HEAT-PIPE MICROREACTORS

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Fast Reactor Technology Training
U.S. Nuclear Regulatory Commission

ACKNOWLEDGEMENTS

Heat Pipe Basics

- NASA/Goddard Space Flight Center has many excellent, detailed materials on heat pipe technology
- Credit for many of the following figures to Jentung Ku of NASA

Heat Pipe Challenges and Testing Experience

- Institute for Space and Nuclear Power Studies, “Challenges and Fundamentals of Modeling Heat Pipes’ Startup from a Frozen State,” Proceedings of the AIP Conference, 2002.
- Ranken, W.A., “Irradiation of High Temperature Heat Pipes,” VI International Heat Pipe Conference, France, May 25-28, 1987.

Special Purpose Reactor

- INL, “Special Purpose Nuclear Reactor (5MW) for Reliable Power at Remote Sites Assessment Report,” INL/EXT-16-40741, 2017.
- INL, “Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor,” INL/EXT-17-43212, 2018.

OBJECTIVES

- Understand the basics of heat pipes
- Understand heat pipe applications
- Understand heat pipe reactors

Basics of Heat Pipes

Heat Pipe Applications

Heat Pipe Reactors

Basics of Heat Pipes

Heat Pipe Applications

Heat Pipe Reactors

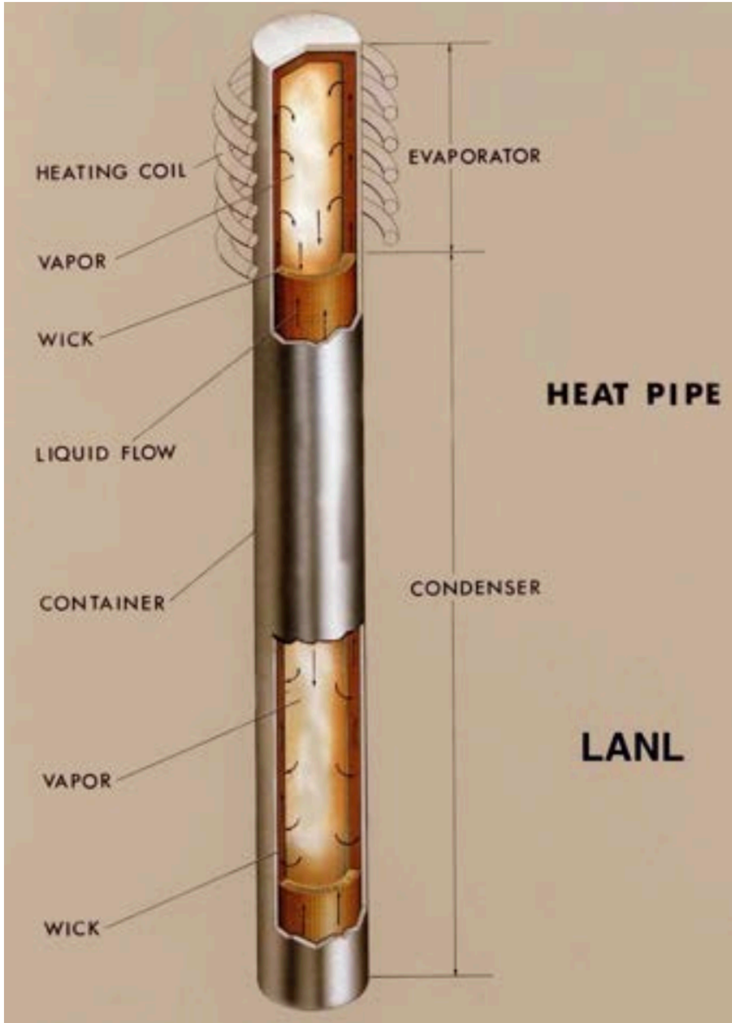
HEAT PIPES: THE BASICS

■ Principles

- Heat pipes are heat transfer devices
- Utilize thermal conduction and phase transition of a working fluid
- Two-phase (boiling and condensation) allow large heat transfer with minimal △T between heat source and sink

■ Benefits

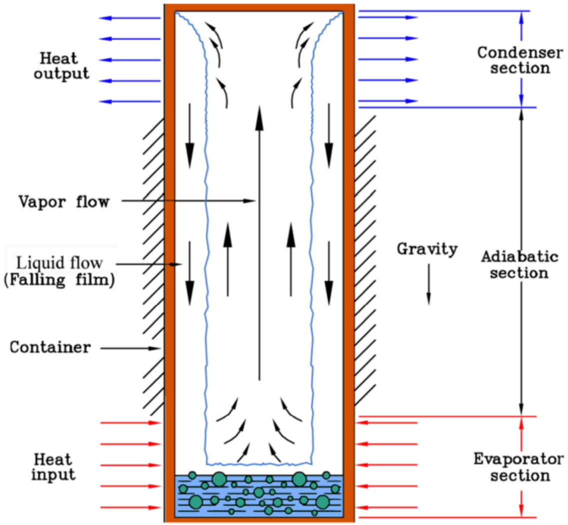
- Excellent heat transfer rates
- Completely passive, no power sources, no moving parts (other than fluid)
- Completely sealed system, no exchange of fluid or interfacing systems



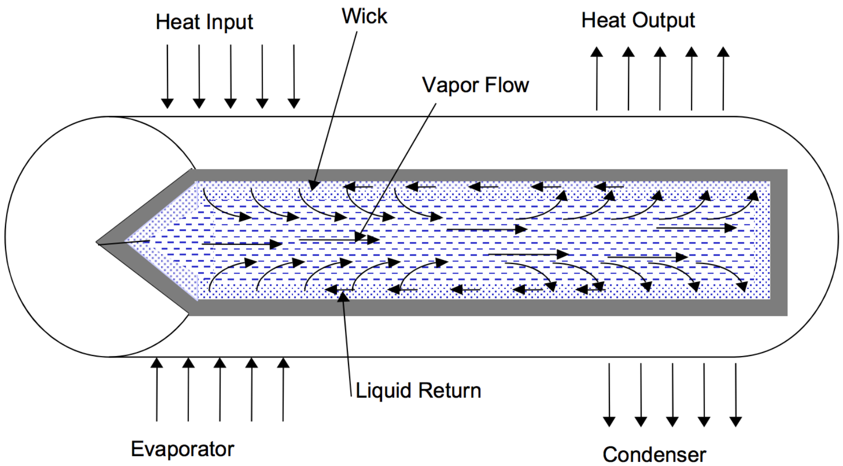
HEAT PIPES: THE BASICS

- Types
  - The term “heat pipe” is applied to several similar but different devices
  - The two most common forms are:

Gravitational
(thermosyphon or Perkins tube)



Capillary
(wicking)

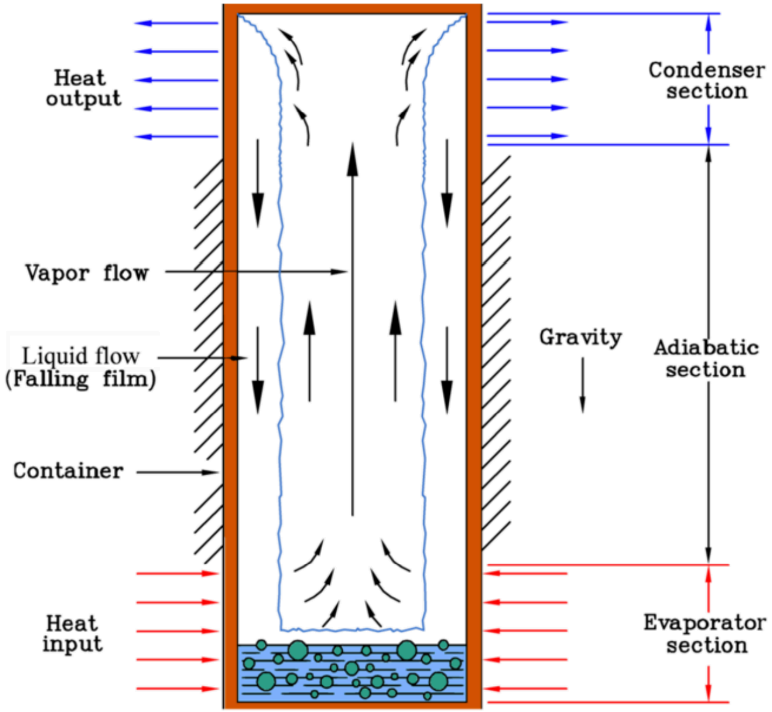


HEAT PIPES: GRAVITATIONAL

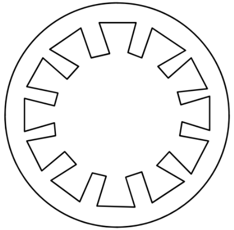
- Principle
  - Somewhat similar to a natural circulation loop
  - Working fluid is heated until evaporation and rises in pipe
  - Vapor cools and condenses at the top of the pipe
  - Liquid falls back to bottom of pipe due to gravity

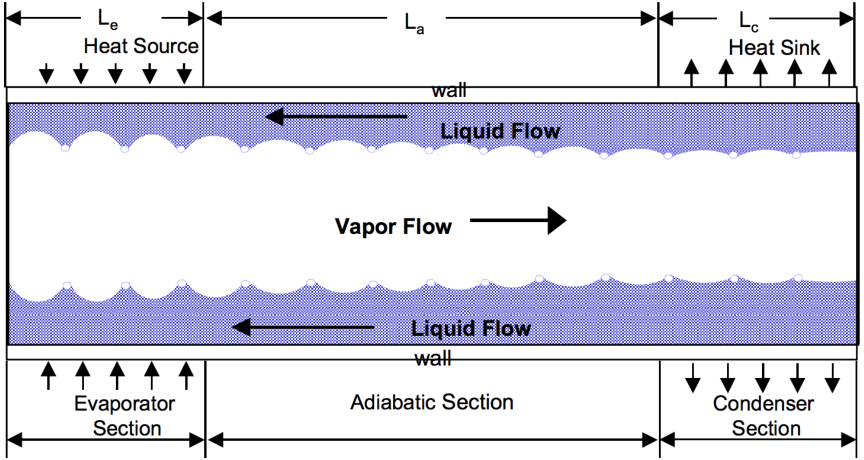
- Benefits
  - Very simple

- Limitations
  - Only works in one orientation (with gravity)



HEAT PIPES: CAPILLARY





Principle

- Working fluid is heated until evaporation
- Vapor travels to cooler area of the pipe due to vapor pressure difference
- Vapor condenses onto an internal wick
- Capillary forces transport liquid back to evaporator portion of the pipe due to liquid pressure differential

Benefits

- Very simple
- Can be used in any orientation
- Can be two-sided

Limitations

- Pressure drop can't exceed capillary pressure head

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HEAT PIPES: THE BASICS

■ Heat Transfer Rates

- Very high heat transfer rates are possible due to energy of phase transitions
  - Heat capacity of water:
    - ~4.22 kJ/kgK (100ºC)
  - Enthalpy of vaporization of water:
    - ~2250 kJ/kg (100ºC)

- Very high thermal conductivity
  - Thermal conductivity of solids
    - Aluminum (~200 W/mK)
    - Copper (~400 W/mK)
    - Diamond (~1,000 W/mK)
  - Effective thermal conductivity of heat pipes
    - 5,000 – 200,000 W/mK

- Very high heat transfer rates
  - Heat transfer rates of 23,000 W/cm^2 have been achieved with lithium heat pipes
  - For comparison, the heat emitted from the sun is 6,000 W/cm^2

In this photo taken in the early 1960s, physicist George Grover tests a heat pipe.

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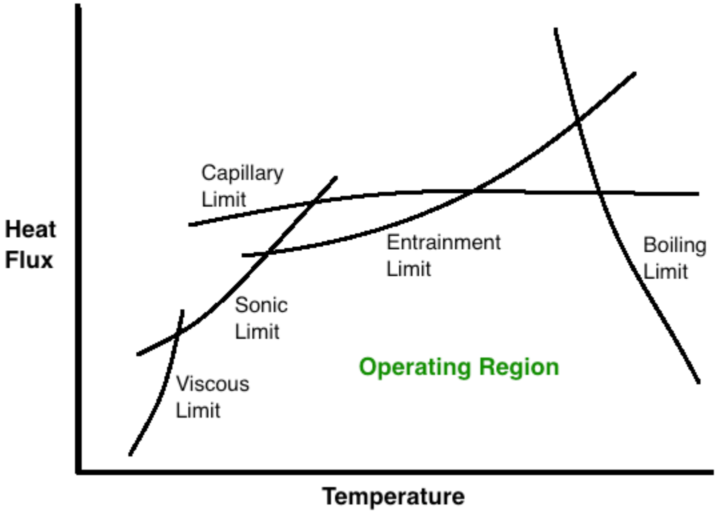
HEAT PIPES: COMMON FLUIDS AND MATERIALS

Fluid	Approximate Operating Temperature Range (ºC)	Heat of Vaporization (kJ/kg)	Heat Pipe Material
Helium	-271 to -269	~20	SS, Titanium
Ammonia	-75 to 125	~1,300	Aluminum, SS
Water	1 to 300	~2,250	Copper, Titanium
NaK	500 to 800	~2,500	SS
Sodium	500 to 1,200	~4,000	SS
Lithium	1,000 to 1,825	~21,000	Tungsten, Niobium

- Operating temperatures are generally limited to a region around working fluid saturation temperature

HEAT PIPES: CHALLENGES

- Limits
  - **Viscous**: Near triple point or melting point of fluid, high viscosity prevents circulation back to the evaporator
  - **Sonic**: At high power but low temperature, the vapor flow reaches sonic velocity, choking the flow
  - **Entrainment**: High vapor velocity strips the liquid from the walls (larger concern for thermosyphons with no wick)
  - **Capillary**: Capillary force is insufficient to overcome pressure drop
  - **Boiling**: Rapid boiling and surface bubbles in the evaporator prevent condensate from entering and re-wetting



HEAT PIPES: CHALLENGES

- **Startup**
  - For certain fluids, starting from a frozen state can be challenging, partly due to viscous limit and sonic limit
    - High viscosity prevents return of fluid to the evaporator
    - Choked flow prevents condenser from heating up causing fluid to solidify on condenser section and not flow back to evaporator
    - At sonic limit, high vapor velocities near the condenser sweep fluid out of wick (entrainment limit)
    - Choked flow limits heat transfer to condenser until pressure drop becomes higher than capillary limit, resulting in dryout

- **Scalability**
  - Scalability becomes an issue at larger heat fluxes due to capillary, entrainment, and boiling limits

- **Lifetime**
  - Working fluid degradation with time (more on this in reactor applications section)

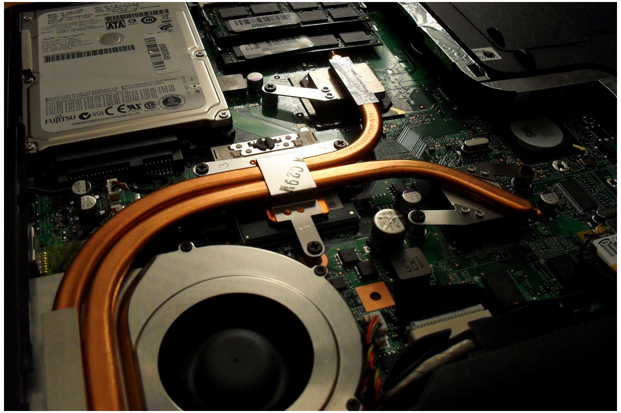
Basics of Heat Pipes

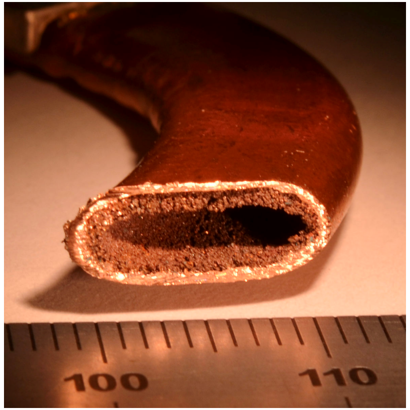
Heat Pipe Applications

Heat Pipe Reactors

HEAT PIPE APPLICATIONS:

- Computers
  - CPU and GPU heat is passed to fans or finned heat exchangers through heat pipes
- Cell Phones
  - Micro heat pipes utilized to dissipate CPU heat
- Aerospace
  - Component temperature control, such as equilibrating satellite temperatures during different orientations
  - Dissipation of electronic component heat to the environment





https://commons.wikimedia.org/wiki/File:Laptop_Heat_Pipe.JPG

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HEAT PIPE APPLICATIONS:

- Ovens
  - Acts as heat exchanger between heat source and oven allowing separation of combustion products and oven contents
- Pipelines
  - Over 120,000 heat pipes along the Trans-Alaska pipeline ensure the soil remains frozen and stable
- Solar Power
  - Solar collectors for heating water
- Geothermal
  - For residential or industrial heating, typically in combination with a heat pump
- HVAC Systems
  - Passive pre-cooling/heating

https://commons.wikimedia.org/wiki/File:Trans-Alaska_Pipeline_(1).jpg

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Basics of Heat Pipes

Heat Pipe Applications

Heat Pipe Reactors

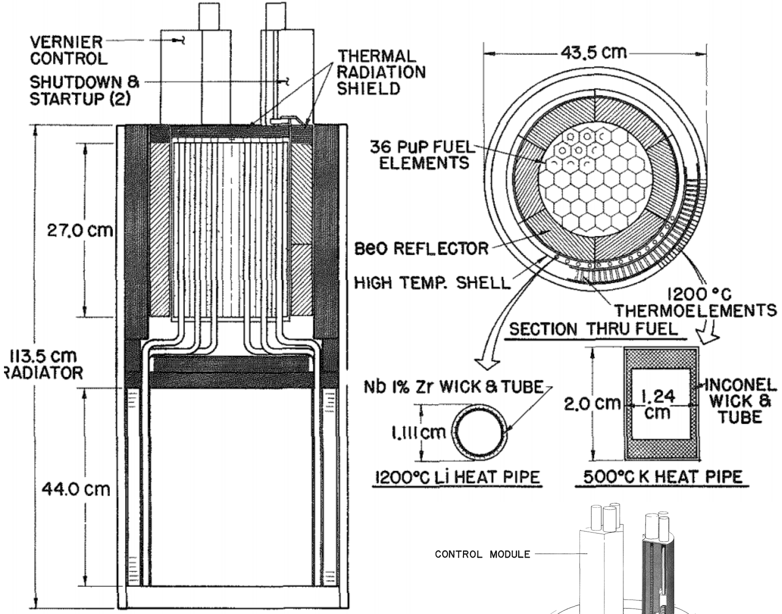
HEAT PIPE APPLICATIONS: REACTORS - SPACE

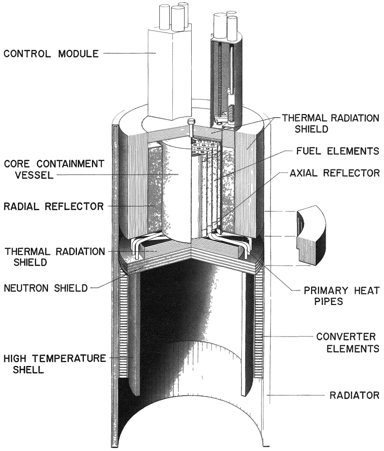
■ Long History

- First capillary heat pipes developed at Los Alamos National Lab in the early 1960s as part of research for space reactors
- Since that time, many heat pipe-based space reactors have been proposed
  - Ideal for space conditions (zero gravity, necessity of high reliability/simplicity, etc.)
- Decades of testing and billions of dollars in research
- Following slides provide an overview of some of the major projects

■ Early Concepts

- 1960s – 1970s
- Many different concepts from Los Alamos, Argonne, and Oak Ridge
- Thermoelectric, thermionic, stirling generators all considered

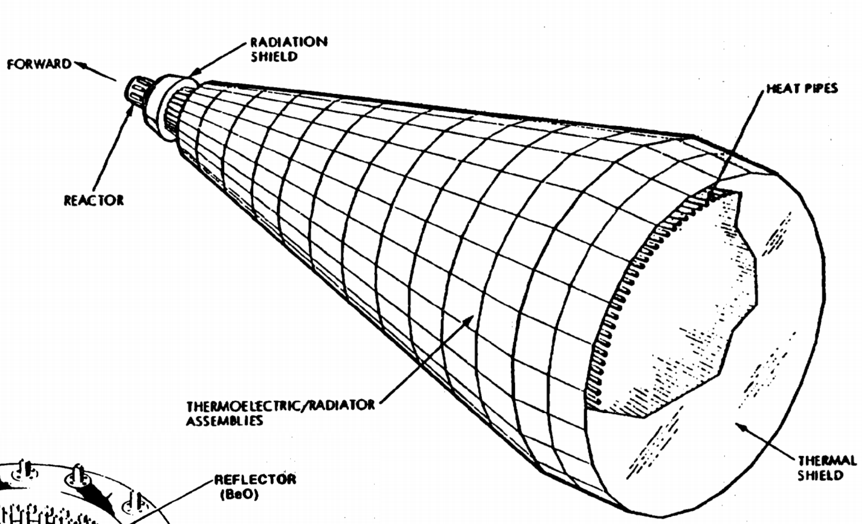


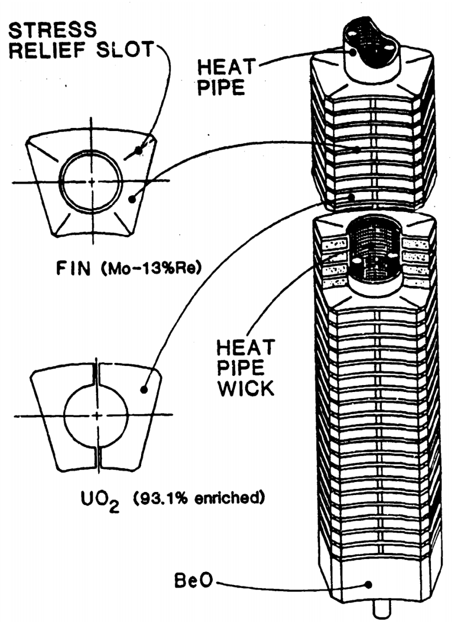


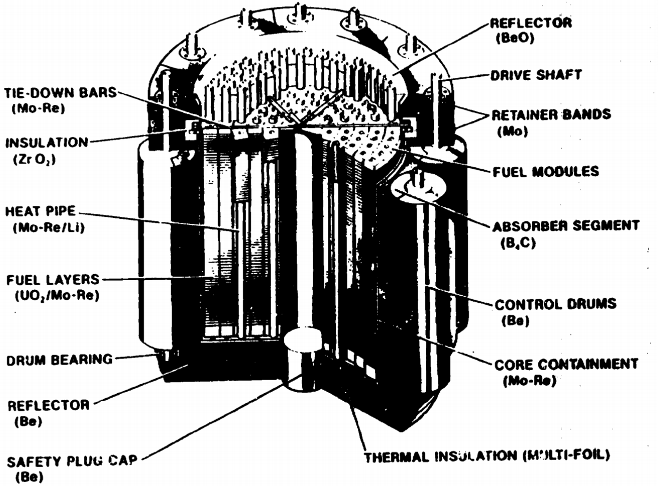
Early Argonne Space Reactor Concepts

HEAT PIPE APPLICATIONS: REACTORS - SPACE

- SPAR/SP-100 Program
  - 1977 - 1994
  - 40-100kWe, thermoelectric generators
  - Heat pipe (Li) evaporator temp: ~1200ºC
  - Never built but components tested







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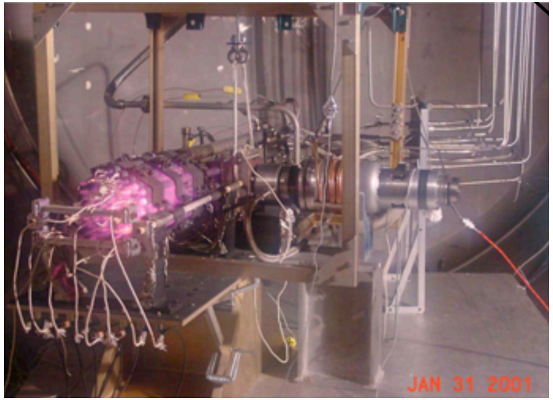
HEAT PIPE APPLICATIONS: REACTORS - SPACE

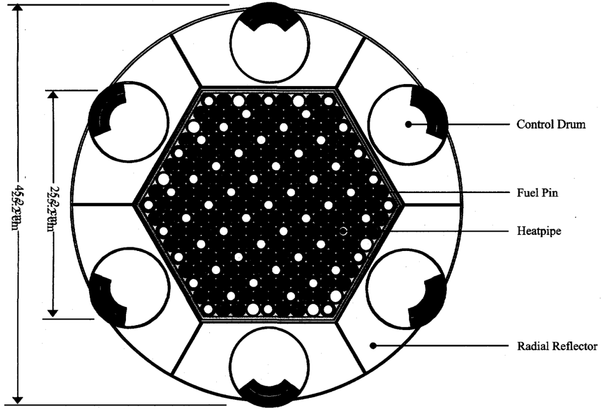
■ SAFE Program

- Safe Affordable Fission Engine
- 100kWe, thermoelectric generators
- Heat pipe (Na) evaporator temp: ~1000ºC
- Reactor never built, but electrically-heated demonstration conducted



■ HOMER Program

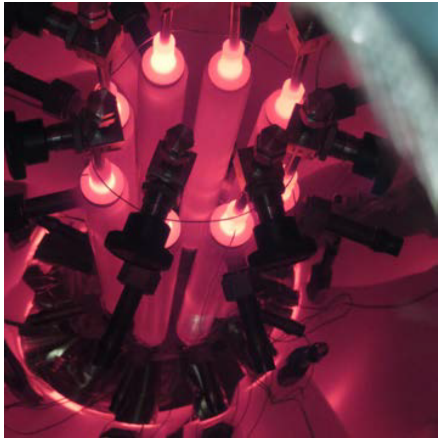
- Heatpipe-Operated Mars Exploration Reactor
- >20kWe, multiple conversion options
- Heat pipe (Li) evaporator temp: ~1000ºC
- Heat pipes tested

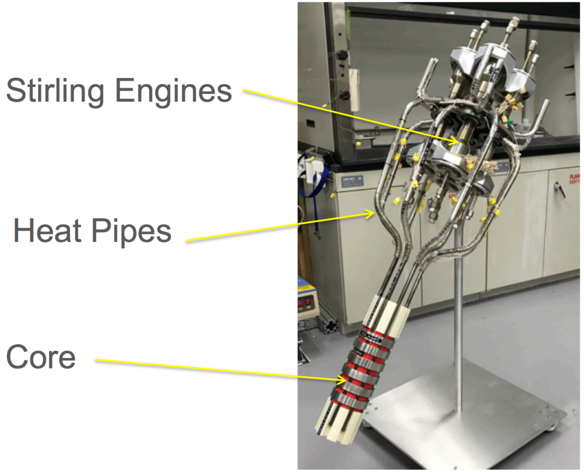


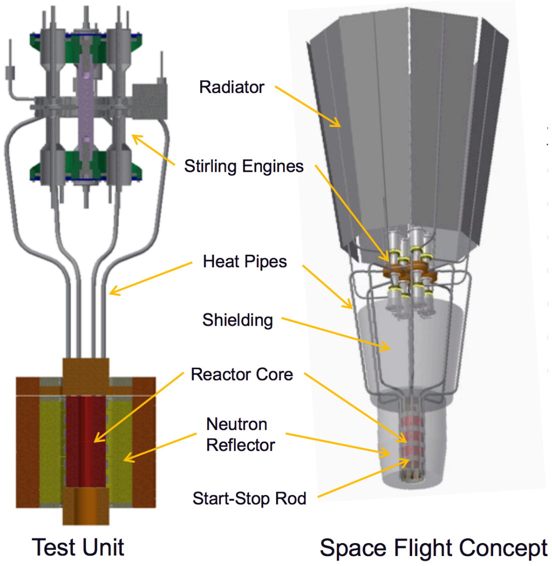
HEAT PIPE APPLICATIONS: REACTORS - SPACE

- KiloPower Program
  - 10kWe, Stirling converters
  - Heat pipe (Na) evaporator temp: ~800ºC
  - Kilopower Reactor Using Stirling Technology (KRUSTY)
  - Test reactor (1kWe) built and operated (2017 - 2018), including transient scenario testing such as heat pipe failure
  - First U.S. space reactor built and tested since 1960s

Electrical heating heat pipe testing







HEAT PIPE APPLICATIONS: REACTORS

Design Advantages

- Very compact
- Can operate at high temperatures
- No positive void coefficient
- Strong negative temperature feedbacks
- Reduced corrosion issues
- Passive heat removal pathways
- Orientation independent (capillary)

Design Disadvantages

- Working fluids usually have high thermal neutron absorption (which is why they are typically fast reactors)

Operation Advantages

- Load following
- Multiple coolants loops, which eliminates major LOCAs
- Small coolant inventory
- Fewer components (no pumps, valves, etc.)
- Fewer moving parts

Operation Disadvantages

- Heat pipe degradation and lifetime
- Lack of long-term operation data (exposure to radiation, formation of decay products, etc.)
- Creation of non-condensable gases from activation product decay or chemical processes, which may reduce the effective length of the condenser

HEAT PIPE APPLICATIONS: REACTORS

- EBR-II Tests
  - 27 heat pipes tested (Na and K)
    - Between 1,100 and 23,000 hours each (137,000 hours total)
    - 1.9 – 5.4m length
    - 0.5 to 5kW, 570 to 830ºC
    - Gravity assist and opposed
    - No failures
    - Demonstrated frozen startups
    - Gas controlled
      - Gas controlled heat pipes use an inert cover gas to control the length of the available condenser. As temperature and internal pressure changes, the inert gas expands/contracts, changing the condenser length
      - Provides precise temperature control
      - Also called variable conductance heat pipes (VCHPs) or pressure controlled heat pipes (PCHPs)
  - Two additional heat pipes irradiation-tested at LANL Omega West Reactor

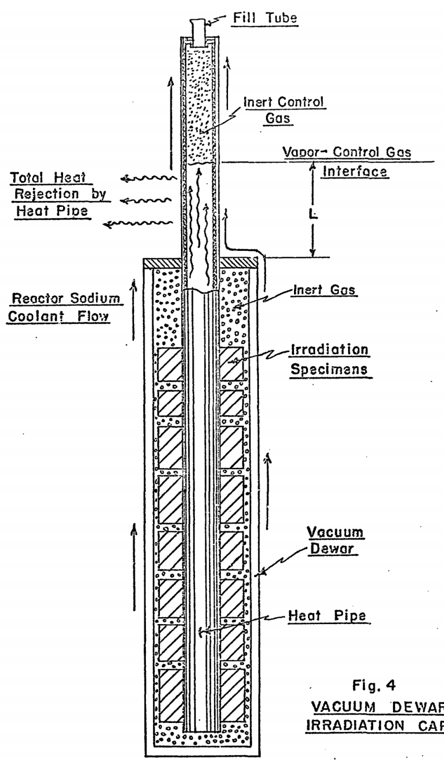


Fig. 4
VACUUM DEWAR IRRADIATION CAPSULE

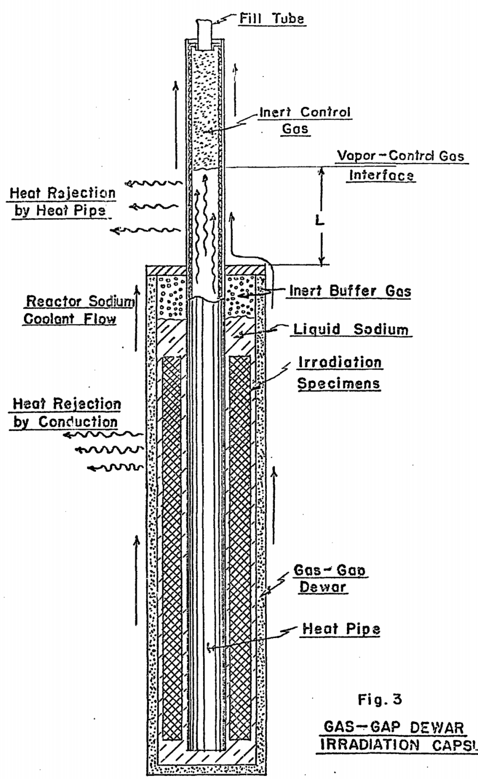
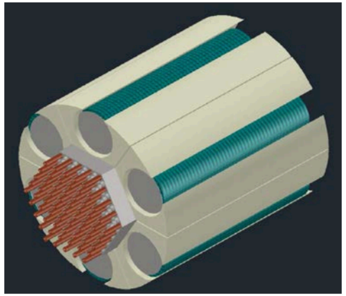
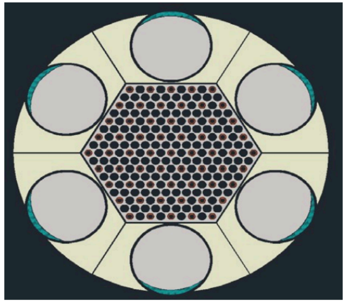


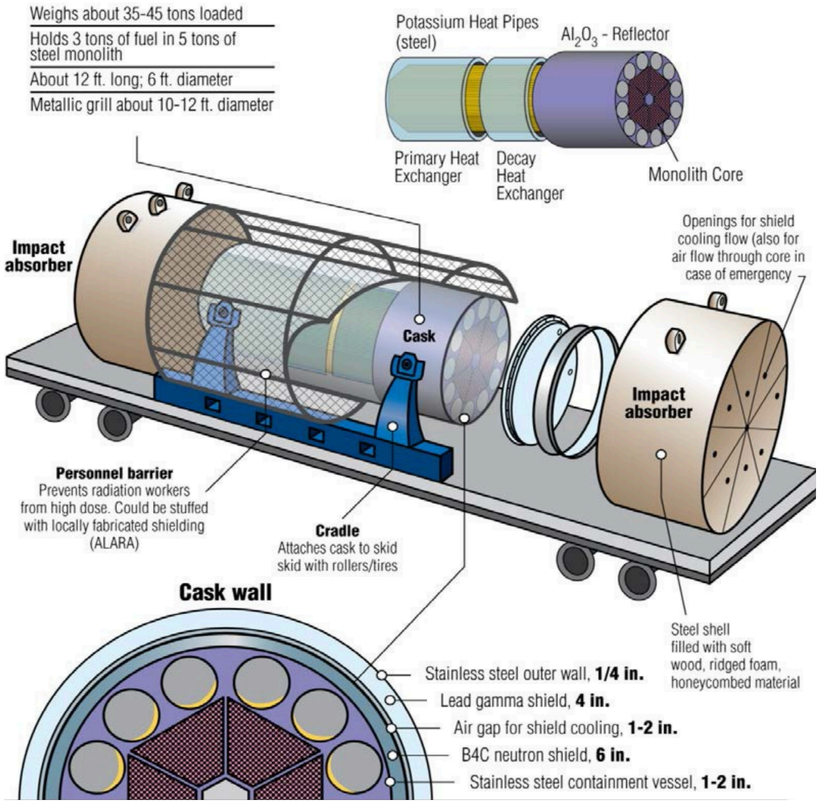
Fig. 3
GAS-GAP DEWAR IRRADIATION CAPSULE

HEAT PIPE APPLICATIONS: REACTORS

- **Example**: Special Purpose Reactor (SPR)
  - LANL patented design
  - 5MWth, 2MWe
  - Evaporator temperature: 675ºC
  - Solid steel core with UO_2 fuel
  - Potassium (K) heat pipes
  - Rotating control drums
  - CO_2 Brayton cycle
  - Three potential core designs outlined on following slides







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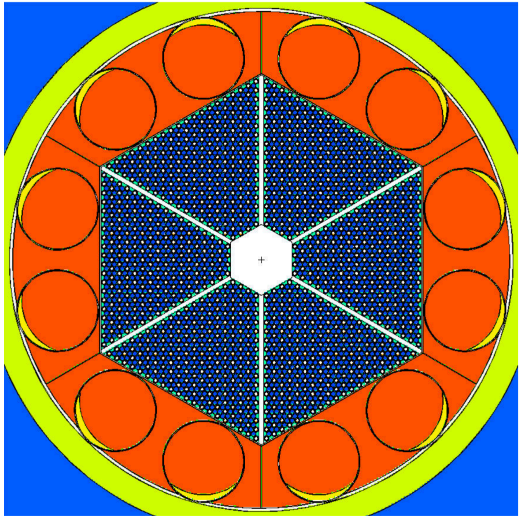
HEAT PIPE APPLICATIONS: REACTORS

- LANL Base Design (MegaPower)
  - Core consists of 6 solid stainless steel monoliths
  - Monoliths contain channels for heat pipes and fuel pellets



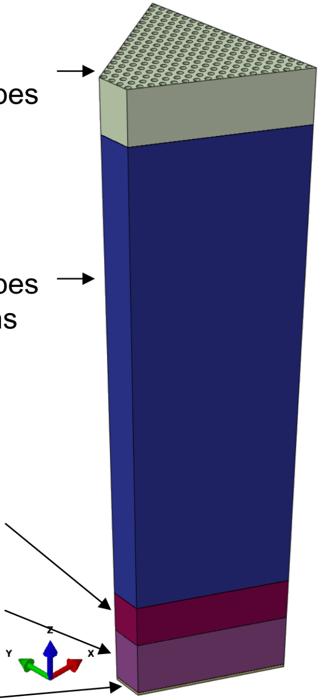
Upper Reflector
- Holes for Heat Pipes

Monolith
- Holes for Heat Pipes
- Holes for Fuel Pins

Lower Reflector
- No holes

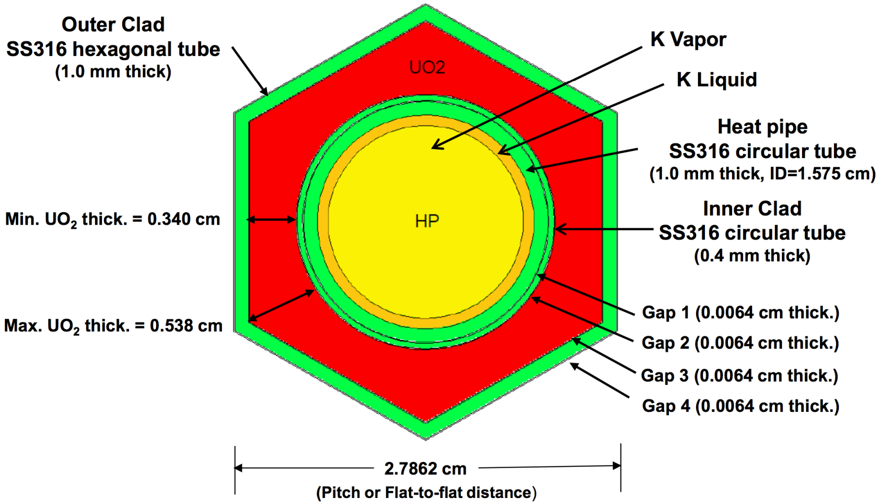
Gas Plenum
- Holes for Helium

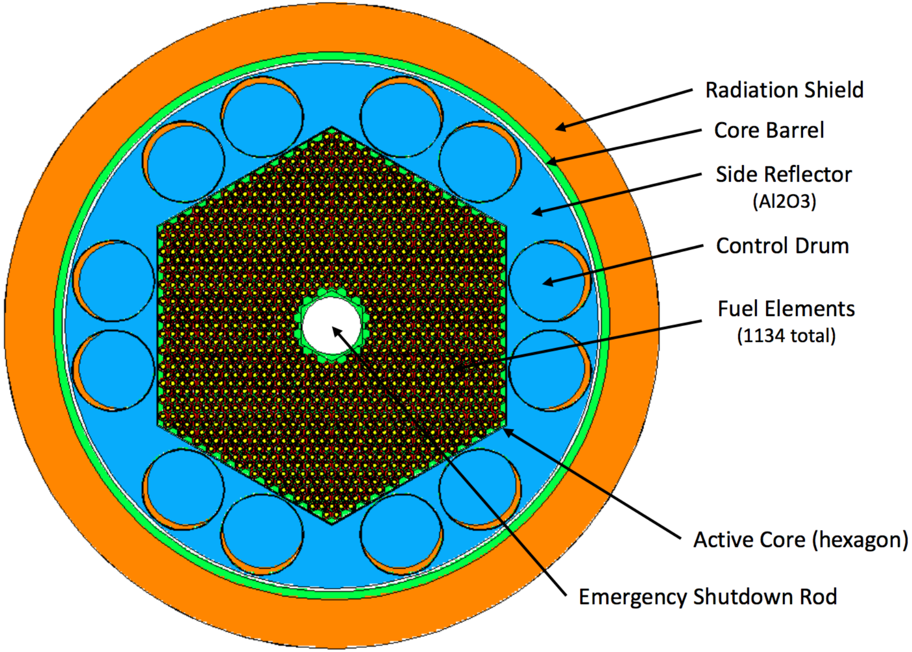
Bottom Plate
- No Holes



HEAT PIPE APPLICATIONS: REACTORS

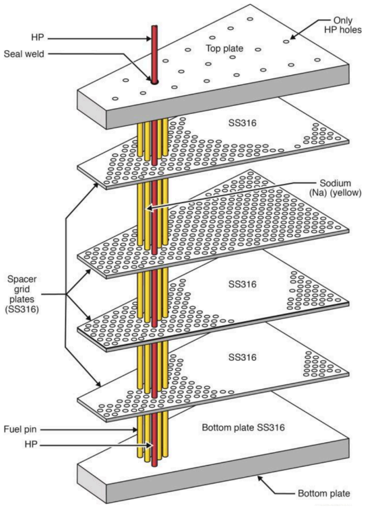
- Design Alternative A
  - Hexagonal fuel elements with center heat pipes
  - Potential for Na or K bonding of fuel to cladding

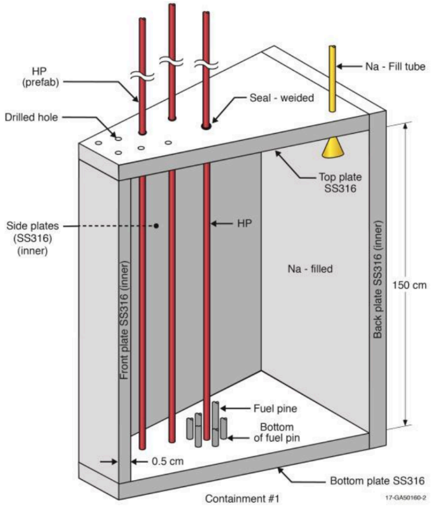


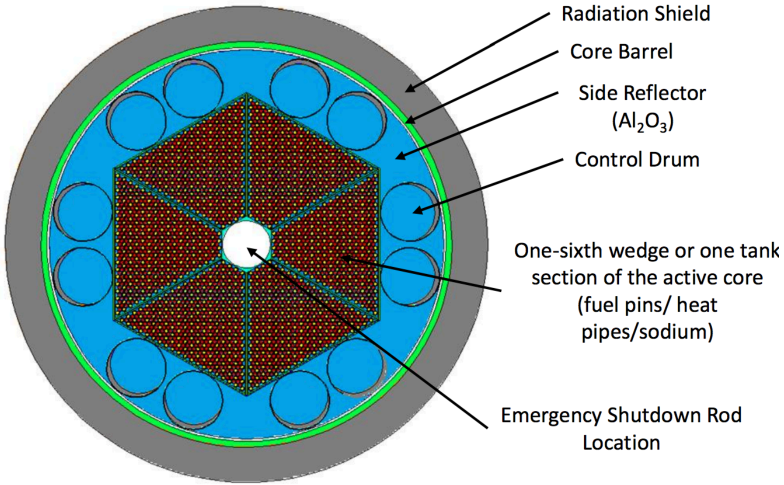


HEAT PIPE APPLICATIONS: REACTORS

- Design Alternative B
  - Conventional fuel pins and heat pipes inside Na-filled tanks







QUESTIONS?