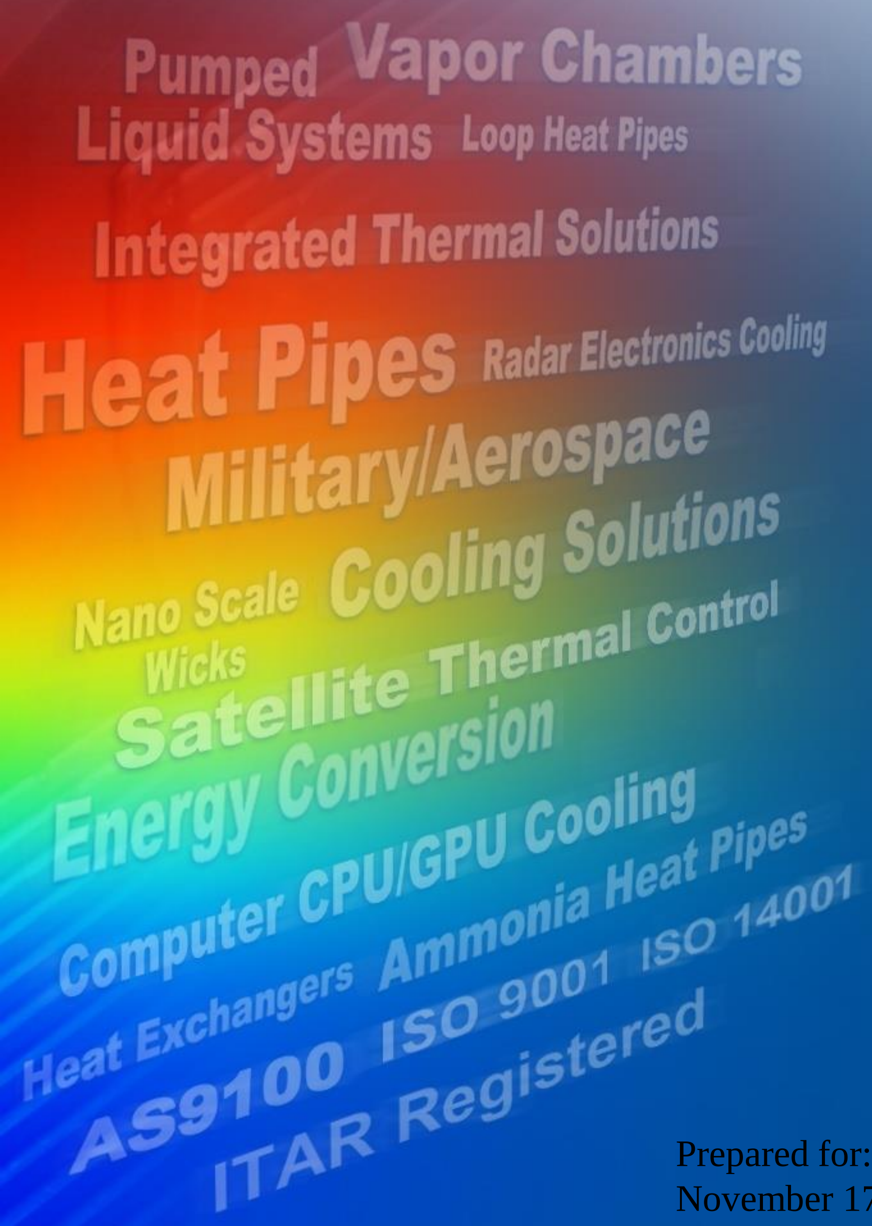

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Advancing Space Propulsion Technology through Additive Manufactured Heat Pipe Structures

- Past Work
- Current Work
- Envisioned Future Work

Prepared for: Advanced Spacecraft Propulsion Workshop.
November 17-19, 2014.
Ohio Aerospace Institute Cleveland, Ohio.

High Temperature Heat Pipe Applications Past Work

- High Temperature Space Radiators
- Alkali Metal Thermal to Electric Converters (AMTEC)
- Magnetoplasmadynamic (MPD) Thrusters
- Hypersonic Vehicle Leading Edges
- Rocket Nozzles
- Turboshaft Engine Components
- Solar Receivers
- Isotope Separation
- Isothermal Furnaces
- Chemical Processing
- Fusion Applications
- Thermionic Converters

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High Temperature Heat Pipe Capabilities

- High Temperature Heat Pipe Operation:
  - Cesium: 300-600 ˚C
  - Potassium: 400-1000 ˚C
  - Sodium: 500-1200 ˚C
  - Lithium: 900-1700 ˚C
- Temperature Uniformity: <10mK Pressure-controlled IFL
- Thermacore has the facilities to handle this work.
- High volume low temperature heat pipe manufacturing exists at Thermacore. This would need to be adapted to this high temperature application.

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Alkali Metal Handling Facilities

- Specialized Alkali Metal Handling Rooms (3)
  - Fire Resistant and Protected
  - All Concrete Construction
  - Registered and Approved by Local Fire Department
  - Designed to protect employees and the company from the potential for accidents.
- Alkali Metal Disposal Room (1)

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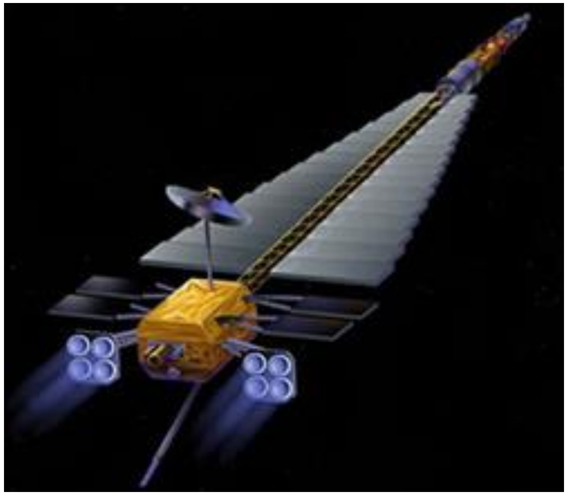
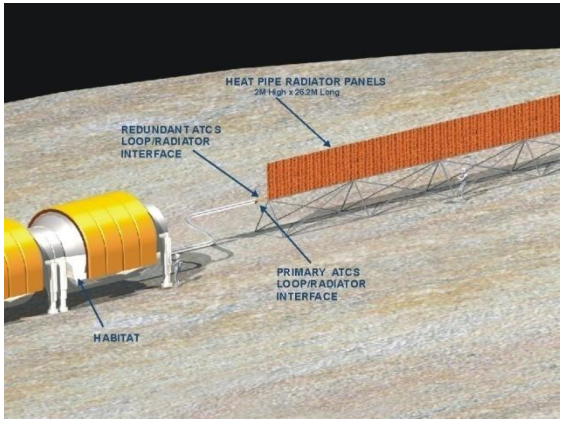
High Temperature Space Radiators



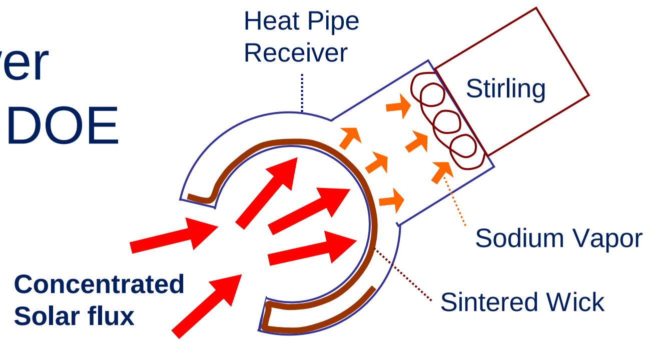


- Titanium/ Potassium Heat Pipes were considered for Prometheus/JIMO long duration spacecraft.

- Titanium/ Potassium Heat Pipes are being considered for Lunar Surface Power Heat Rejection
- $400^{o}C$ – $500^{o}C$ Operation

Heat Pipe Solar Receiver with Stirling

- With Cummins Power Generation Inc and DOE
- Sodium @ 675°C (1247°F)
- Haynes 230 Shell
- Nickel Wick
- Linear AC Generator



Heat Pipe Receiver with Integral Stirling Heater Heads

30 kW_t, 10 kW_e Demo at Thermacore (1993)

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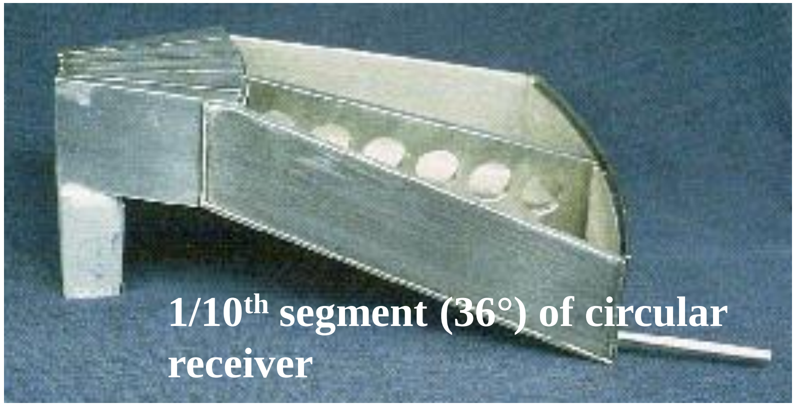
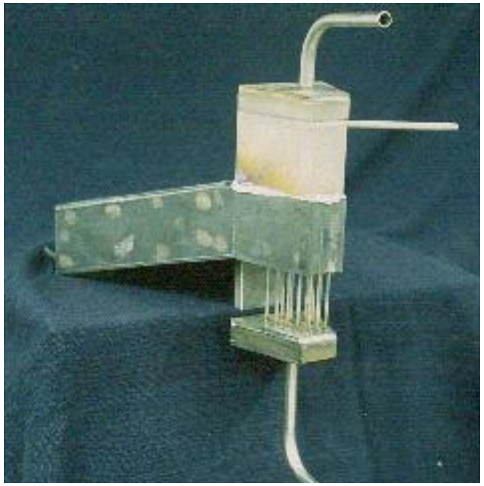
Stirling Space Power Converter

- For NASA Glenn
- Sodium @ 750°C (1382°F)
- Inconel 718 Envelope
- Stainless Screen Wick
- 4500 W for 1/10th segment of "Starfish" receiver

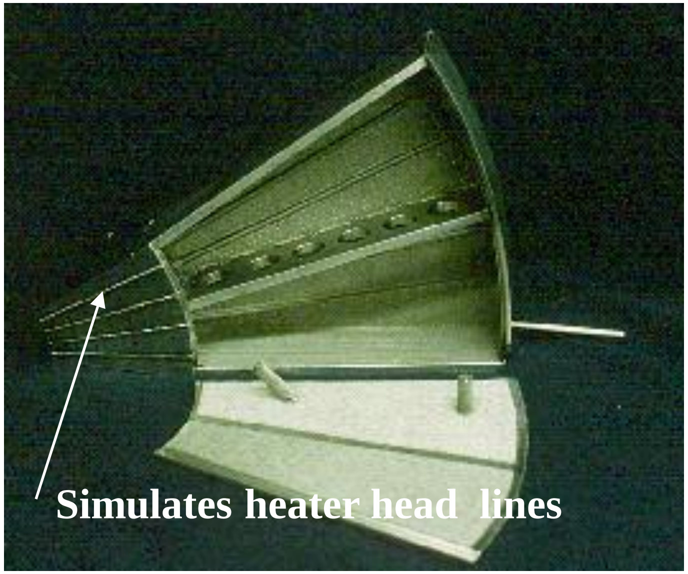


1/10th segment (36°) of circular receiver



Segment with gas gap calorimeter

- More than 70,000 hours of life testing and counting



Simulates heater head lines

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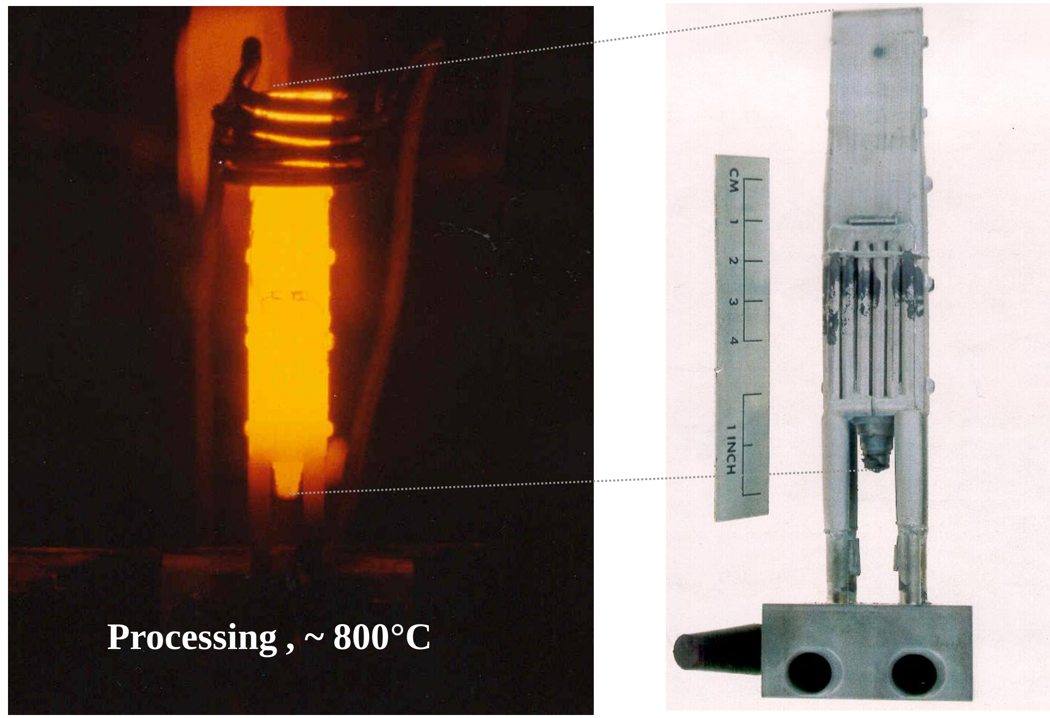
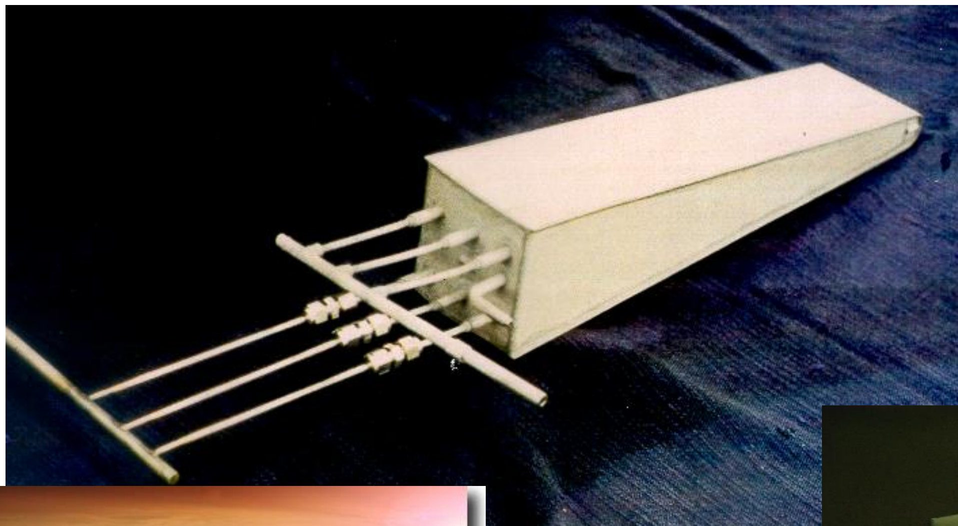
Leading Edge - Extreme High Temperature

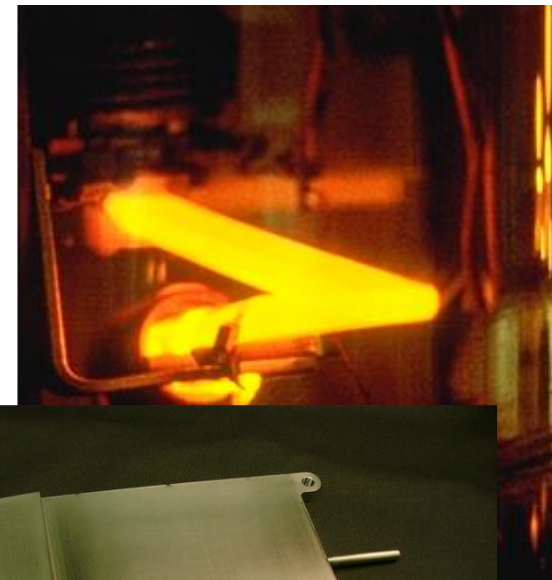
- 1700°C Peak
- 129,000 W/cm^2 spot
- >79,000 W/cm^2 overall
- CVD Tungsten body
- Lithium working fluid
- For Pratt & Whitney under USAF prime for NASP Program



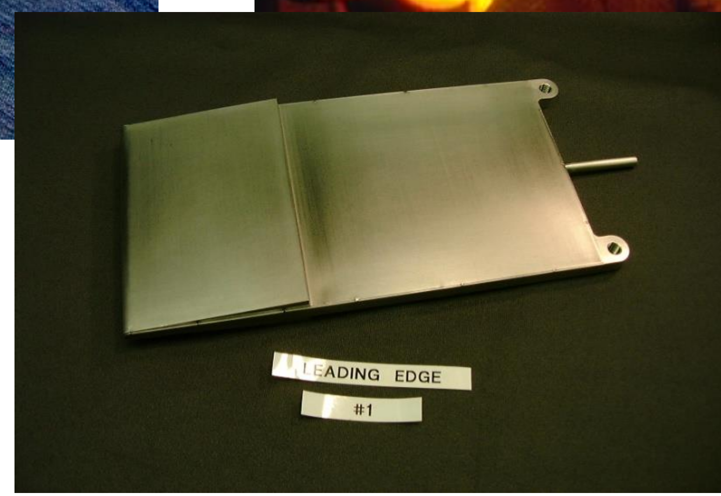
Prototype Heat Pipe for NASP Cowl Leading Edge

Heat Pipes for Hypersonic Vehicle Leading Edges





U.S. Falcon



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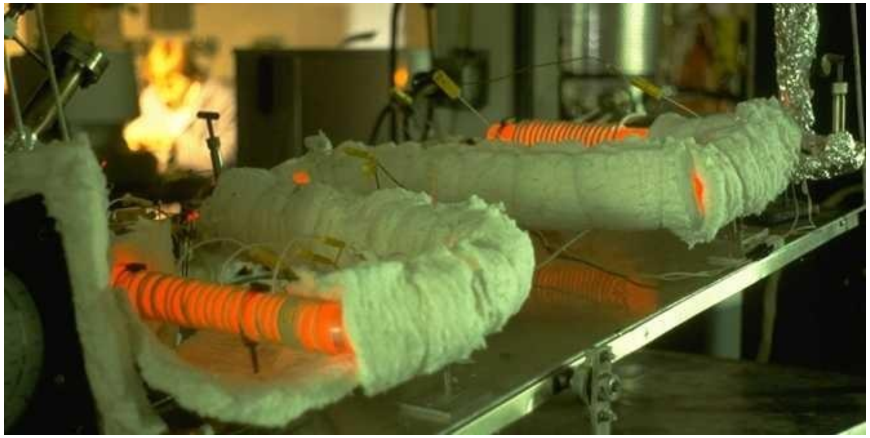
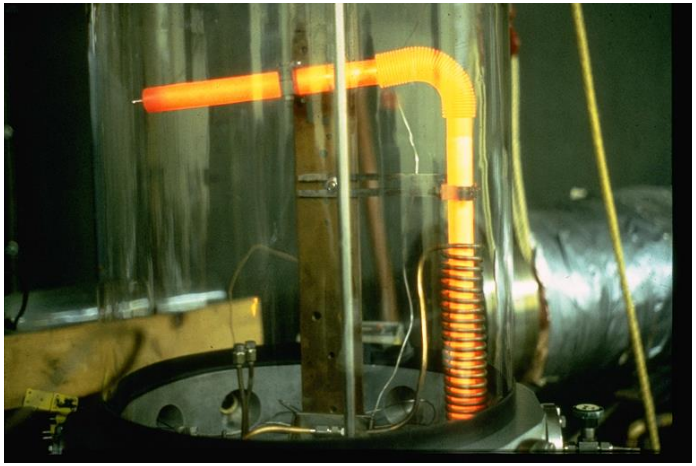
Sodium Heat Pipes

- Heat Pipes
- Flexible, deployable
- Chemical Processes

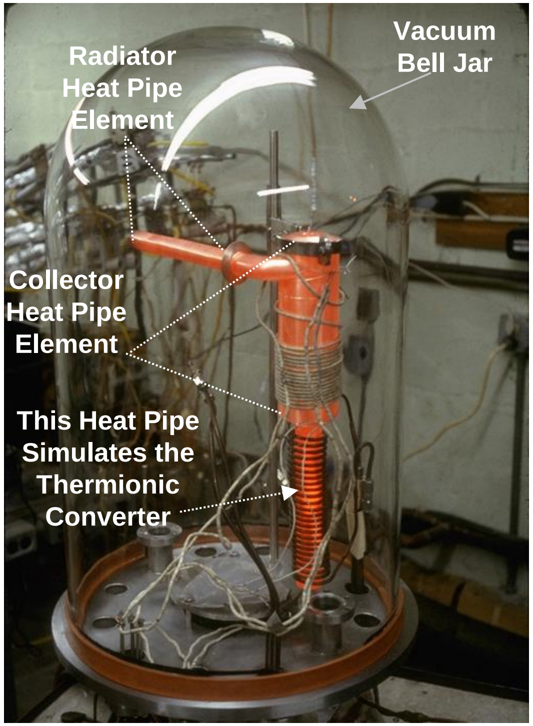


Sodium Heat Pipes

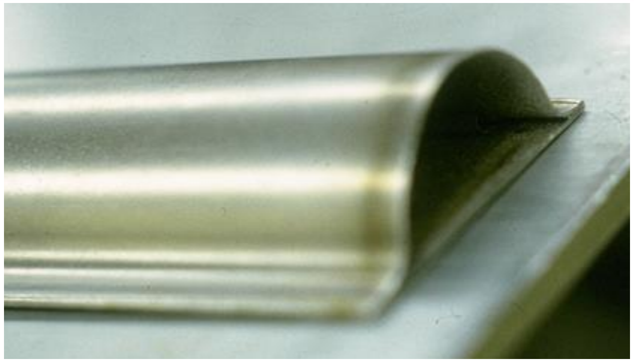


SP100 – NEP – Prometheus – JIMO

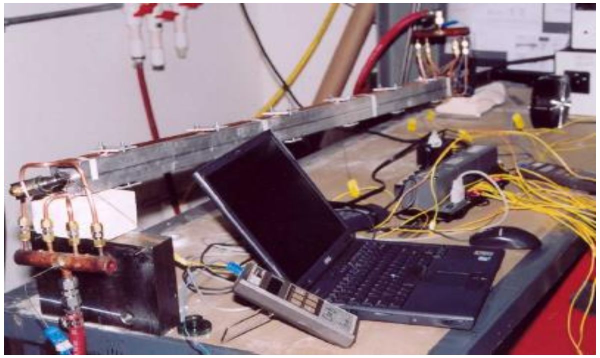
- Working Hardware



SS/Potassium Heat Pipe
650°C Radiator for NEP



Titanium/Potassium Heat Pipe
5.5 m long, 1.86 kW @ 760K



Titanium/Water Heat Pipe
1500 W at 300°C with Adverse Tilt
Ongoing Life Test

SS/Sodium Heat Pipe
15 ft long, 3312 W @ 908K

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High Temperature Heat Pipes
Turboshaft engine components

- First demonstration of a heat pipe cooled turboshaft engine blade.
- Demonstrated the assembly and processing techniques required for this application.
- Operated successfully at temperatures up to 850ºC
- Superalloy single crystal envelopes w/ Sodium working fluid
- Fabrication challenges..

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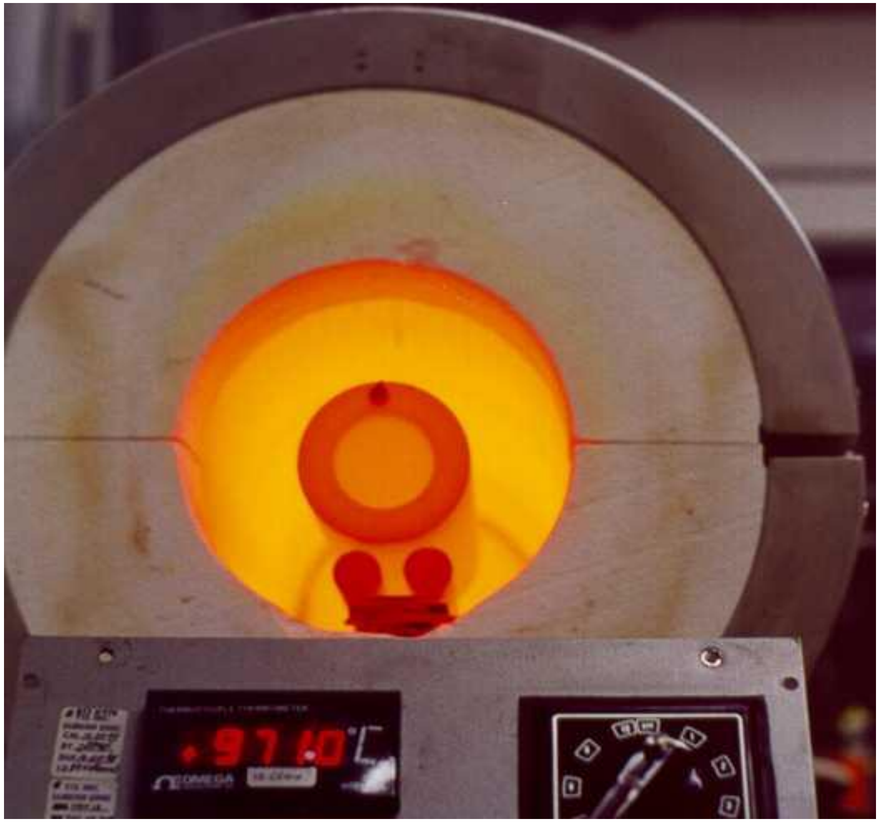
High Temperature Heat Pipes: Isothermal Furnace Liners



High Temperature Heat Pipes

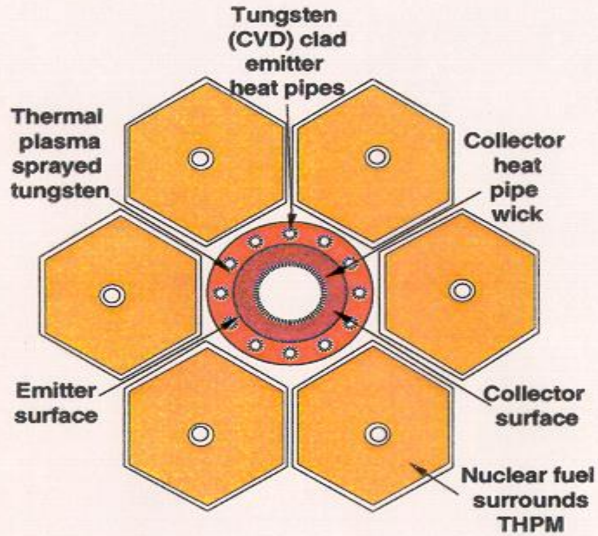
Thermionic Heat Pipe Module (THPM)

Design Advantages

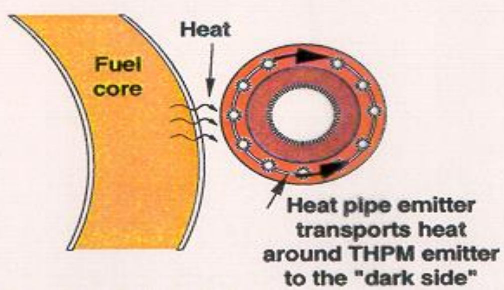
- separates nuclear fuel from thermionics for simplified fabrication and testing
- H_2 compatible for BiModel Reactors
- eliminates fuel swelling problems

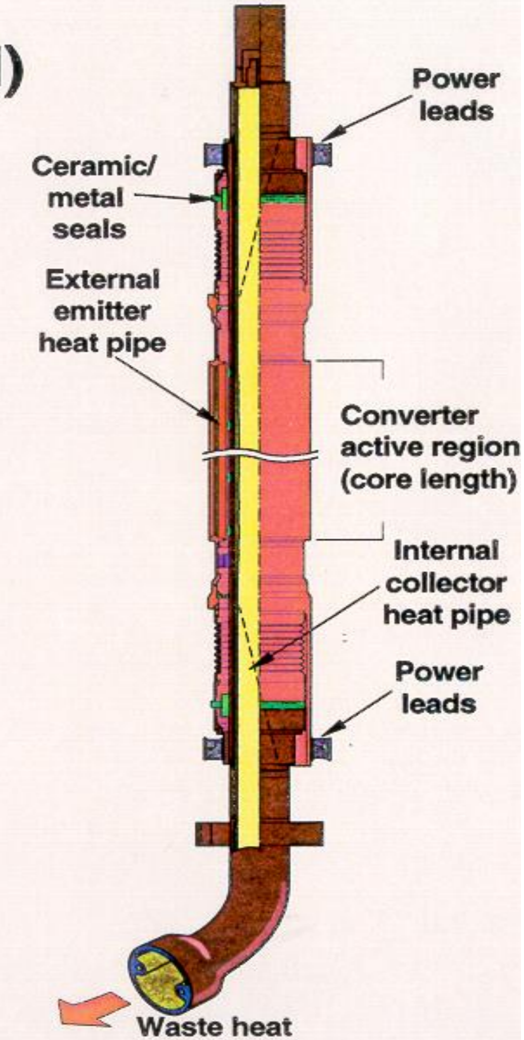
Dual Uses

- can provide both power and propulsion capabilities
- can be used for generic power conversion , such as solar power for home heating applications
- readily available high temperature waste heat improves efficiency of conventional conversion cycles



EXCORE CONFIGURATION





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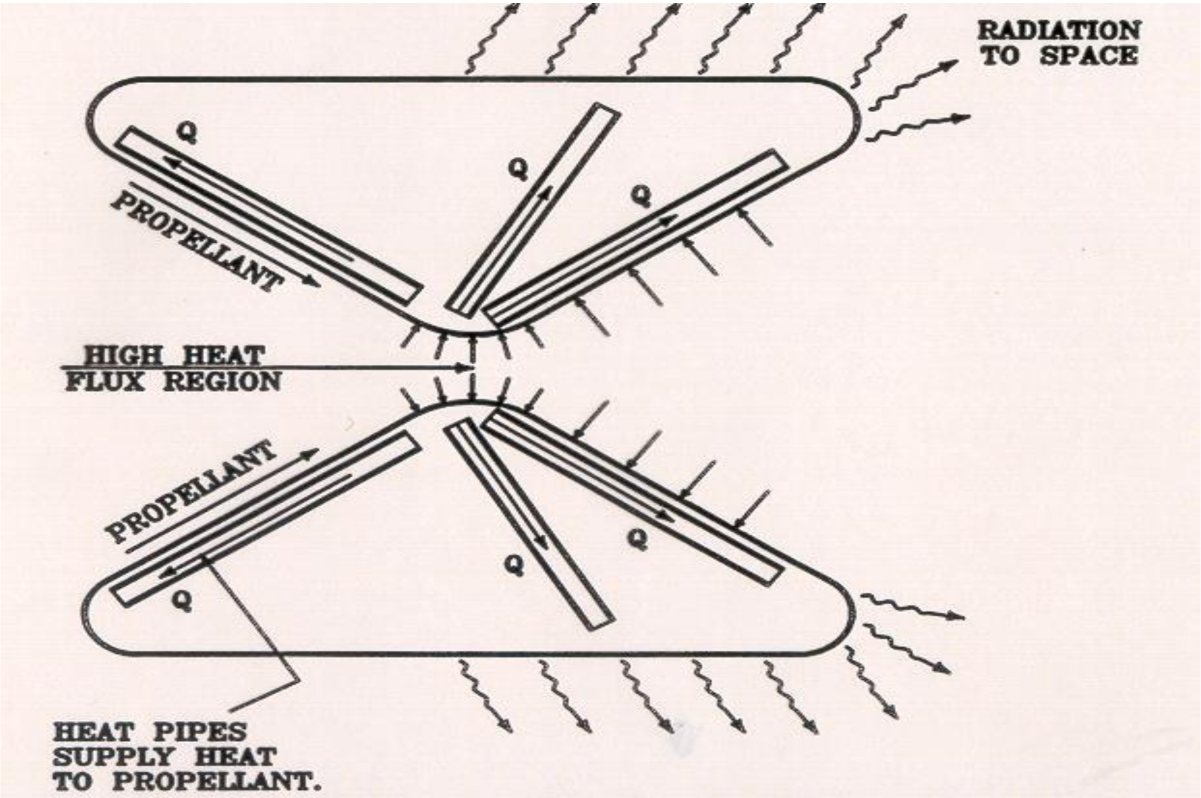
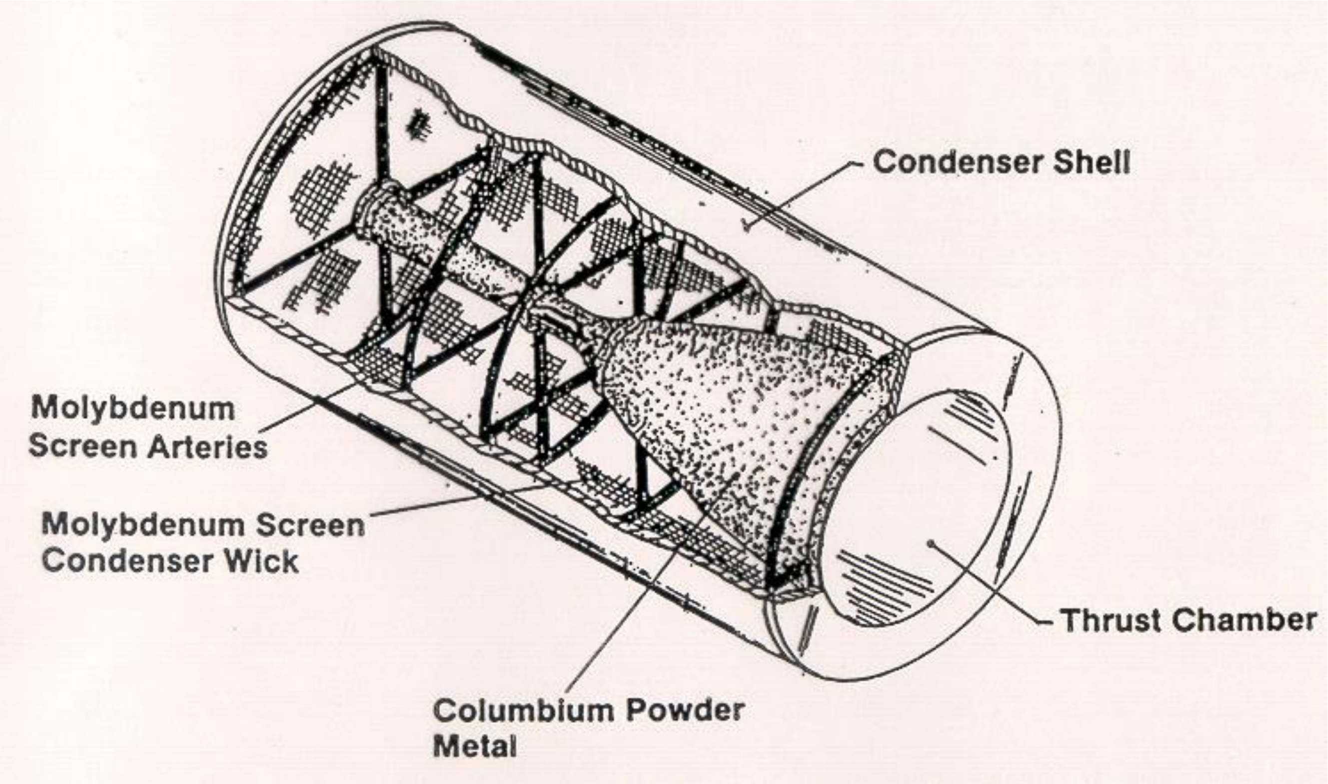
High Temperature Heat Pipes
Magnetoplasmadynamic (MPD) thrusters



This structure can be fabricated by CVD forming the thruster around pre-assembled tungsten/lithium heat pipes.

High Temperature Heat Pipes: Heat pipe Cooled Rocket Nozzle



This structure was fabricated from formed Nb/1%Zr sheet to form a vapor chamber. It was silicide coated and operated in air. No method was found to coat the fill tube.

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Current Work

- NASA Phase 1 SBIR
  - Use additive manufacturing to produce advanced lightweight radiator heat pipes
- Hypersonic vehicle leading edges
  - Arc jet test results confirm operation
  - Additive manufactured complex shapes

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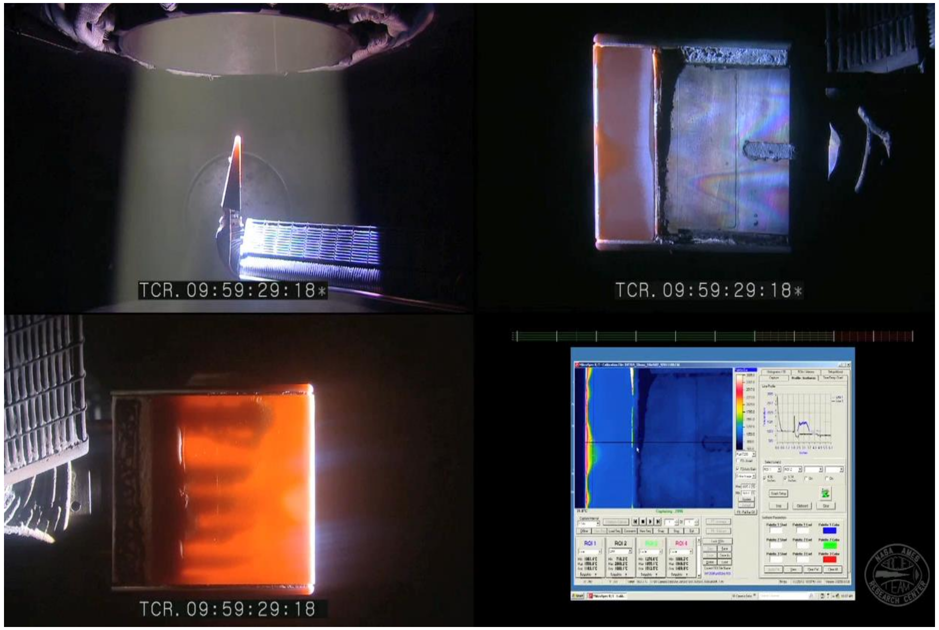
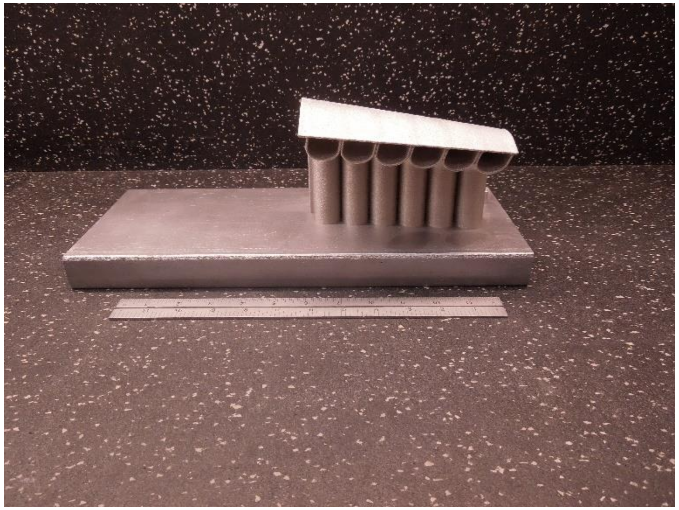
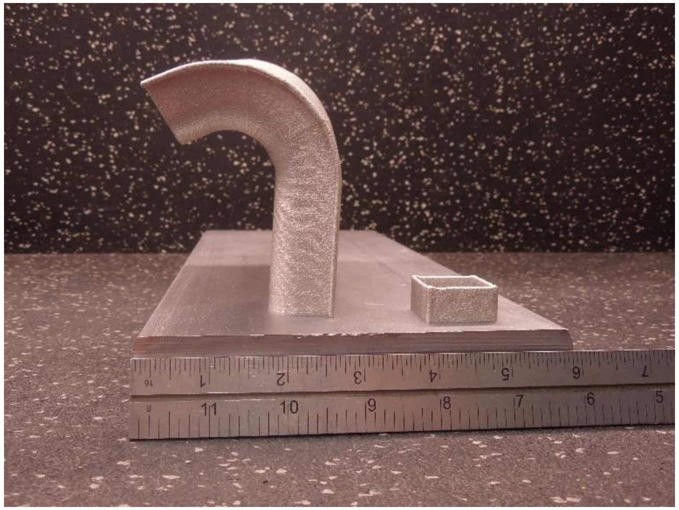
Leading Edge Heat Pipe Development

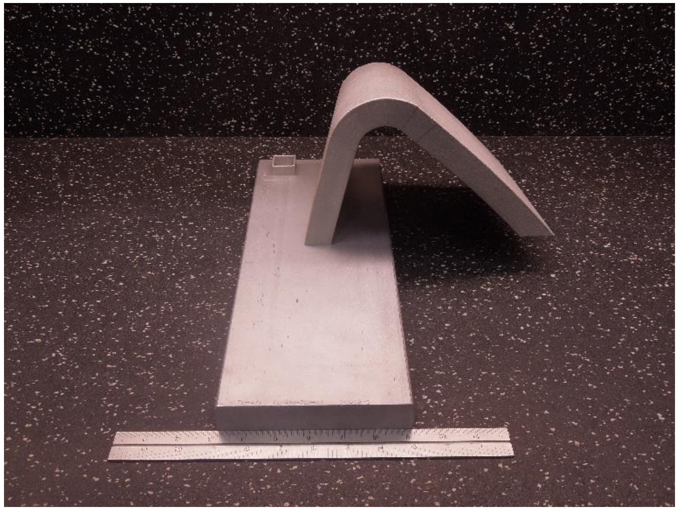
- Arc jet testing at NASA Ames Research Center.
- Tests completed in November 2013.
- Materials system is similar to that required for advanced thrusters.
- First demonstration of its type in arc jet tests.
- Report is available to NASA.



Leading Edge Sections Produced by Additive Manufacturing, Laser Deposition Technology (LDT) using H230







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Future Work

- Niobium alloy thrusters with multiple lithium heat pipes.
  - Material system and oxidation coating has been validated in leading edge arc jet tests.
  - Additive manufacturing has not been demonstrated with refractory metals; however recent technology advances show that this is now potentially achievable.
- Turboshaft engine heat pipes.
  - Additive manufacturing offers the promise to make complex shapes and avoid multiple braze runs that damage metallurgy.

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Summary / Conclusions

- Recent development work has demonstrated enabling technologies that will be applicable to advanced spacecraft propulsion applications.
- Additive manufacturing of refractory metal thrusters with multiple embedded heat pipes is now potentially achievable.

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