Heat Pipe Cooled Micro-reactor

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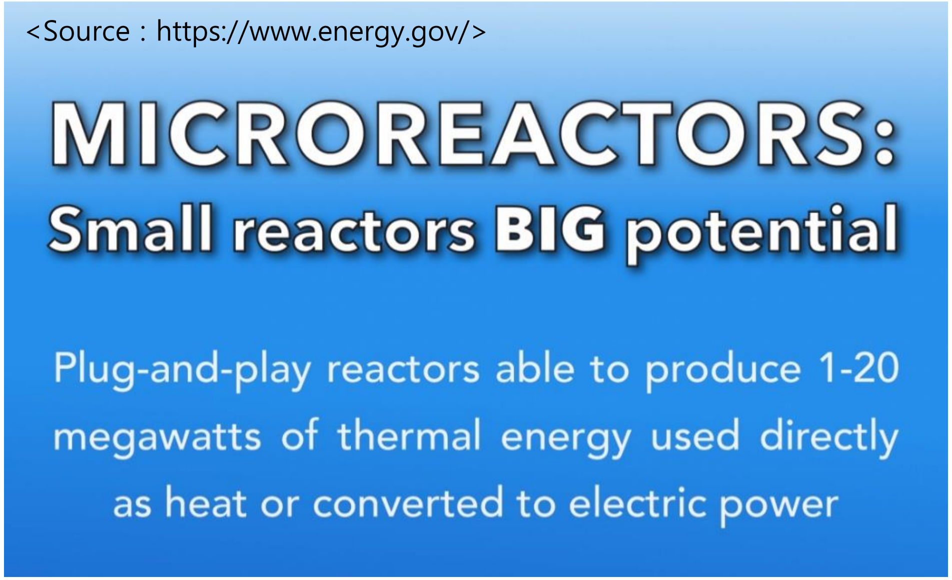
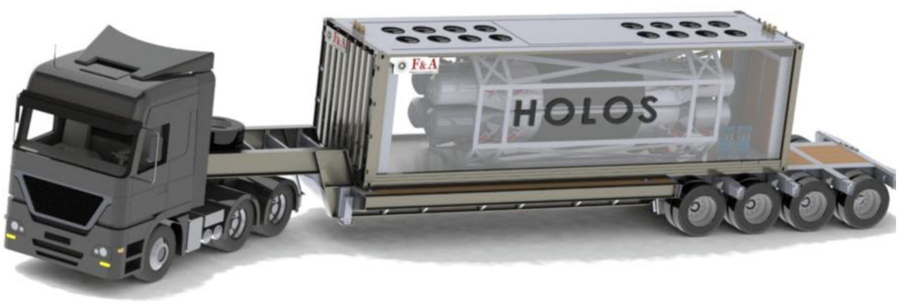
Micro Nuclear Reactors



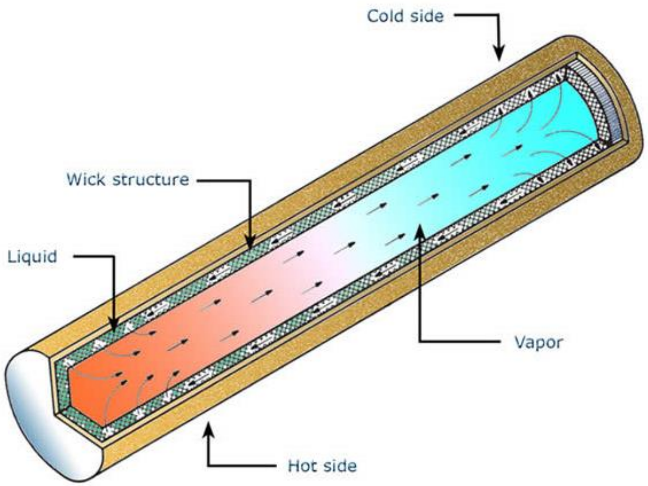


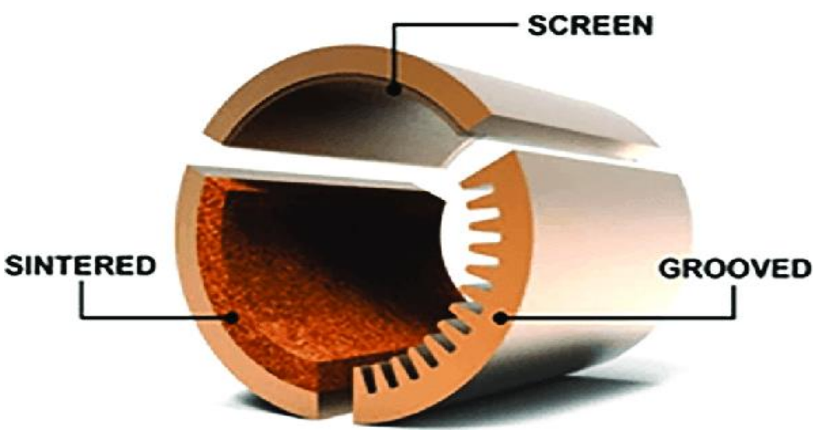
Micro Nuclear Reactors

Heat Pipe

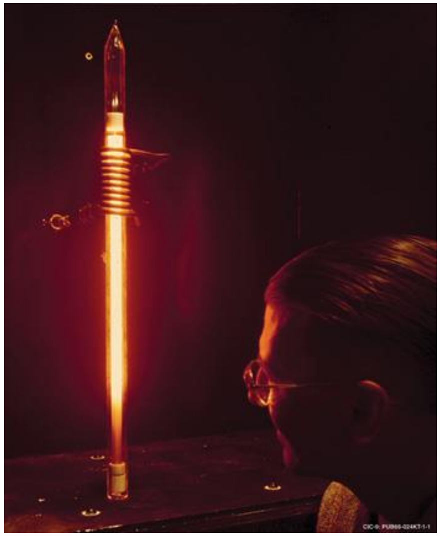
❖ Heat pipe configuration and applications

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





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



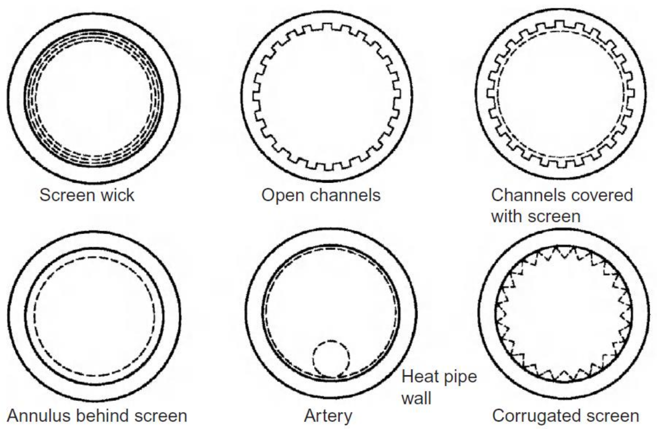
<Source:https://www.lanl.gov/science/NSS/issue1_2011/story6full.shtml>

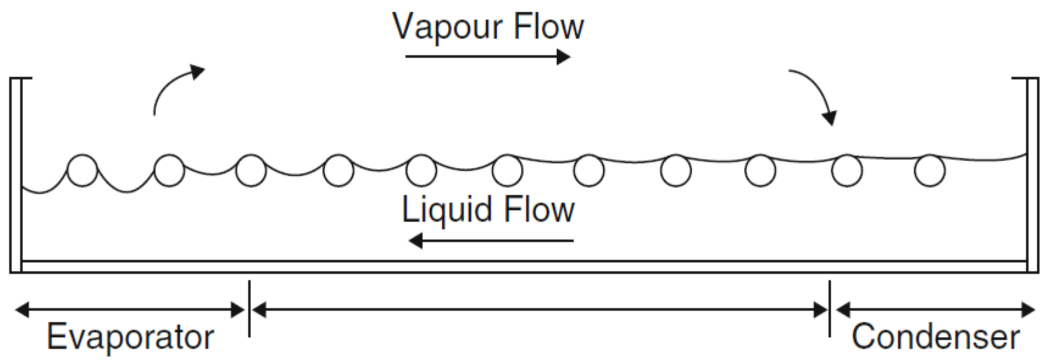
History

- 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

Heat Pipe

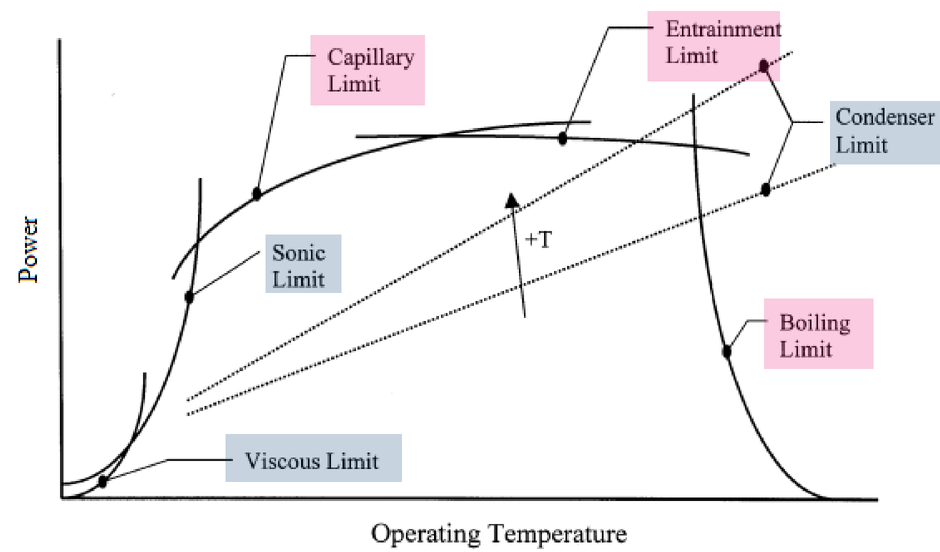
❖ Heat pipe wick structure and operational limits





<Source : Heat Pipes: Theory, Design and Applications, Reay, Kew and McGlen>

<Source : A. Bejan and A.D. Kraus, “Heat Transfer Hand Book”, Published by John Wiley & Sons, Inc. 2003.>

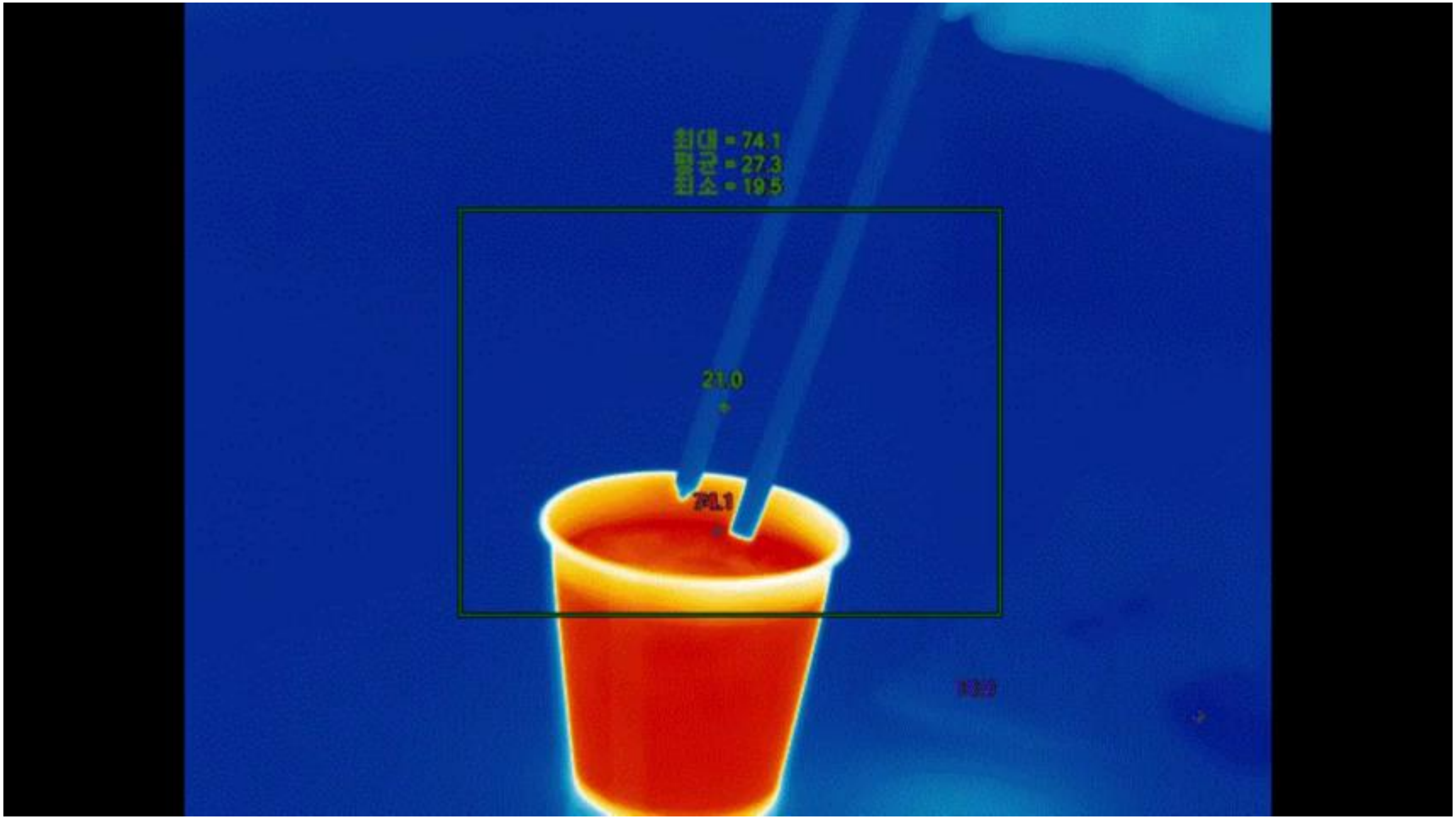


Performance limits

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

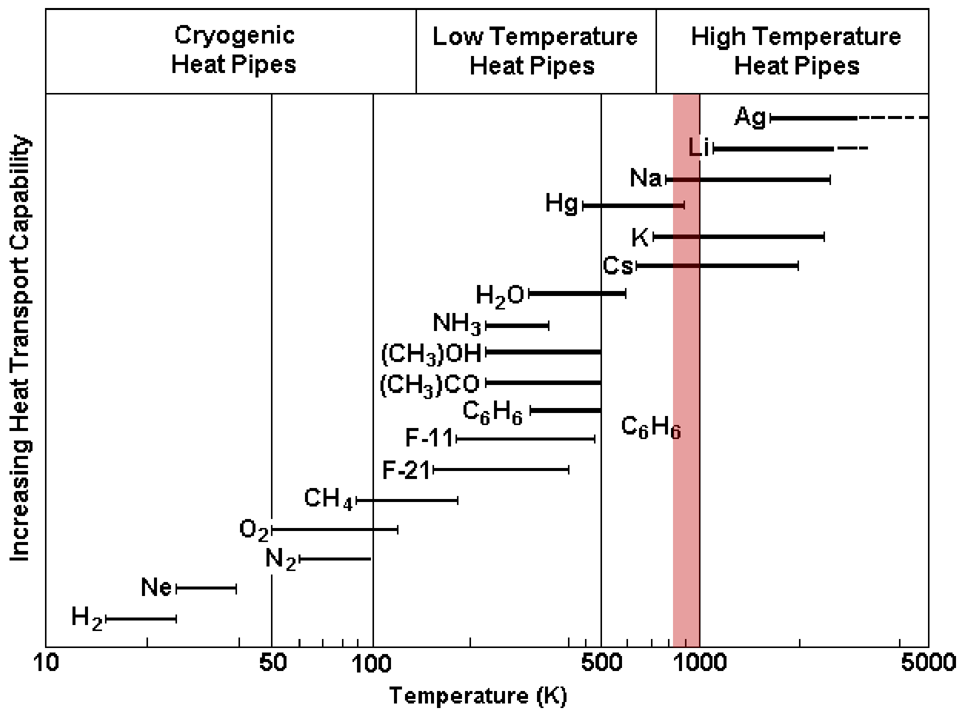
Heat Pipe

❖ **Fast heat transfer**



Heat Pipe

Fluids of heat pipe



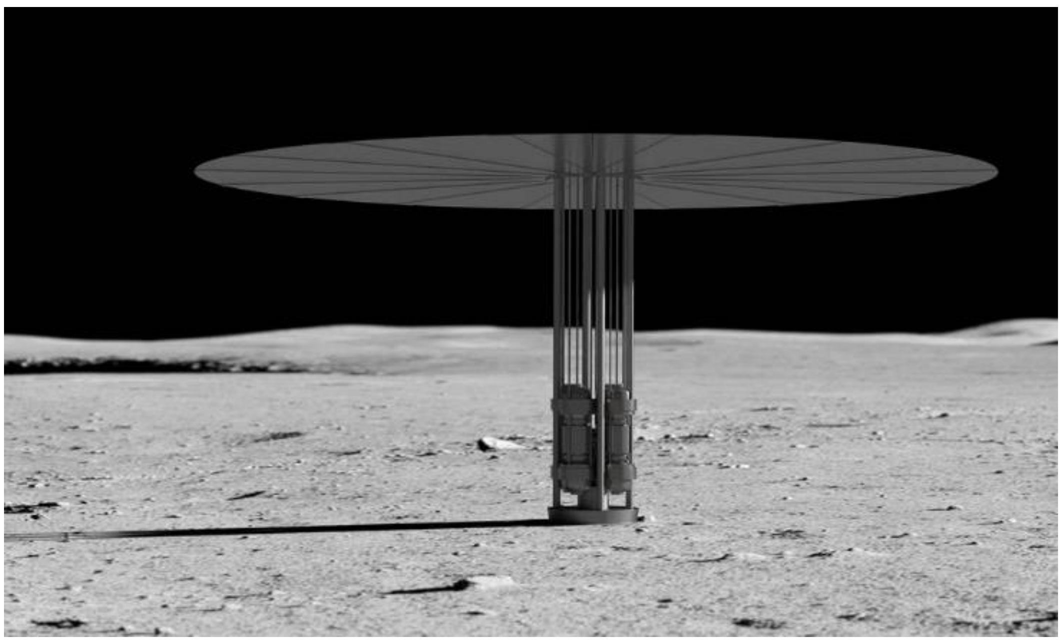
Heat Pipe Working Fluids

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

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.

Oil sands

- Steam for SAGD and electricity for upgrading at **96 facilities**
- 210 MWe average size for both heat and power demands
- 5% replacement by SMRs between 2030 and **2040 could provide** $350-450M **in value annually**

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 **in value annually**

Remote communities and mines

- 79 remote communities in Canada with energy needs > 1 MWe
- SMRs replacing costly diesel and heating oil could **reduce energy costs to the territorial government**
- **The high cost of energy from diesel is a barrier. SMRs could facilitate and enable new mining developments**
- 24 current and potential off-grid mines

Replacing conventional coal-fired power:

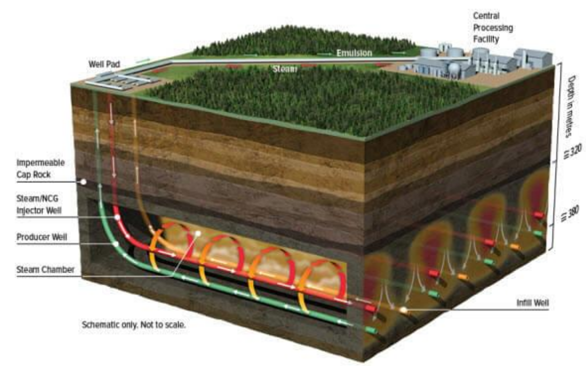
- 29 units in Canada at 17 facilities
- 343 MWe average size
- 10% replacement by SMRs between 2030 and 2040 could **provide** $469M **in value annually**

<Source: 'A Canadian Roadmap for Small Modular Reactors' (NRCan, November 2018).>

Diavik diamond mine

<Source : Dominion Diamond Mines>

Steam assisted gravity drainage



<Source: www.megenergy.com>

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

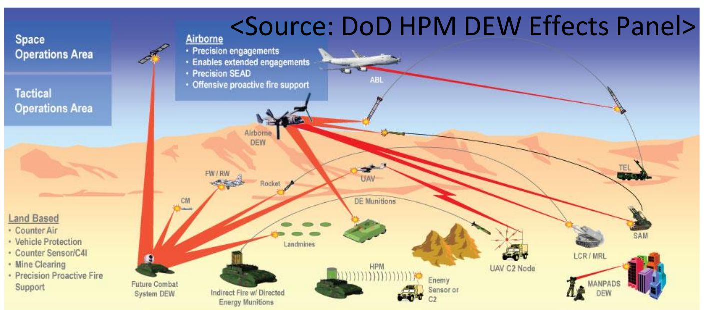
U.S. Department of Defense

❖ 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"



<Source :https://www.defensenews.com>

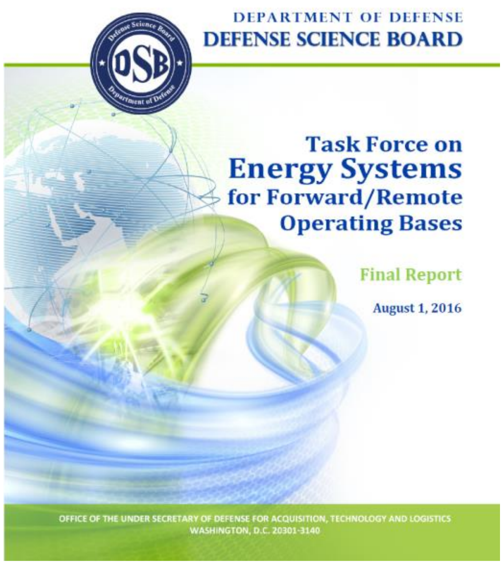
<Source : https://defense-update.com/>

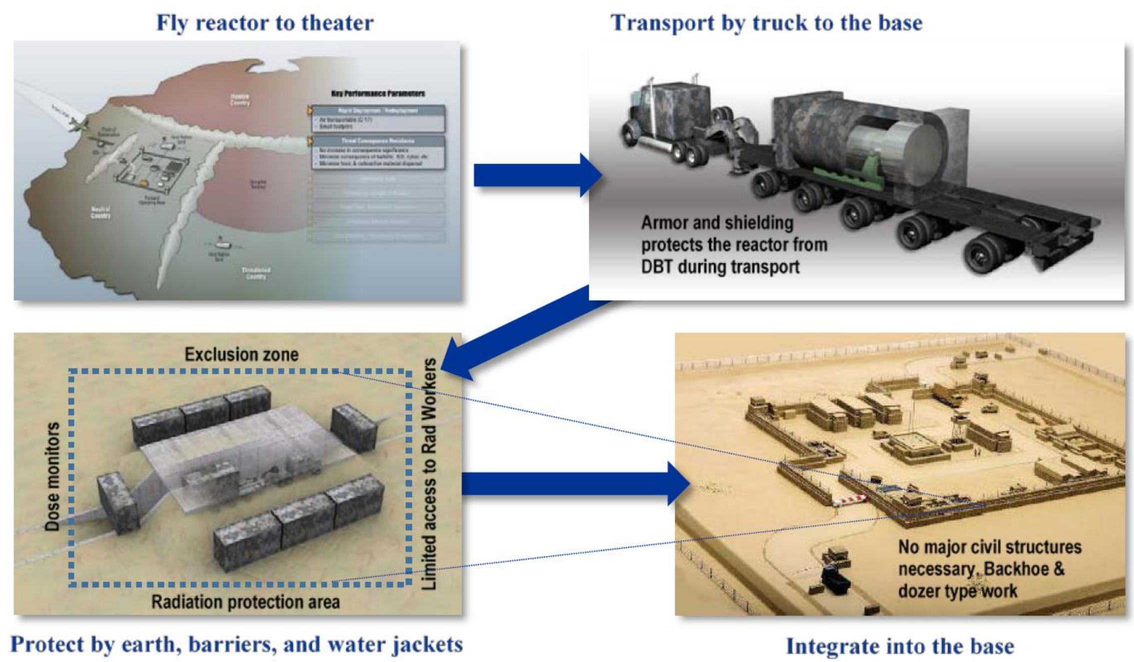
<Source : US ARMY DARPA>

U.S. Department of Defense

❖ vSMR (very Small Modular nuclear Reactor)

- ✓ 1~10 MWe, several years with out 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)

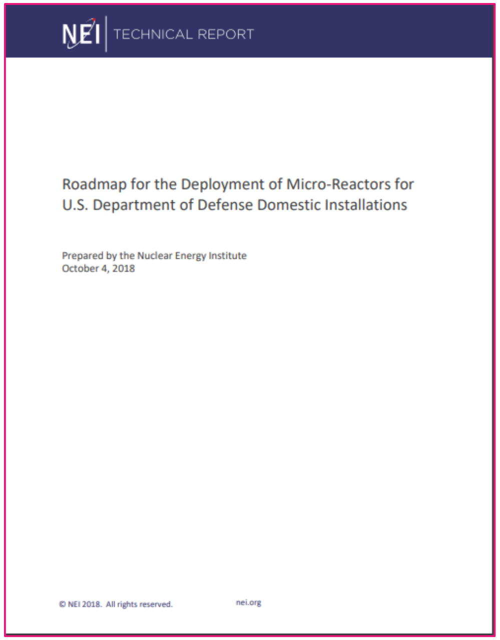
- **Outputs**
  - ✓ Modular and scalable units capable of producing 2–10 MWe
  - ✓ Potentially useful heat (which could facilitate water or fuel production)
- **Size and transportability**
  - ✓ 25–40 tons; transportable by truck or C-17 aircraft
- **Ultimate heat sink**
  - ✓ Ambient air; capable of 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

<Source : Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations>


NEI | TECHNICAL REPORT

Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations

Prepared by the Nuclear Energy Institute
October 4, 2018

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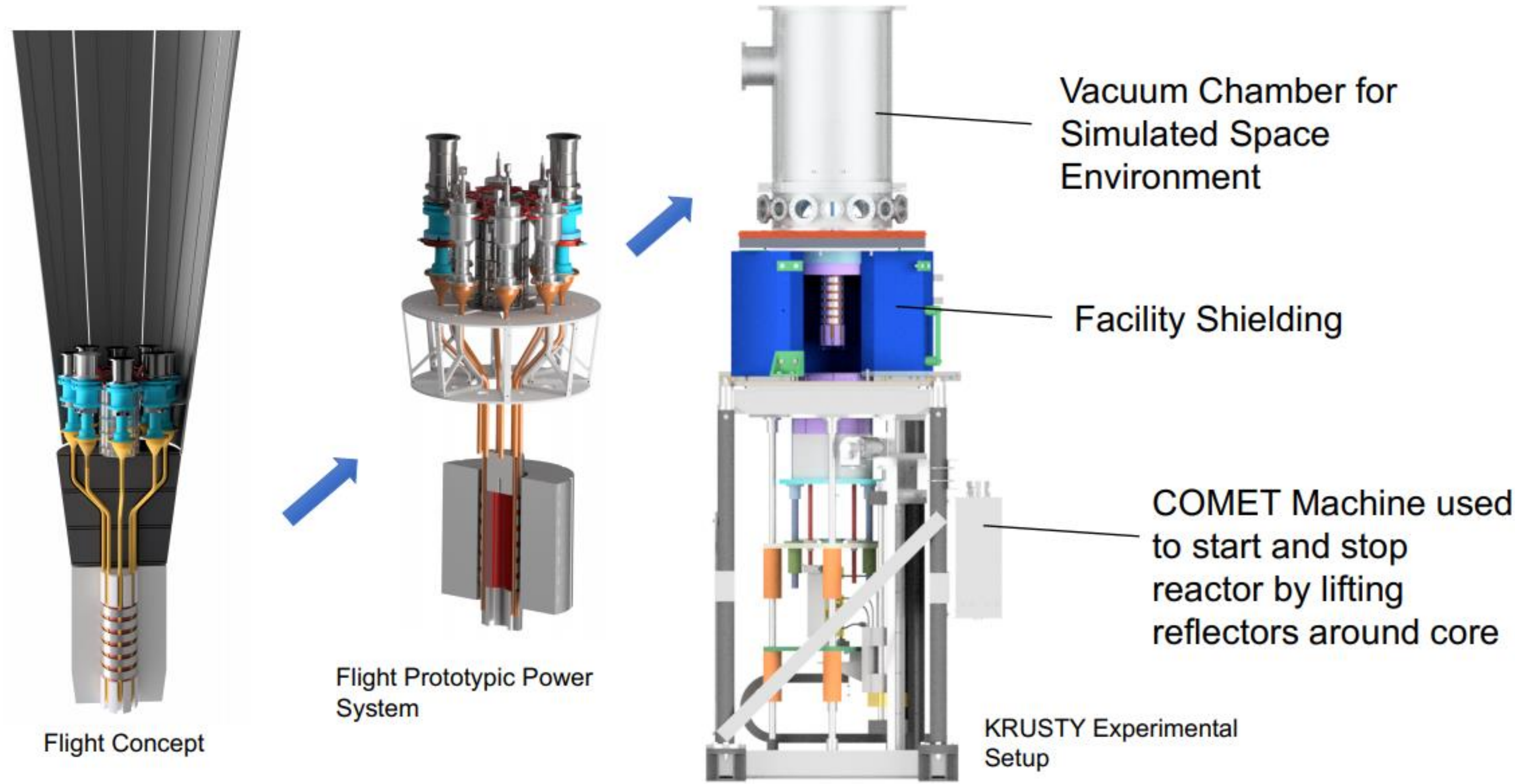
Heat Pipe Cooled Nuclear Reactor Development at LANL

- **KRUSTY (Kilopower Reactor Using Stirling Technology)**
  - ✓ Testbed for Kilopower reactor

<Source: KRUSTY Design and Modeling, LA-UR-16-28377>



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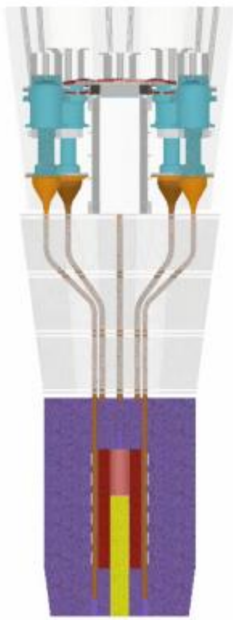
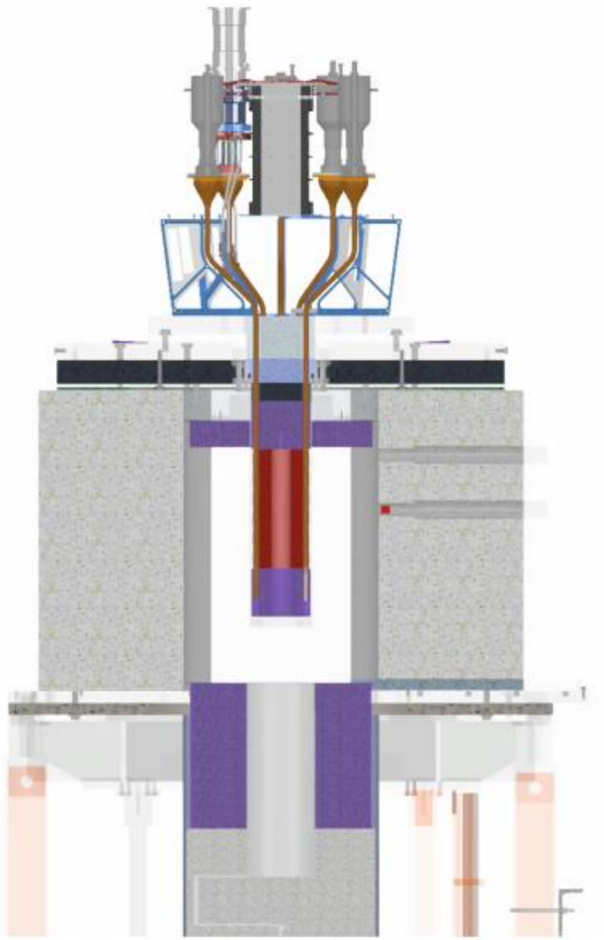
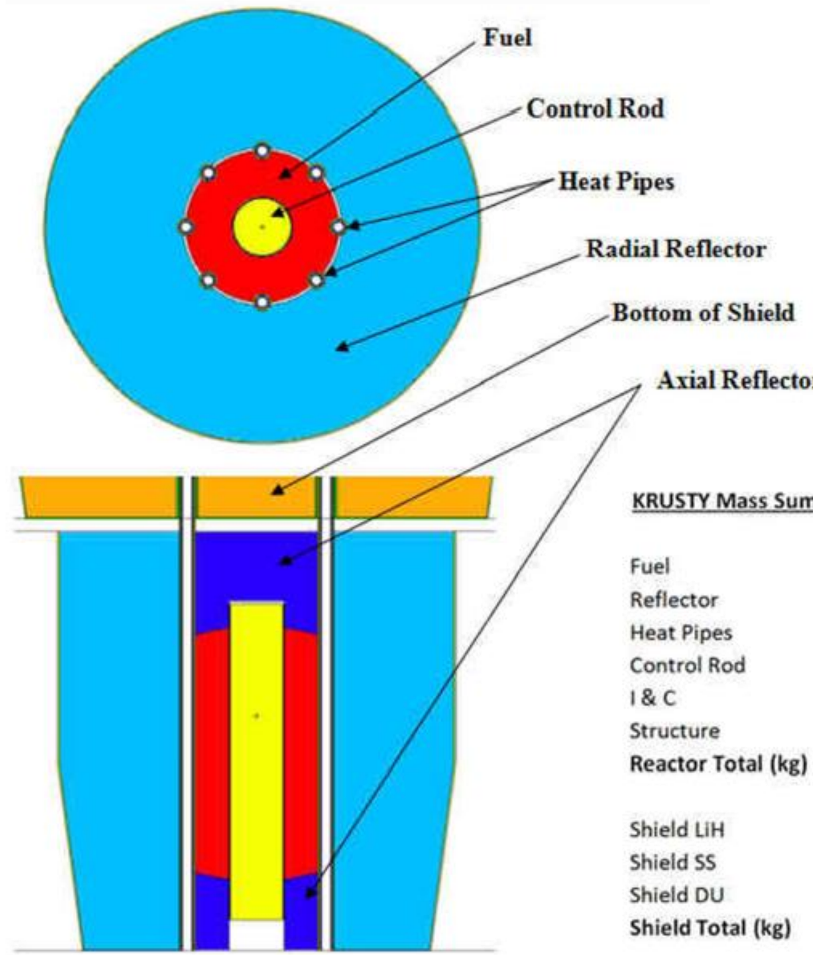






KRUSTY Mass Summary (kg)

Fuel	26.7
Reflector	70.5
Heat Pipes	4.1
Control Rod	0.8
I & C	10.0
Structure	10.0
Reactor Total (kg)	**122.1**
Shield LiH	40.4
Shield SS	13.0
Shield DU	45.3
Shield Total (kg)	**98.7**

Heat Pipe Cooled Nuclear Reactor Development at LANL

- **KRUSTY (Kilopower Reactor Using Stirling Technology)**
  - ✓ Specification

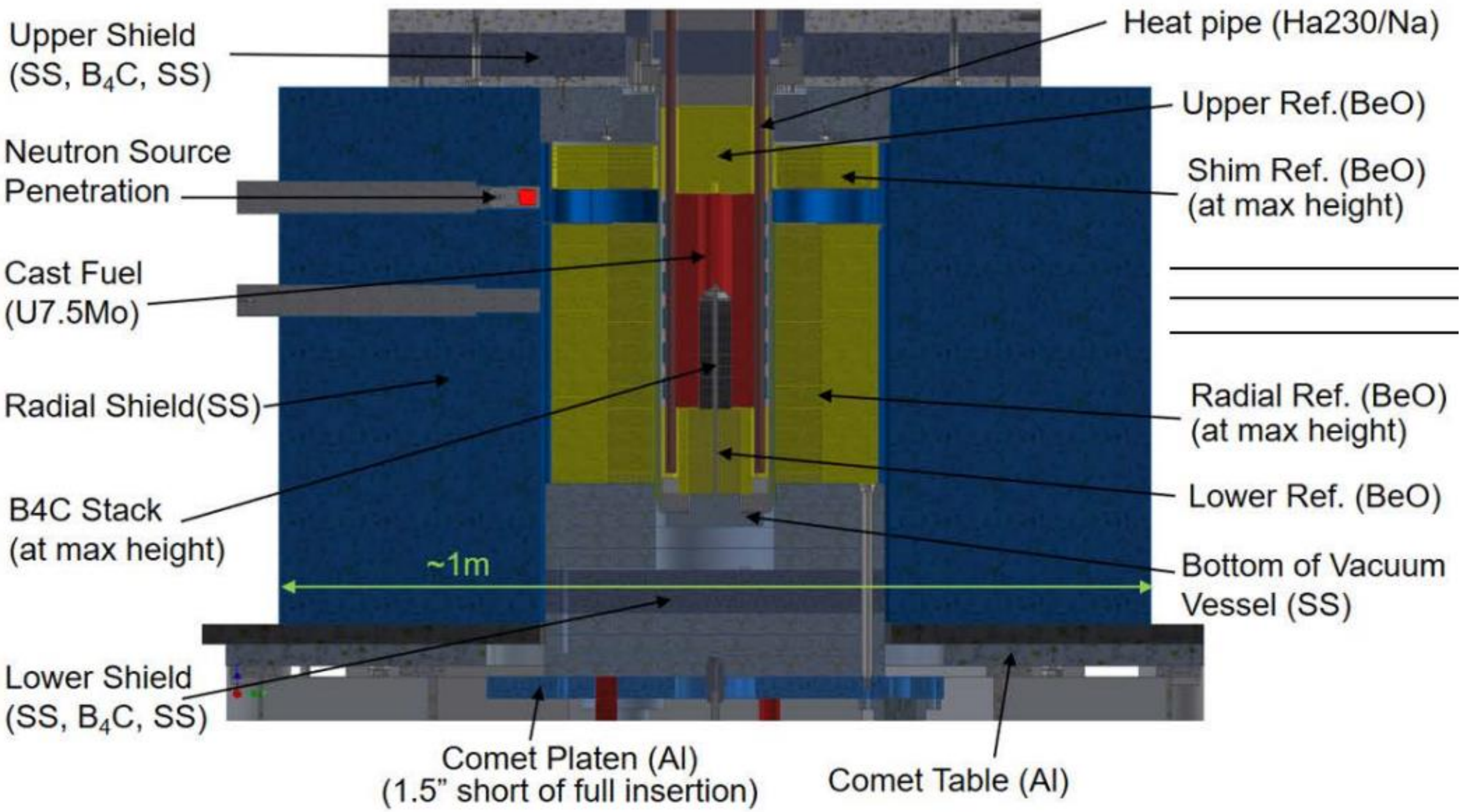
<Source: KRUSTY Design and Modeling, LA-UR-16-28377>

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

Heat Pipe Cooled Nuclear Reactor Development at LANL

- **KRUSTY (Kilopower Reactor Using Stirling Technology)**
  - Nuclear test

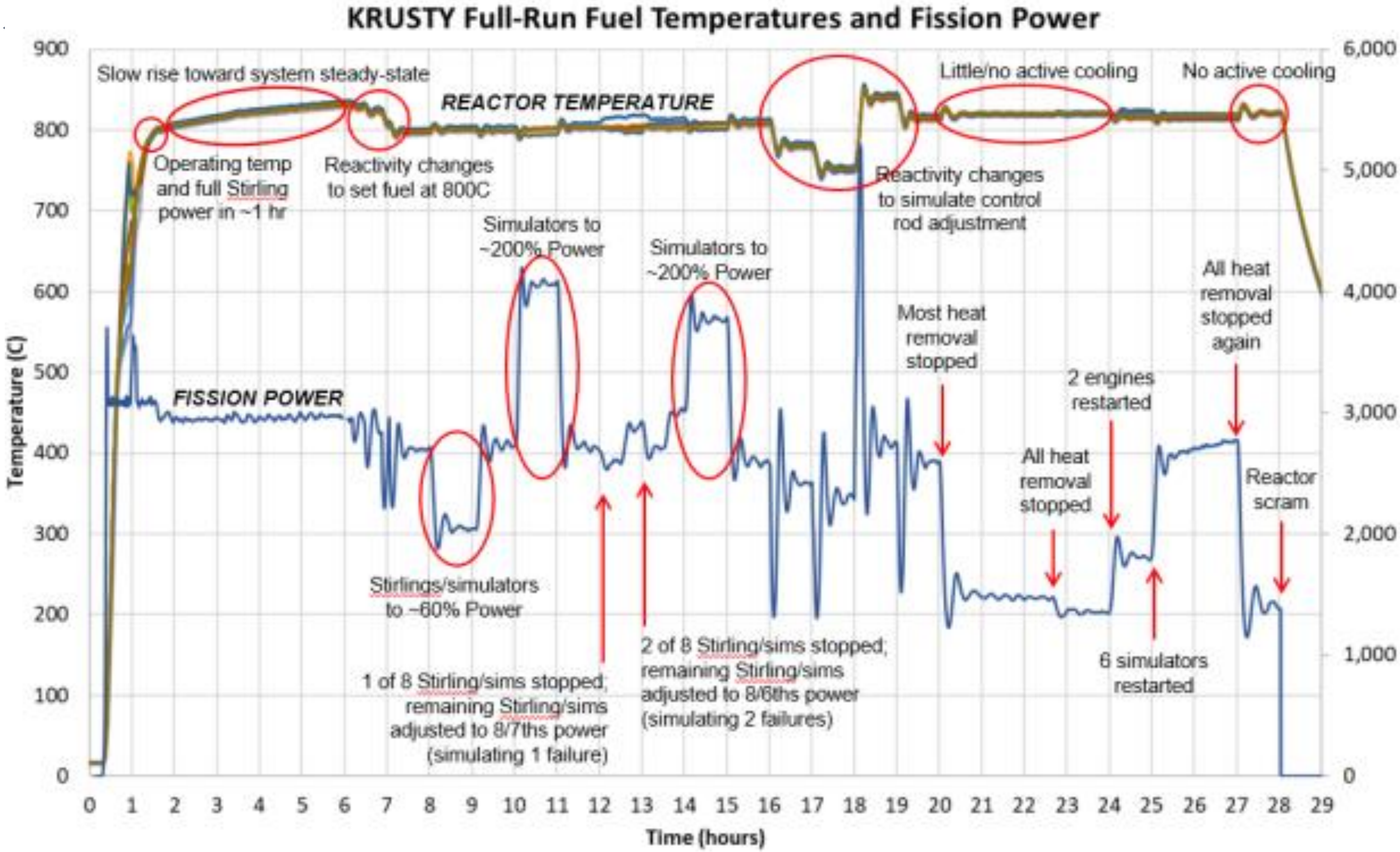
<Source: KRUSTY Design and Modeling, LA-UR-16-28377>



Heat Pipe Cooled Nuclear Reactor Development at LANL

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

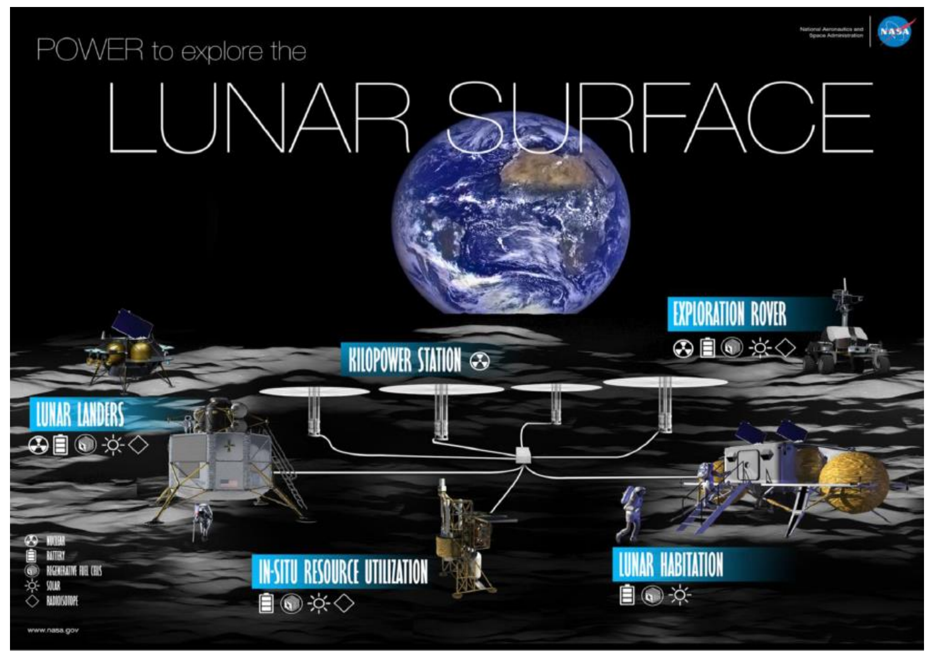
<Source : The Kilopower Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned, LA-UR-19-23192>



Heat Pipe Cooled Nuclear Reactor Development at LANL

- **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)

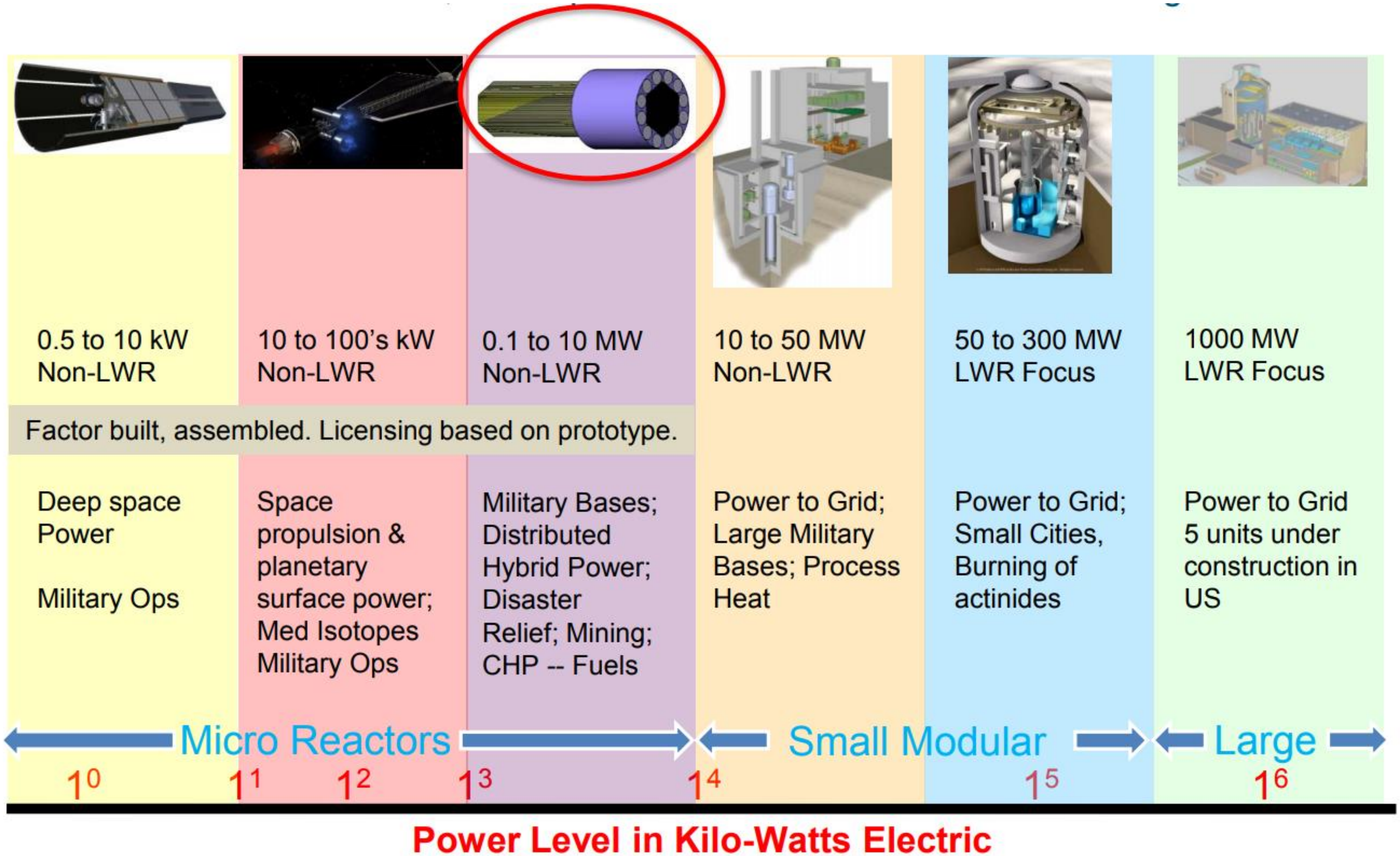
<Source : Dionne Hernandez-Lugo, Special Topic for Nuclear CLT: Kilopower Project 1, 2018>



Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations

Heat Pipe Cooled Nuclear Reactor Development at LANL

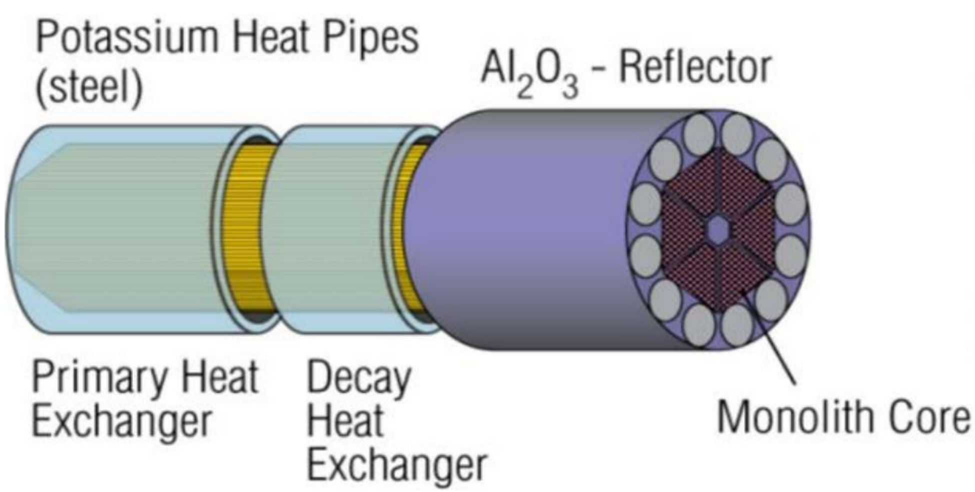
- **MegaPower (TRL : 6 or better)**

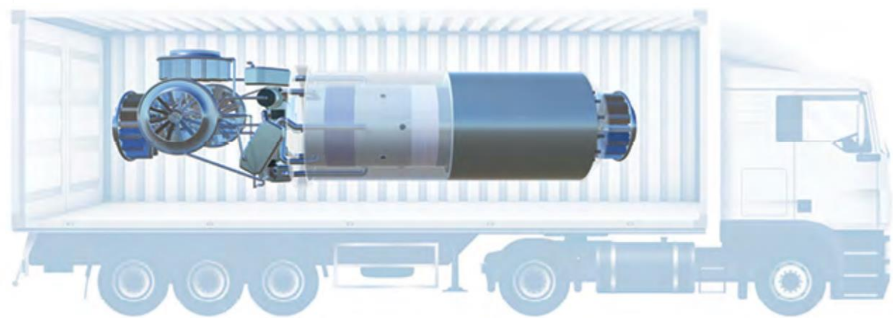


LA-UR-15-28840, DESIGN OF MEGAWATT POWER LEVEL HEAT PIPE REACTORS

Heat Pipe Cooled Nuclear Reactor Development at LANL

- **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



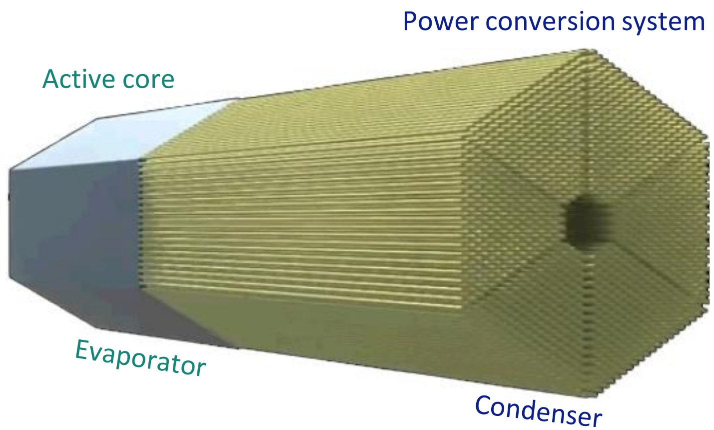


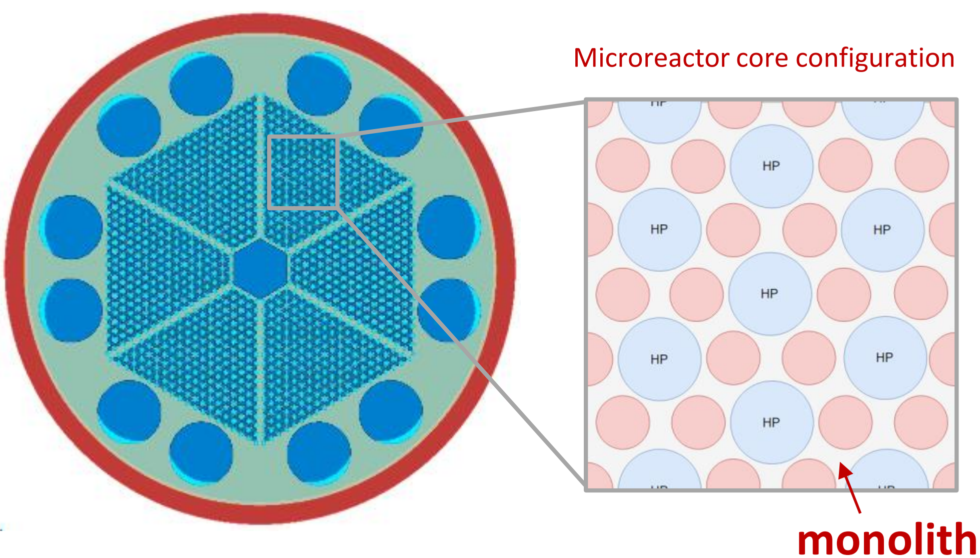
LA-UR-15-28840, DESIGN OF MEGAWATT POWER LEVEL HEAT PIPE REACTORS

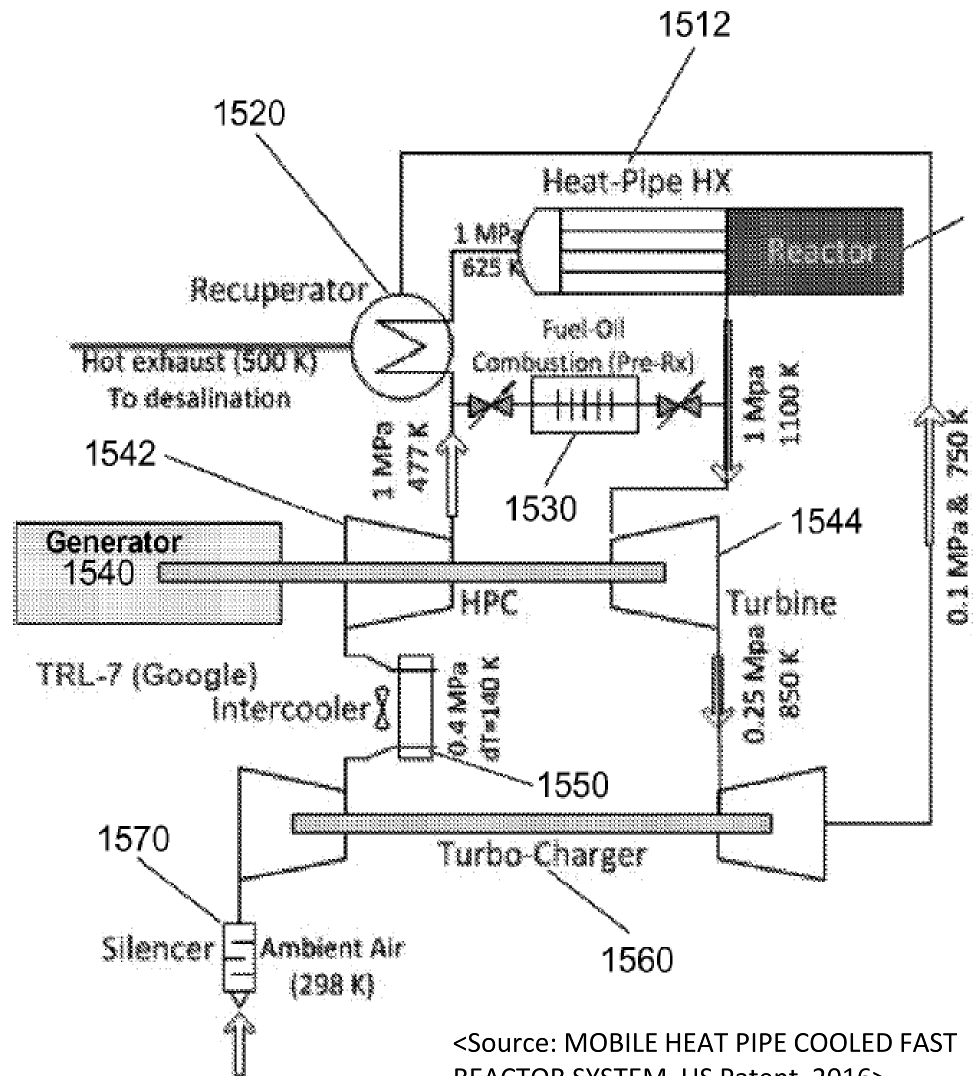
Heat Pipe Cooled Nuclear Reactor Development at LANL

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

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







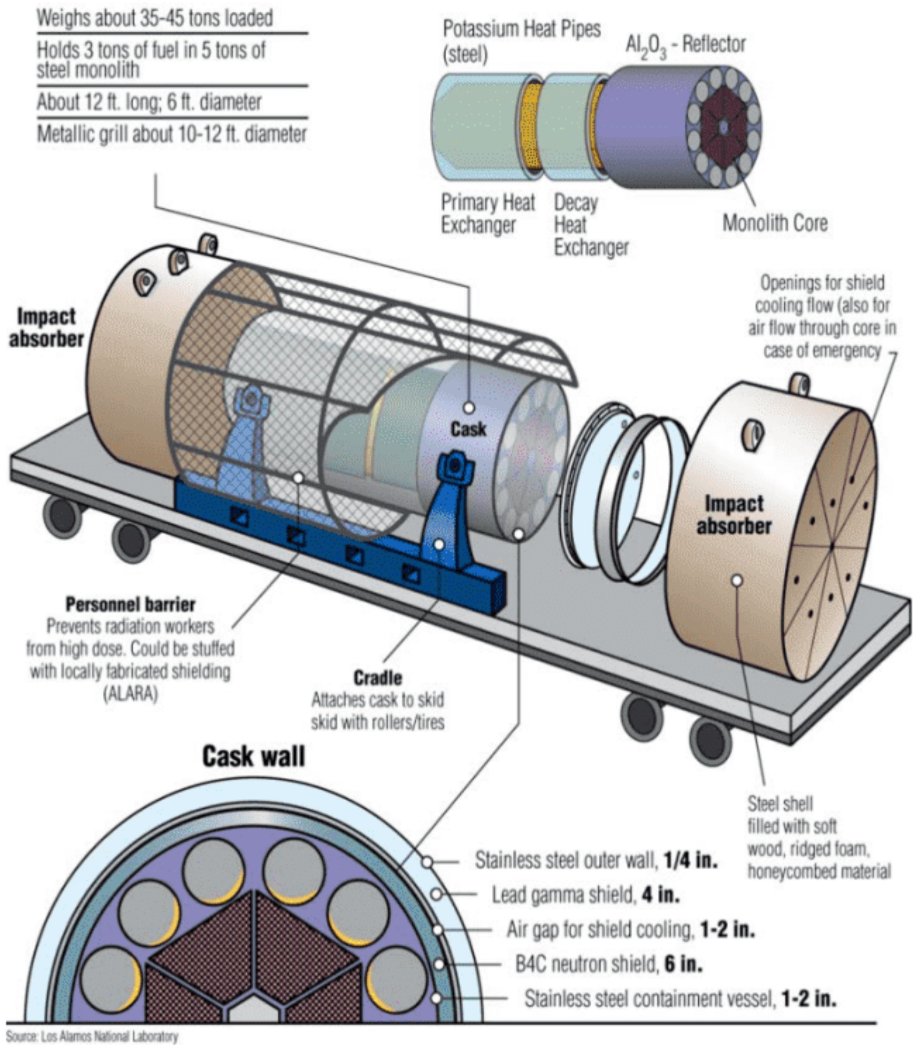
<Source: MOBILE HEAT PIPE COOLED FAST REACTOR SYSTEM, US Patent, 2016>

Heat Pipe Cooled Nuclear Reactor Development at LANL

LANL MegaPower Reactor

LA-UR-15-28840, DESIGN OF MEGAWATT POWER LEVEL HEAT PIPE REACTORS

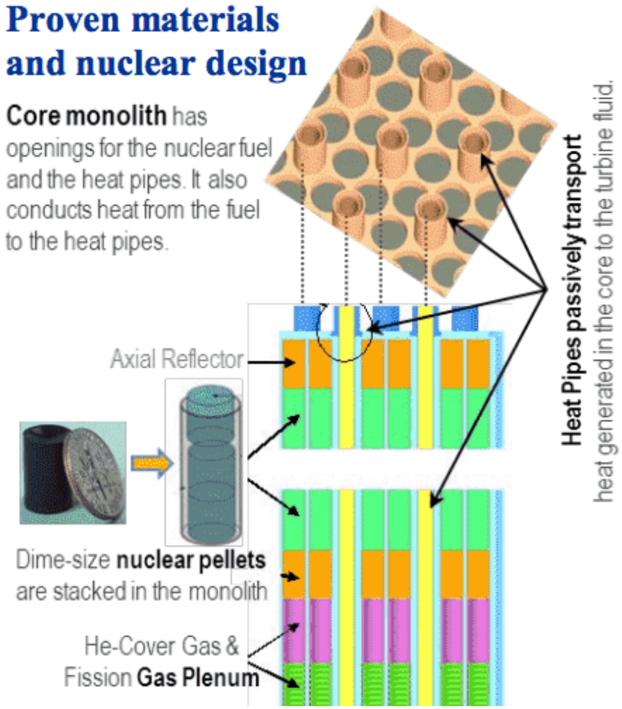
Nominal 2 MWe (5 MWth) Mobile Reactor Package



- 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

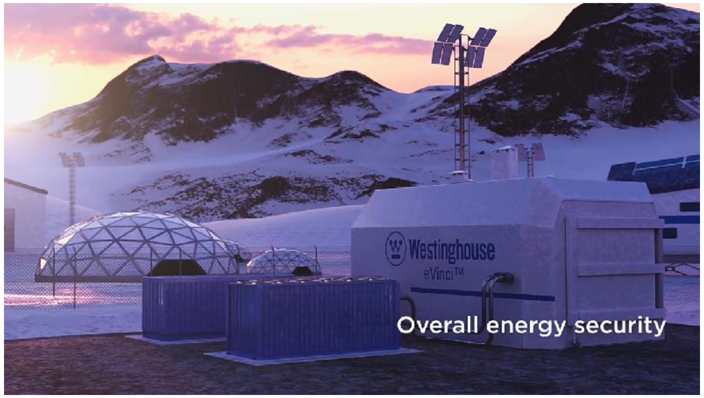
Proven materials and nuclear design

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



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

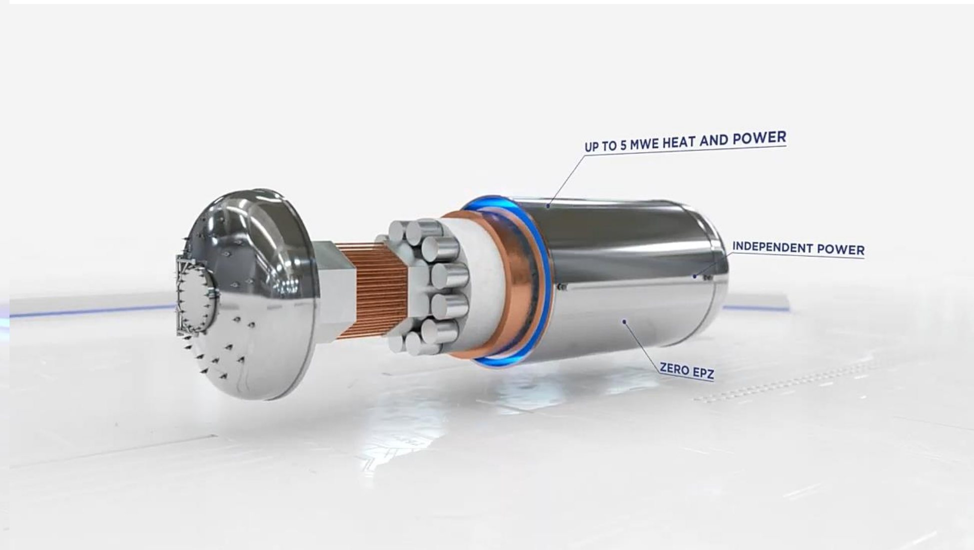


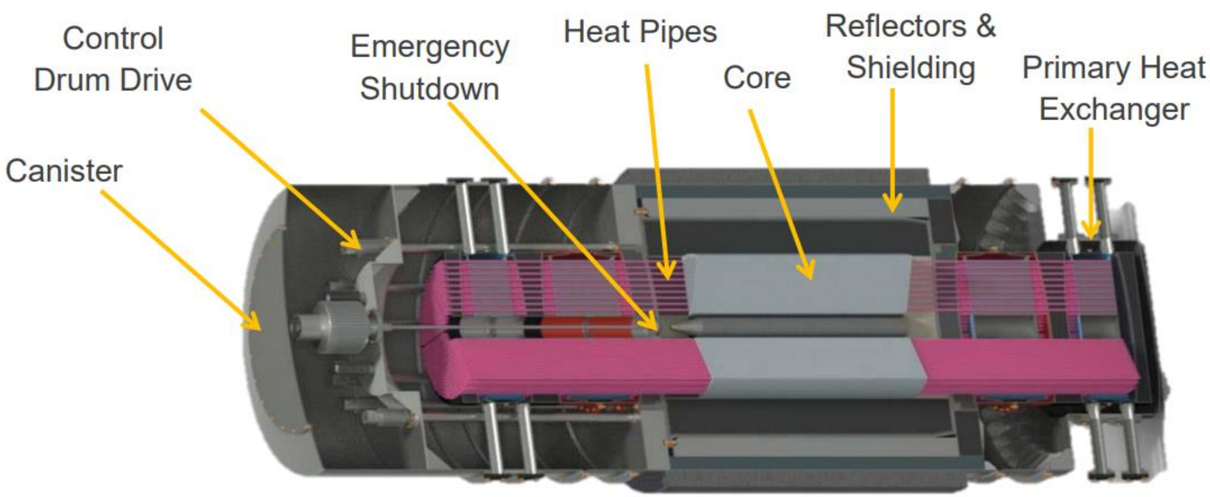
<Source: http://www.westinghousenuclear.com/new-plants/evinci-micro-reactor>

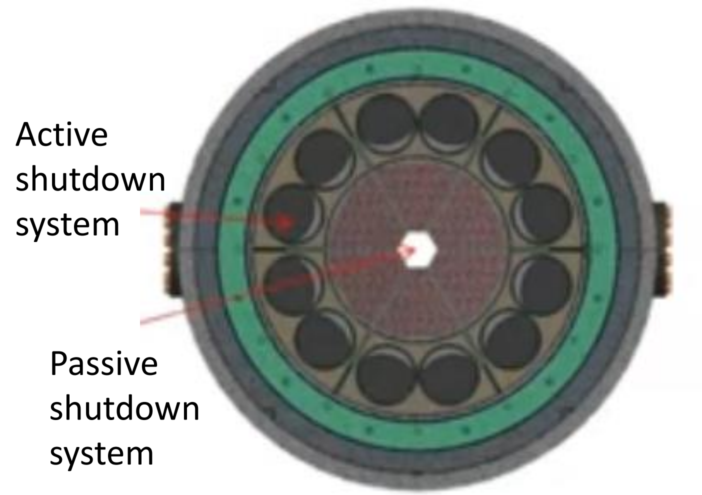
Westinghouse eVinci Micro Reactor

- **eVinci**

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



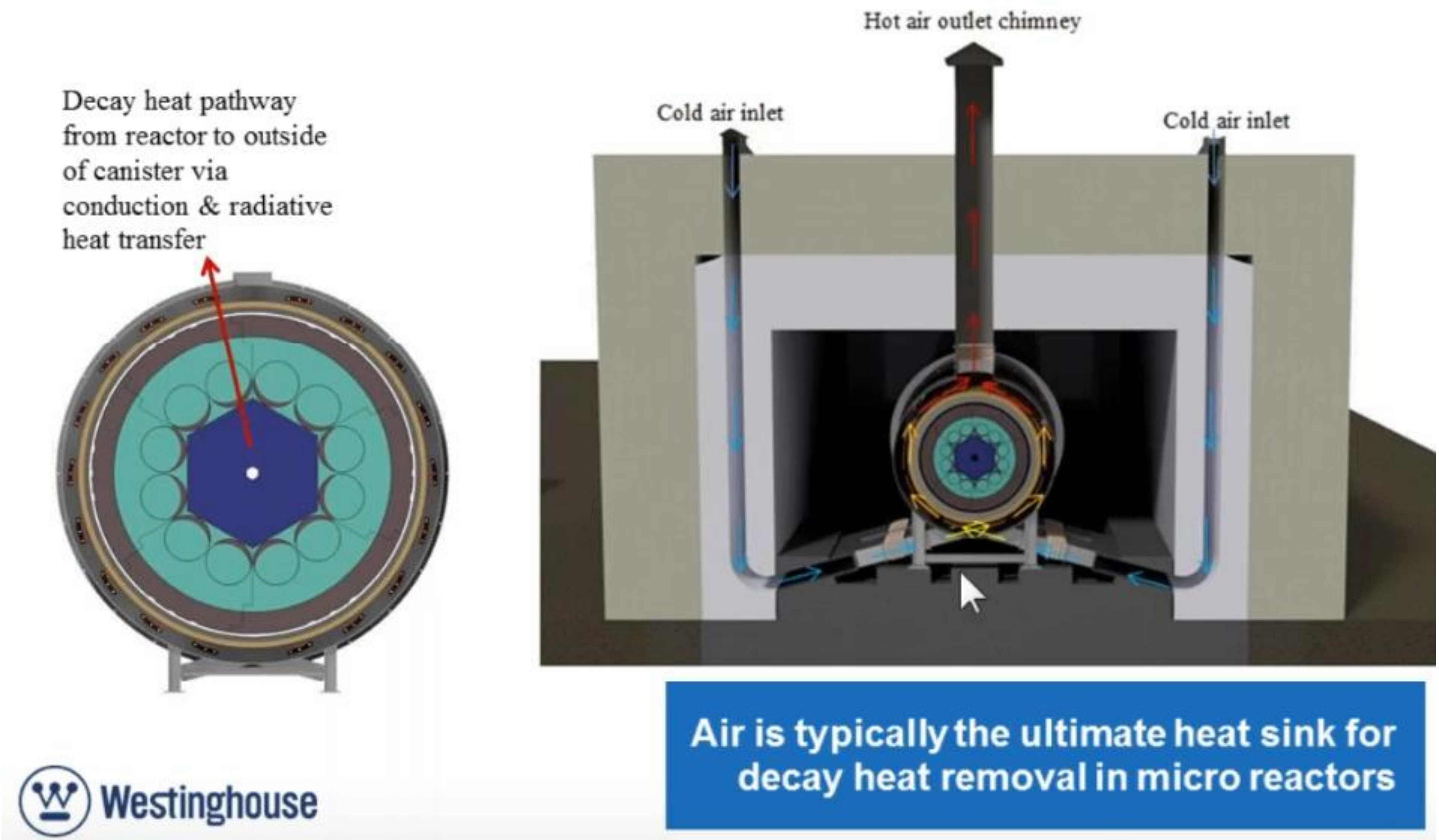




Westinghouse eVinci Micro Reactor

- **eVinci**

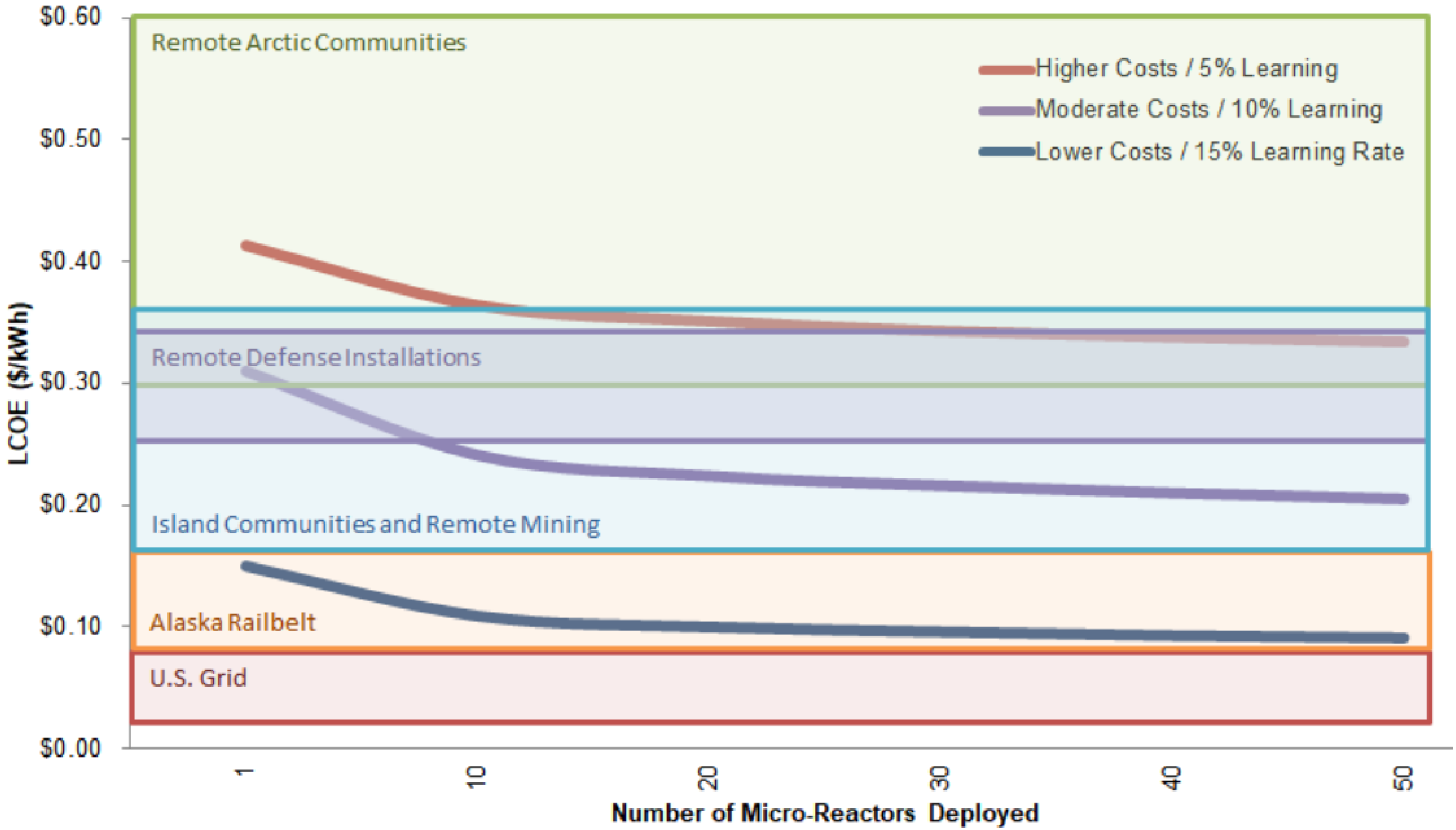
<Source: ENS webinar Micro reactor technology applications Westinghouse Electric Company>



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

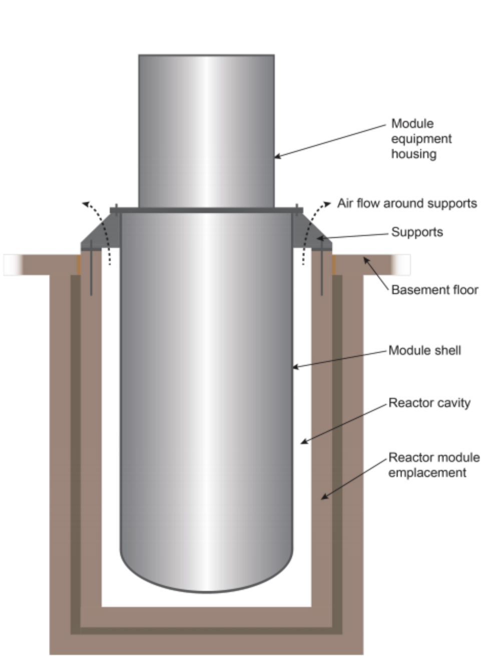
U.S. DEPT OF DEFENSE

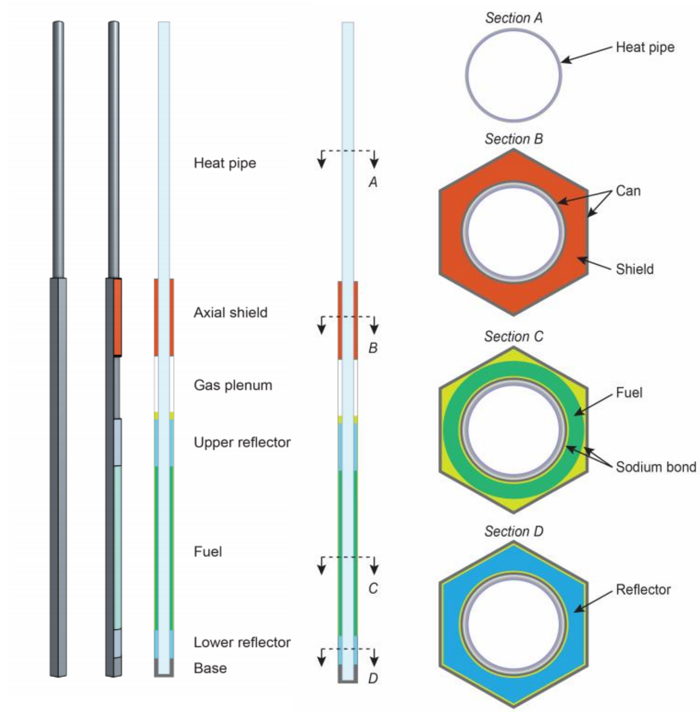
Aurora (OKLO)

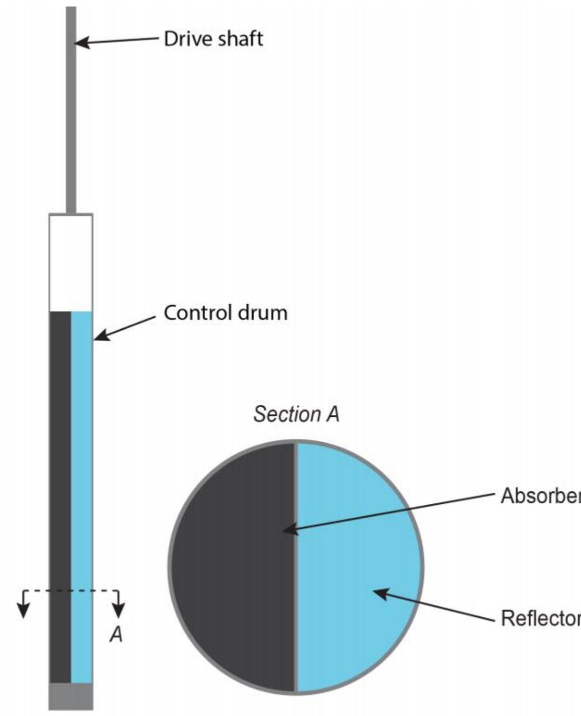
- **Compact fast reactor, heat pipe cooled reactor, site: INL**
  - ✓ Power: 4 MW_{th} (~ 1.5 MW_e), supercritical CO_2 Power Conversion System
  - ✓ Containment Type: underground, reactor contained in several layers, including a robust cask-like module
  - ✓ Metallic uranium-zirconium. High Assay Low Enriched Uranium (HALEU)
  - ✓ FSAR submitted

Aurora (OKLO)

❖ Aurora (OKLO)



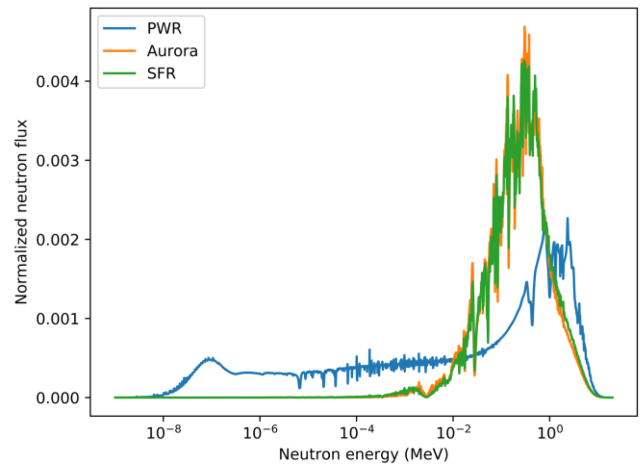


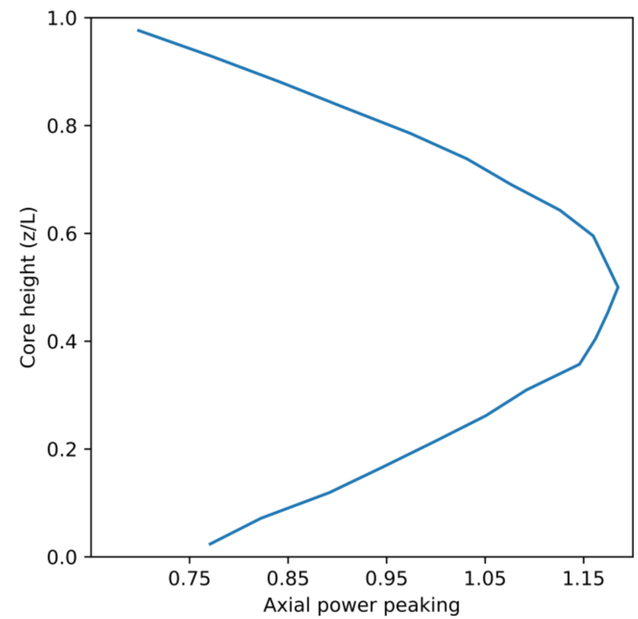


Aurora (OKLO)

❖ 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





Component	Reactivity coefficient (pcm/K)
Fuel thermal expansion	-0.50
Fuel doppler	-0.15
Reactor cell thermal expansion	-0.07
Baseplate thermal expansion	-1.40
Net	**-2.12**

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

Type	Goal	Limit	
Safety	Control release of radionuclides by maintaining fuel integrity	T_{fuel} < 1200 C	Melting point
Operational	Maintain reactor cell can integrity by keeping fuel-steel temperatures within time-temperature limits	T_{fuel} < 720* C	

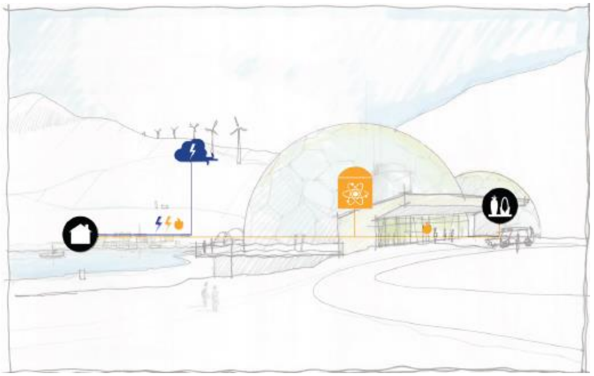
*Onset of eutectic formation is conservatively defined to begin at 720, but is very slow if it occurs at all at these temperatures, and no cliff-edge effects occur

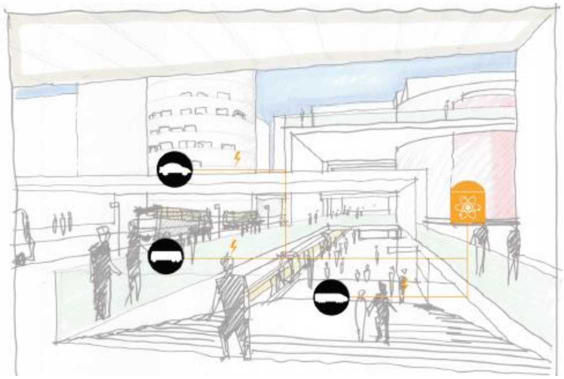
- ✓ Safety analysis using
  - – ANSYS Mechanical + Serpent, in-house Oklo point kinetics solver

Nuclear Reimagined with Microreactors

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

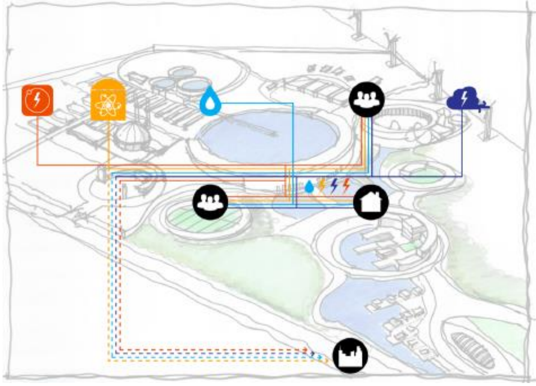
Remote Arctic Community





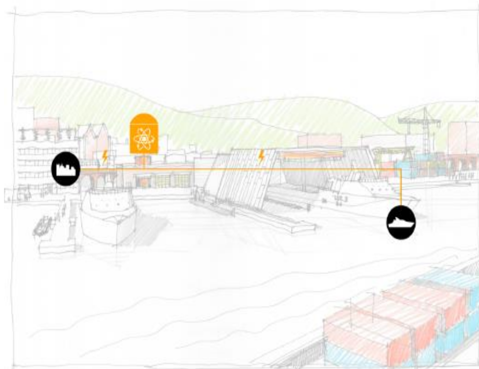
Clean Transit Hub

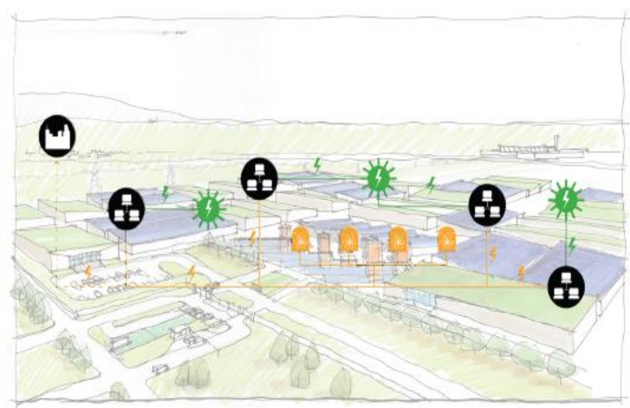
Catalyst for Clean Growth



Nuclear Reimagined with Microreactors

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





Design Issues in Heat Pipe Cooled Reactor Core

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

- **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

Design Issues in Heat Pipe Cooled Reactor Core

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

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

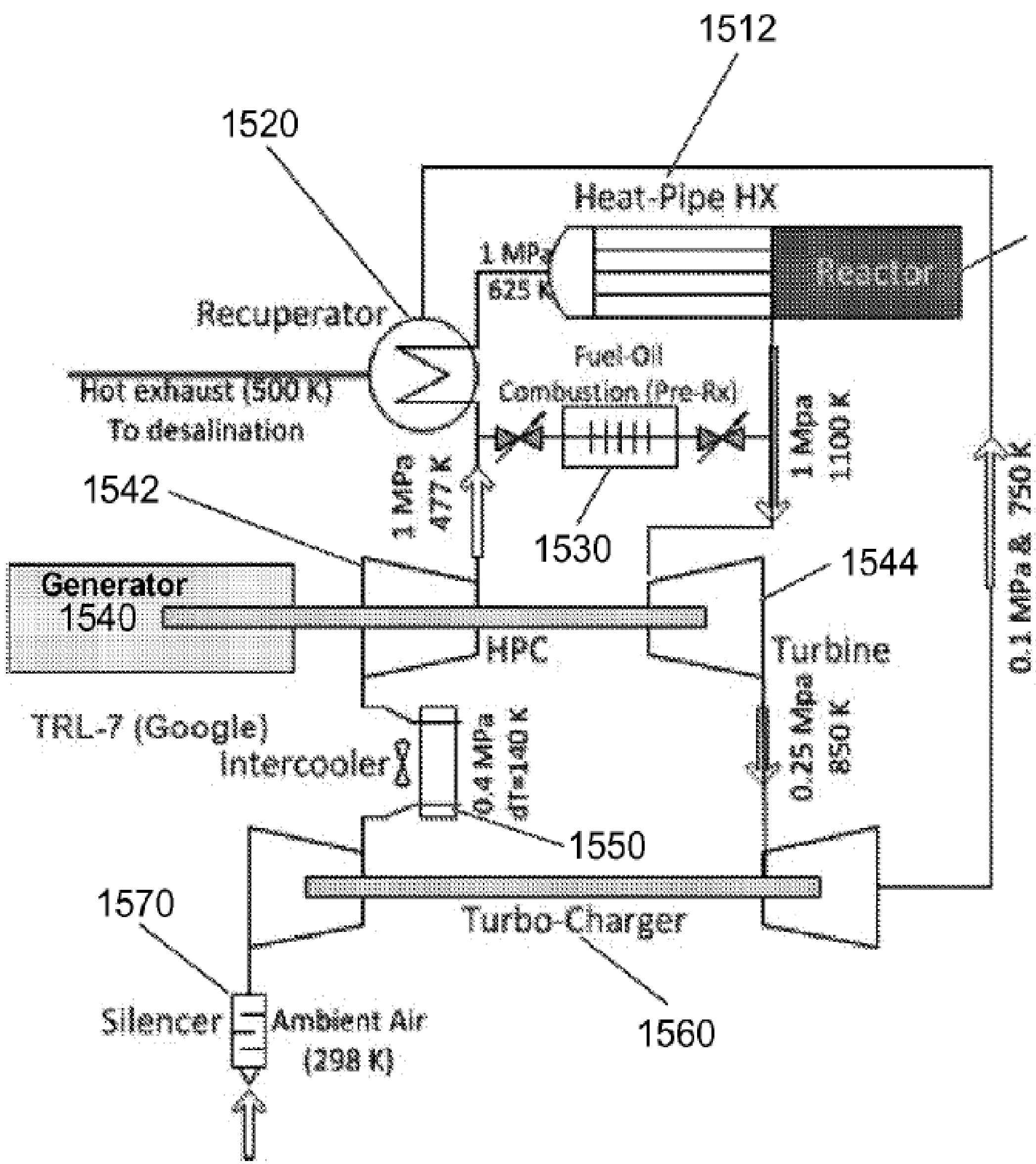
Monolith structure

- ✓ 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

HW-5



<Source: MOBILE HEAT PIPE COOLED FAST REACTOR SYSTEM, US Patent, 2016>