THE AEROSPACE CORPORATION

Small Satellite Deployable Radiator Study

Trystan Madison, PhD
Abdiel Agramonte-Moreno
Adon Delgado
John McHale, PhD

Thermal Control Department
The Aerospace Corporation

CubeSat Developers Workshop, April 23rd, 2024

Background

The growth of small satellite missions

- Civil, commercial and defense sectors are moving toward small satellites with more capabilities
  - NASA Smallsat/Cubesat fleet
  - Starlink
  - Space Force missions

- Smaller form factors with improved capability will lead to warmer temperatures of the spacecraft
  - Leads to challenging thermal management issues and a need to dissipate additional heat

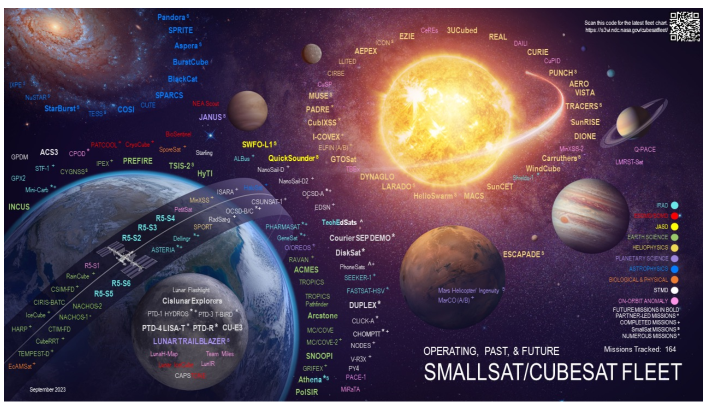


Image credit: NASA SmallSat/CubeSat Fleet Missions Graphic

Image used under license from SpaceX (https://www.spacex.com/trademark/)

Space Force sets sights on small geostationary communications satellites

The military also is interested in buying direct-to-cell satellite services

Sandra Erwin October 22, 2023

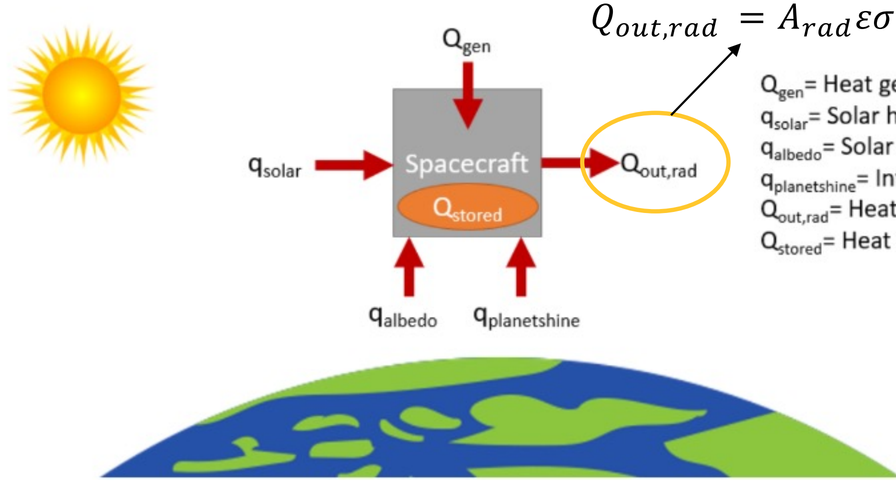
Article in Space News, "Space Force sets sights on small geostationary communications satellites", by Sandra Erwin, October 22nd, 2023

Industry is moving toward more small satellites with increased capability and challenges with thermal management

Heat Rejection in Small Satellites

The need for additional radiator area

$$Q_{out,rad} = A_{rad}\varepsilon\sigma(T_{rad}^4 - T_{sink}^4)$$



- Q_{gen} = Heat generated by spacecraft
- q_{solar} = Solar heating
- q_{albedo} = Solar heating reflected by planet
- $q_{planetshine}$ = Infrared heating from planet
- $Q_{out,rad}$ = Heat emitted via radiation
- Q_{stored} = Heat stored by the spacecraft

Energy balance then gives:

$$q_{Solar} + q_{albedo} + q_{planetshine} + Q_{gen} = Q_{stored} + Q_{out,rad}$$

Increased capability can be associated with increased heat generation:

$$q_{Solar} + q_{albedo} + q_{planetshine} + Q_{gen} = Q_{stored} + A_{rad}\varepsilon\sigma(T_{rad}^4 - T_{sink}^4)$$

Environmental Heat loads remain the same.

Internal heat generation increases

Stored energy remains similar

Therefore, for a fixed radiator temperature the radiator area must increase

Enhancing Heat Rejection in Small Satellites

Radiator metrics to consider

- Increase the heat rejection area
  - Performance metric: **Total Radiator Area**
    - Per Unit volume [m^{-1}]
    - Per unit mass [m^2/kg]
    - Operating temperature range [K or °C]
  - Common Design Choices:
    - Deployable radiators
    - Alternate form factors

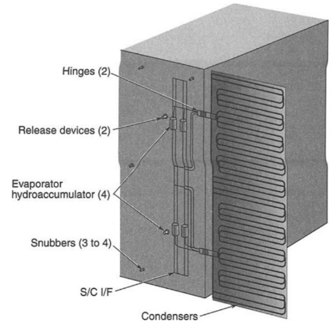


Image credit: Spacecraft Thermal Control Handbook, 2nd Ed.

Image credit: https://aerospace.org/sites/default/files/2022-08/DiskSat_0822.pdf

- Improve the efficiency of the radiator
  - Performance Metric: **Radiator Efficiency**
    - Ratio of Net radiated power to:
      - Blackbody with perfect sink
      - Isothermal at maximum local temperature
  - Common Design Choices
    - High conductance interfaces and components
    - Coatings

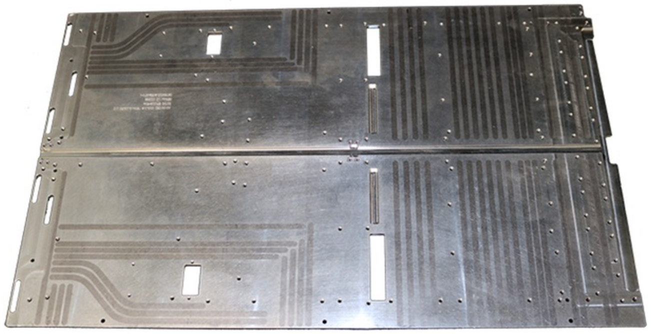


Image used under permission from Advanced Cooling Technologies, Inc.

- Improve conductance to radiator panel
  - Performance Metric: **Conductance**
    - Heat transport per degree [W/K]
    - Measured from bus to radiator panel
  - Common Design choices
    - High conductance interface
    - Two phase heat transfer technologies

Integrated design strategies require increased area, improved efficiency, *and* conductance to fully enhance heat rejection

Deployable Radiator Study

Study Overview

- Objective
  - Survey existing and proposed deployable radiator technology.
  - Develop useful performance metrics
  - Propose technical performance targets

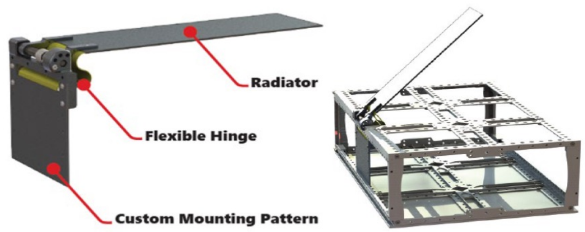
- Approach
  - Literature search
  - Interviews with industry and academia
  - Independent calculations as necessary

- Overview:
  - 11 different companies & universities surveyed
  - 14 technologies reviewed with performance metrics available
    - TRL range from 6 to 2

Objective: Survey the existing deployable radiator technologies for economical high performance small satellites

Deployable Radiator Study

Technology Overview



Redwire: Q-Rad

- High-efficiency deployable radiator panel with conductive coupling across hinge
- Passive spring deployment (single)
  - 0° to 180° in less than 1 second
- TRL 5
  - AFRL/RVSV SBIR Phase 1 & 2
  - TVAC, Vibe
- Up to 1 m^2 heat rejection area
- 100W to 300W heat rejection
- -196ºC to +150ºC

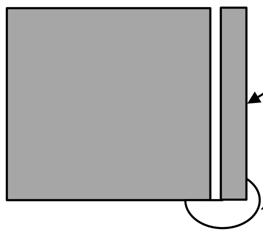
Thermal Management Technologies

- High-efficiency embedded heat pipe radiator with high conduction hinge
- Active deployment via actuator and coil spring mechanism (single)
  - 0° to 180°
- TRL 6
  - SBIR Phase 2
  - TVAC, Vibe, Deployment
- Up to 1 m^2 heat rejection area
- 100W heat rejection
- -20ºC to +45ºC

Industry technologies consists of conductive and two-phase heat transfer solutions

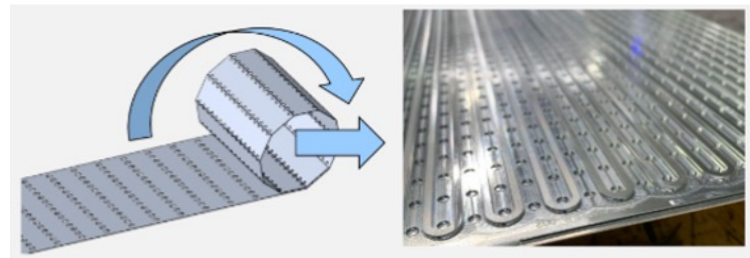
Deployable Radiator Study

Technology Overview



ThermAvant: Local Plastic Deformation

- OHP-integrated deployable radiator
- Passive deployment using actuator with coil spring, motor + paraffin wax (single)
  - 0° to 180° in > 90 seconds
- TRL 3/4 (SBIR Phase 1 & 2)
  - TVAC, Vibe, Deployment
- 0.136 m^2 Heat rejection area
- 140W heat rejection (80°C source temperature)
- -65ºC to 100ºC



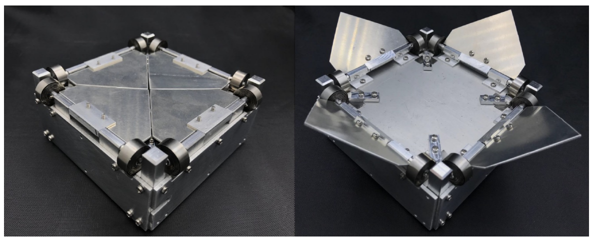
ThermAvant: Unspooling

- High-performance unspooling radiator with oscillating heat pipes
- Active deployment with unspooling motor (single)
  - 0° to 180° in > 90 seconds
- TRL 4
  - SBIR Phase 1 & 2
  - Deployment, Vibe, Some TVAC
- 0.34m^2 rejection area
- 1500W heat rejection (105°C source temperature)
- -65ºC to +100ºC

Industry technologies consists of conductive and two-phase heat transfer solutions

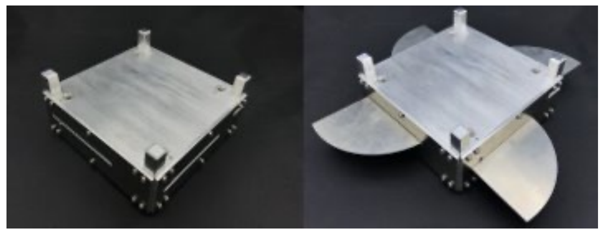
Deployable Radiator Study

Technology Overview



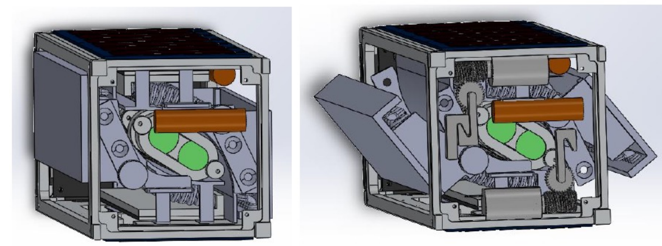
BYU: Triangular Fin

– Triangular deployable radiator fins
– Passive deployment (multiple) on bimetallic coils
– TRL 4
  - TVAC
– 0.0085 m^2
– 35 W @ 30% duty cycle (90-minute orbit)
– -50°C to +90°C



BYU: Radial Fin

– Radial deployable radiator fins
– Passive deployment (multiple) on bimetallic coils
  - 0° to 90° deployment angle
– TRL 4
  - TVAC
– 0.0085 m^2
– 30 W @ 20% duty cycle (90-minute orbit)
– -50°C to +90°C



JPL/Cal Poly: AMDROHP

– Additively Manufactured Deployable Radiator with Oscillating Heat Pipes
– Passive deployment (single) on pre-loaded flexible helical joints
  - 0° to 90° deployment angle
– TRL 2/3
– 0.101 m^2
– 50 W heat rejection (evaporator at 65°C)

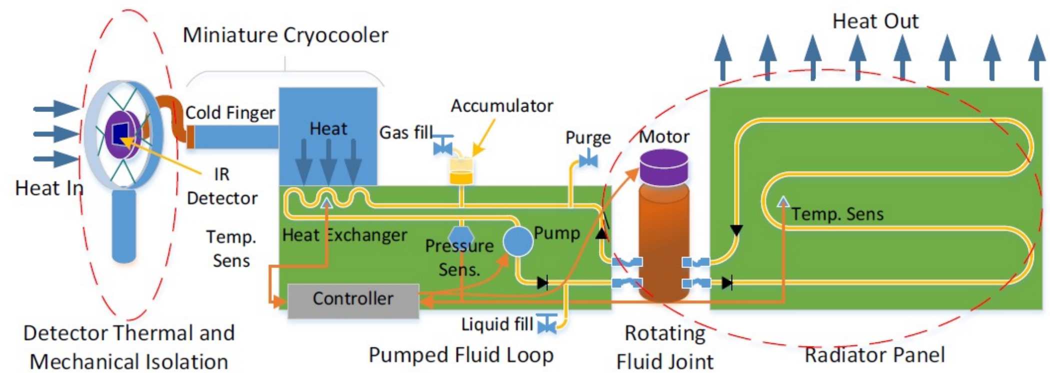
Academia advancing research in small satellite thermal management using novel solutions

Deployable Radiator Study

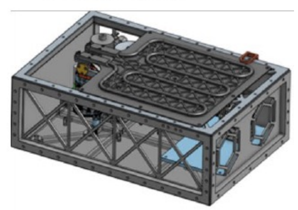
Technology Overview

Utah State University: Active Thermal Architecture (ATA)

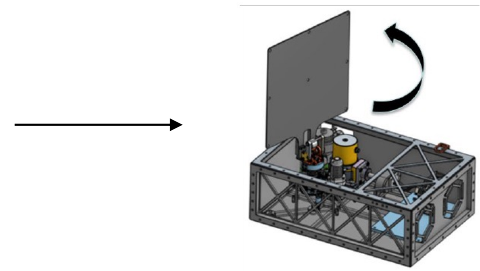
- High-performance deployable MFPL radiator panel with active sun tracking
- Active deployment using rotary fluid joint (multiple)
  - 90° lock out
- TRL 6
  - SSTP Office
  - TVAC
- 0.04 m^2
- 60W (6U) vs 150W (16U)
- -20°C to +100°C



ATA System in: Stowed State



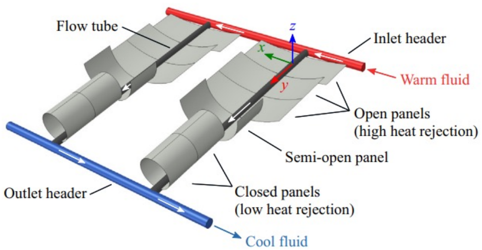
Radiator Full Deployment



Academia advancing research in small satellite thermal management using novel solutions

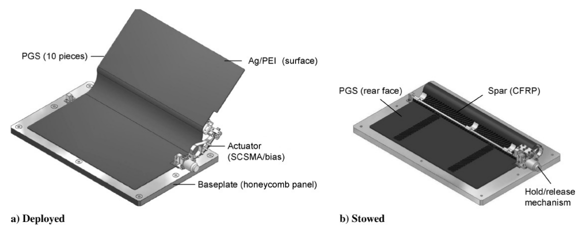
Deployable Radiator Study

Technology Overview



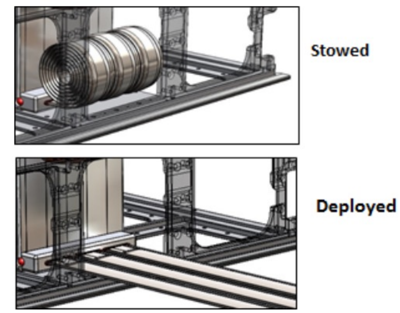
NASA/Texas A&M: SMA Morphing Radiator

- Passive deployment on Ni-Ti shape memory alloy system (multiple)
- TRL 4
  - Ambient Deployment testing
- 0.065 m^2
- 10W
- 30°C to 120°C



JAXA: Re-Deployable Radiator

- Deployed using shape memory alloy and bias spring (400 open/close cycles)
  - 5° to 150°
- TRL 6
  - TVAC, Deployment
- 0.28 m^2
- 100W at 45°C surface temperature
- 0°C to +30°C



Pumpkin/YSPM: Rollout Deployable Radiator (RDR)

- Rollout deployable radiator
- TRL 3
  - Prototype in process
  - Testing in TVAC expected, Path to TRL 5/6
- 0.56 m^2
- 330W, double sided radiation
- -70°C to +50°C

Shape memory alloys are being used to actuate radiators. Cylindrically stowed radiators provide alternative storge requirements

Small Satellite Heat Rejection Technologies

Deployable Radiator Matrix

- Performance Trends:
  - *Deployable radiators need TRL investment*
    - Max: TRL 6
    - Min: TRL 2
  - *Radiating power target of 100W for most panels*
  - *Temperature ranges*
    - Application or fluid specific
    - Customers have options
  - *Deployed Area/Stowed volume largest for panel/hinge type radiators*
  - *Low aerial densities*

	Max TRL	Radiator Area [m^2]	Radiating Power [W]	Operating Temperature Range [°C]	Deployed Area/Stowed Volume [m^{-1}]
Redwire Space: Q-Rad	5	0.04 to 1	100 to 300	-196 to 150	242
Thermal Management Technologies	6	.10 to 1	100	- 20 to 60	32
ThermAvant: Unspooling	4	0.34	1500	Up to 105	109
ThermAvant: Local Plastic Deformation	4	0.136	140	Up to 80	398
JPL/Cal Poly: AMDROHP	2/3	0.069	50	Up to 65	32
BYU: Triangular Fin	4	0.0085	35 (30% DC in LEO)	-50 to 90	234
BYU: Radial Fin	4	0.0085	30 (20% DC in LEO)	-50 to 90	266
Utah State University: Active Thermal Architecture	6/7	0.04	60 (6U), 150 (16U)	-20 to 100	20
JAXA: Re-Deployable Radiator	4	0.29	100	0 to 30	79
NASA/Texas A&M: SMA Morphing Radiator	4	0.0065	10	30 to 120	98
Pumpkin/YSPM: Rollout Deployable Radiator	2	0.56	330 (double sided radiation)	-70 to 50	124

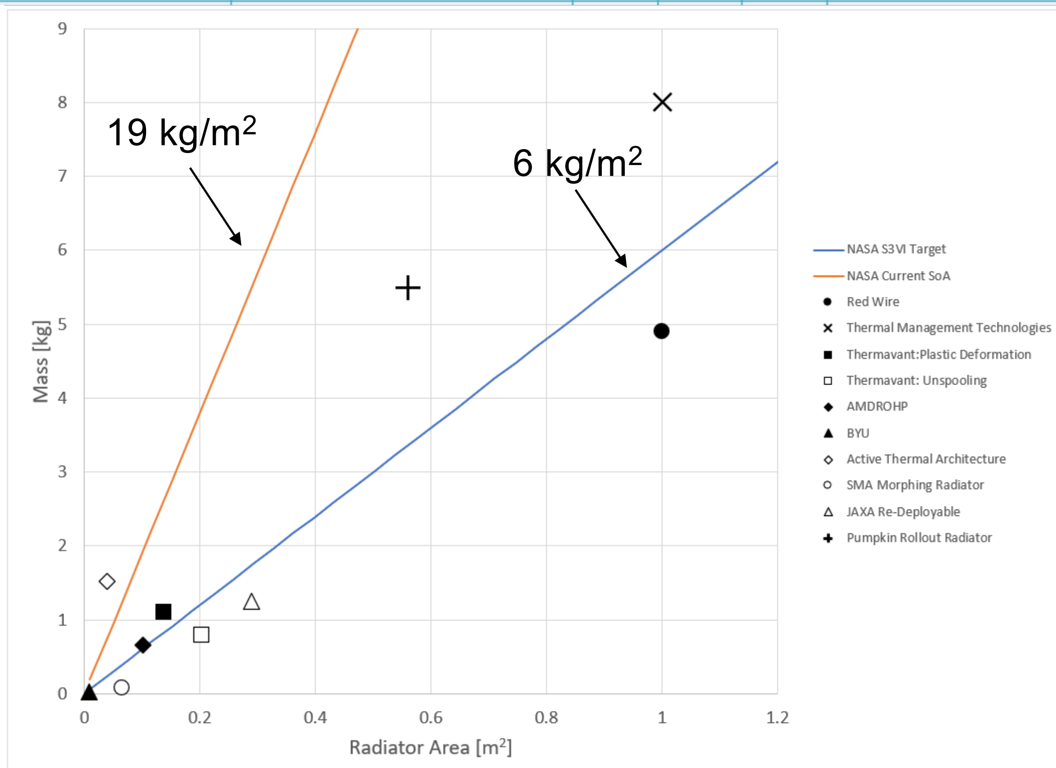
Solution space for deployable radiator technology is vast: Low aerial densities are a must and wide temperature ranges provide customers with mission flexibility

Small Satellite Heat Rejection Technologies

Deployable Radiator Matrix Performance Metrics

Technology Area	SoA (Flight Heritage)	Current NASA Investments (Technologies in Development)			Goal
		TRL 1-3	TRL 4-6	TRL 7-9	
Variable Heat Rejection	Turn Down Ratio ~3:1 (Human class) Turn Down Ratio ~30:1 (Rover class)	✓	✓	--	Turn Down Ratio > 12:1 Turn Down Ratio > 100:1
Advanced Radiators	19 kg/m^2 (Deployable) 6 kg/m^2 (Body Mounted)	✓	--	--	< 6 kg/m^2 (Deployable) < 3 kg/m^2 (Body Mounted)

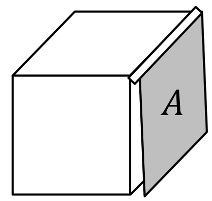
- Aerial Density [kg/m^2]
  - *NASA Space technology mission directorate identifies current deployable radiator aerial density as 19 kg/m^2. Identified goal of < 6 kg/m^2 to enable lunar missions and beyond.*
  - *Technologies surveyed are below current state of the art (19 kg/m^2), and very near to the target goal of < 6 kg/m^2*
  - *TRL advancement of these technologies will allow for expansion of small sat capabilities and new mission opportunities*



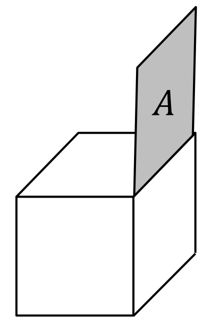
Small Satellite Heat Rejection Technologies

Deployable Radiator Matrix Performance Metrics

- Deployed Area to Stowed Volume [m^{-1}]
  - *Rectangular panel mounted deployable radiators*
    - Maximum value dictated by thickness of panel
    - Trade off: minimizing thickness but maintaining structural integrity
  - *Cylindrically stowed radiators*
    - Assume a baseline of a single panel rolled into a storage diameter, *D*
    - Can increase radiating area, by higher packing
    - Can lead to large turn down ratios
      - *Increases radiating area without affecting stowed volume*
      - *Limited by how tightly the radiator can be packed*



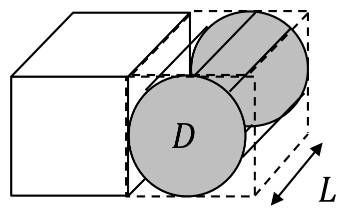
Stowed configuration

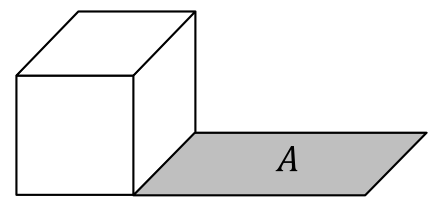


Deployed configuration

$$\frac{Radiating\ Area}{Stowed\ Volume} = \frac{A}{At} = \frac{1}{t}$$

Maximum value for a panel radiator





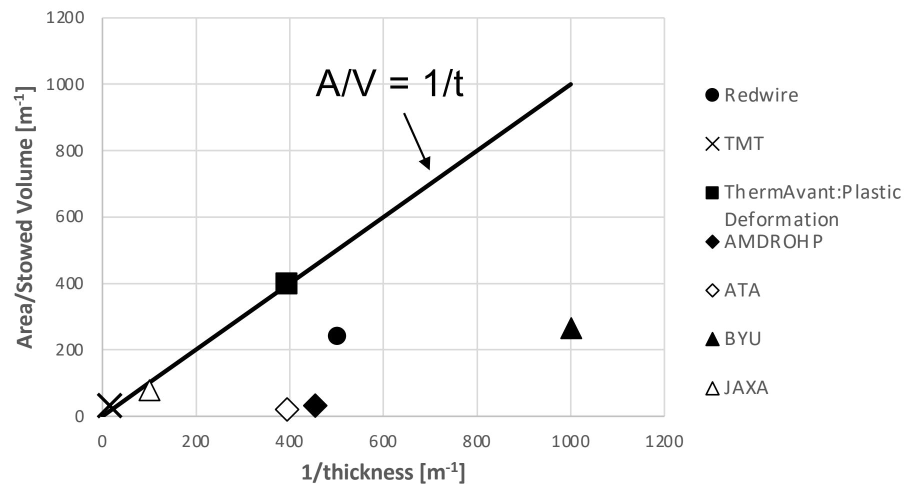
$$\frac{Radiating\ Area}{Stowed\ Volume} = \frac{\pi\ DL}{D^2 L} = \pi/D$$

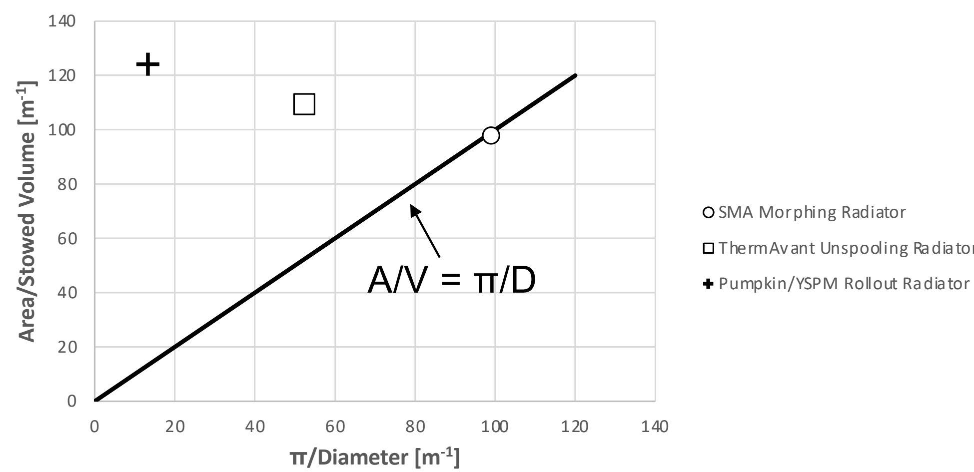
Minimum value for cylindrically stored radiators, assuming support structure can fit into bounding prism

Small Satellite Heat Rejection Technologies

Deployable Radiator Matrix Performance Metrics

- Deployed Area/Stowed Volume [m^{-1}]
  - *Single panel and Rollout radiators currently at Area/Stowed volume ~ 100*
    - Technologies that use conduction tend to have larger values
  - *Provides opportunity to look into alternate ways to increase the deployable area per unit volume (i.e. rollout radiators*
  - *Rollout radiators can have large turn down ratios, however technologies are currently still under development*





Deployable Radiator Study

Summary

- Observing a need for increased heat rejection area on small satellites to enable missions not previously accessed
- Technologies currently being developed already have low aerial densities 6 kg/m^2
  - Need to continue to show development and advance TRL
  - Need to obtain flight opportunities for higher TRL technologies
- More two-phase flow options
  - Embedded heat pipes and oscillating heat pipes provide high heat transfer coefficients, improving the heat transfer from bus to radiator panel
  - Two-phase heat transfer aids in more uniform temperature distribution and increased efficiency
- Some options available to increase the amount of available area
  - Rollout radiators can provide more radiating area by having multiple turns during stow
  - Challenges exist in these systems but benefit of large radiator areas can help enable even more missions

References

[1] NASA SmallSat/CubeSat Fleet. (n.d.). https://s3vi.ndc.nasa.gov/cubesatfleet/

[2] Erwin, S. (2023, October 22). *Space Force sets sights on small geostationary communications satellites*. SpaceNews. https://spacenews.com/space-force-sets-sights-on-small-geostationary-communications-satellites/

[3] 7.0 Thermal Control - NASA. (n.d.). NASA. https://www.nasa.gov/smallsat-institute/sst-soa/thermal-control/

[4] Gilmore, D. G. (2003). *Spacecraft thermal Control handbook: Cryogenics*. AIAA (American Institute of Aeronautics & Astronautics).

[5] DiskSat | The Aerospace Corporation. (2023, August 1). Aerospace Corporation. https://aerospace.org/disksat

[6] Ulrich, M. (2024, March 12). *When to use heat pipes, HIKTM plates, vapor chambers, and conduction cooling*. Advanced Cooling Technologies. https://www.1-act.com/resources/blog/when-to-use-heat-pipes-hik-plates-vapor-chambers-and-conduction-cooling/

[7] Redwire Corporation. (2021). *Leveraging ultra-high thermal conductivity solid-state materials, Q-Rad is a compact, lightweight, modular, and passive thermal control solution for a wide-range of demanding needs*. https://redwirespace.com/wp-content/uploads/2023/06/redwire-qrad-flysheet.pdf

[8] Thermal Management Technologies. (n.d.). *Thermally efficient deployable radiators*. https://www.tmtipe.com/_files/ugd/4ab2a3_021e51d068fd456483d8ff2c4211ebf3.pdf?index=true

[9] Cannon, J., Iverson, B. D., & Mulford, R. B. (2022). *Passively deployed, unfolding radiator panels for small satellite thermal management* (TFAWS 2022). NASA

[10] Miesner, S., Shibata, G., Bautista, N., Wolk, K., Furst, B., Daimaru, T., ... & Kuo, J. (2023, October). Thermal Orbital Spacecraft Analysis of an Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP) CubeSat. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 87677, p. V010T11A014). American Society of Mechanical Engineers.

[11] NASA, *LIVE: Thermal Management Systems,* NASA Space Technology Directorate, August 2023. https://techport.nasa.gov\framework

[12] Sawada et al. *Development of an Engineering model of the Re-Deployable Radiator for Deep Space Explorer*, 51st International Conference on Environmental Systems, July 2022

[13] Yendler, B., Meginnis, A., Reif A. (2020), Thermal Management for High Power Cubesats, *34th annual Small Satellite Conference*

[14] Anderson, L., Swenson, C., Mastropietro, A. J., & Sauder, J. *The Active Thermal Architecture:Active Thermal Control for Small-Satellites*. 2020 Small Satellite Conference. https://smallsat.org/

[15] Bertagne, C. L., Cognata, T. J., Sheth, R. B., Dinsmore, C. E., & Hartl, D. J. (2017). Testing and analysis of a morphing radiator concept for thermal control of crewed space vehicles. *Applied Thermal Engineering*, *124*, 986-1002.

Thank you