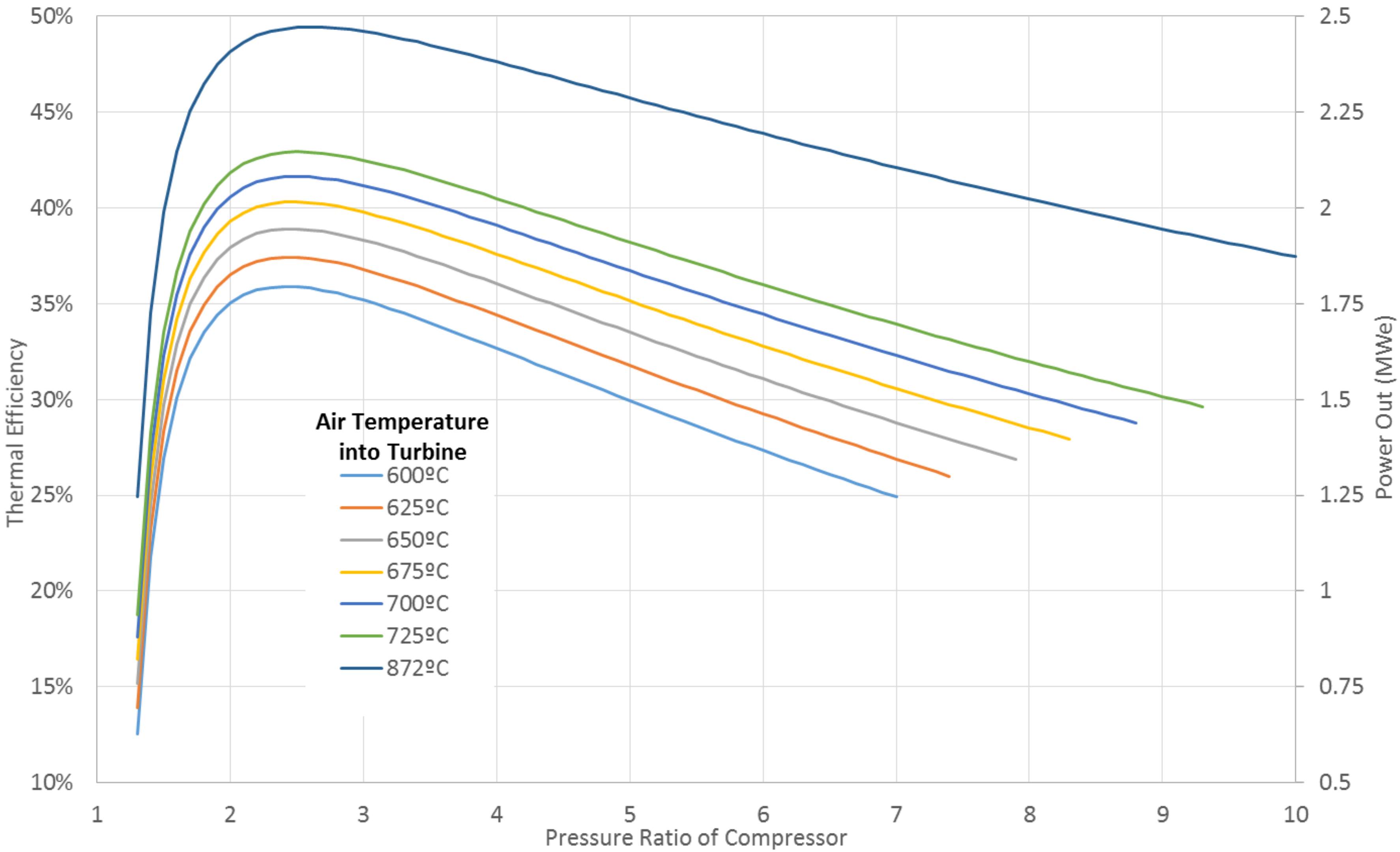
Recuperated Air Brayton Cycle

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





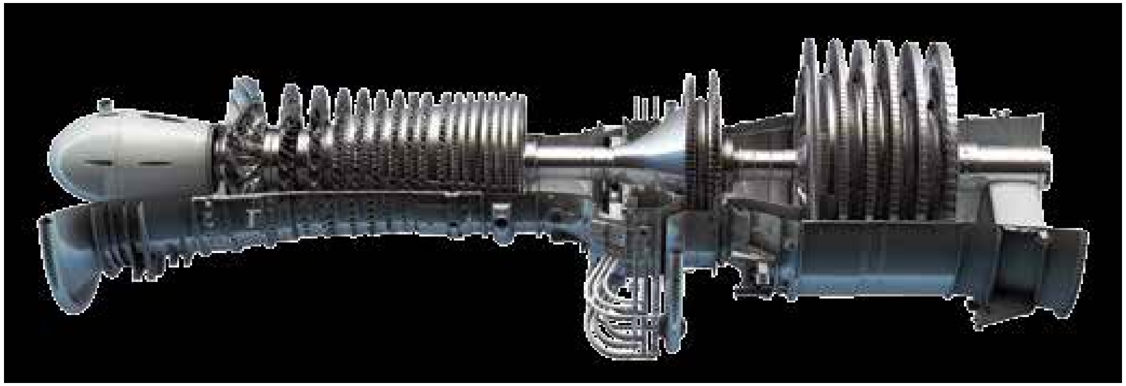
Thermal Efficiency & Power Out



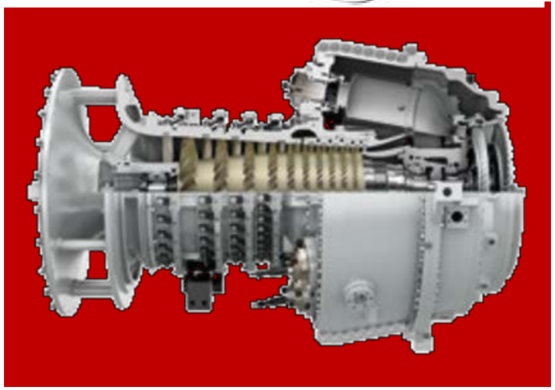
Available Natural Gas Commercial Units

Kawasaki

	Power Output (MWe)	Thermal Efficiency
Siemens Industrial 501-K	5.1	30.2%
GE **LM2500**	23-34	38%
Kawasaki M1A-13A	1.45	23.8%



GE



Siemens

Idaho National Laboratory

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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