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# Lightweight Damage Tolerant Radiators for In-Space Nuclear Electric Power and Propulsion

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<u>Partners</u>

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# Abstract

Nuclear electric propulsion (NEP) is a promising option for high-speed in-space travel due to the high energy density of nuclear power sources and efficient electric thrusters. Advanced power conversion technologies for converting thermal energy from the reactor to electrical energy at high operating temperatures would benefit from lightweight, high temperature radiator materials. Radiator performance dictates power output for nuclear electric propulsion systems. Pitch-based carbon fiber materials have the potential to offer significant improvements in operating temperature and mass.

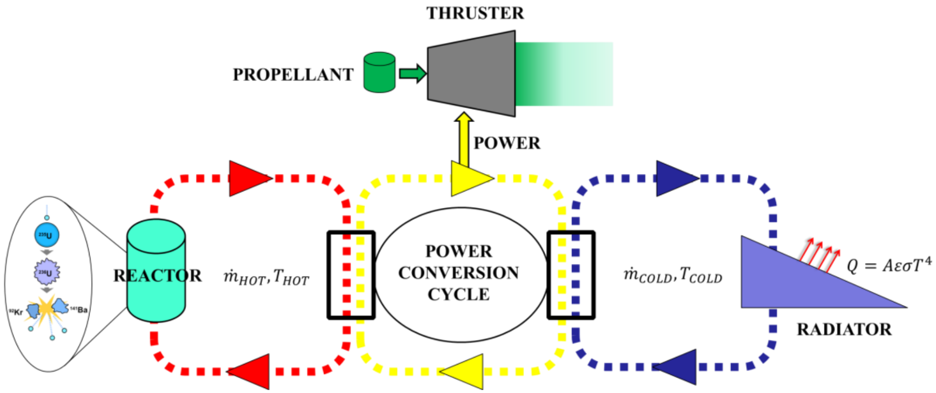
An effort at the NASA Marshall Space Flight Center to show that woven high thermal conductivity carbon fiber mats can be used to replace standard metal and composite radiator fins to dissipate waste heat from NEP systems is ongoing. The goals of this effort are to demonstrate a proof of concept, to show that a significant improvement of specific power (power/mass) can be achieved, and to develop a thermal model with predictive capabilities. A description of this effort is presented.

## Vision

Our vision is to enable NEP for deep space missions by improving the specific power (kW/kg) of the radiator system by a factor of at least 10.

# Role of Radiators for In-space Nuclear Electric Propulsion (NEP) Systems

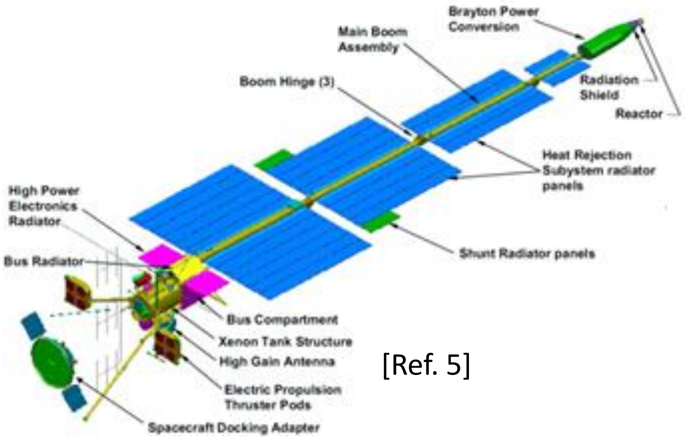
- NEP is a promising option for in space propulsion and power due to the high energy density of nuclear fission sources
- Thermal energy to electrical energy
  - Dynamic:Brayton cycle – ~500°K
  - Static:Rankine Cycle – ~1000°K
  - Direct:MHD – ~2000°K
- Waste Heat –> Radiators



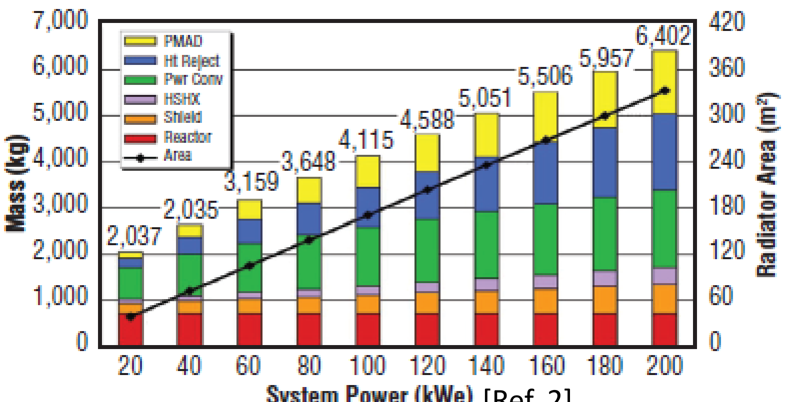

[Ref. 6]

# Radiator System Resources

- High power systems operated at low temperature require large area arrays
  - JIMO (Prometheus)
  - 450m$^2$ (200kWe)
- Radiators are a significant fraction of the total mass of the system
- There is a definite need for radiator mass reduction
- **Of the high temperature options for radiator fin material, low density, carbon fibers are a promising alternative**




[Ref. 5]




[Ref. 2]

# Objective

To show that high thermal conductivity carbon fiber fins can be used to replace standard metal and composite radiator fins to dissipate waste heat from NEP systems and with a concurrent increase in specific power.

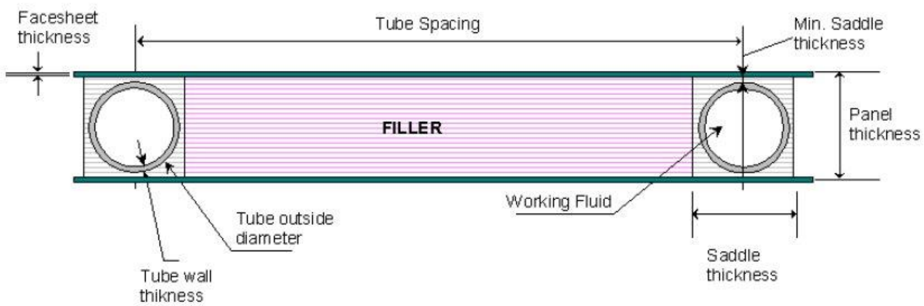
# Goals

- To demonstrate a proof of concept
- To demonstrate that a significant improvement of specific power (power/mass) can be achieved
- To develop a thermal model with predictive capabilities

# Tasks

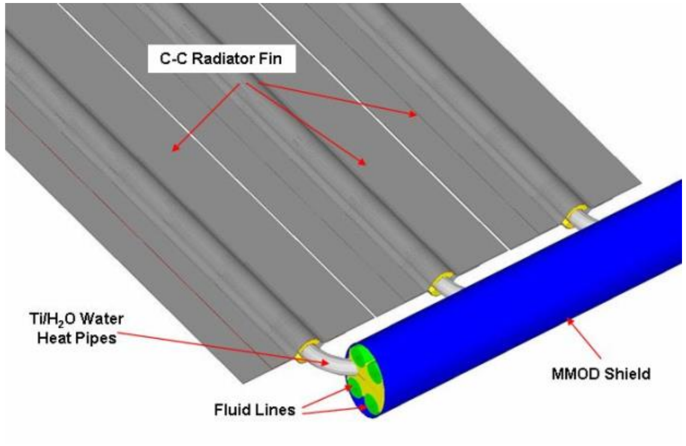
- Test article design
- Manufacturability of fiber fins
- Attachment
- Model
- Metric

# Current Existing Configurations




Proposed JIMO radiator panel [Ref. 3]

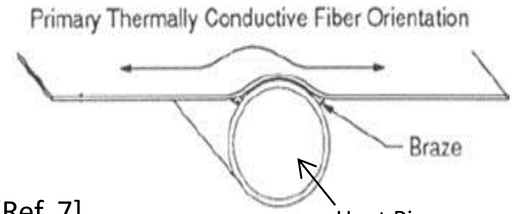
C-C Radiator [Ref. 1}




- Several existing radiator designs using high thermal conductivity carbon materials
- Structural Panel
  - Heavy
- Wrapped fin
  - Brittle
  - Thermal expansion

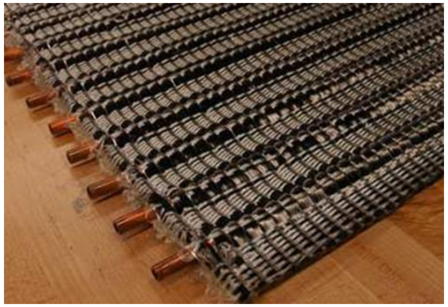
# Proposed Design

- Separate structural from thermal
- Use the woven high thermal conductivity carbon fibers with no matrix material
- Attach fibers directly to metal heat pipe through high temperature brazing
    - ceramics to metal




[Ref. 7]

Carbon fiber radiator design



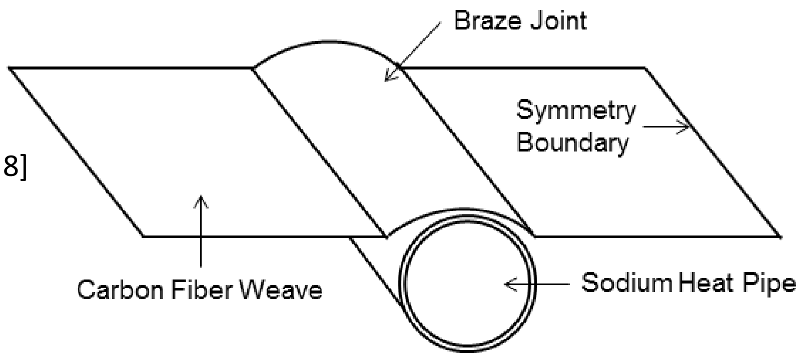
[Ref. 4]

# Characteristics of Pitch Carbon Fiber K13D2U

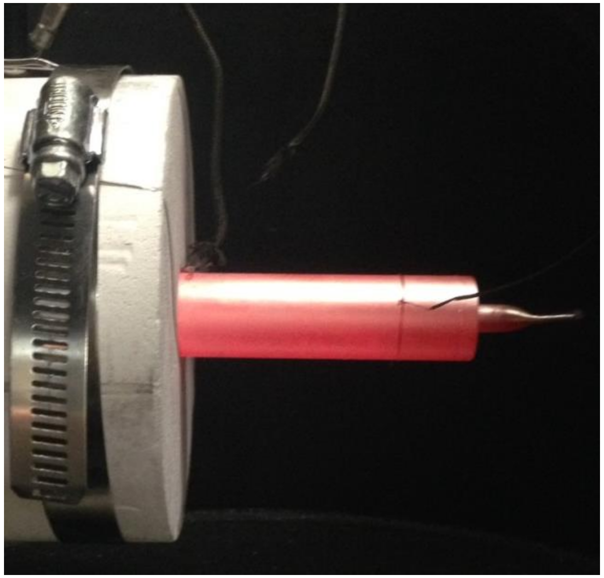
- Low density (2.2 gm/cm$^3$)
- High axial thermal conductivity (800 W/mK)
- Broad operating temperature range (0->2000°C)
- High emissivity (0.8)
- Readily available

# Test Article Design

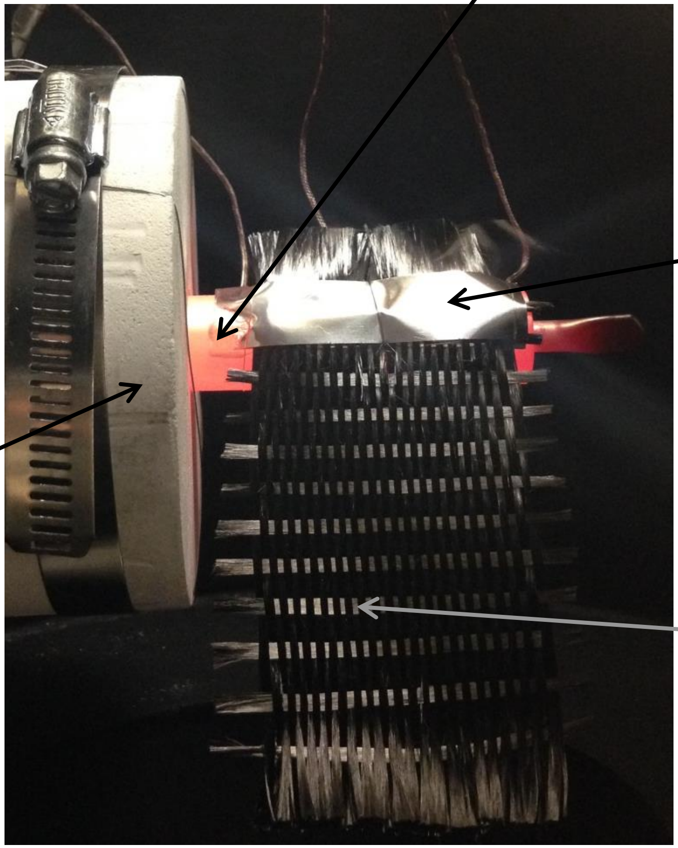
- Heat pipe
  - Simulated
  - Actual
- Radiator Fin
  - Design for optimum specific power
    - Length
    - Thickness
- Fin Attachment




[Ref. 8]



# Heat Pipe Test Article

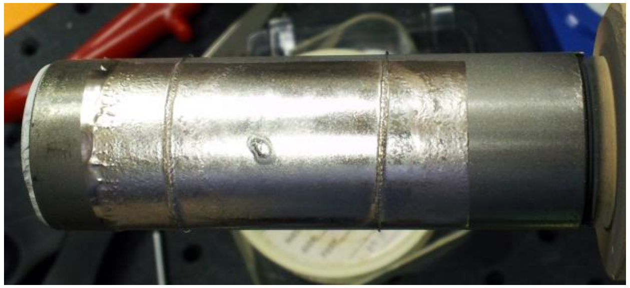


# Early Attachment

- High-Temp adhesive
  - Did not work well
  - Poor thermal conductivity
- Brazing
  - Active braze materials
  - TiCuSil
    - Thermal conductivity (approx. 200 W/mK)

# Brazing

- Two important considerations for braze
  - Thermal contact
  - Strength of attachment
- Two methods
  - Heating from within in vacuum
  - Isothermal furnace in vacuum
- Early efforts were fairly good

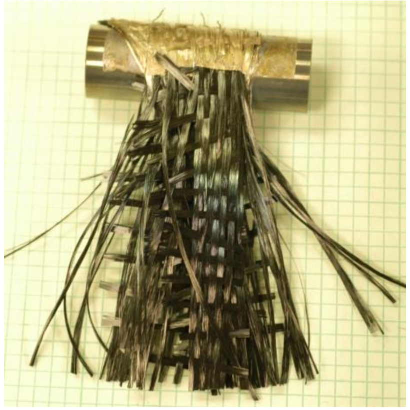


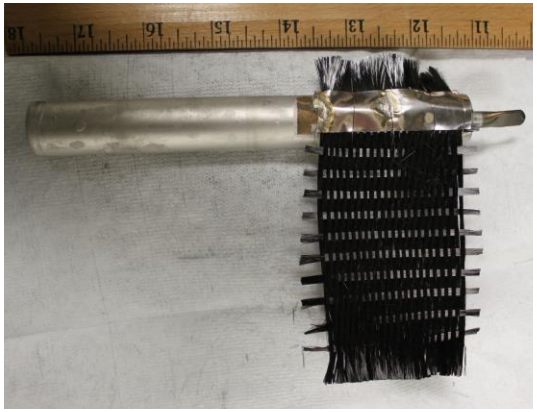


- With carbon fibers
  - More dense weave, brazing quality drops with internal heating
    - Radiative losses
  - Isothermal furnace-external heating of all components

# Manufacturability of fins

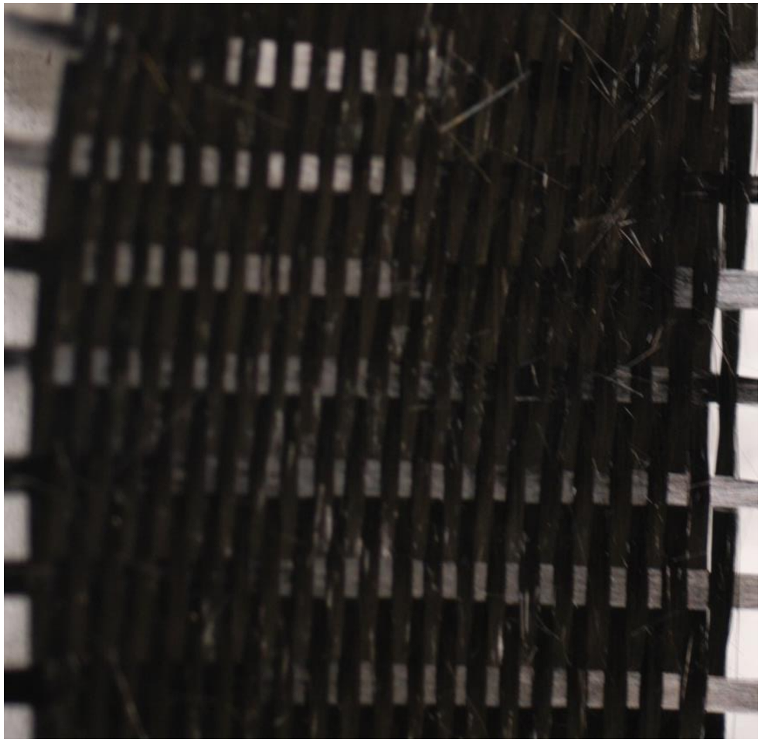
- No commercial mats made with this material
- First articles were with unwoven fibers across tube
- Developed a method to hand weave fibers in the laboratory
- Collaborated with a textile manufacturer* to develop a method to weave fibers on a mass scale





* Textile Engineering And Manufacturing

# Fin Construction

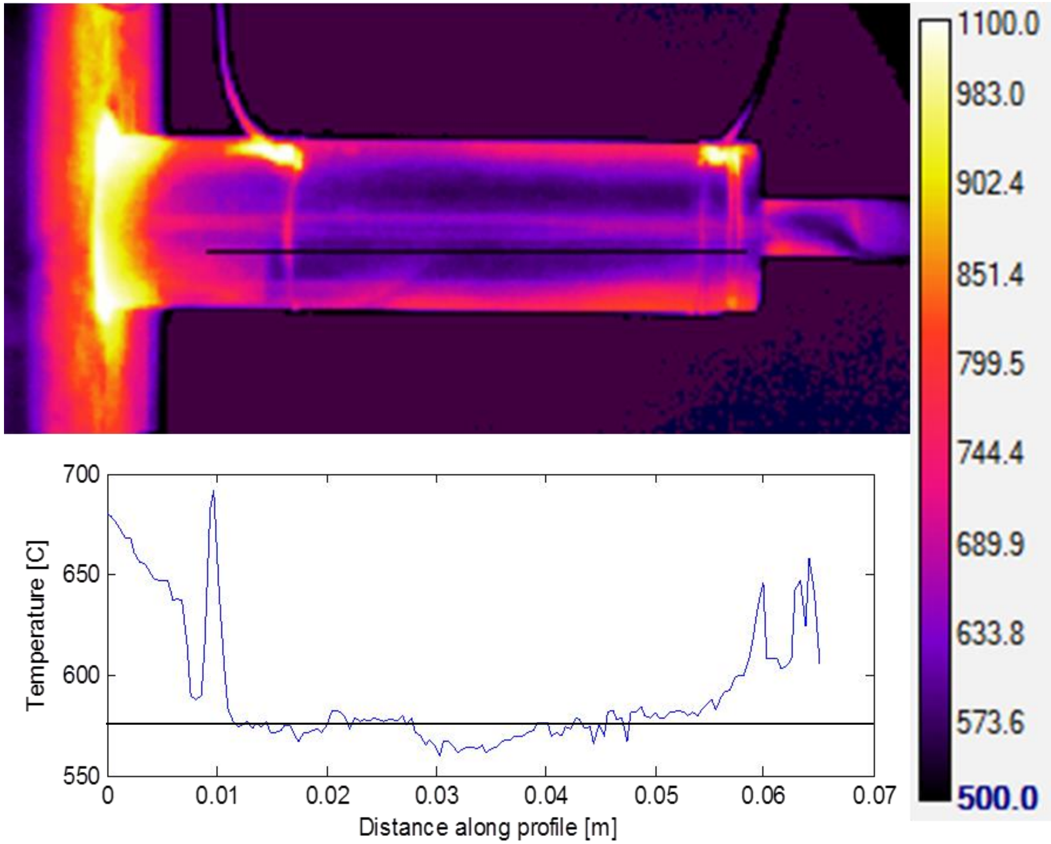


Hand woven in the lab

Textile from Manufacturer

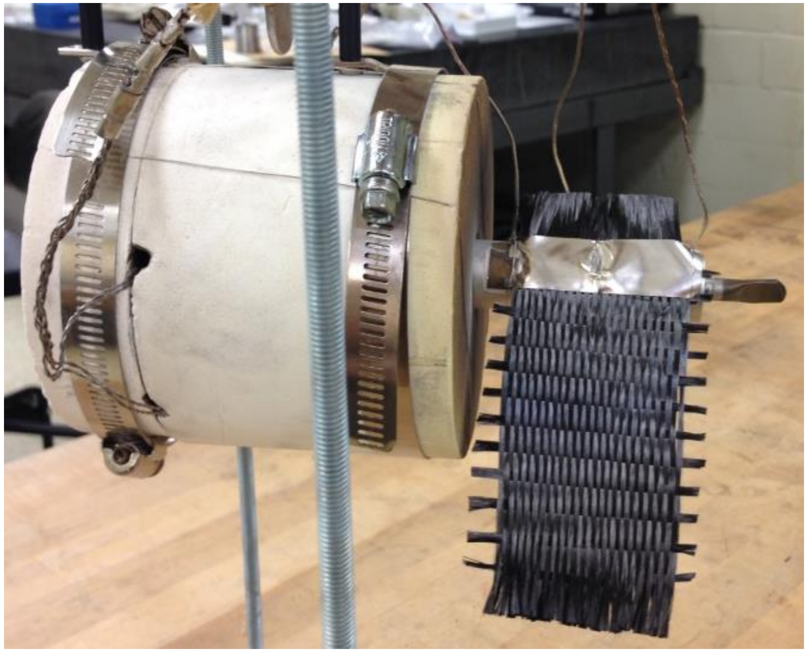
# IR Image of Sodium Heat Pipe

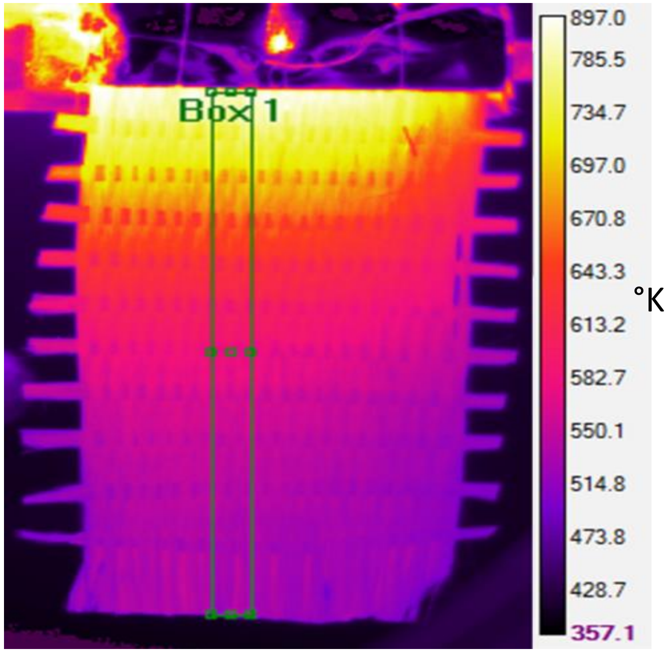
- Sodium heat pipe
  - 500-1100°C
- Represents a step up in fidelity in the simulations
- The temperature profile is generally isothermal



# Test Setup for Heat Pipe Sample

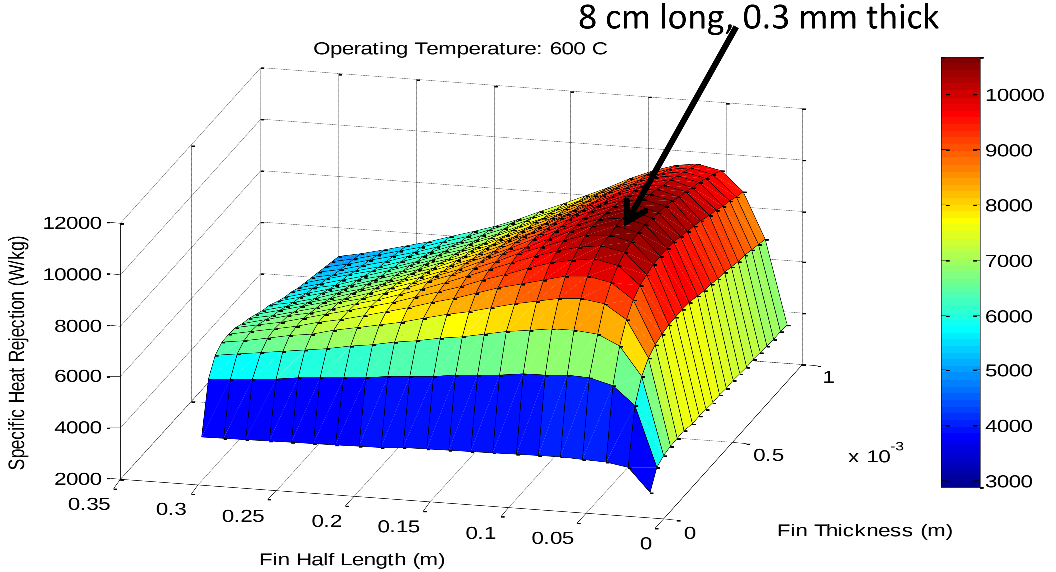
- Left image is current setup for testing heat pipe samples.
- Right IR image is a heat pipe with fin sample under test.
- Analysis of the surface temperature indicates:
  - power rejected per meter of heat pipe ~980 W/m
  - a specific power of 38.1 kW/kg for that fin.



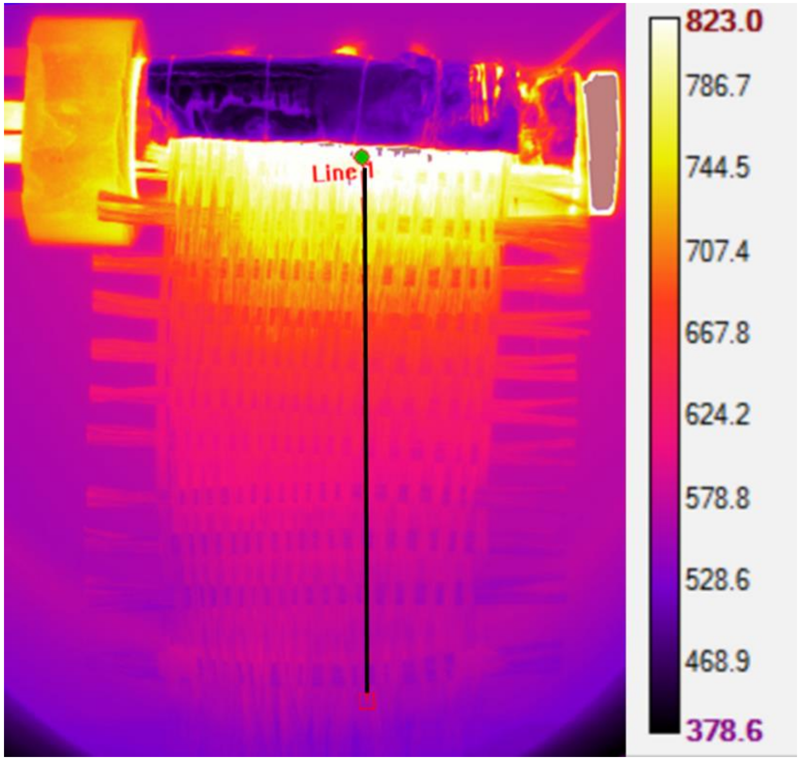


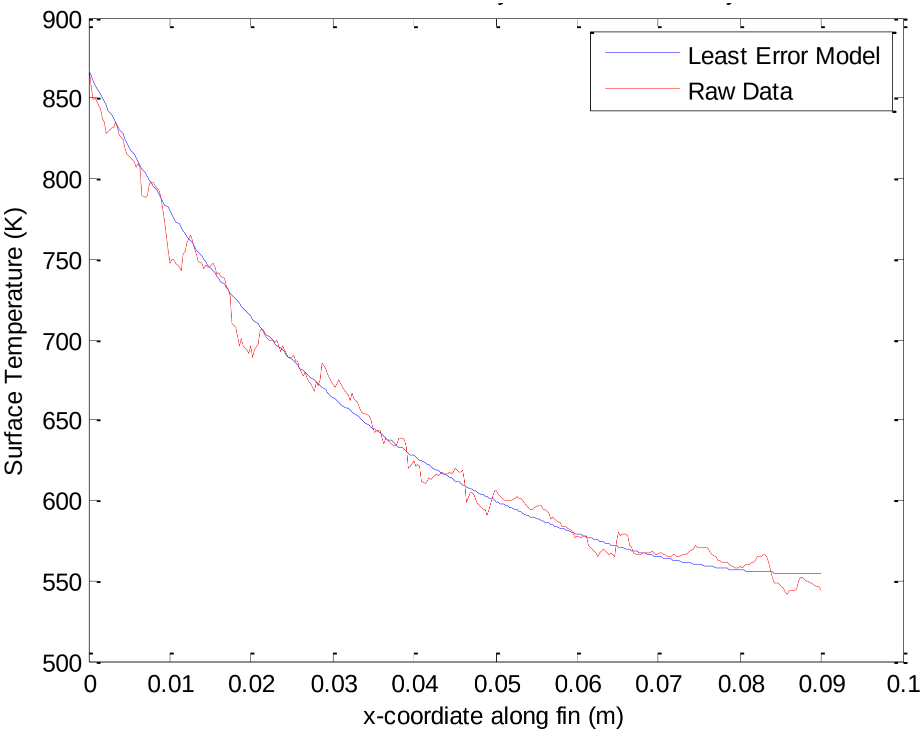
# Modeling: NSTRF Collaborator/Support

- Develop predictive capabilities
- Compare effectiveness between materials
- Optimize radiator (maximum specific power, minimum mass, minimum area)
  - fin size (widths and thicknesses)
- Estimate thermal conductivity of the bulk fibers (in combination with tests)



# Estimating Fin Axial Thermal Conductivity

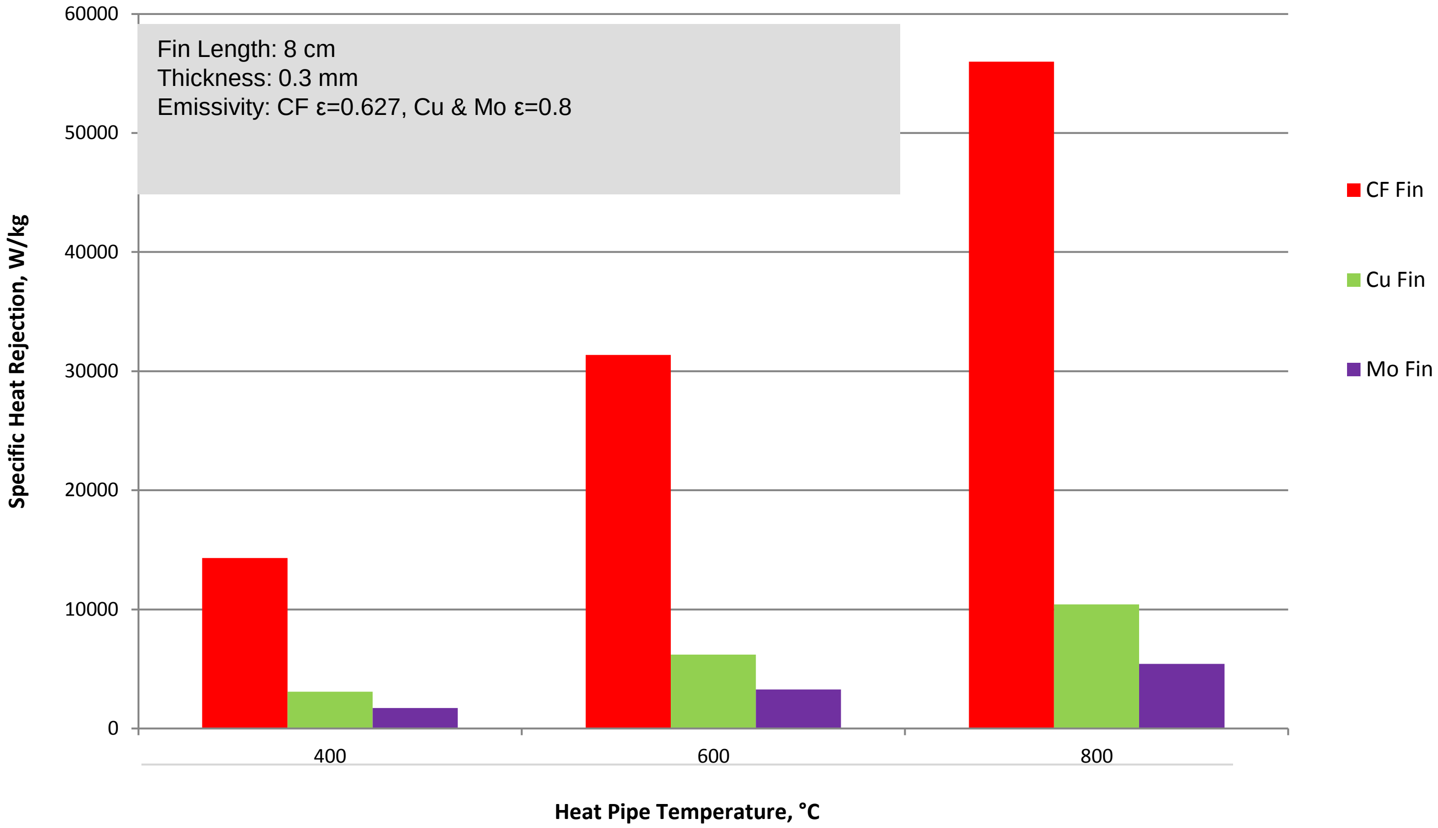


# Thermal Conductivity Estimate

- The latest thermal conductivity estimate for the bulk carbon fiber material at elevated temperatures is about 710 ± 100 W/m-K.
- This verifies that the fibers are functioning well in this application.
- The uncertainty can be reduced by conducting experiments with better controlled radiation boundary conditions.

# Metric – Specific power (kW/kg)



# Summary

- Innovative approach
- Demonstrated proof of concept
- Showed that mats fins can be woven with this material
- Operated at 600°C
- Operated with heat pipe at 600°C
- Improved fidelity of samples and model
- Specific power is factor of approximately 10 over that of Mo, a high temperature metal
- Presently testing to improve the method of brazing fin to heat pipe

# Future work

- Continue improving brazing technique
- Continue to refine measurements, i.e. reduce uncertainties
- Continue to look for potential opportunities for further advancement and implementation

# References


1. Siamidis, John, Lee S. Mason, *A comparison of Coolant Options for Brayton Power Conversion Heat Rejection Systems*, NASA/TM-2006-214121, 2006
2. Mason, Lee S., *A Power Conversion Concept for the Jupiter Icy Moons Orbiter*, Journal of Propulsion and Power, vol. 20, No. 5, 2004
3. Siamidis, John, Lee Mason, Duane Beach, James Yuko, *Heat Rejection Concepts for Brayton Power Conversion Systems*, 2nd International Energy Conversion Engineering Conference, 16-19 August, AIAA 2004-5653, 2004
4. D.G.Walker, E.A Vineyard, R. Linkous, *Modeling and Analysis of a Heat Exchanger with Carbon-Fiber Fin Structures*, <http://www.heatpumpcentre.org/en/projects/completedprojects/annex%2033/publications/Documents/Vineyard%20carbon %20fiber%20hx.pdf>, accessed June 4, 2014.
5. Project Prometheus Final Report, Jet Propulsion Laboratory, NASA Report No. 982-R120461, 2005
6. Tomboulian, Briana N., Lee S. Mason, Robert W. Hyers*, Lightweight Carbon Fiber Radiator for High-Temperature Nuclear Electric Powered Spacecraft,* Proceedings of Nuclear and Emerging Technologies for Space 2013, Albuquerque, NM, February 25-28, 2013, Paper 6752
7. Denham, H. B., J. K. Koester, W. Clarke, A. J. Juhasz, *NASA Advanced Radiator C-C Fin Development*, American Institute of Physics Conference Proceedings, 301, p. 1119, 1994
8. Tomboulian, B. N. and R. W. Hyers, *High-Temperature Carbon Fiber Radiator for Nuclear Electric Power and Propulsion: Project Overview and Update*, Nuclear and Emerging Technologies for Space 2014, Infinity Science Center, MS, February 24-26, 2014

# Questions?

# IR Image of Heat Pipe Simulator

- Inconel tube heat pipe simulator.
- Testing issues because of thermal edge effects.