

Lightweight, High-Temperature Radiator for Space Propulsion

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For high-power nuclear-electric spacecraft, the radiator can account for 40% or more of the power system mass and a large fraction of the total vehicle mass. Improvements in the heat rejection per unit mass rely on lower-density and higher-thermal conductivity materials. Current radiators achieve near-ideal surface radiation through high-emissivity coatings, so improvements in heat rejection per unit area can be accomplished only by raising the temperature at which heat is rejected. We have been investigating materials that have the potential to deliver significant reductions in mass density and significant improvements in thermal conductivity, while expanding the feasible range of temperature for heat rejection up to 1000 K and higher. The presentation will discuss the experimental results and models of the heat transfer in matrix-free carbon fiber fins. Thermal testing of other carbon-based fin materials including carbon nanotube cloth and a carbon nanotube composite will also be presented.

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Lightweight, High-Temperature Radiator for Space Propulsion

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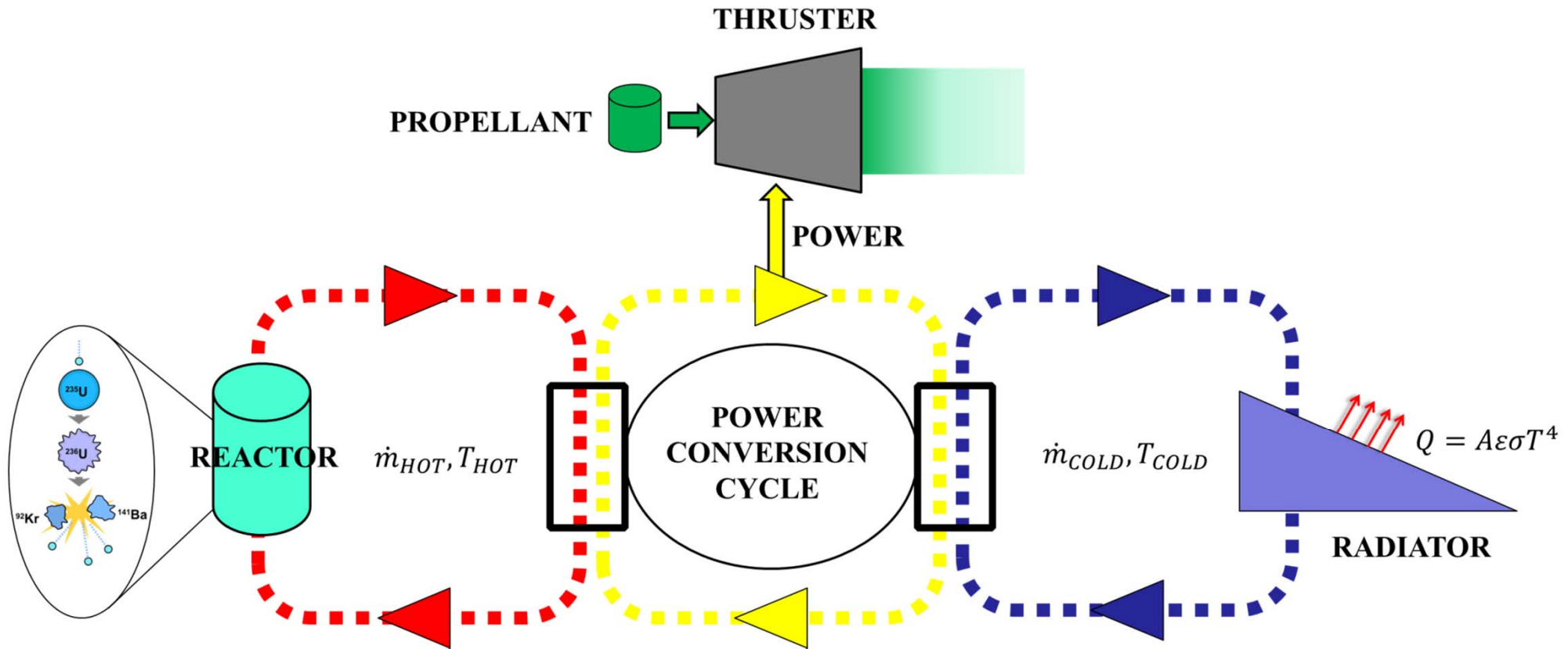
Paul Craven and Jan Rogers
NASA MSFC

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Outline

- Radiators for advanced propulsion
- Materials for radiators
- Modeling and testing novel radiator materials
- Results to date
- Conclusions and Future Work

Nuclear Electric Propulsion (NEP)



NASA's Target Power Level: 100kWe

Heat Rejection

- Radiation is the only heat rejection mechanism to space (no conduction/convection)

- Waste heat depends on

- Power level
- Thermal efficiency of the engine

$$\eta_{Th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{waste}}{Q_{in}}$$

- Amount of heat rejection per unit area of radiator

- Cold-side temperature, T
- Environmental temperature, T_{env}
- Surface emissivity, ε

$$q = \varepsilon\sigma(T^4 - T_{env}^4) \quad \left[\frac{W}{m^2} \right]$$

$$\downarrow$$

$$Area = \frac{Q_{waste}}{\varepsilon\sigma T^4}$$

Why are better radiators required?

- To Date:
 - Previous propulsion methods did not require large radiators:
 - Chemical rockets reject most heat with the exhaust gas
 - Electric propulsion systems have used solar power, which does not require much heat rejection
 - Low temperature heat rejection $<100^{\circ}\text{C}$
 - Existing radiator designs don't meet NASA's areal density goal for NEP of $2\text{-}4\text{ kg/m}^2$
- Goals:
 - Decrease areal density
 - Increase capabilities
 - High temperature applications
 - Damage tolerance \rightarrow extended lifespan

Radiator Mass Reductions

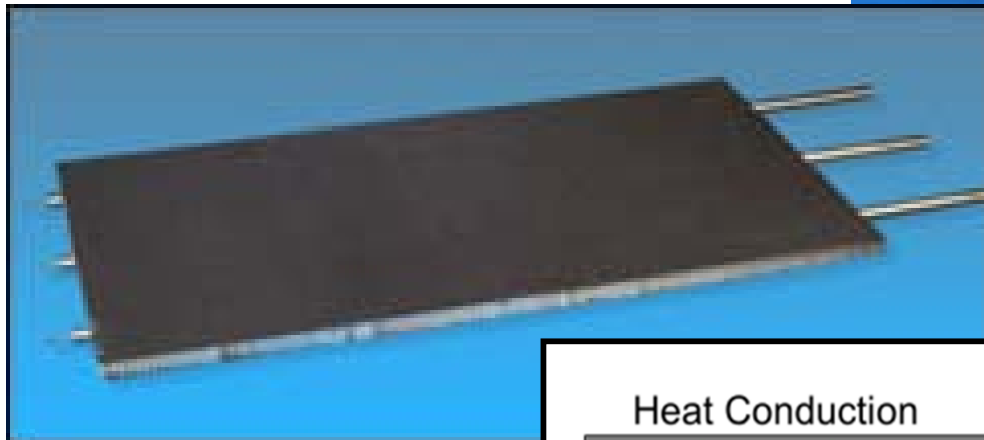
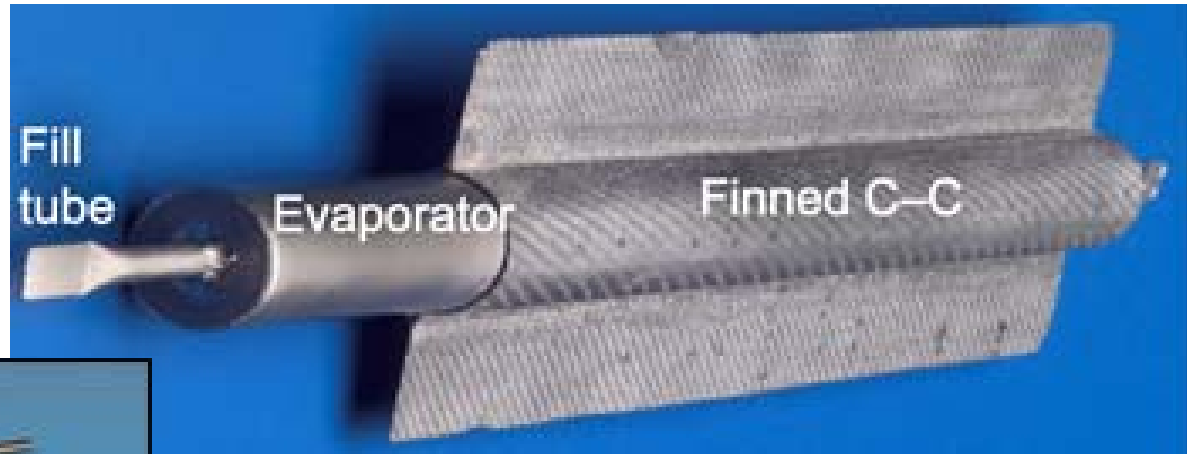
1. Decrease fin areal density
2. Increase fin emissivity (but already $\rightarrow 1$)
3. Increase cold-side temperature (decreases the fin area)
4. Reduce thermal resistances at interfaces



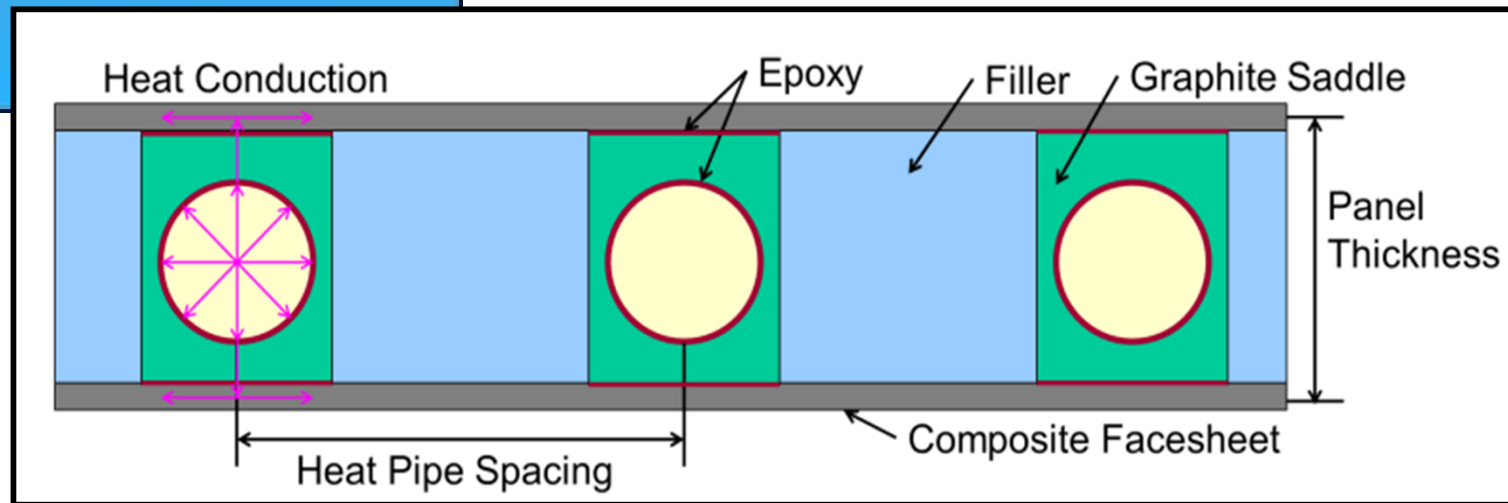
Even a small increase in efficiency can have a significant impact for a component this large

Typical Fin Constructions

Wrapped Fin



Structural Panel



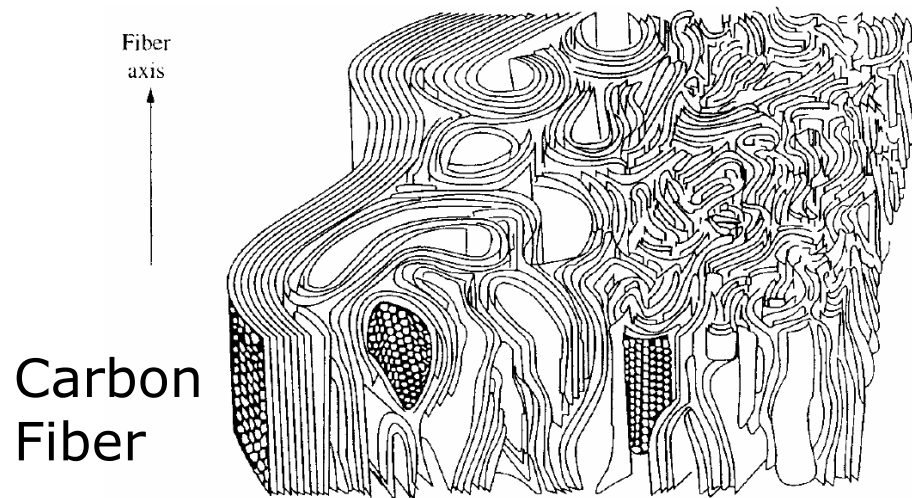
Fin Material Comparison

Fin Material	High Temperature Tolerance (Want HIGH)	Axial Thermal Conductivity (Want HIGH)	Density (Want LOW)
Aluminum	Low	Moderate	Low
Stainless Steel	Moderate	Low	Moderate
Molybdenum	High	Moderate	High
Carbon-Carbon Composite	High	Moderate	Low
Carbon-Polymer Composite	Low	Moderate	Moderate
Bare Carbon Fiber	High	High	Low

Materials

Thermal Conductivity of Carbon Materials

Measured Axial/In-Plane Thermal Conductivity at Room Temperature (300K) [W/(m-K)]	
Graphene Sheet	3080–5300
Carbon Nanotube (CNT)	
Single-Walled (SW)	3500
Multi-Walled (MW)	3000
SW-CNT Bundles	1750-5800
Diamond	2200
Carbon Fiber	600-1500
Natural Graphite	130
CNT Cloth	40, 250 (600°C)
CNT "As-Grown" Mat	35



Carbon Nanotube



Graphene

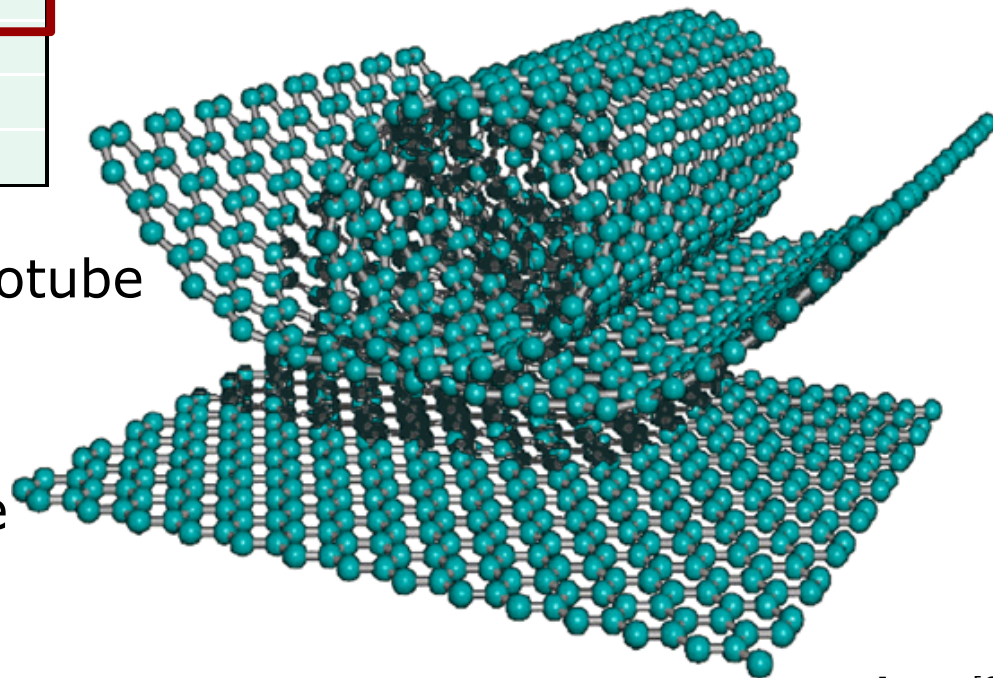
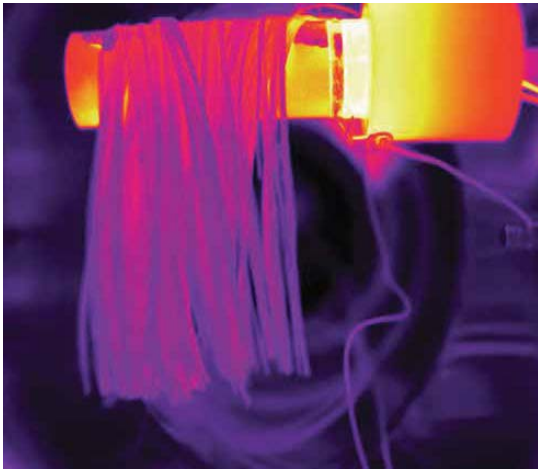
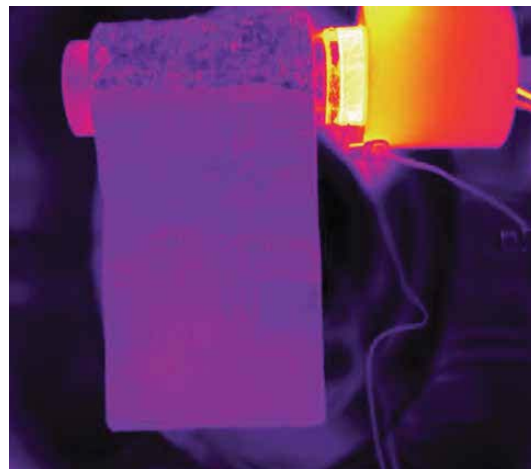


Image: [67]

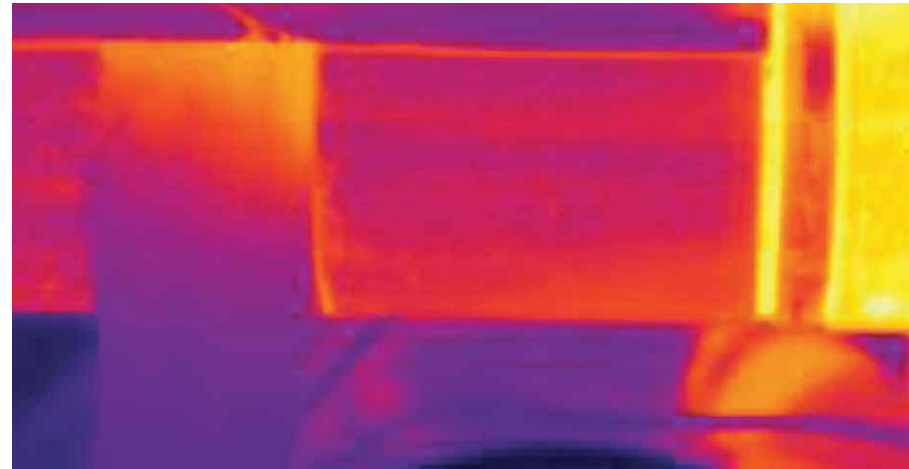
Materials Used in Test



IR image of carbon fibers with a heater temperature of 600°C.

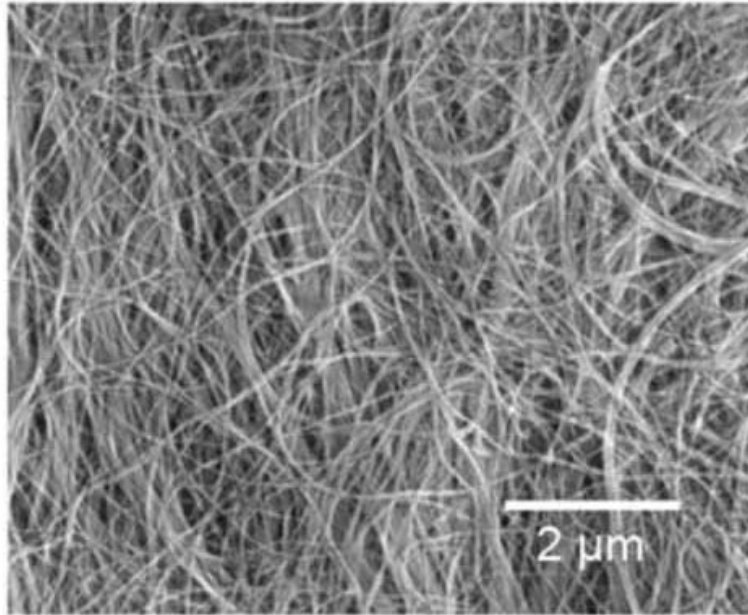


IR image of carbon nanotube cloth with a heater temperature of 600°C.

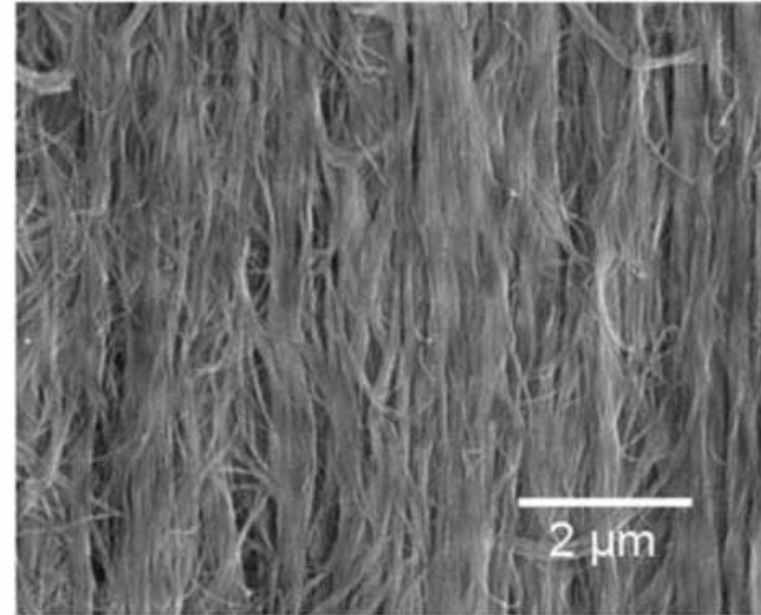


IR image of oriented CNT composite (Dennis Tucker) with a heater temperature of 600°C.

(a)



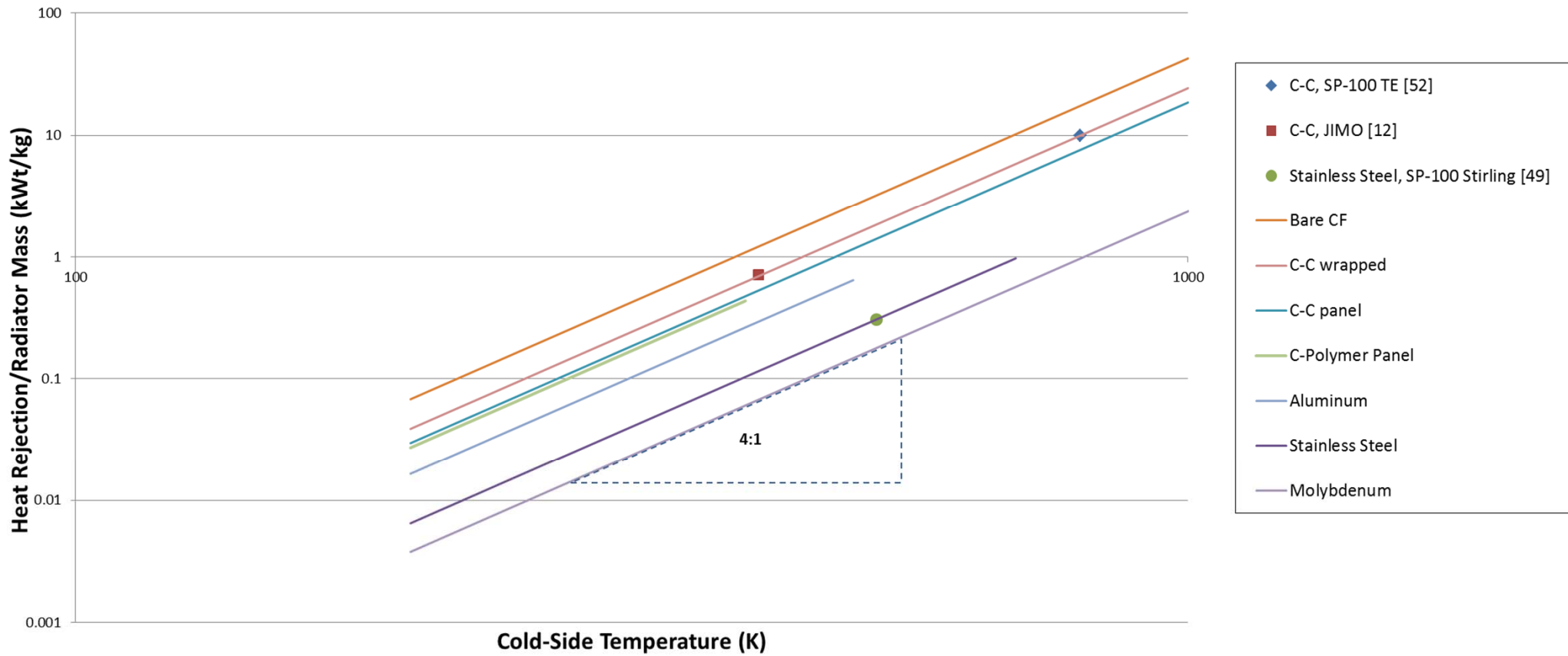
(b)



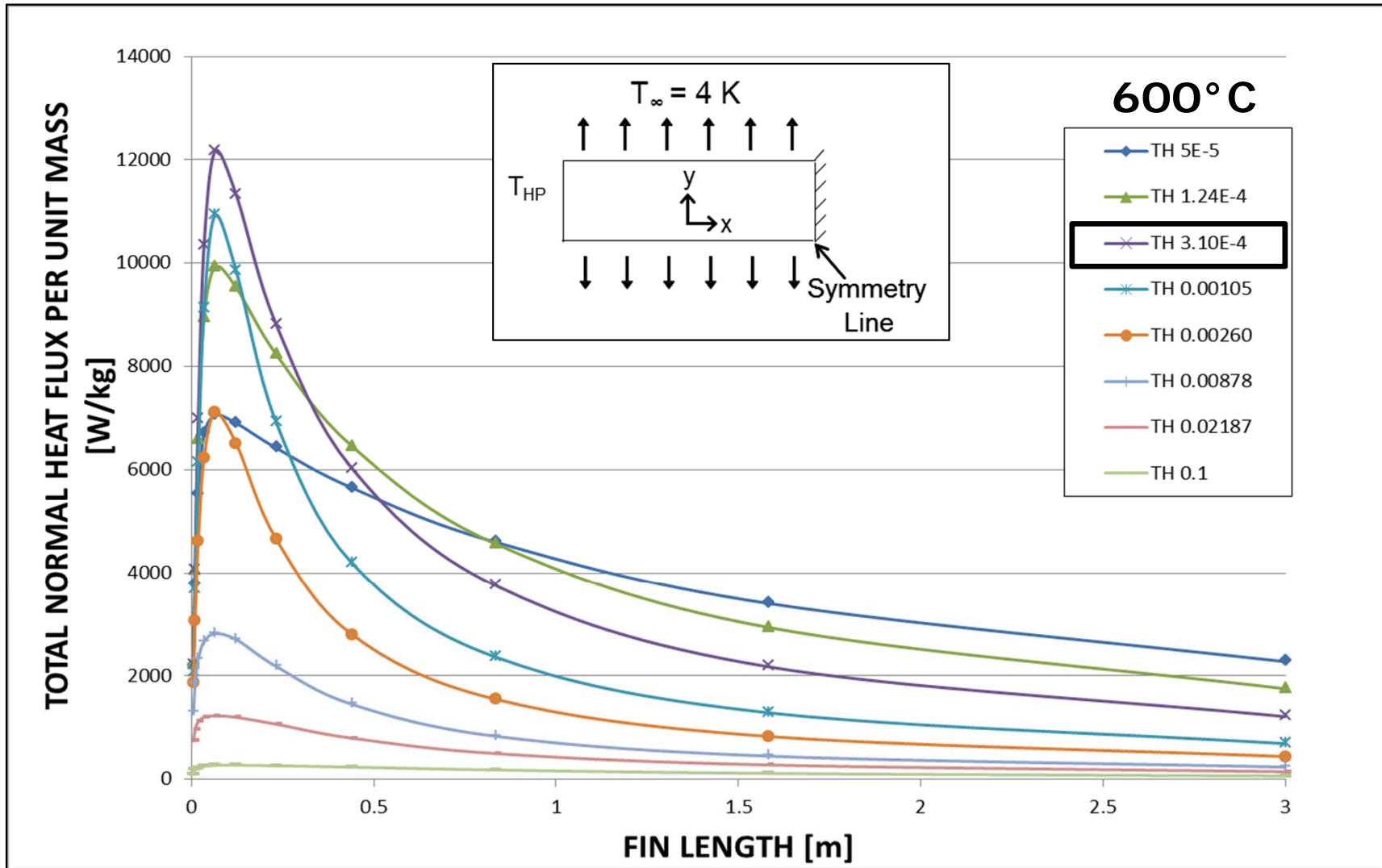
(a) An unstretched composite sheet with wavy nanotubes and microscale porous structure and (b) a composite sheet stretched by 12%, showing straight, well-aligned and closely-packed nanotubes.[*]

*X. Wang, Z. Z. Yong, Q. W. Li, P. D. Bradford, W. Liu, D. S. Tucker, W. Cai, H. Wang, F. G. Yuan & Y. T. Zhu (2012): Ultrastrong, Stiff and Multifunctional Carbon Nanotube Composites, *Materials Research Letters*, DOI:10.1080/21663831.2012.686586

Fin Material Comparison



Fin Geometry Optimization



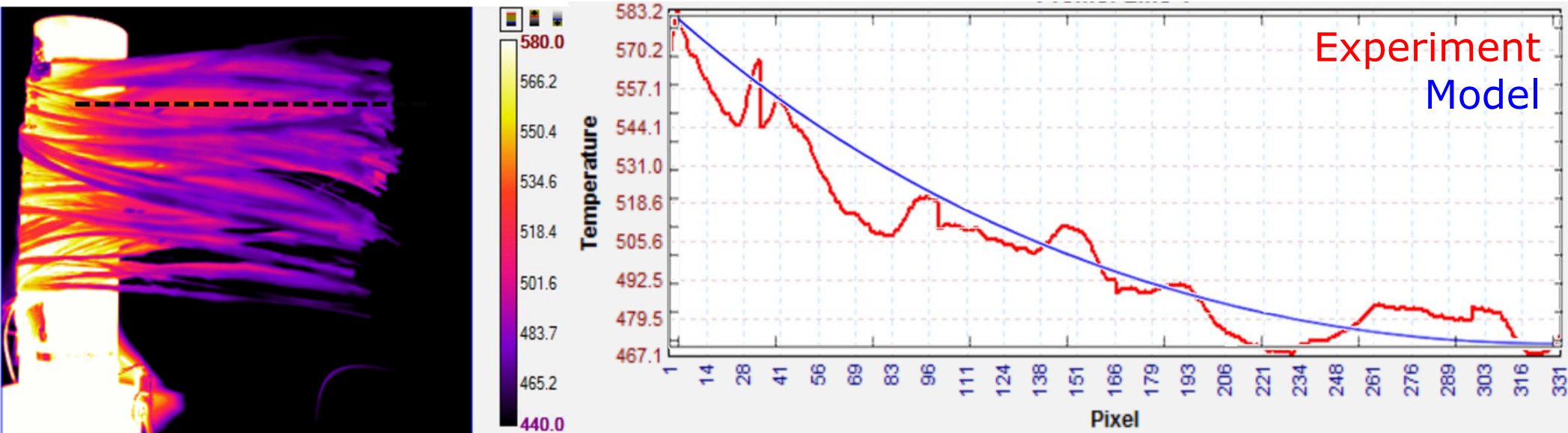
Preliminary Tests

- Test article: Inconel 718 pipe, TiCuSil braze, Mitsubishi KI3C2U (pitch) carbon fiber
- Evaluate basic fin performance and component compatibility
- Verify imaging capabilities
- Validate basic model



Model Progress

- May campaign: good qualitative fit



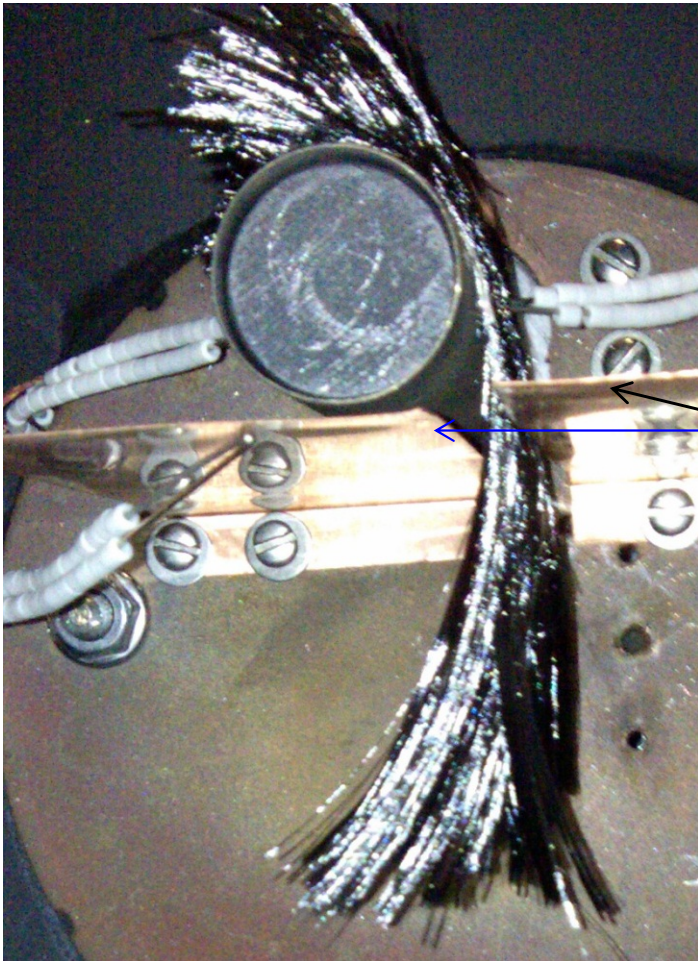
$$t_{meas} = \frac{\left(\frac{mass}{length} \right)}{(density)(width)}$$

Unshielded Fin

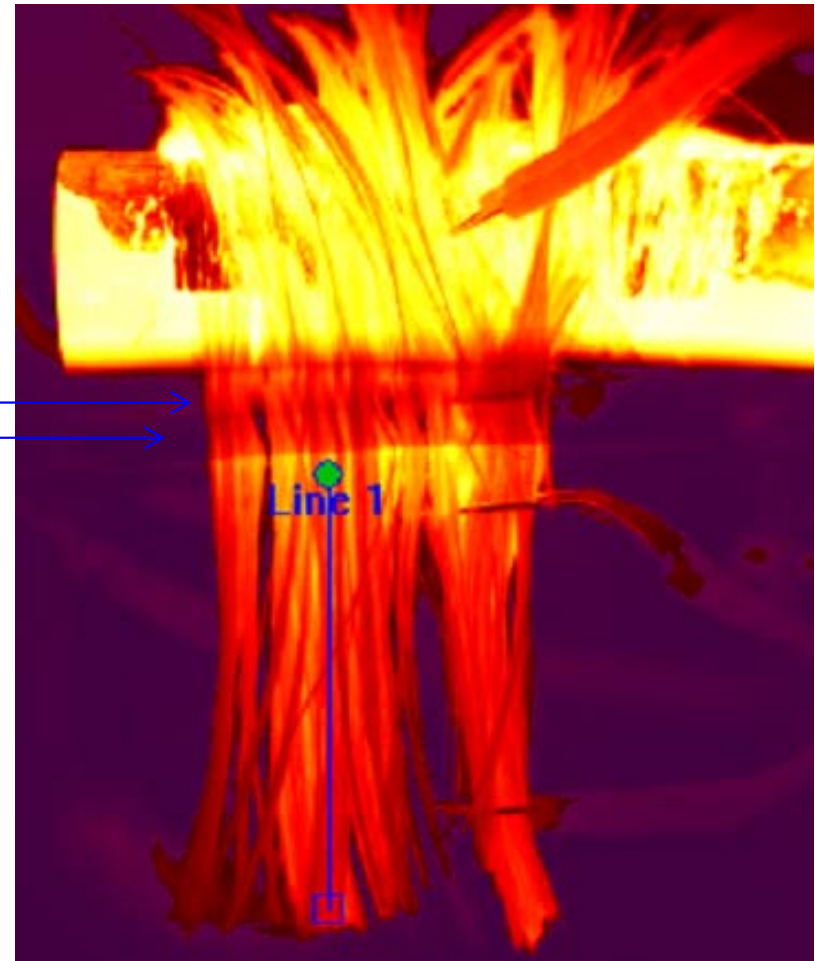
- Each element of the fin is heated by direct radiation from the tube, as well as by conduction along fin.
- Analytic calculation shows radiation from tube is about 9.8W/m of width, vs. conduction about 7.4 W/m.
- Total heat transfer is sum of radiation and conduction.
- Apparent thickness would be 2.3 X measured.
- Discrepancy between model and experiment explained.

Shielded Fin

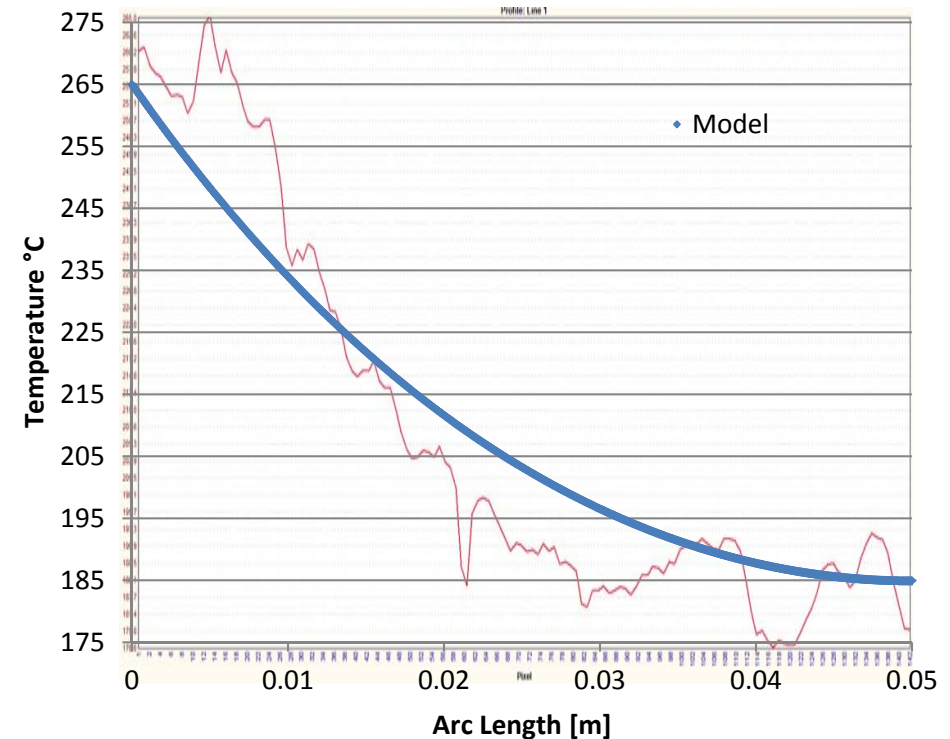
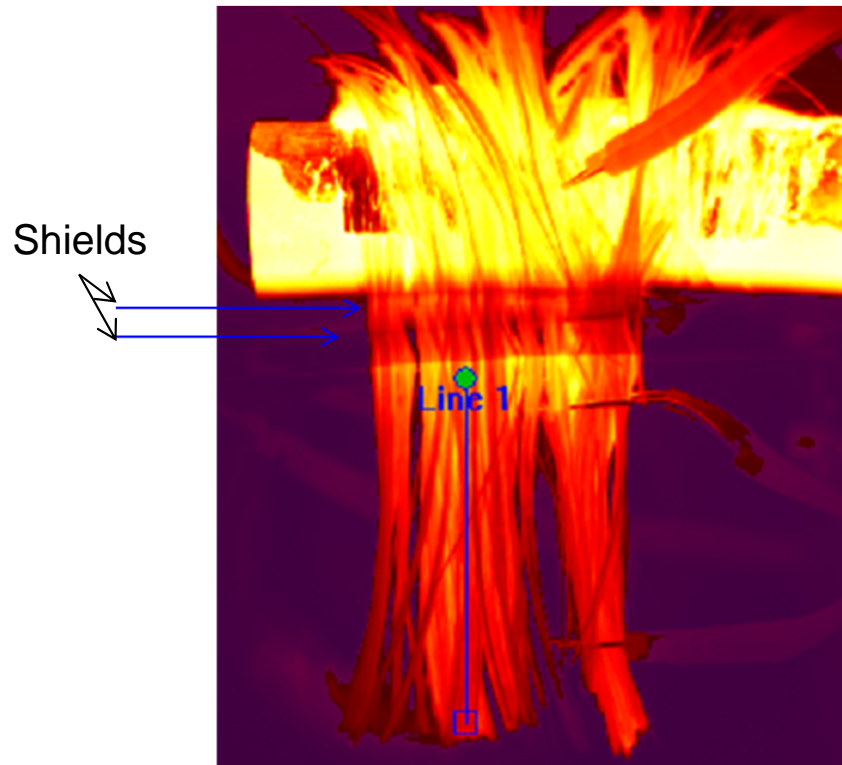
- Isolate conduction along fin
- Water-cooled copper heat shields added.



Shields



Model Progress: Shielding Fins



Quantitative agreement between model and experiment using measured thickness and no free parameters.

Lessons from Comparison of Model and Experiment

- Quantitative agreement between model and experiment for best samples, shielded fins.
- Large variability in temperature distribution in IR images, particularly for irregular samples.
 - Need very controlled sample geometry
 - Braided fiber specimens?

Woven High-conductivity Carbon Fiber



Woven carbon fiber manufacturing pathfinder, made at MSFC from Mitsubishi K13D2U high-conductivity carbon fiber. This article is approximately 30 cm x 3 and contains 30 tows, approximately 90,000 carbon fibers.



Commercial unidirectional carbon structural fiber

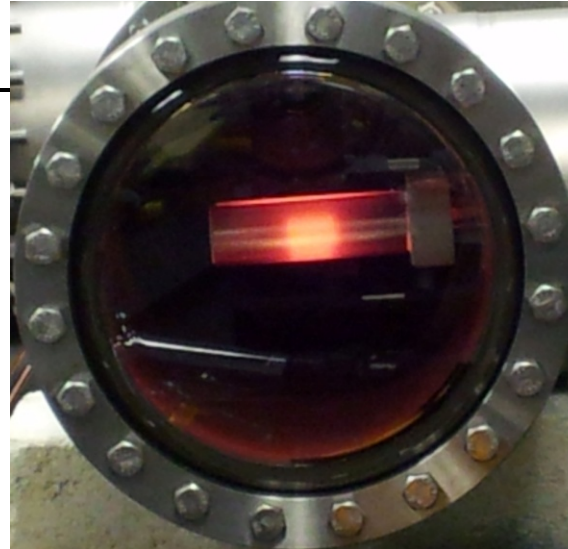


First generation article brazed from individual tows.

Facilities / Components



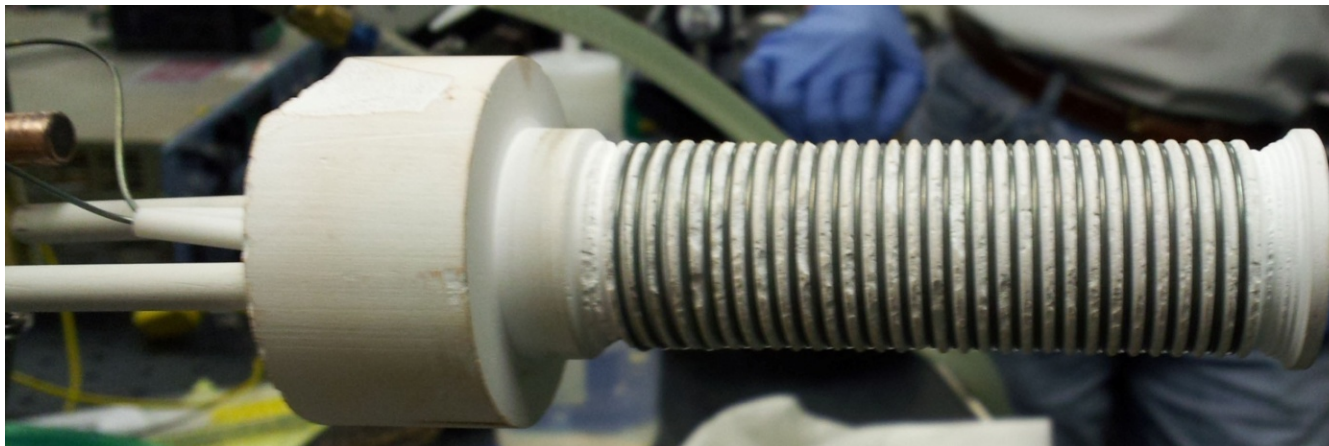
Generic Heater Setup



Vacuum Braze Facility



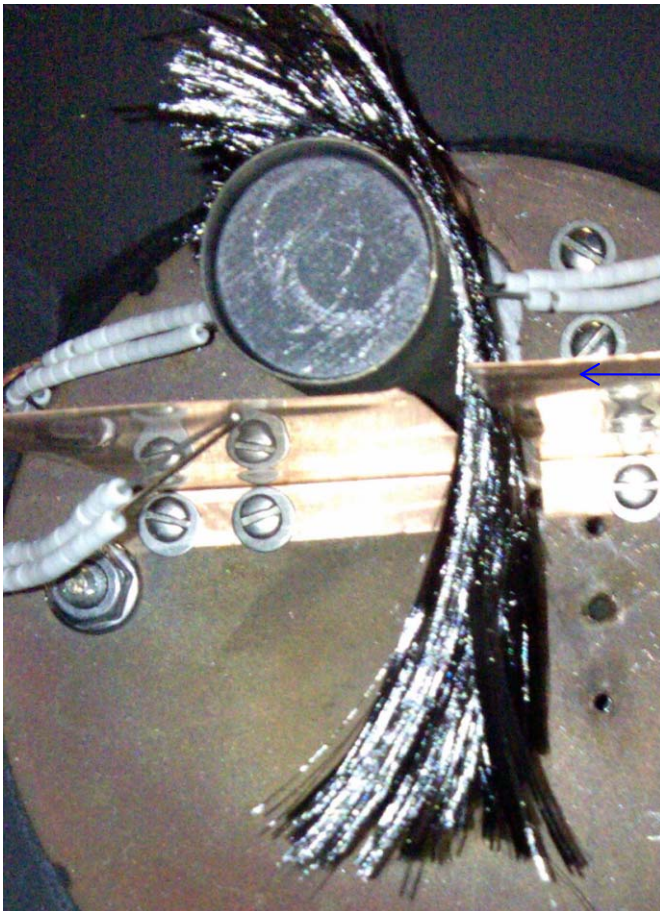
Sample Braze



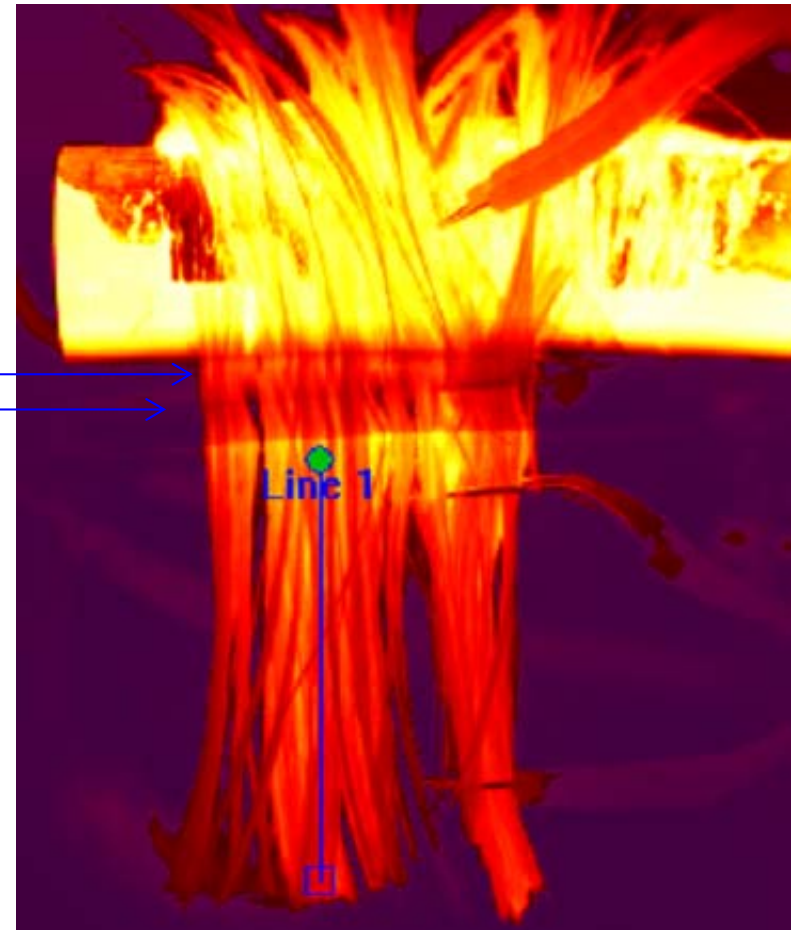
Latest Version of Heat source for Radiator and Braze Facility

Shielding Fins

- Isolate conduction along fin
- Water-cooled copper heat shields added.



Shields



Future Work

- Increase the upper operating temperature
- Quantify device performance
- Assess the potential of such devices and materials to meet NASA's needs for high-temperature radiators for spacecraft
- Recommend further refinement and characterization of similar devices

Questions



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BACKUP SLIDES

Radiators are an Essential Cross Discipline Supporting Technology

- ***TA02 In-Space Propulsion Systems***

Supporting technologies...

2.4.4 Heat Rejection

Heat rejection is a key supporting capability for several in space propulsion systems. Some examples include rejection of the waste heat generated due to inefficiencies in electric propulsion devices ... In general the key heat rejection system metrics for in-space propulsion are cost, weight, operating temperature, and environmental durability (e.g. radiation, MMOD).[1]

- ***TA03 Space Power and Energy Storage***

5.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy:.... "Fission: Nuclear reactor systems can provide relatively high power over long periods of time. ... Other components have reached higher TRLs in past programs such as the SP-100 and Prometheus programs, but technology capability has been lost and must be redeveloped. Key subsystems that must be addressed include ... heat transfer, heat rejection...." [3]

- ***TA14 Thermal Management Systems***

2.2.3.1. Radiators

Radiator advancement is perhaps the most critical thermal technology development for future spacecraft and space-based systems. Since radiators contribute a substantial portion of the thermal control system mass. For example, the Altair (Lunar Lander) vehicle radiator design represents 40% of the thermal system mass. Radiators can be subdivided into two categories; the first is for rejection at temperatures below 350 K and the second is for nuclear or high power systems at temperatures around 500 K.[2]

Stated Goals

- A test bed facility and methods for quantification of the performance of radiators made from novel materials
- Demonstration of fabrication methods for novel radiators
- A validated predictive model to support future design and analysis efforts
- Quantification of device performance/assessment of potential.
- Identification of refinements to improve the model and device design.
- Model validation against the experimental results
- Integrate modeling efforts with the test efforts so that test data can be used to anchor and validate the existing model
- Assessment of the potential of such devices to meet NASA's needs for high-temperature radiators for spacecraft
- Recommendations for further refinement and characterization of similar devices

Accomplishments

- The use of carbon fibers for the radiator material.
- The fabrication and testing of several sub-scale test articles.
- The quantitative agreement between modeled and experimental temperature distribution.
- The design and construction of a heater arrangement that isolates the conductive properties of the samples from the radiative effects of the heat pipe.
- The construction of a vacuum brazing facility for attaching the carbon based fibers to the heat pipe simulator.

Score Card

Stated Objectives

- A test bed facility and methods for quantification of the performance of radiators made from novel materials.
- Identification of refinements to improve the model and device design
- Demonstration of fabrication methods for novel radiators.
- A validated predictive model to support future design and analysis efforts.
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Accomplishments

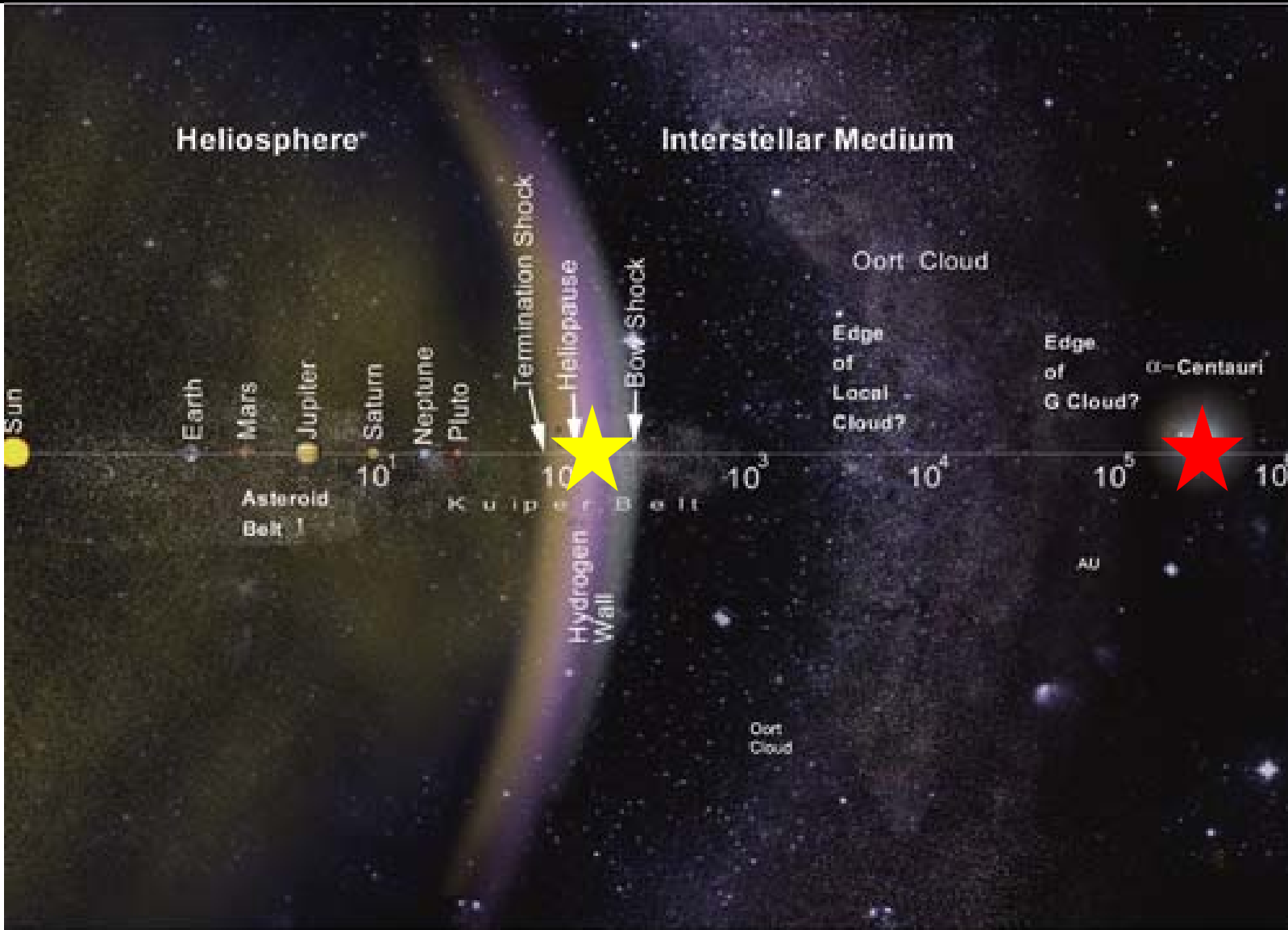
- The design and construction of a heater arrangement that isolates the conductive properties of the samples from the radiative effects of the heat pipe.
- The construction of a vacuum brazing facility for attaching the carbon based fibers to the heat pipe simulator.
- The use of carbon fibers for the radiator material.
- The fabrication of sample radiator fins.
- The fabrication and testing of several sub-scale test articles.
- The quantitative agreement between modeled and experimental temperature distribution.

Importance of Model

The model is the link between the experiments and the flight radiator. If we can model the experiment accurately, then we can make a quantitative prediction of the performance of a flight radiator.

It is through the model that we transform what is measured (temperature distribution along the sample, areal density, mass, etc) and what we know about the material (emissivity, thermal conductivity, etc.) into a useful measure in a full scale model of radiative power/mass, possibly turndown ratios(very much environment dependent), and anything else used to measure radiator efficiency, keeping four metrics in mind, mass of the radiator, operating temperature, environmental durability, and cost.

Motivation: Farther & Faster Space Exploration



Graphic from the Interstellar Probe Science and Technology Definition Team NASA/JPL

Image: [21]

Objectives

NASA's Objective: Increase efficiency and capabilities of deep-space travel

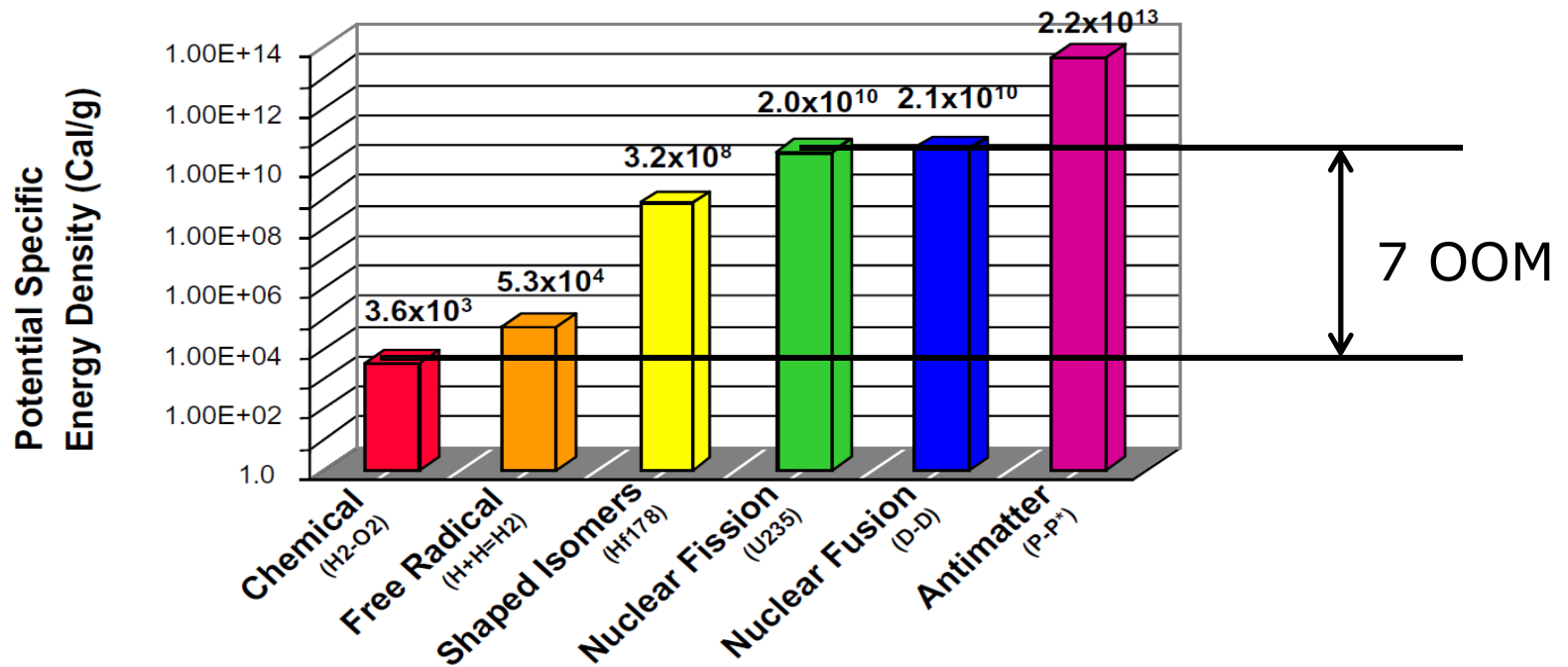
Improved Propulsion:
Increase power-to-mass & speed

Promising Propulsion Option:
Nuclear-Electric Propulsion (NEP)

Required Technology for NEP:
Improved Heat Rejection

"Radiator advancement is perhaps the most critical thermal technology development for future spacecraft and space-based systems." -NASA

Potential Propulsion Energy Sources



x 50 =



S.L.Rodgers, "Propulsion Research Center." Proceedings of the Workshop on Materials Science for Advanced Space Propulsion, Huntsville, Alabama, October 9-10, 2001.

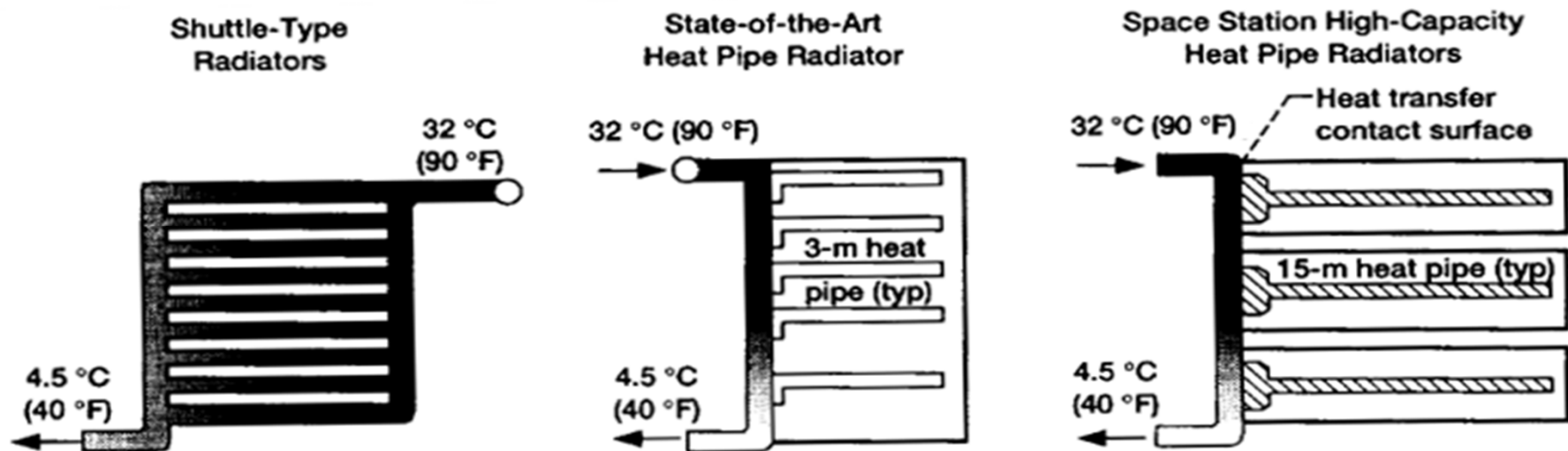
Thruster Comparison

	Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Chemical	Cold gas	50–75	—	—	Various
	Chemical (monopropellant)	150–225	—	—	N ₂ H ₄ H ₂ O ₂
	Chemical (bipropellant)	300–450	—	—	Various
Electric	Resistojet	300	0.5–1	65–90	N ₂ H ₄ monoprop
	Arcjet	500–600	0.9–2.2	25–45	N ₂ H ₄ monoprop
	Ion thruster	2500–3600	0.4–4.3	40–80	Xenon ← Electrostatic
	Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
	PPTs	850–1200	<0.2	7–13	Teflon

$$I_{sp} = \frac{\text{thrust}}{(\text{time})(\text{weight of propellant used})} = [1/\text{time}]$$

Heat Transport System Evolution

- Pumped (1970's-1980's)
 - Vulnerable: one pipe failure causes system failure
 - High pumping power required
- Heat Pipe (1990's-present)
 - Independent heat pipes decrease vulnerability
 - 2-phase system quickly transports heat far from source



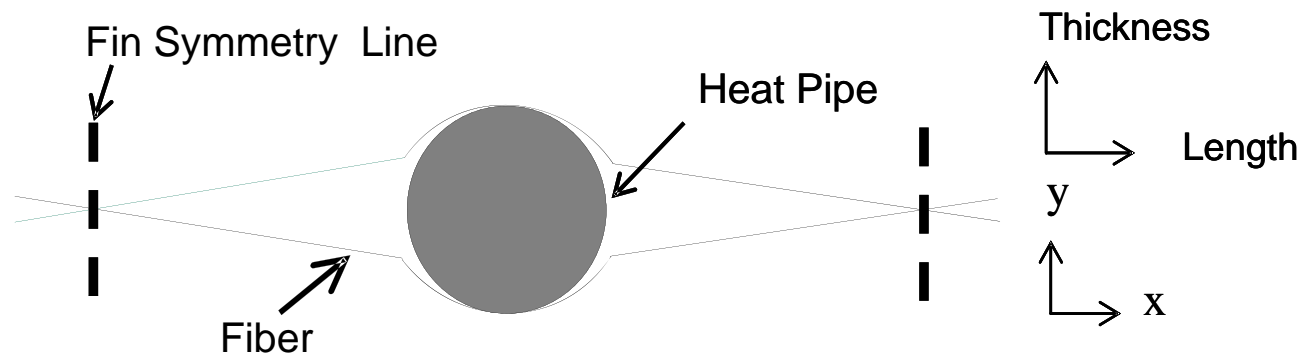
Current Work

Evaluating bare carbon fiber fin material as a high performing alternative to metals and composites

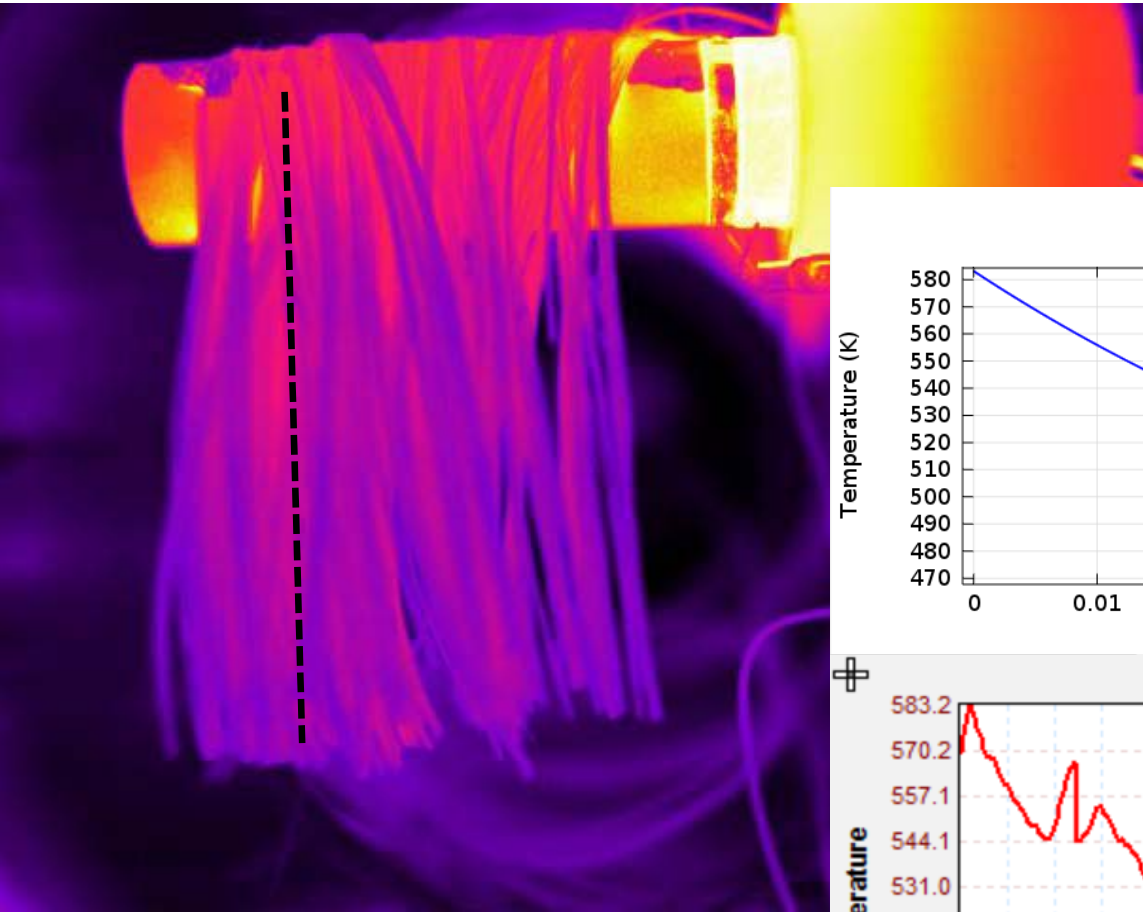


Proposed Carbon Fiber Radiator Fin

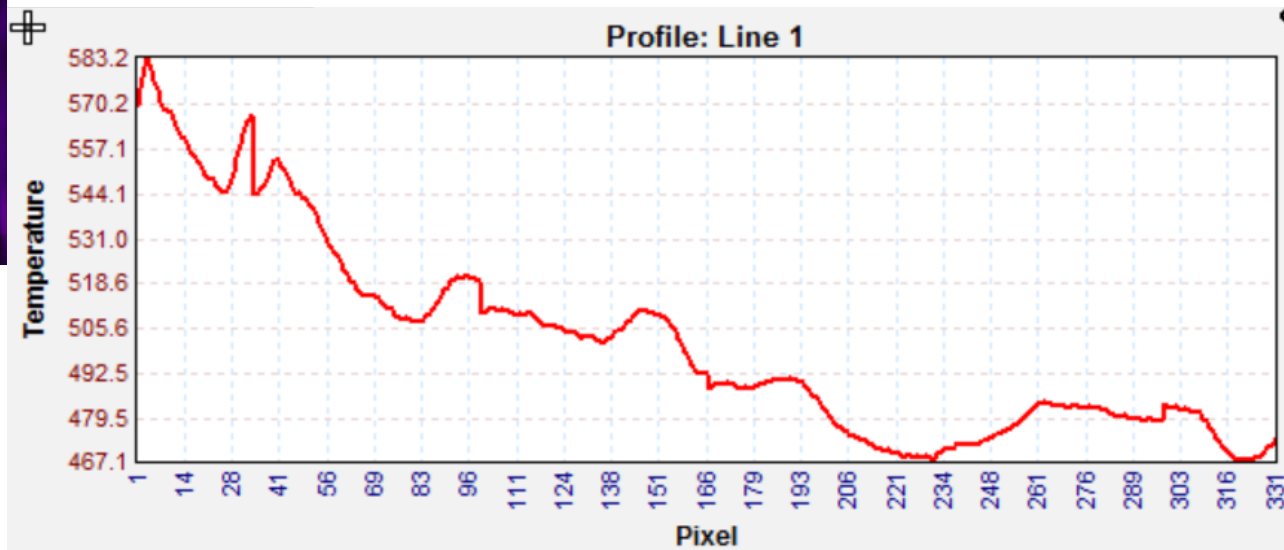
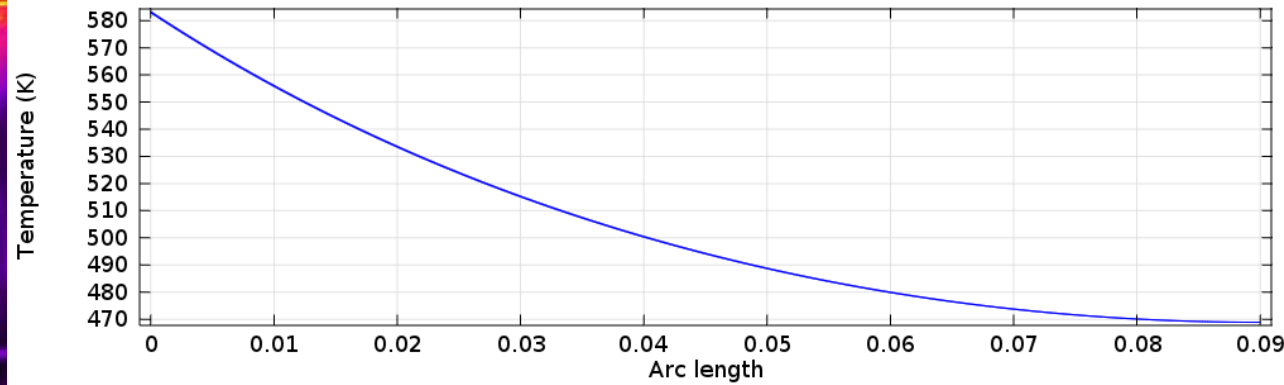
- Replace metal and composite fins with carbon fibers bonded directly to heat pipe
- Eliminate matrix & align majority of fibers normal to heat pipe axis for maximizing thermal performance
- Radiation from top and bottom surfaces



Preliminary Tests

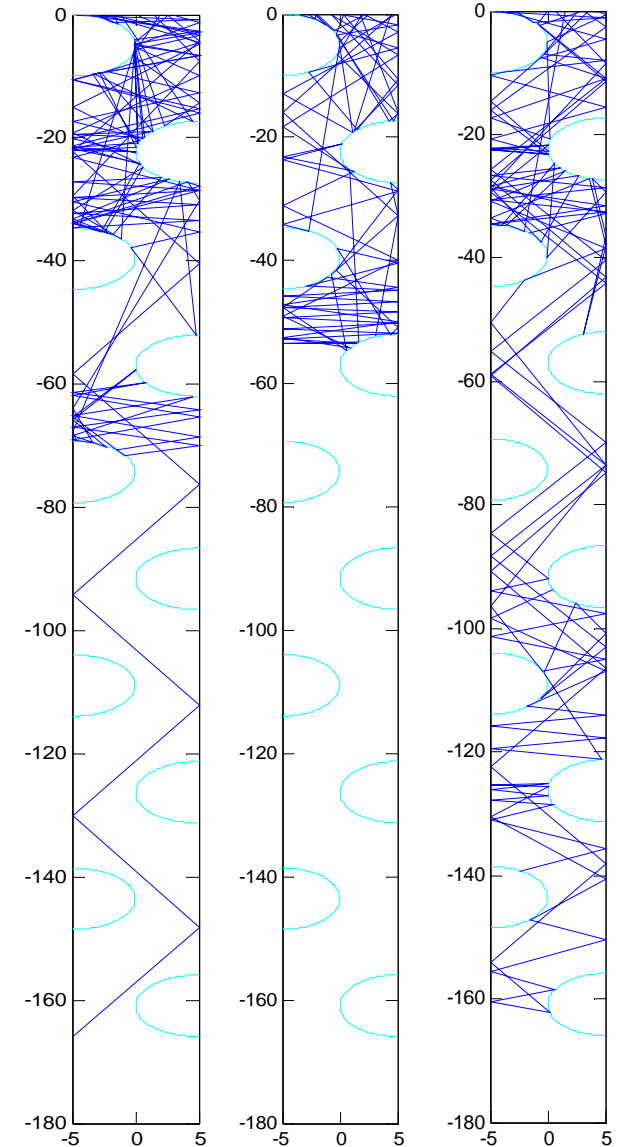


Line Graph: Temperature (K)

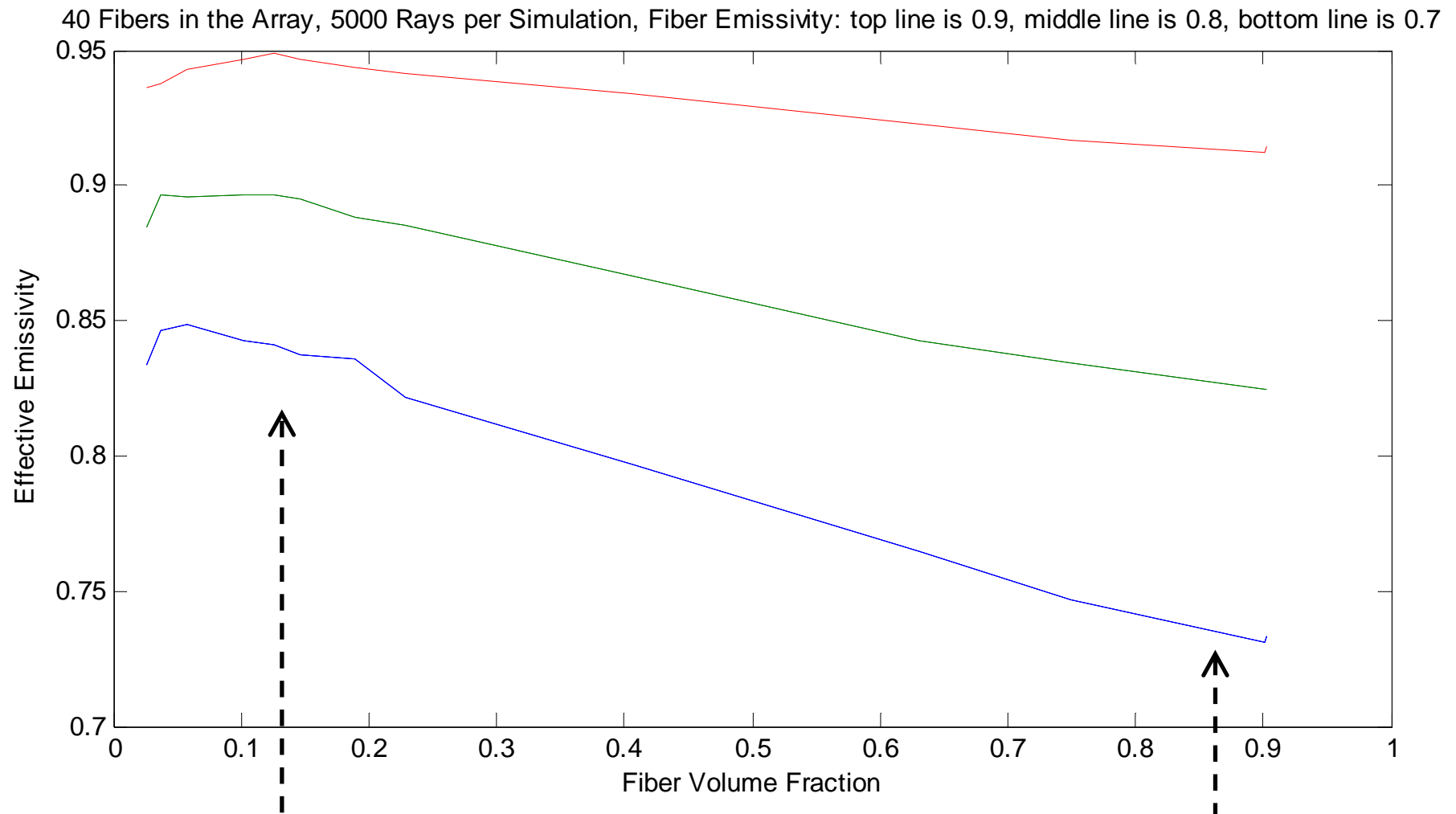


Predicting Fiber Mat Emissivity

- Monte Carlo Ray Tracing
 - Uniform close-packed fibers
 - Diffuse incident radiation from top
 - Gray-Diffuse fibers
 - Symmetry boundary conditions on side walls
 - Top and bottom boundaries are perfect absorbers to scattered radiation
- $\alpha = \varepsilon$ for a grey body



Effective Emissivity Results



Maximum due to multiple scattering within fiber array

Effective emissivity approaches individual fiber emissivity

Fin & Tube Space Radiator Designs Examples

- International Space Station (ISS)
 - Deployable radiator influenced many subsequent designs
 - Implemented, in-use
- Space Power 100kW (SP-100)
 - High-temp, fission power application
 - Designed, not implemented – program ended in 1994
- Jupiter Icy Moon Orbiter (JIMO)
 - NEP application
 - Designed, not implemented – program ended in 2005
- Fission Surface Power (FSP)
 - Fission power application
 - On-going research

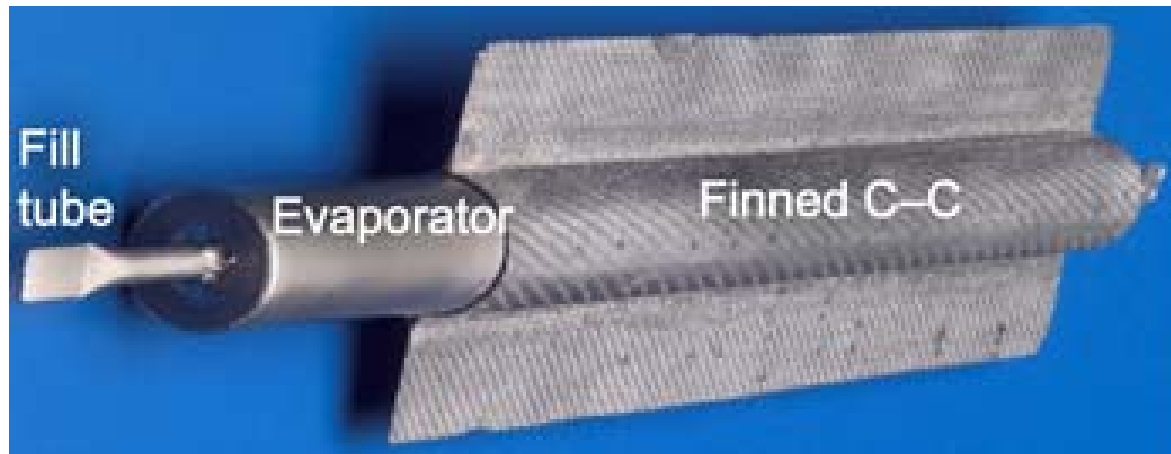
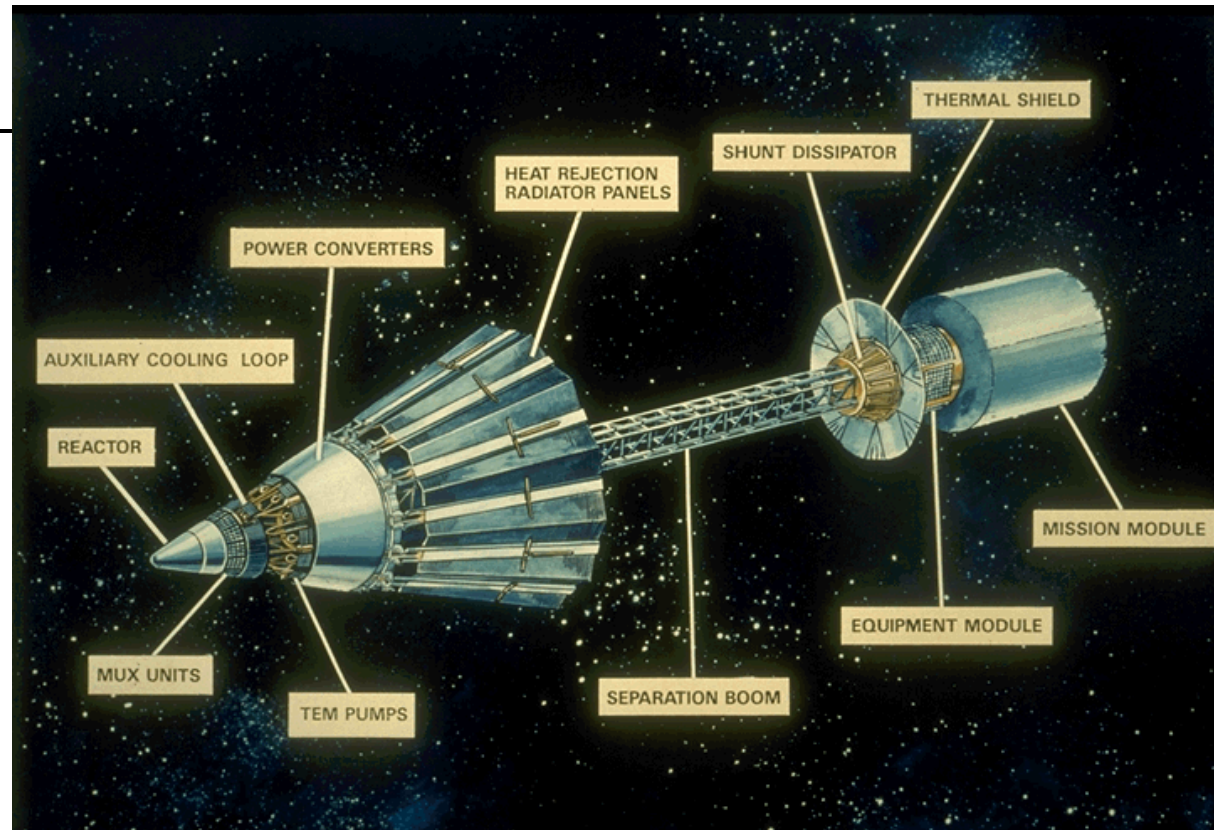
ISS Radiators

- Operating temperature 100°C
- Panels:
 - Aluminum facesheets
 - Aluminum honeycomb filler
 - Inconel tubes
 - Emissive ceramic coating
- Pumped ammonia heat transport system
- Scissor deployment mechanism



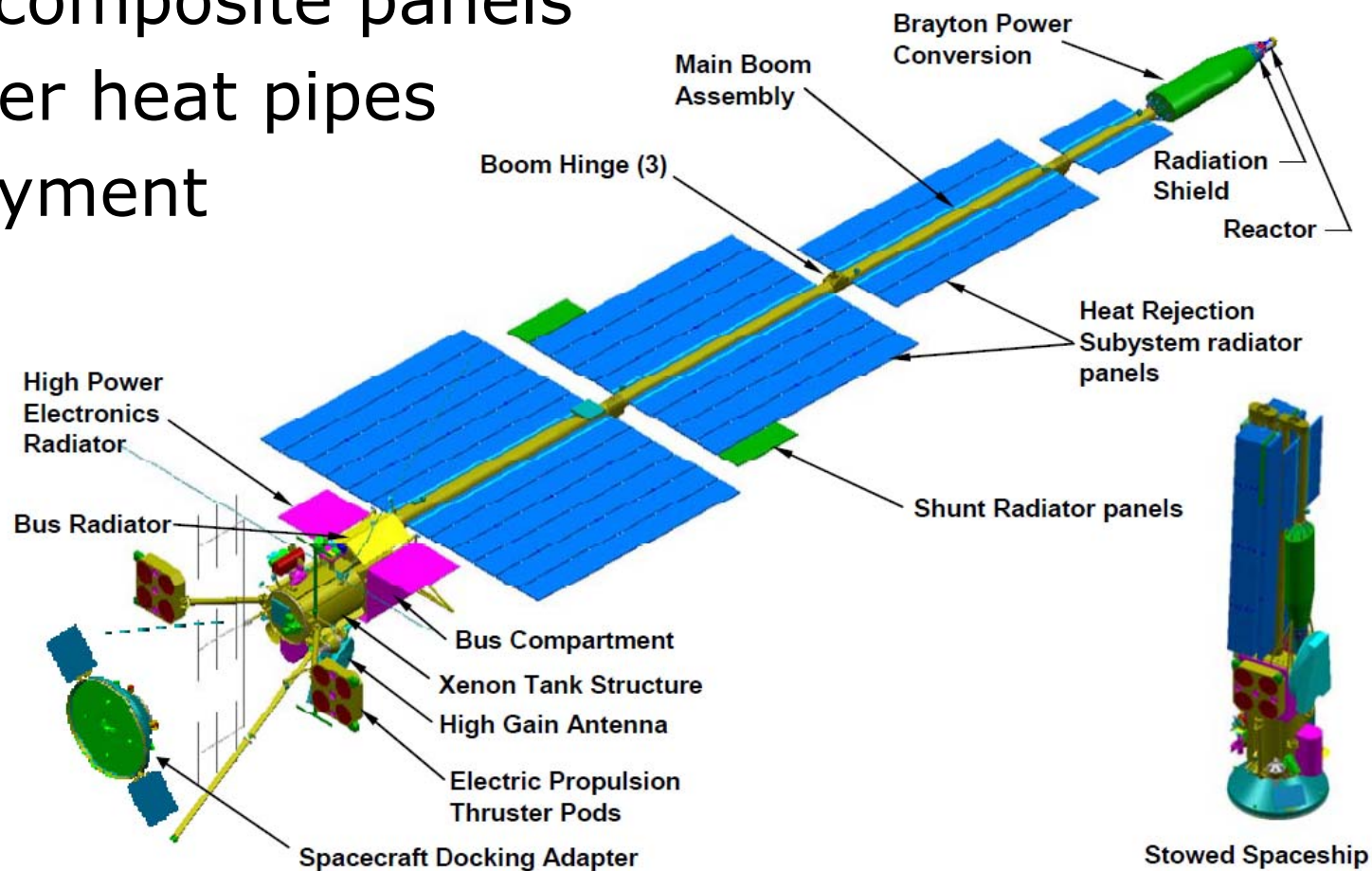
SP-100 Radiators

- Operating temp. 600°C
- Main fluid loop: NaK
- C-C composite panels
- Heat Pipe:
 - Niobium-Zirconium shell & wick
 - Potassium fluid



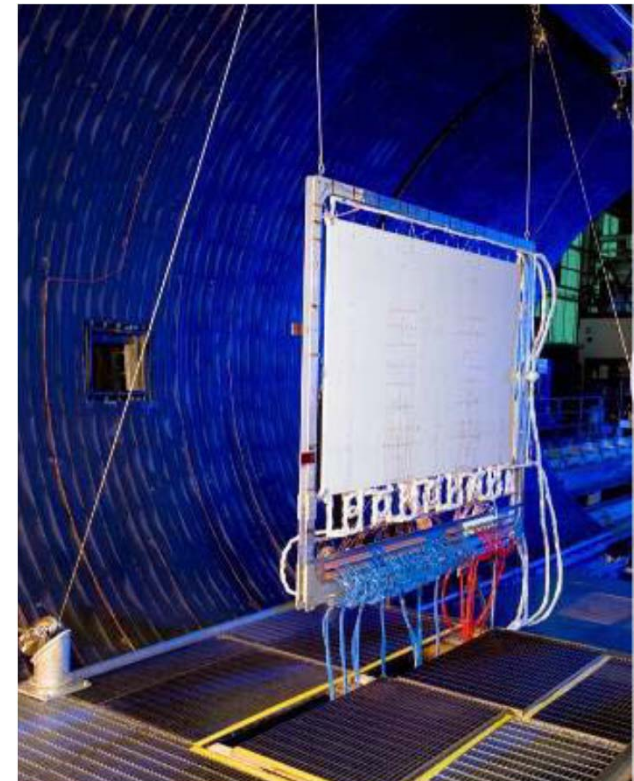
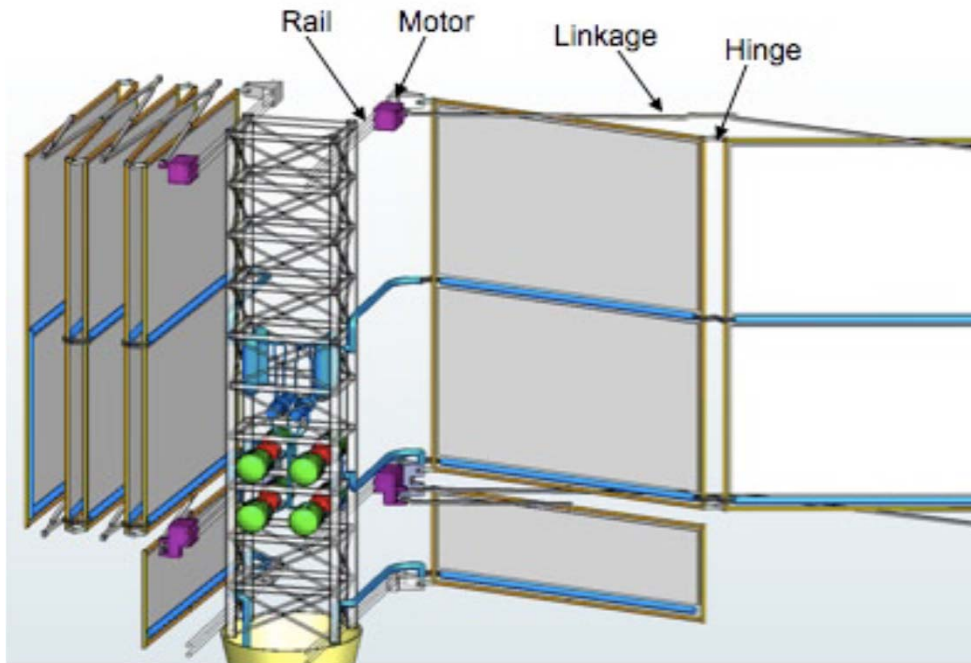
JIMO Radiators

- Operating temperature: 100°C
- Main fluid loop: NaK
- Carbon fiber composite panels
- Titanium-water heat pipes
- Scissor deployment



FSP Radiators

- On-going work on nuclear fission energy for Lunar & Martian outposts
- Continuation of JIMO radiators: 100 °C operating temp., carbon-polymer panels, Ti-water heat pipes, emissive coating
- Demonstration panels



Nuclear Fission Reactor

- Core: fuel elements & working fluid
- Nuclear fission chain reaction:
 1. The nucleus of an atom is struck by a neutron and becomes unstable
 2. Nucleus splits apart in an exothermic reaction releasing kinetic energy of fission products, gamma radiation, and free neutrons
 3. The heat is absorbed by surrounding media and the free neutrons initiate subsequent reactions
- Heat of reaction absorbed by working fluid and delivered to the hot-side of the power generator

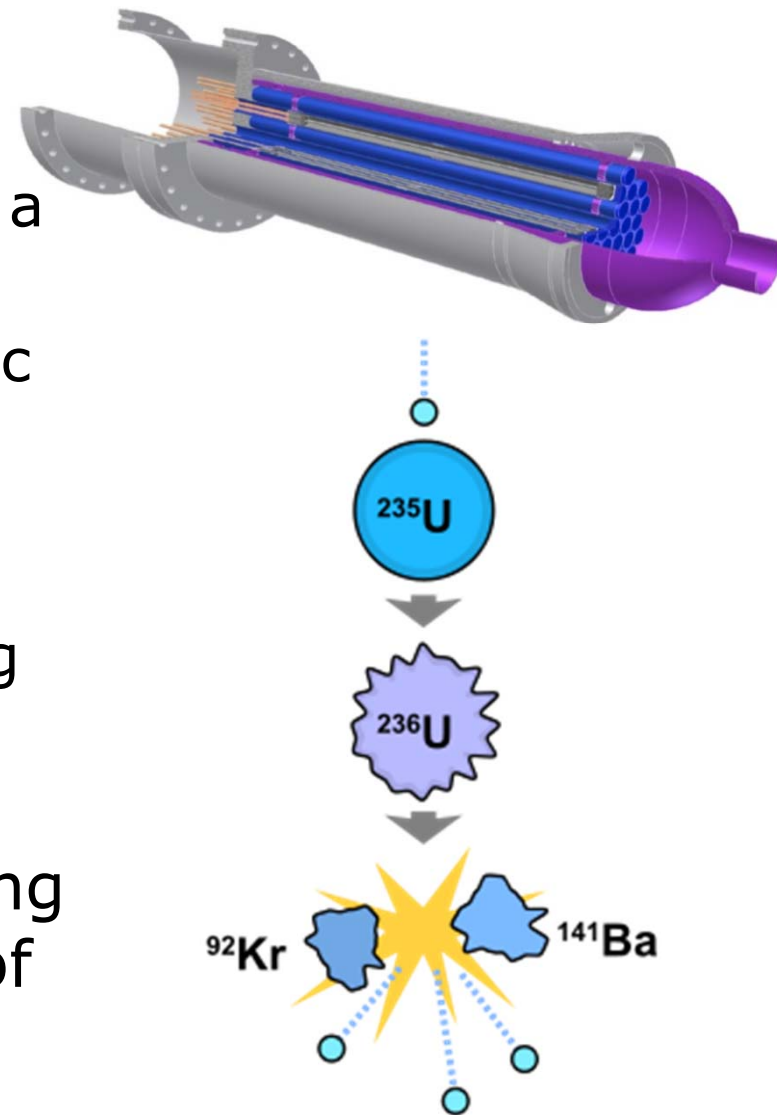


Image: [11]

Space Nuclear Reactors

	SNAP-10 US	SP-100 US *	Romashka Russia	Bouk Russia	Topaz-1 Russia	Topaz-2 Russia-US	SAFE-400 US *
dates	1965	1992	1967	1977	1987	1992	2007?
kWt	45.5	2000	40	<100	150	135	400
kWe	0.65	100	0.8	<5	5-10	6	100
converter	†electric	†electric	†electric	†electric	†ionic	†ionic	†electric
fuel	U-ZrH _x	UN	UC ₂	U-Mo	UO ₂	UO ₂	UN
reactor mass, kg	435	5422	455	<390	320	1061	512
neutron spectrum	thermal	fast	fast	fast	thermal	thermal/ epithermal	fast
control	Be	Be	Be	Be	Be	Be	Be
coolant	NaK	Li	none	NaK	NaK	NaK	Na
core temp. °C, max	585	1377	1900	?	1600	1900?	1020

SNAP-10A



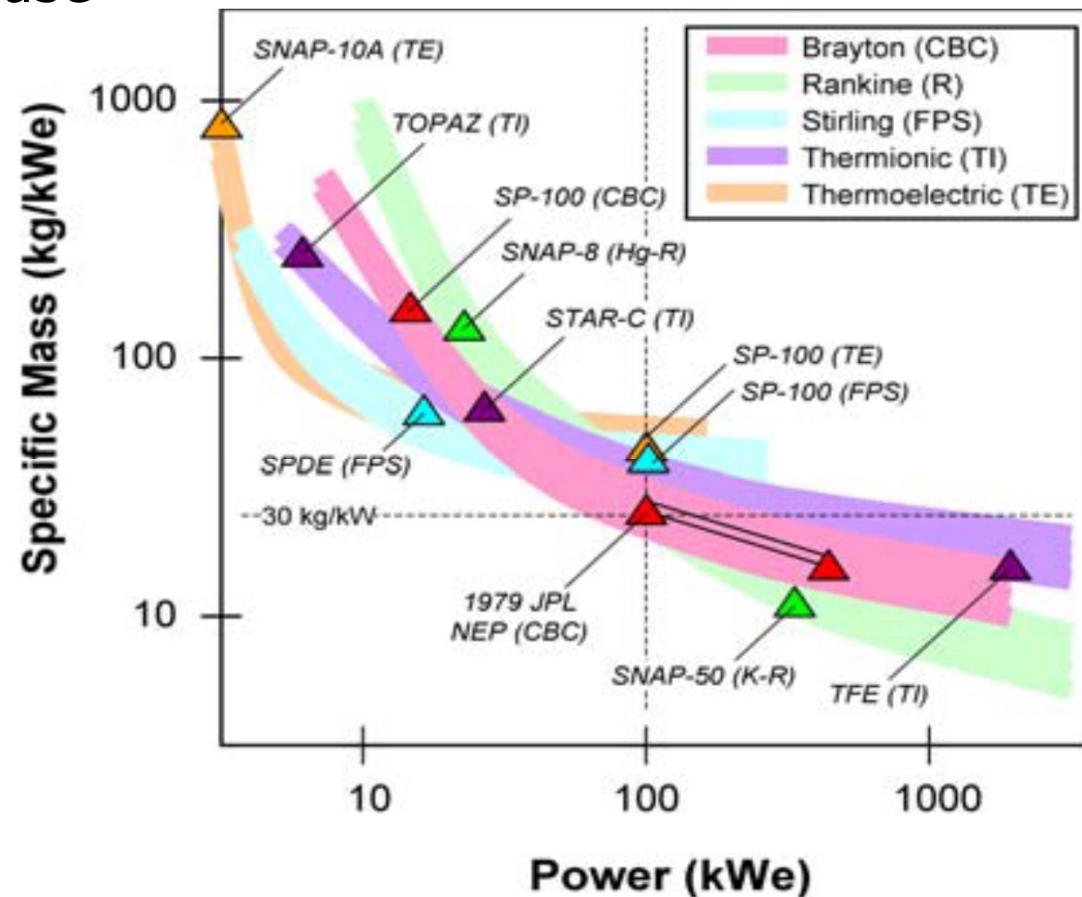
Images: [64,24]

*Designed but not implemented

Total No. Vehicles: ~37 Russian & 1 US

Power Generation Options

- Dynamic
 - Thermodynamic cycle
 - **Brayton, Stirling**: single-phase
 - Rankine: 2-phase
 - Moderate efficiency (15-30%)
 - Typ. lower-temp.
- Static
 - No moving parts
 - Thermoelectric, Thermionic
 - Typ. low power
 - Low efficiency (1-10%)
 - High-temperature



S. Johnson. "Project Prometheus Two-Phase Flow, Fluid Stability and Dynamics Workshop." NASA Technical Memorandum #212598 (2003).

Spacecraft with Electrostatic Propulsion

- Numerous Earth-orbiting satellites (mostly Russian)
- Deep Space 1 (1998, NASA, ion) first interplanetary probe to test EP with solar power
- Hayabusa (2003, JAXA, ion) study near-Earth asteroid
- SMART-1 (2003, ESA, Hall) orbit Moon, ended with controlled collision
- DAWN (2007, NASA, ion) investigate evolution of small planetary bodies



Advanced Radiator Concepts

