A novel thermal paradigm for SmallSats: Breakthrough in Design and Functionality

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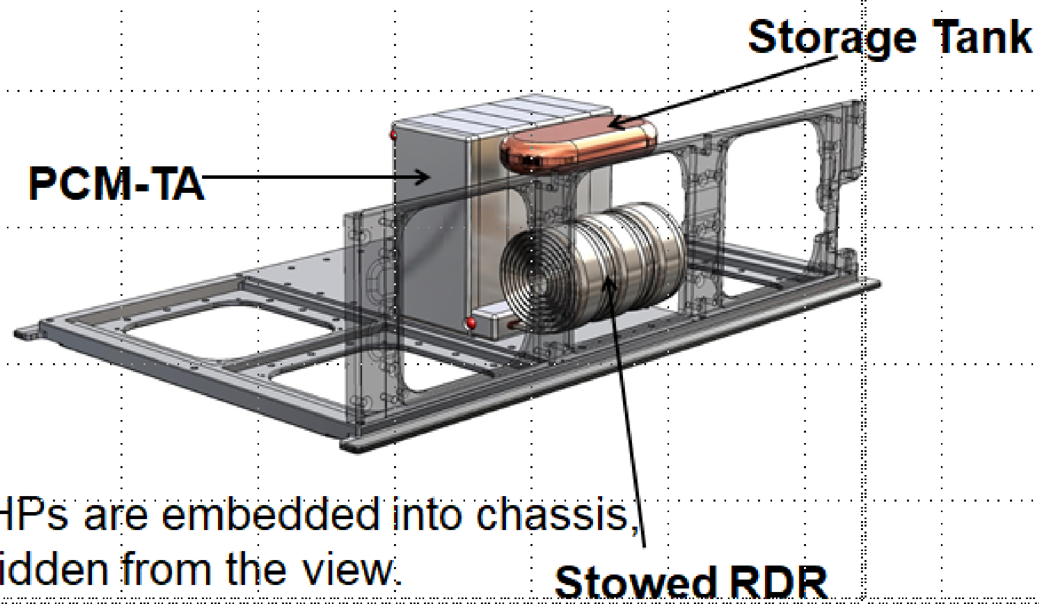
Introduction

- Driving Needs
  - High power payloads are in development for deployment on small satellites in the coming years, effective heat dissipation is required for sustained operation
  - No Commercial Off the Shelf (COTS) small satellite thermal control available
  - NASA's technology shortfalls highlights a demand for improved s/c thermal control and waste heat rejection
- Solicitation Requirement
  - To **develop** and to **prove** feasibility of thermal control technology with capabilities to dissipate up to 1kW in a small satellite form factor
- Our Solution
  - Multi-component thermal management system
  - Components are Modular, Scalable and Versatile

Our Dream - 2020 CDW

Combined TMS

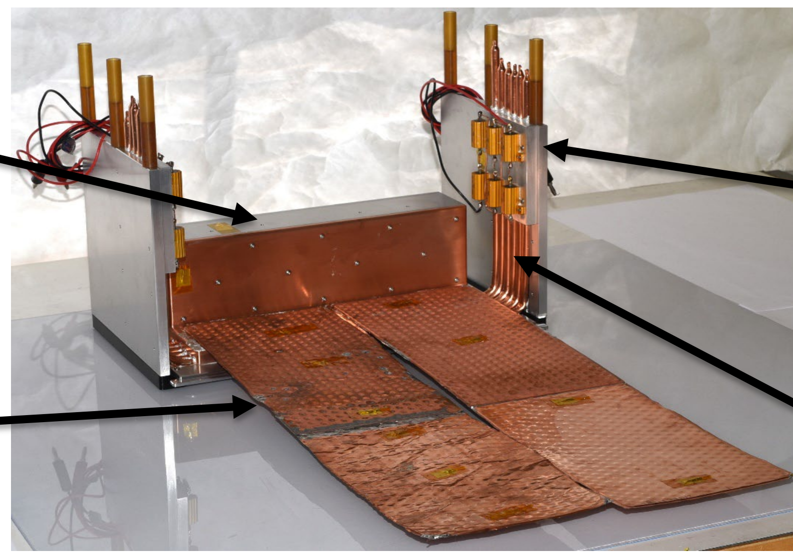


IHPs are embedded into chassis, hidden from the view.

All three components separately or combined TMS can be mounted at any place per mission requirements

Thermal Management System (TMS)

- Consists of three components:
  - Rollout Deployable Radiator (RDR)
  - Structurally Integrated Heat Pipes (IHP)
  - Phase Change Material Thermal Accumulator (PCM-TA)
- Components can be used individually or jointly



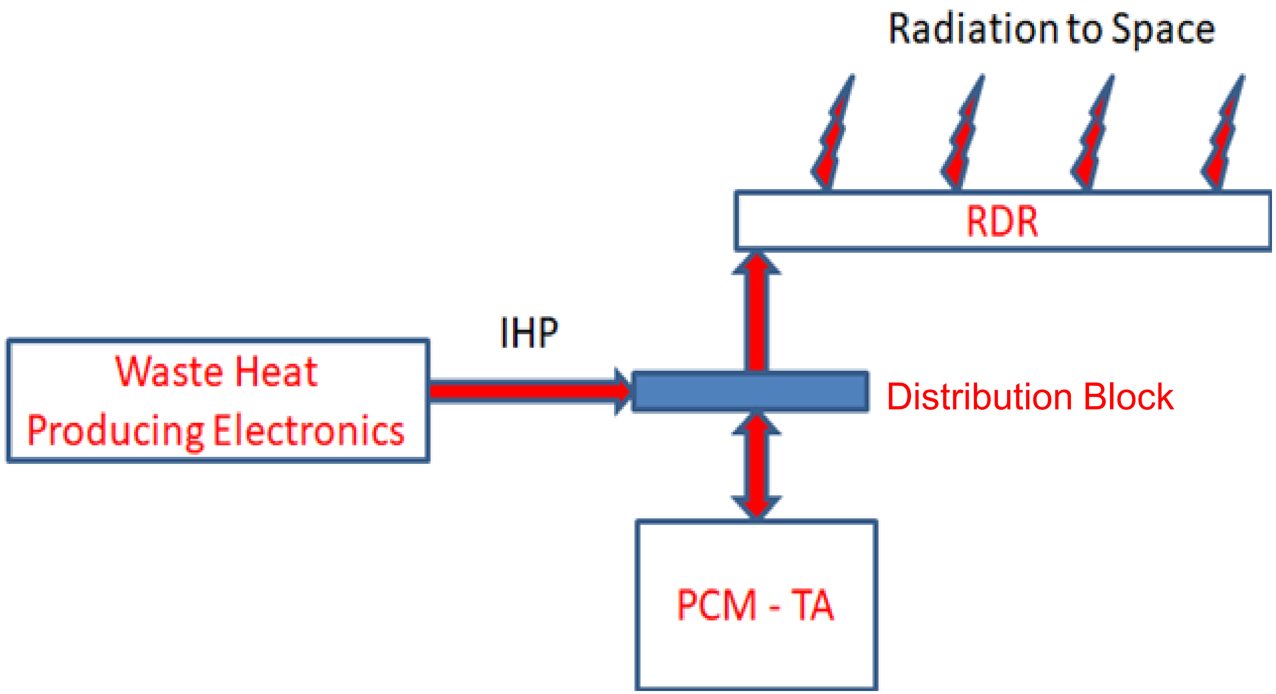
TMS Prototype

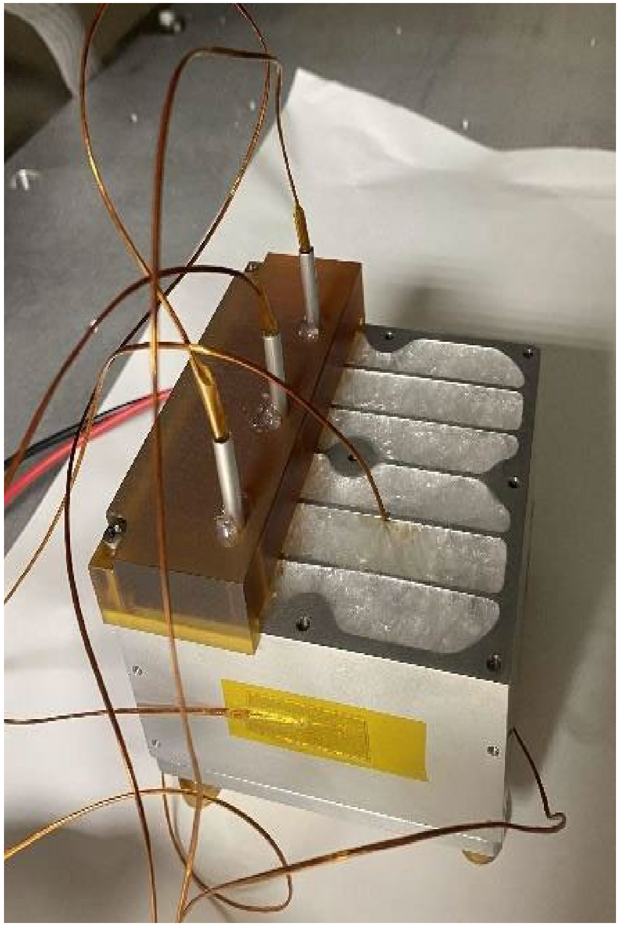
Thermal Management System (TMS)- cont'd

- Functions and Capabilities
  - TMS prototype units are able to reject 300 W of waste heat
  - Capable of rejecting 1 kW or more with multiple TMS units
  - Applicable to small satellites ranging from CubeSat to ESPA class* spacecraft
  - Can be scaled to mission requirements
  - Can be used together as a complete system, or separately
  - Provides a large radiative surface area with minimum storage volume
  - Minimizes thermal resistance between heat source(s) and radiative surfaces

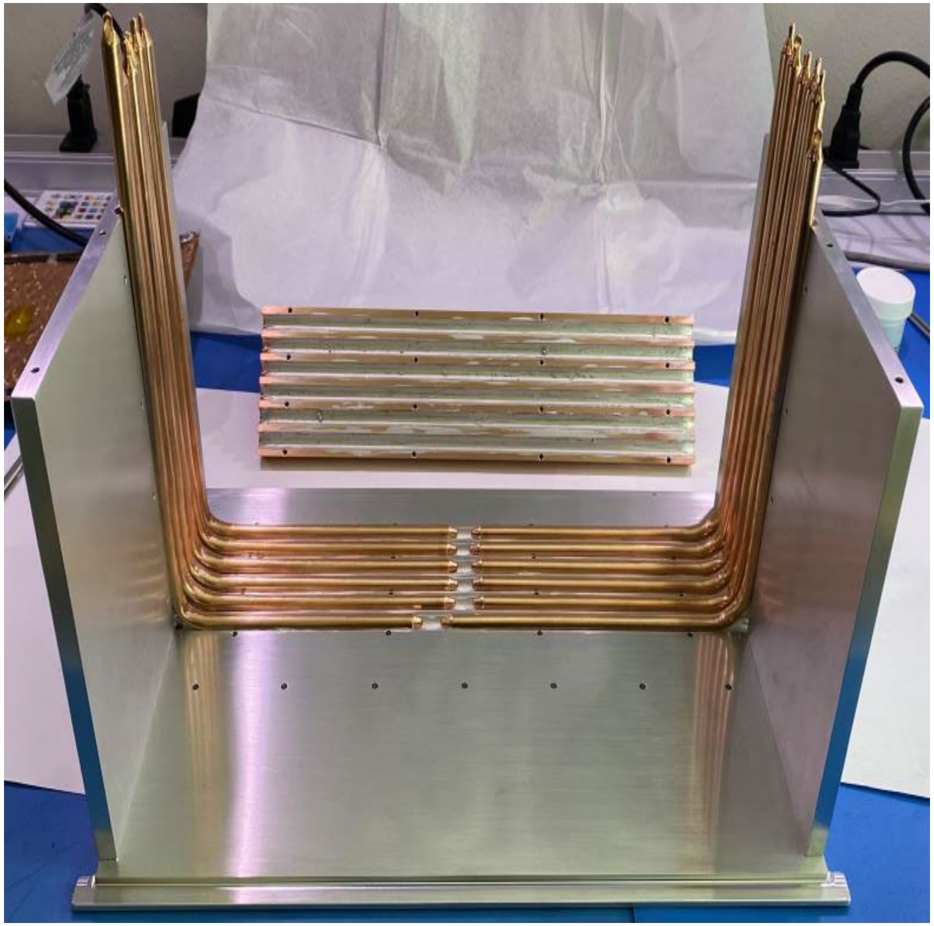
* (EELV Secondary Payload Adapter, 200kg+)

Heat Flow Diagram



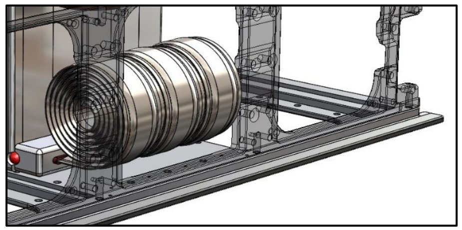
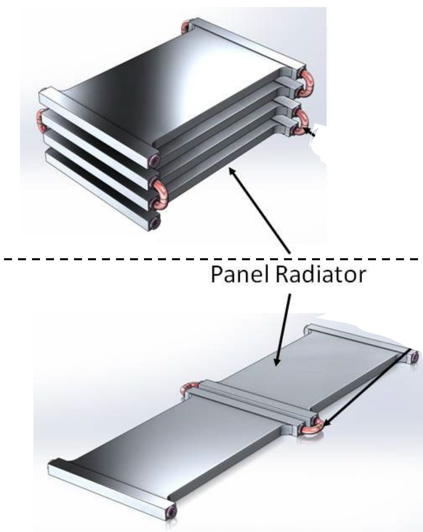
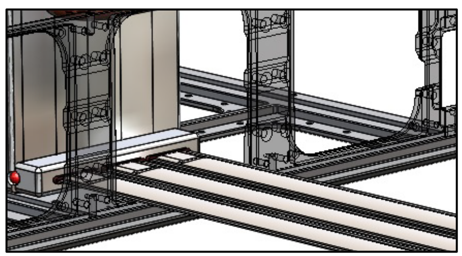


Phase Change Material Thermal Accumulator (PCM-TA)



Integrated Heat Pipes (IHP)

Deployable Radiators

	Flexible Rollout	Rigid Panel
Stowed		
Deployed		

Flexible Rollout

- Efficient stowed volume
- High thermal conductivity (heat pipe)
- Efficient mass/power ratio (no hinges)
- Scalable (width and length)

Rigid Panel

- When stowed, takes up more volume
- High thermal resistance across the hinges

Video RDR roll out goes here

Video 1: Rollout Deployable Radiator (RDR) demonstration – (click-to-play)

Rollout Deployable Radiator (RDR)

Rigid Radiator vs. RDR

parameter	rigid	RDR
Mass efficiency [kg/kW]	3.15*	3.54
Storage volume efficiency [m^3/kW]	0.036	0.0022

* Does not include hinges

Table 1: Rigid vs. RDR comparison

RDR is more volume efficient than traditional rigid radiator

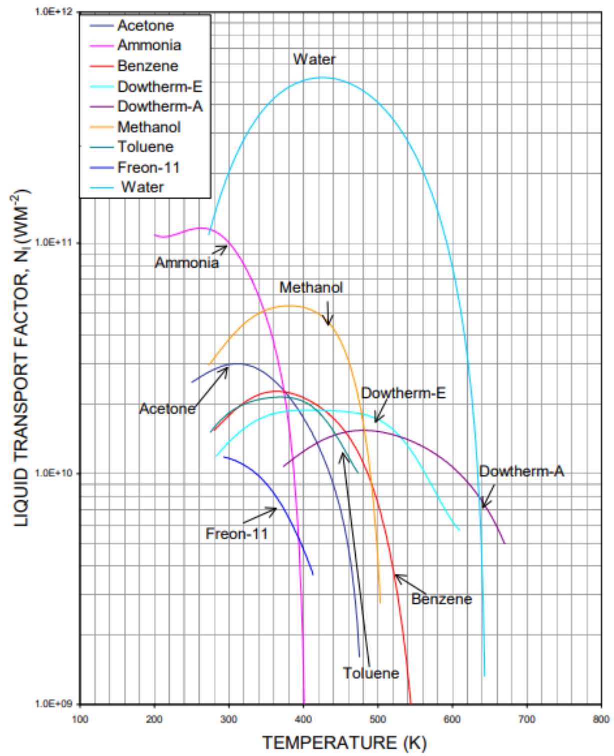
Choice of working liquid for RDR

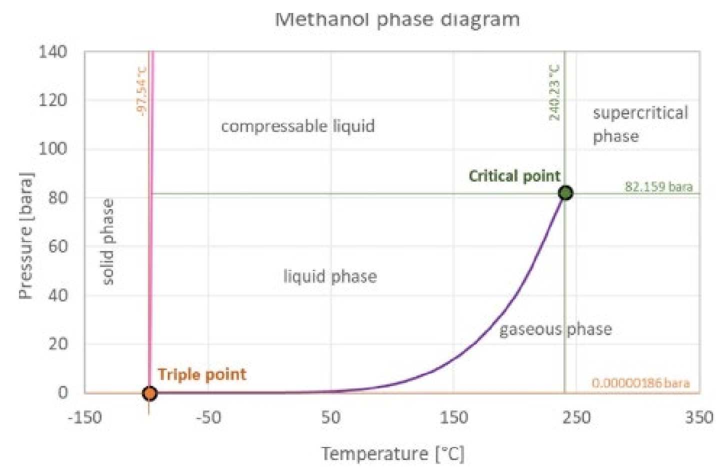
Liquid Transport Factor vs Temperature

- **A convenient figure of merit is the liquid transport factor, N_l,**

$N_l = \lambda\sigma\rho_l/\mu_l$

N_l = Latent Heat * Surface Tension * Density/ Viscosity





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Introduction to Heat Pipes - Ku 2015 TFAWS

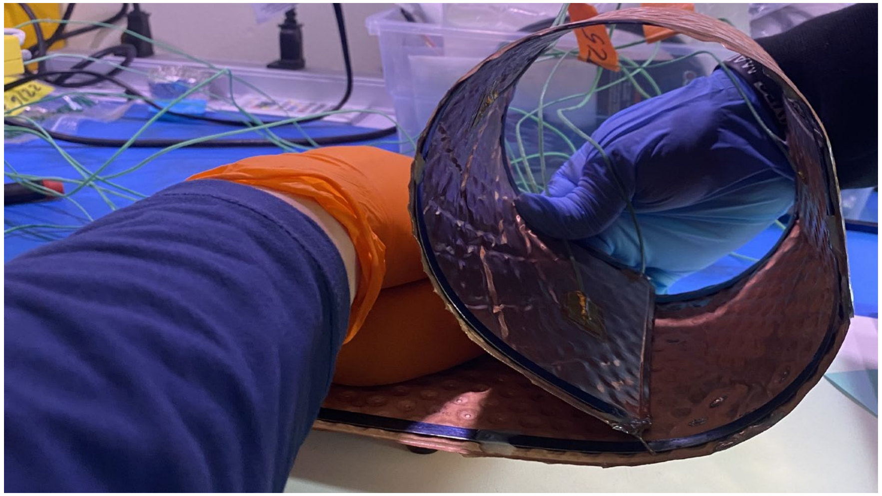
Methanol was the optimal choice

RDR development history

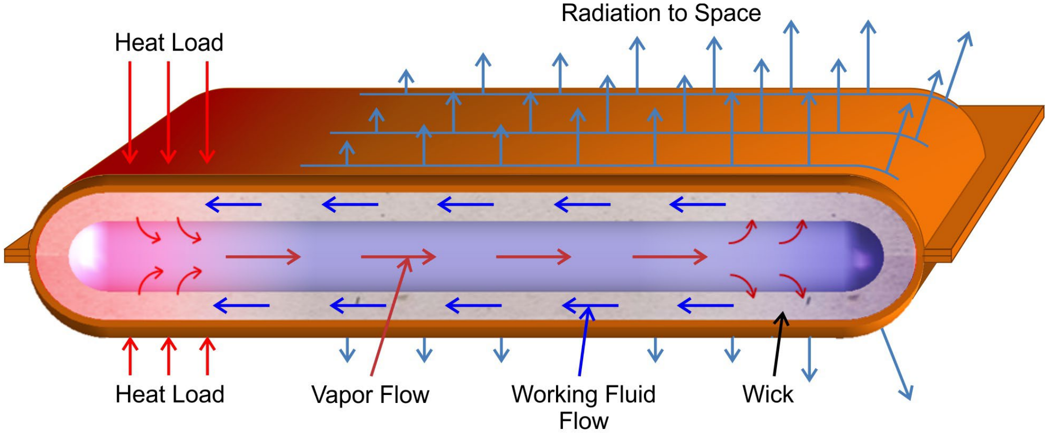
- Several different fabrication processes have been tested:
  - *Friction welding*
  - *Epoxy bonding*
  - *A/C welding*
  - *Laser welding*
  - *Ultrasonic welding*
  - *Diffusion bonding*
- Several different materials, in different gauges have been tested:
  - *Aluminum*
  - *Mylar laminates*
  - *Copper*
  - *Copper laminates*
- Different vapor-core wick materials have been tested:
  - *Aluminum wool*
  - *Copper wool*
  - *Aluminum screen*
  - *Copper screen*
- Several different working fluids have been tested:
  - *Acetone*
  - *Methanol*

Only the design solution (in yellow) was successful, to date.

Flexible RDR Concept



RDR is a roll-able thin 2-D vapor chamber



RDR Flow Diagram

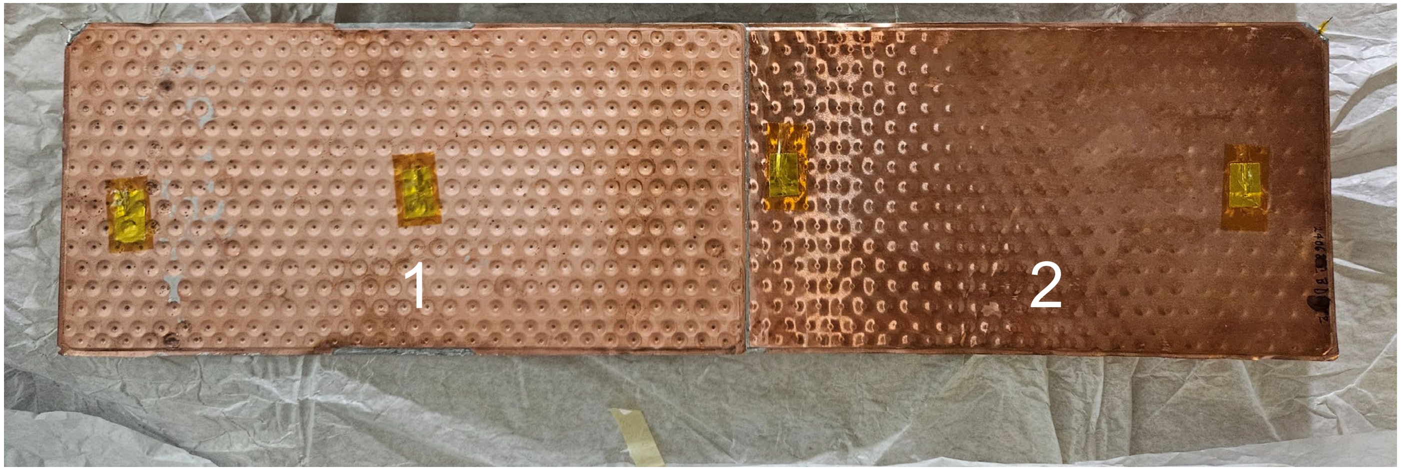
RDR Parameters

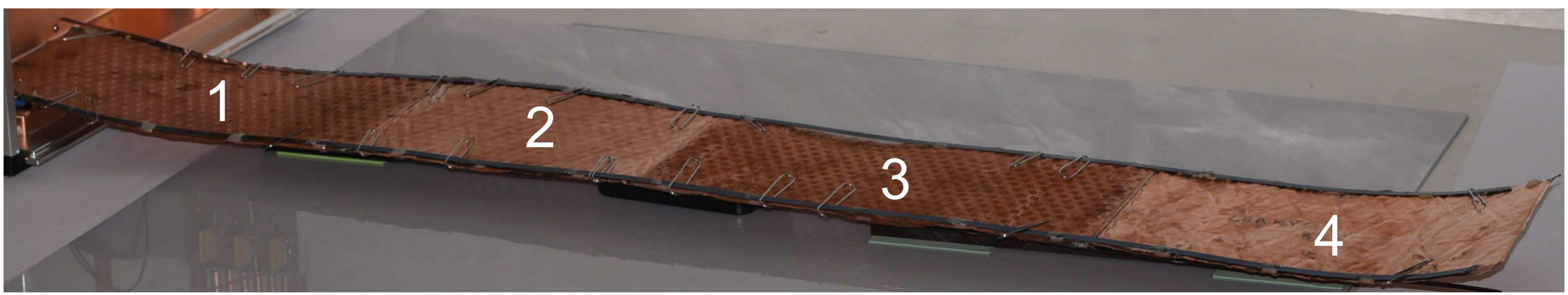
The RDR is a thin 2-D vapor chamber designed for optimized heat flow and dissipation to space

The Prototype RDR currently has the following performance characteristics:

- Thickness: 2.5mm
- Mass: approximately 3.3 g/cm^3
- Flexibility: capable of bending with minimum radius of 50mm
- Length: scalable up to 1 m long
- Heat Flux Handling: effective performance 384 W/cm^2
- Thermal Conductivity: effective thermal conductivity 1,500 W/mK
- Sustain internal/external pressure difference
- Will use methanol as the working liquid

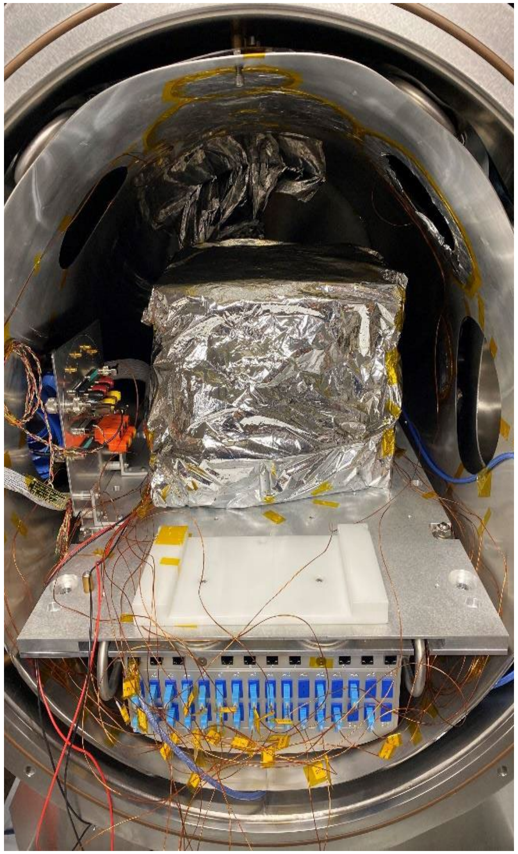
RDR daisy chain design



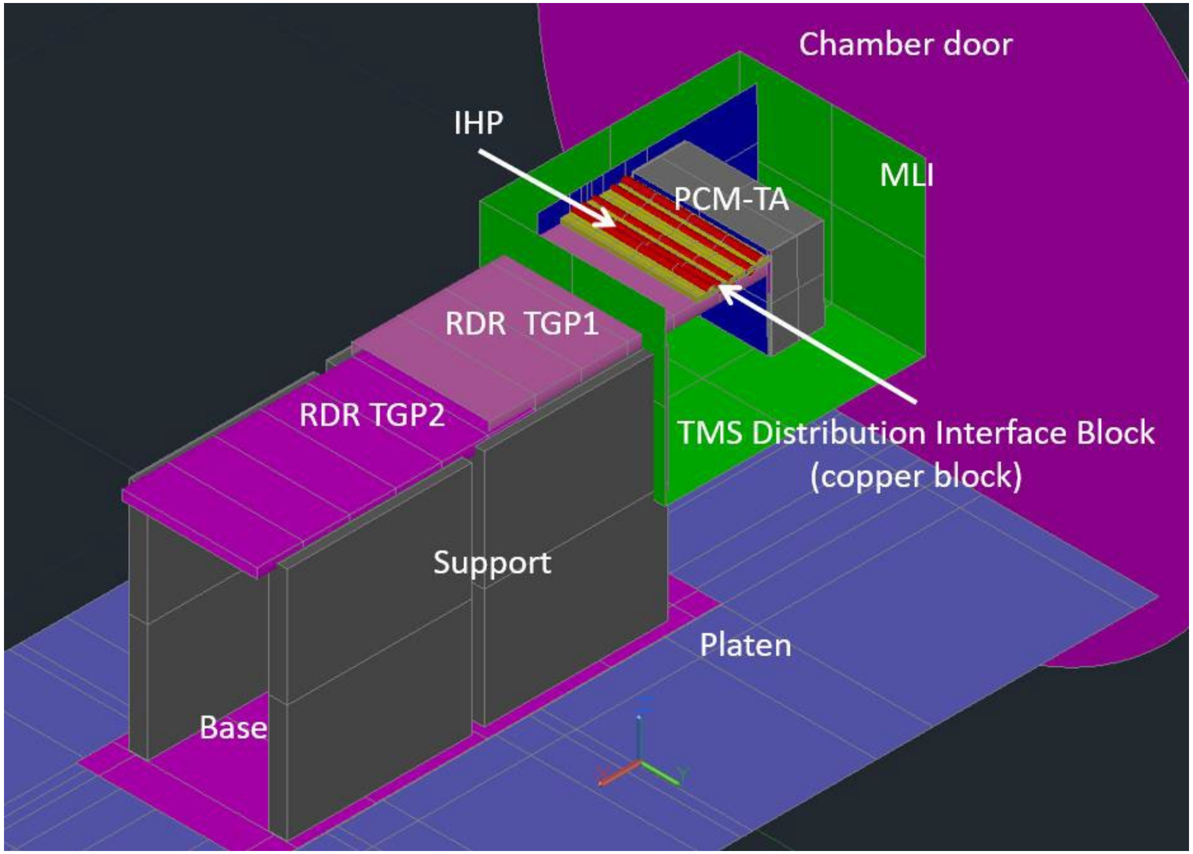


Daisy Chain prototypes

RDR testing - TV chamber

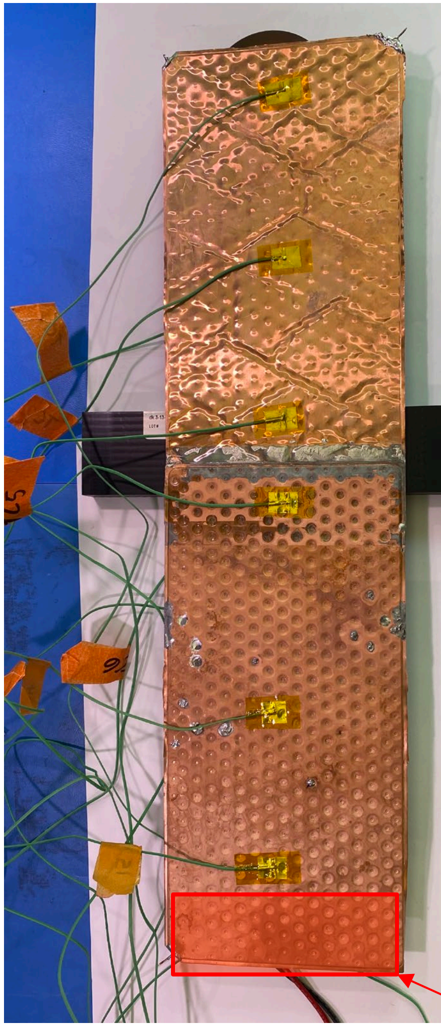


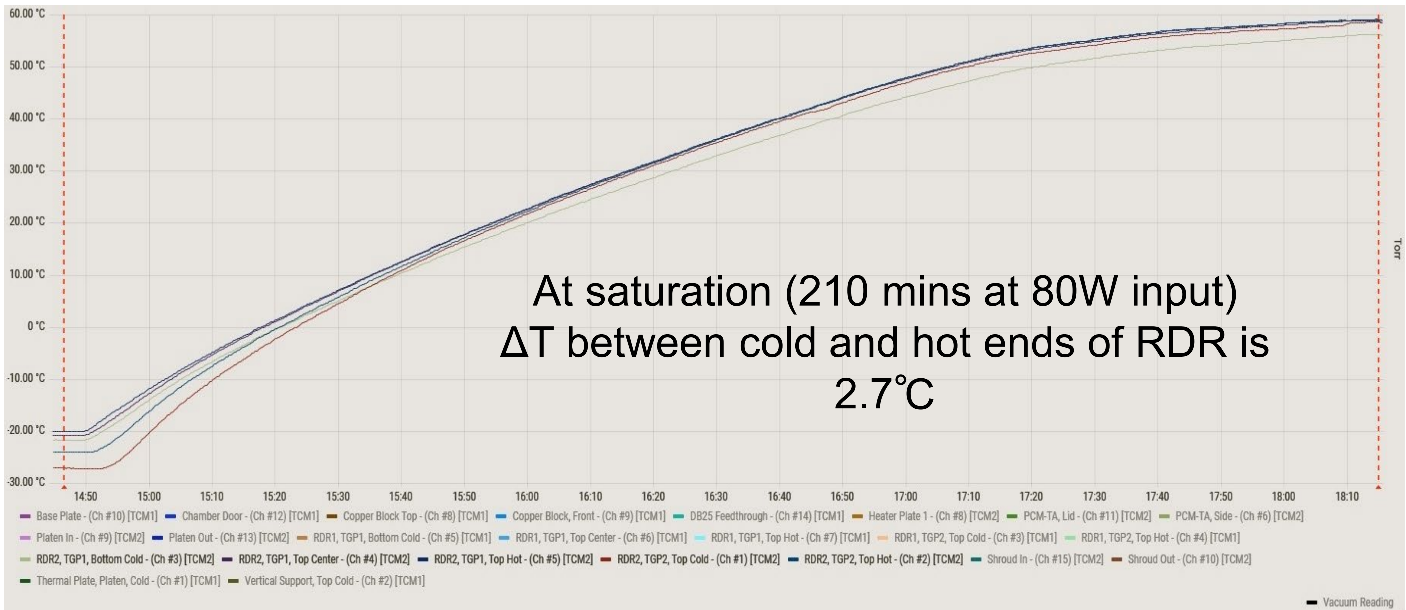
Thermo-Vacuum Chamber



Prototype TV testing configuration (half system)

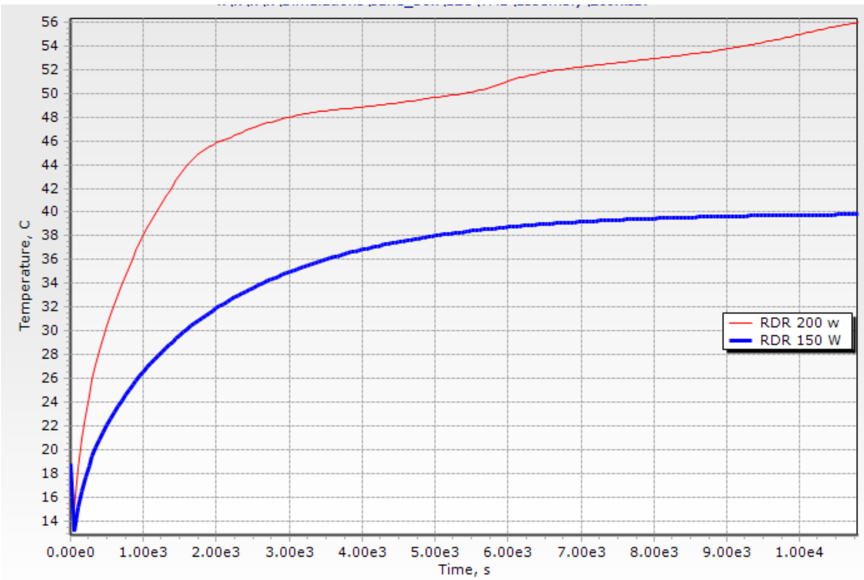
Results



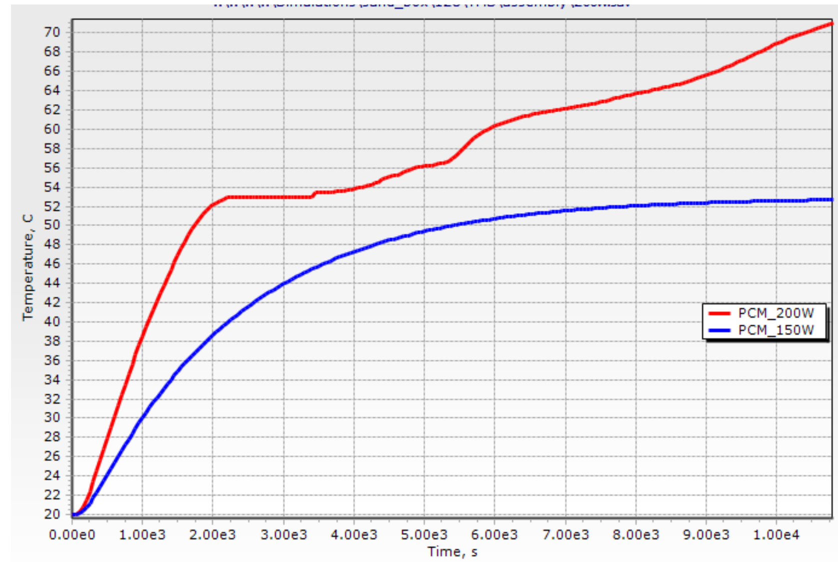


Temperature Distribution is almost Isothermal

Results – cont'd



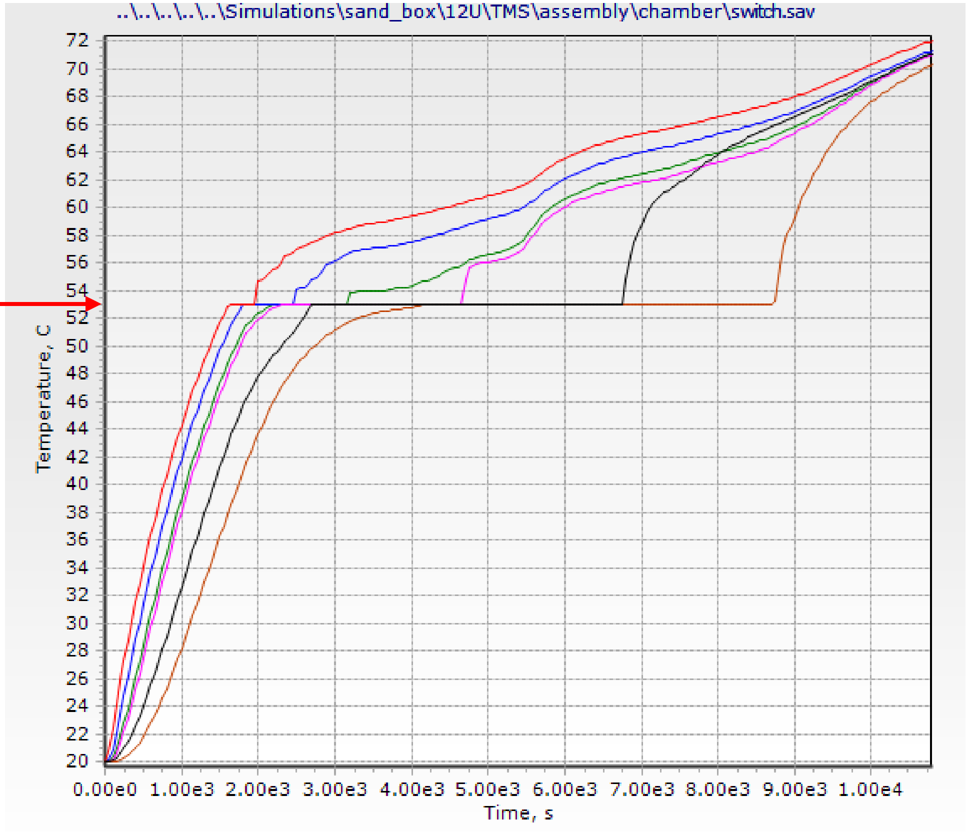
Heat Pipe temperature at different heat loads: 150W (blue) & 200W (red)



PCM temperature at different heat loads: 150W (blue) & 200W (red)

Results - cont'd

53° C PCM melting temperature



Temperature trends inside of PCM- TA

TRL status

- Current status is TRL 5
  - Component and/or breadboard validated in relevant environment
- RDR will reach TRL 7
  - Based on successful TV test results and flight tests
  - Test over several orbits is required to demonstrate TMS efficiency and operational status
  - Flight tests requirements: 150 W of power, ~20 kg mass allocation, and 10 × 10 × 30 cm volume (~3U)

RDR Features

RDR offers significant improvement in spacecraft thermal control by overcoming heat transfer limitations.

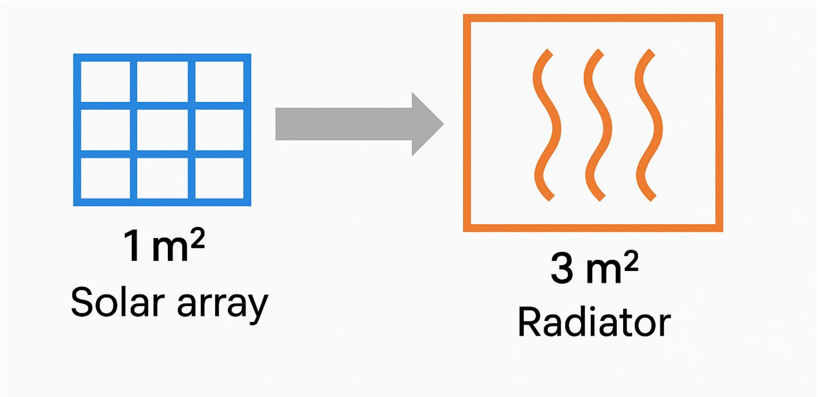
- Key RDR features
  - Hinge-free design enables direct thermal pathways from electronics to space, significantly boosting heat rejection capacity
  - Multi-fold improvement in heat rejection over fixed radiators—enabling higher power generation and system performance
  - Adapts radiating surface area to mission requirements, removing thermal limitations

RDR Features – cont'd

- Key RDR features – cont'd
  - Achieves a nearly 16-fold reduction in stowed volume compared to rigid deployable radiators.
  - Removes Energy Generation Constraints:

Satellite Energy Generation Is Bounded by Radiator Size:

assuming 50% generated energy is converted to waste heat, every 1 m^2 of solar array (energy generation 1300 W/m^2) requires almost 3 m^2 of radiator (heat rejection 300 W/m^2).



Applications of TMS

- The TMS integrates thermal management with structural elements, significantly reducing overall mass.
- The TMS is modular, allowing it to adapt to various mission and system requirements while maintaining a low **SWaP-C** (Size, Weight, Power, and Cost).
- Its true "plug-and-play" capability enables seamless integration across different platforms without extensive engineering modifications.
- The TMS is designed for batch production and additive manufacturing, supporting cost-effective scalability.

Applications of TMS – cont'd

- By reducing development and integration complexity, this technology expands the use of advanced thermal management solutions for lower-cost missions.
- The RDR provides maximum heat transfer efficiency while maintaining a lightweight design, offering a superior alternative to fixed radiators.
- The RDR features a hinge-free design, which significantly reduces thermal resistance between heat-generating components and the radiating surface. This maximizes heat transfer efficiency, ensuring that waste heat is transported as effectively as possible. Additionally, the hinge-free architecture minimizes structural mass, making the radiator lighter and more efficient for space applications.

Adaptation Beyond Conventional Missions

- Enables More Powerful Satellite Functions
- Higher power availability supports
  - advanced avionics, communication lasers, enhanced payloads, etc.
- Military Applications
  - Enables high-power lasers for satellite self-defense, improving spacecraft survivability

*SatNews: **"US on high alert"***
China's satellites display unprecedented combat maneuvers in space

Adaptation Beyond Conventional Missions-cont'd

- Nuclear Space Power Integration

  Supports space-based fusion reactors, such as:

  - SNAP-10A (50W, U.S.)
  - Topaz 1 & 2 (Kosmos 954, etc., USSR)
  - NASA Kilopower (1-10 kW)

Adaptation Beyond Conventional Missions-cont'd

- TMS can enhance nuclear technologies such as fission surface power and nuclear electric propulsion. These systems require efficient waste heat rejection at high temperatures (around 500 K).
- To adapt the proposed TMS for nuclear applications, the RDR should use
  - **sodium** as the working fluid for high-temperature applications (500 - 1200° C)
  - **potassium** for nuclear thermal propulsion (400 - 1000° C)
  - **cesium** (300 - 800° C)
  - **lithium** (900 - 1600° C)

Adaptation Beyond Conventional Missions-cont'd

- Modifications of other TMS components are required
  - Integrated Heat Pipes (IHP) should use different working liquid
  - Phase Change Material Thermal Accumulator (PCM-TA) should use high temperature PCM
  - Material used to build IHP and PCM-TA must withstand high-temperature environments

Conclusion

The TMS is a novel approach for satellite thermal management and can be applied to a variety of missions due to its flexibility, scalability, and modularity.

The TMS has been rigorously tested in both ambient and thermal vacuum conditions in a Test-as-you-Fly configuration. It is flight-ready, and only needs in-orbit demonstration to fully validate its performance, efficiency, and potential integration into future high-power satellite systems.

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