VG-2023-249
PSI-104868

Low-Alpha, Variable Emissivity Radiator (LAVER) panels for passive thermal regulation of spacecraft

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Presented By

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TFAWS
GSFC · 2023

Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
College Park, MD

Physical Sciences Inc. (PSI) – Space Technologies

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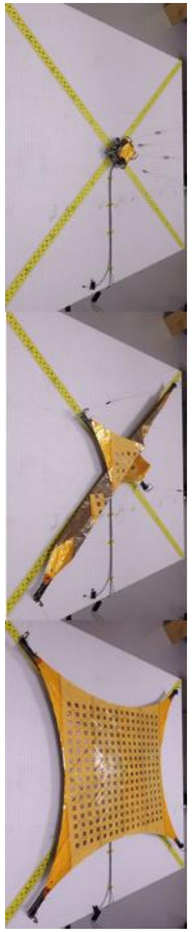
$90M annual revenue small business (~300 employees) with >50 year track record of developing and transitioning aerospace technologies

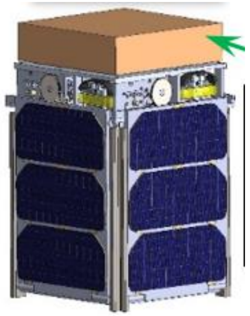
Deployable Structures



Deployment to 1.9m-wide Antenna (0.8 m²/U)

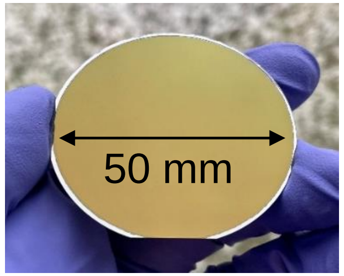
- Experience in CubeSat and ESPA-class designs
- High stowed/deployed volume ratio

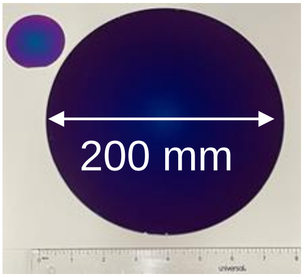
Payload stowed on CubeSat



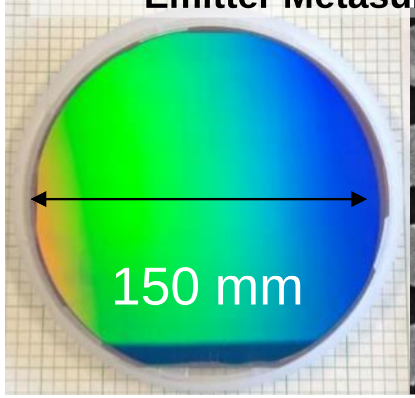
Thermal Photonic Devices

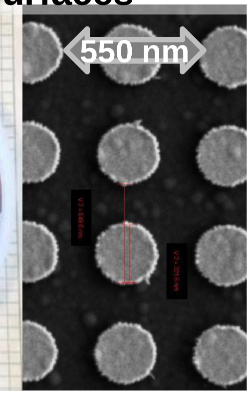
Variable Emissivity Devices



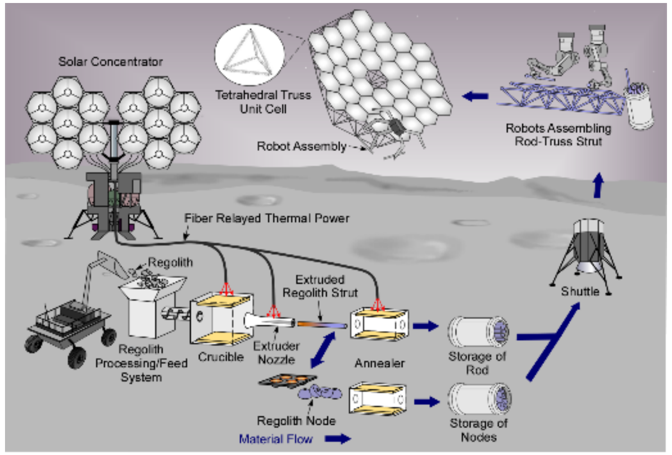


High Temperature Selective Emitter Metasurfaces

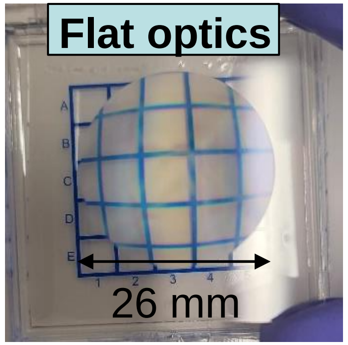


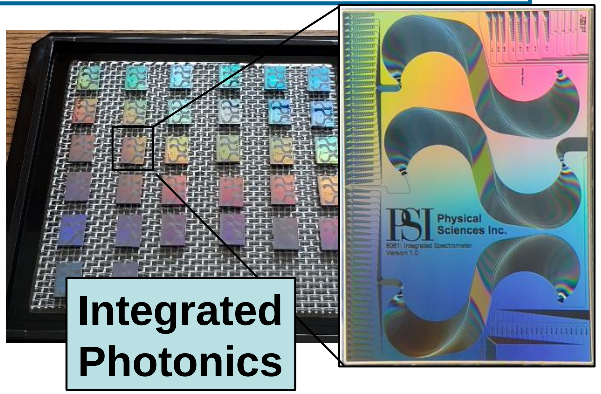


In-Space Manufacturing



Optical Elements and Systems





Passive Thermal Control: A Key Technology for Spacecraft

- Satellites in LEO experience temperature swings between -65° C and 125° C every ninety minutes
  - Rapid changes in temperature coming into and out of eclipse

- The temperature variations can be even larger in other orbits or on the lunar surface
  - Approximately +120° C to -180° C temperature swings for both GEO and lunar surface vehicles
  - -240° C in permanently shadowed regions of the moon

- Thermal management systems on spacecraft have two key functions:
  - Moving heat *around* the spacecraft, and
  - Moving heat *off* of it

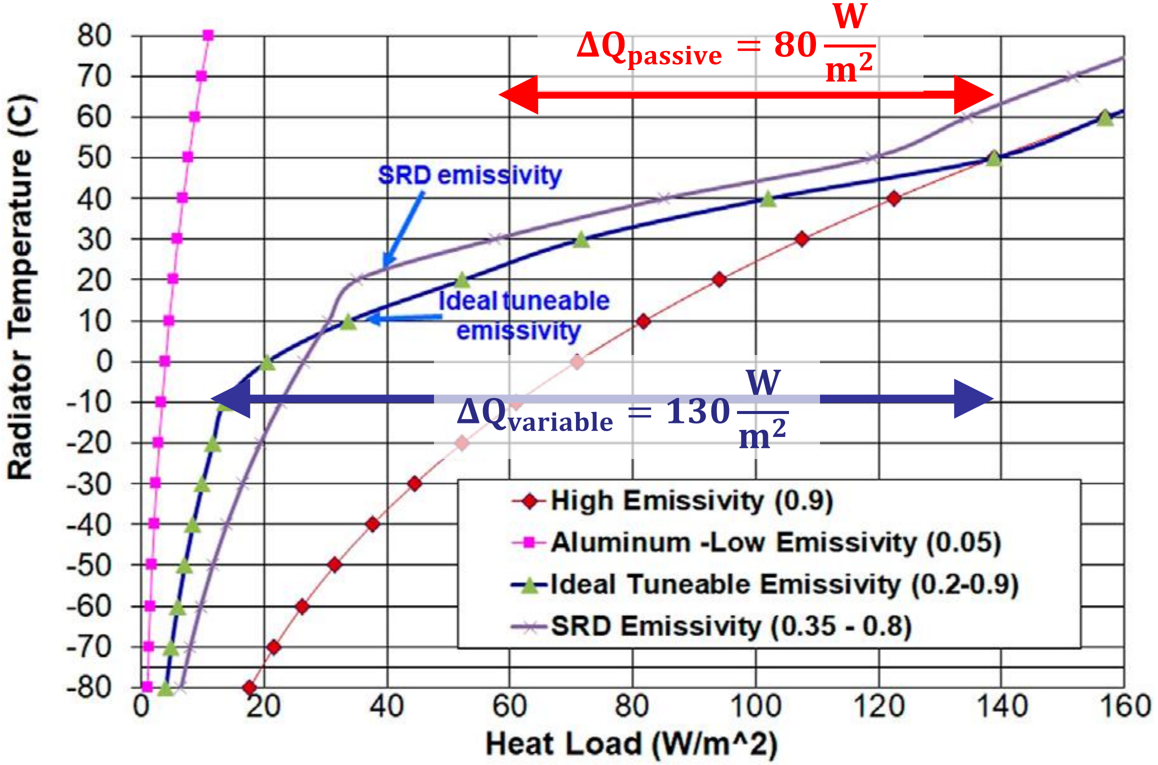
- Heat pipes redistribute heat on spacecraft large enough to warrant them
  - Bulky, heavy, and can require multiple working fluids to handle large temperature variations
  - Mechanical components = source of failure

- Emissive (radiative) surfaces remove heat from the spacecraft
  - Ideal surfaces should sufficiently rejection of solar radiation, e.g. solar $\alpha < 0.2$
  - Ideal surfaces should also radiate variable thermal loads ($\Delta Q_{rad} > 500\ W/m^2$)

Ideal Variable Radiators

- Numerous analyses have shown the advantage of variable emissivity surfaces for space craft radiators
  - For the analysis in *Haddad et al,* a fixed high emissivity radiator must generate ~ 60 W/m^2 of heat to maintain a temperature above -10ºC
    - In eclipse, this heat must come from internal heaters
  - A variable emissivity radiator with minimum emissivity of 0.2 only requires 15 W/m^2 of heat to maintain a temperature above -10ºC
  - Both radiator panels will sit at 50ºC under 140 W/m^2 heat load

- Variable emissivity radiators can thus significantly simplify a spacecraft's thermal control system by maintaining its temperature within an acceptable range over a wider range of thermal loads



Haddad et al, Frontiers in Materials, 2022

Passive and Active Technologies

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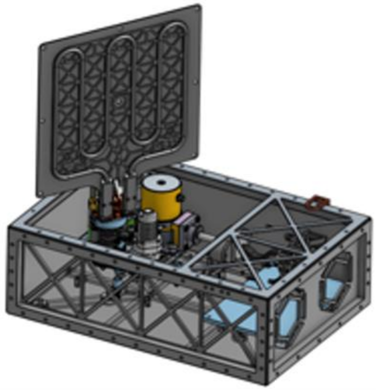
- Many passive and active solutions are in the toolkit of the spacecraft thermal engineer to reject, emit, store, and move variable heat loads

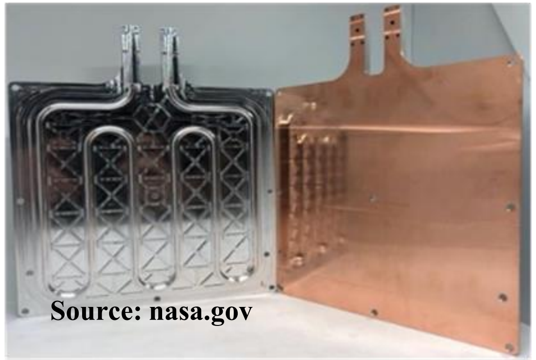
Table 7-2: Passive Thermal Technology

Manufacturer	Product	TRL in LEO Environments
AZ Technology, MAP, Astral Technology Unlimited, Inc., Dunmore Aerospace, AkzoNobel Aerospace Coatings, Parker-Lord, Medtherm	Paint and Coatings	7-9
Sheldahl, Dunmore, Aerospace Fabrication & Materials, 3M	Tapes	7-9
Sheldahl, Dunmore, Aerospace Fabrication & Materials	MLI Materials	7-9
NASA GSFC, Aerothreads, Aerospace Fabrication & Materials	MLI Blanket Fabrication	7-9
Space Dynamics Laboratory, Thermal Management Technologies, Aavid, Technology Applications, Inc., Thermotive Technology	Thermal Straps	7-9
Bergquist, Parker Chomerics, Aerospace Fabrication & Materials, AIM Products LLC, Intermark USA, Indium Corporation, Dow Corning, NeoGraf, Laird Technologies	Thermal Interface Materials and Conductive Gaskets	7-9
Sierra Lobo, Aerospace Fabrication and Materials	Sun Shields	4 – 7
NASA Goddard Space Flight Center (GSFC)	Thermal Louvers	7-9
Aerospace Fabrication and Materials, Thermal Management Technologies	Deployable Radiators	5-6
Aavid Thermacore, Inc., Advanced Cooling Technology, Inc., Redwire Space	Heat Pipes	7-9
Thermal Management Technologies, Active Space Technologies, Advanced Cooling Technology, Inc.	Phase Change Materials/ Thermal Storage Units	7-9
Starsys, Redwire Space	Thermal switches	7-9
Thermal Management Technologies	Multifunctional Thermal Structures	4-5

Table 7-3: Active Thermal Systems

Manufacturer	Products	TRL in LEO Environment
Minco Products, Inc., Birk Manufacturing, All Flex Flexible Circuits, LLC., Fralock, Tayco Engineering, Inc., Omega	Electrical Heaters	7-9
Ricor-USA, Inc., Creare, Sunpower Inc., Northrop Grumman, NASA Jet Propulsion Lab, and Lockheed Martin Space Systems Company	Cryocoolers	5-6
Marlow, TE Technology Inc., Laird	Thermoelectric Coolers (TEC)	7-9
Lockheed Martin	Fluid Loops	4-5
NASA Small Spacecraft Technology program	Active Thermal Architecture (ATA)	4-6





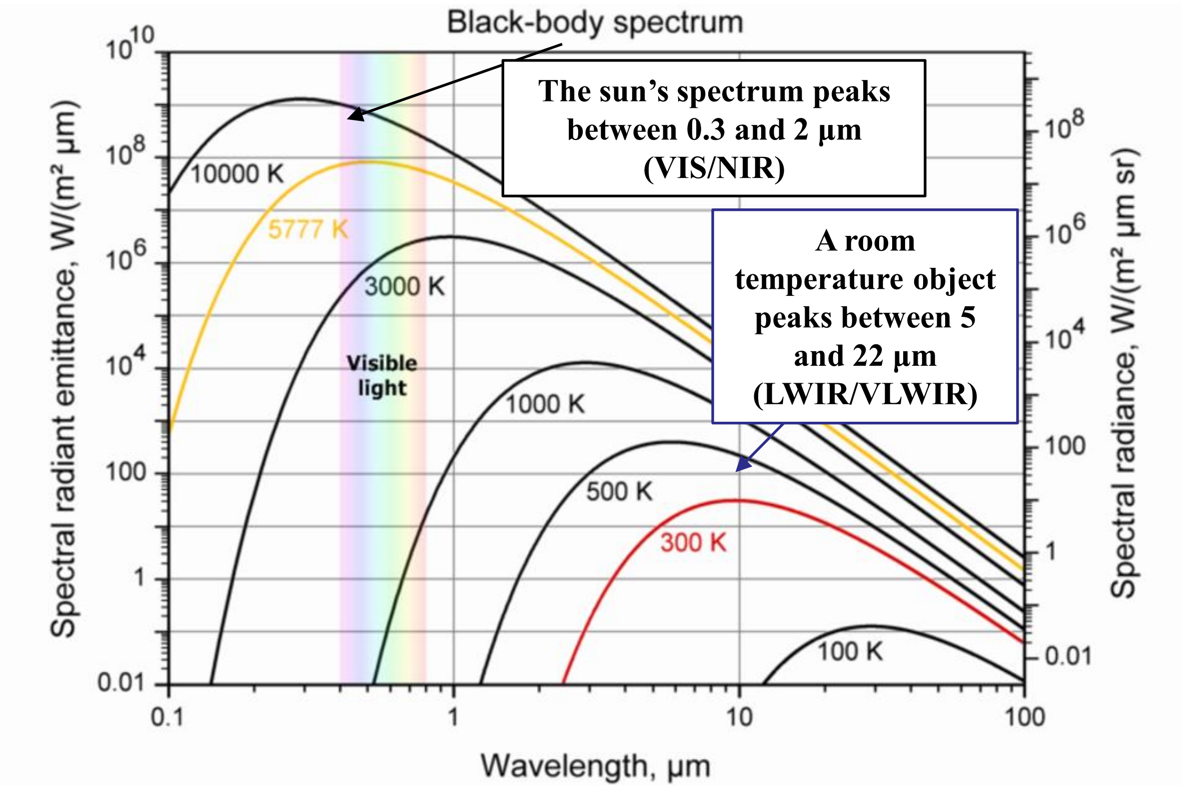
Source: nasa.gov

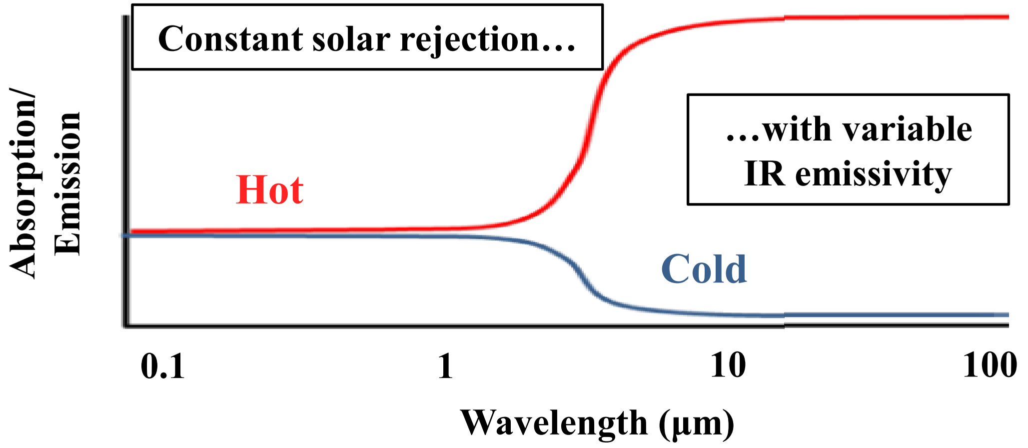
- Not mentioned: thermochromics, which have limited space heritage

Thermochromics in Space

- Emissivity is the opposite of absorptivity, and relates to the ability of an object to radiate energy via photon emission
- Absorption/emission of radiation is determined by the Planck and Stefan-Boltzmann laws, which state:
  - Radiation spectrum is determined solely by object's temperature
  - Total power output: $\frac{P}{A} \sim T^4$
- Intense solar radiation that heats up spacecraft peaks in UV / Vis / NIR, while room temperature spectrum peaks in MWIR / LWIR
- Thermochromic materials change their optical properties as a function of temperature
  - No external power required
- To achieve optimal thermochromic performance:

1. Minimize absorption of intense solar radiation
2. Maximize possible IR emissivity variation





PSI's Variable Emissivity Radiator Technology: LAVER

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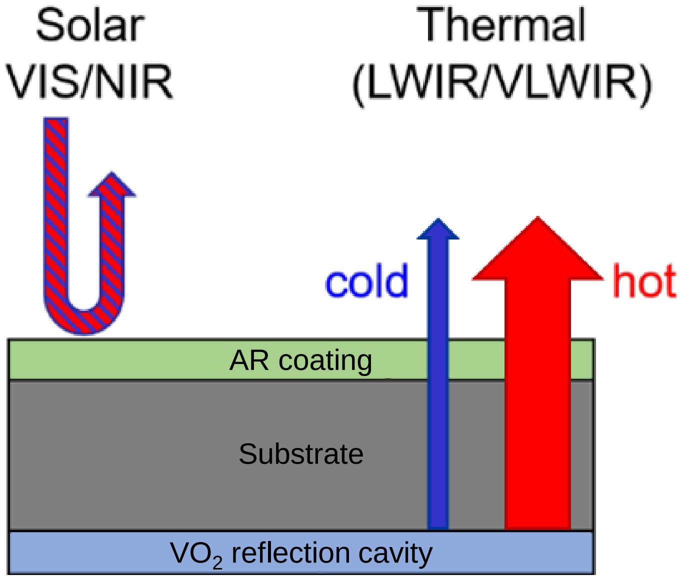
- Technology: ***Low-alpha, variable emissivity radiator (LAVER)*** tiles applied to radiator panels for passive thermal regulation of spacecraft

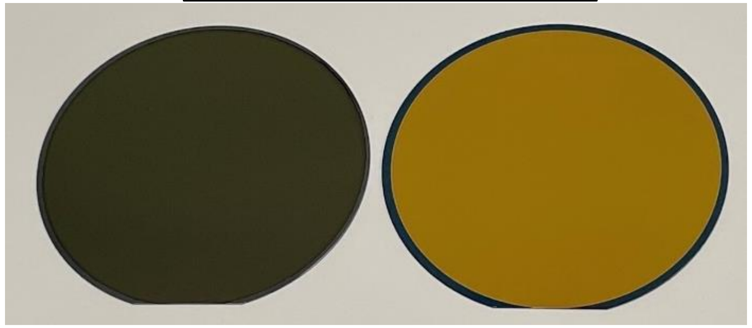
- **Manages radiation with three key features:**
  1. **Passive emissivity switching** – Phase change VO_2 passively modulates emissivity with contrast of >3.25:1 and peak >0.8
  2. **Controllable set-point temperature** – Insulator to metal transition customizable between 15ºC and 67ºC while maintaining emissivity contrast
  3. **Innovative coating design** – Anti-reflection coating with high transparency from ~ 0.4 to 22 microns improves Δε while rejecting >80% of incident solar photon radiation (α < 0.2)

- **Benefits over current state-of-the-art:**
  - Passive regulation of variable thermal loads (>500 W/m^2)
  - Reduced size and weight (<1 kg/m^2 areal density)
  - No moving parts
  - Low complexity of thermal control systems vs. heat pipes

Device Structure and Performance



2" wafer devices



Front Side **Back Side**

Feature 1: Passive Emissivity Switching

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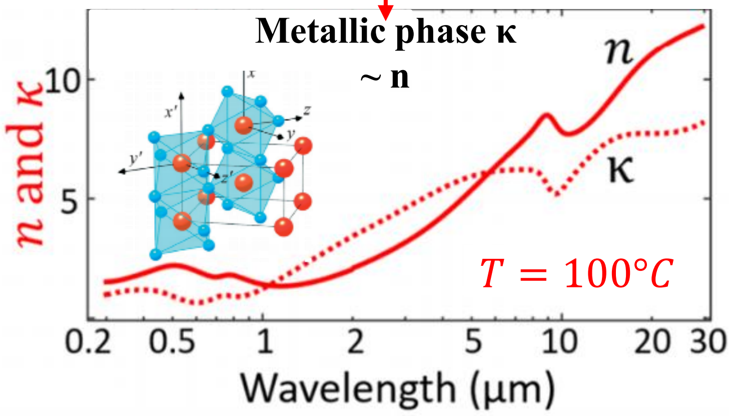
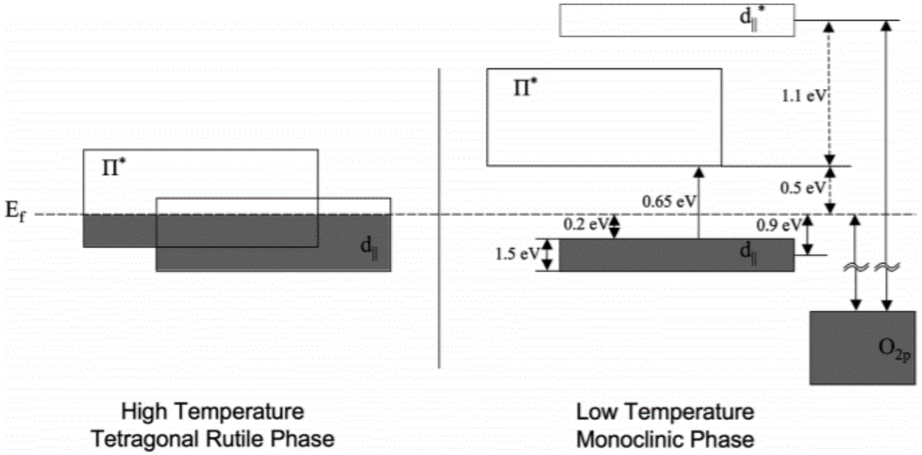
- LAVER passively 'turns on / off' at an engineered set-point temperature
  - Based on phase transition temperature of vanadium dioxide (VO_2) layer
- VO_2 undergoes a semiconductor-to-metal phase transition at a critical temperature (T_c)
  - Phase transition is crystallographic with optical / electronic implications
- Semiconducting phase of VO_2 has bandgap of 0.65 eV (λ > 2 μm)
  - Loss component (κ) of refractive index is significantly different than metallic phase in the thermal IR (5-30 μm)

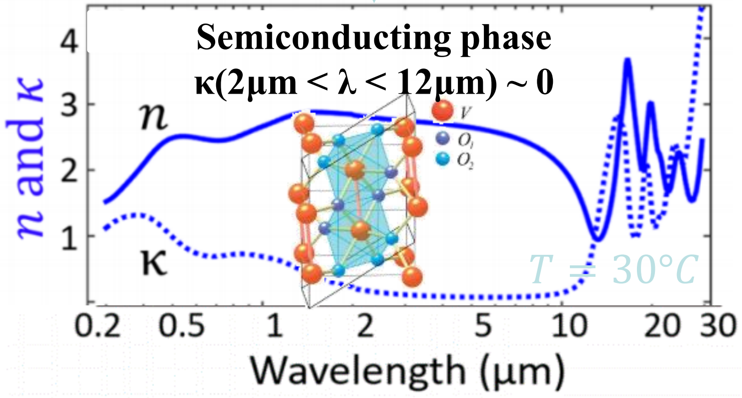
Tc > 67ºC: High Emissivity ('on')

Tc < 67ºC: Low Emissivity ('off')

$$T_C = 67°C$$







Feature 1: Passive Emissivity Switching

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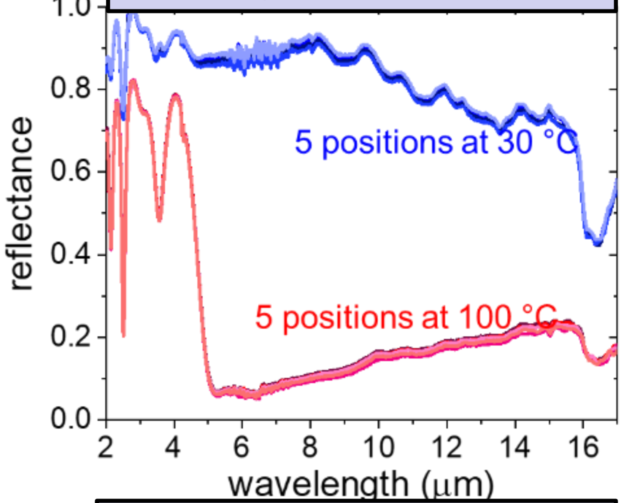
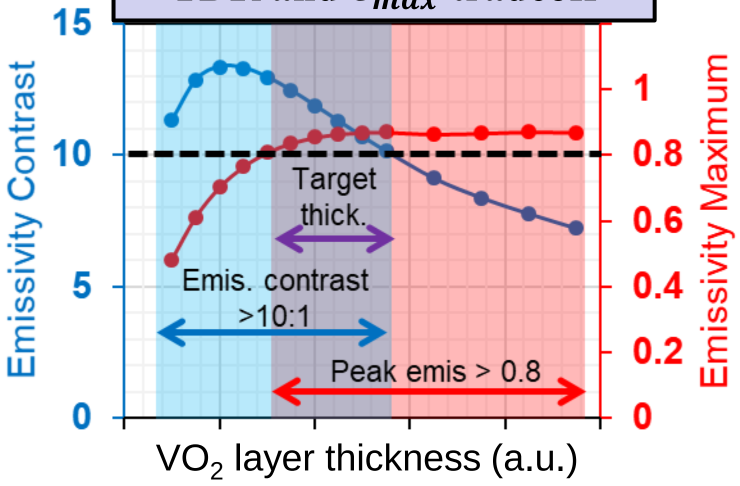
- LAVER exhibits variable broadband emissivity according to the thermochromic modulation of VO_2
  - Emissivity contrast from 0.26 (cold) to 0.86 (hot):
    - TDR ~ 3.25 in current devices
    - Fundamental limit is >10:1
  - High uniformity across 50 mm (2”) substrates
    - Working on scaling to 200 mm substrates
  - Low hysteresis (~4° C)
  - No changes in properties after 10s of thermal cycles

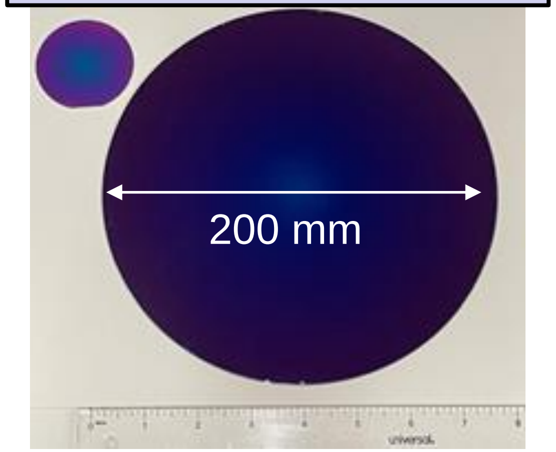
High Uniformity



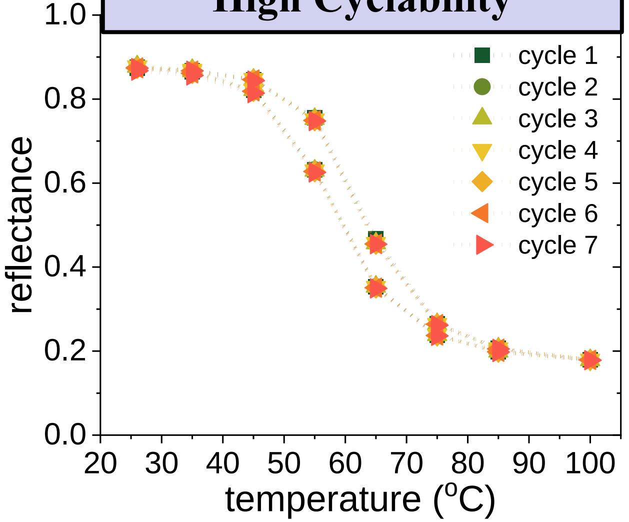
TDR and ϵ_{max} tradeoff



Scaling up fabrication

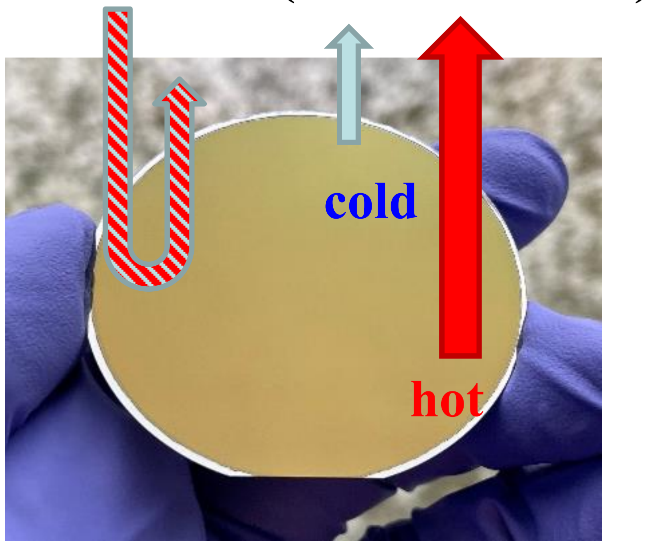


Low Hysteresis High Cyclability



Feature 2: Innovative Coating Design

- The LAVER integrates a coating technology that rejects solar radiation (0.3-2 μm) while acting as an antireflection (AR) coating in the thermal band (5-22 μm)
  - Enables rejection of solar radiation ***regardless*** of device temperature, while enhancing emissivity contrast in the thermal band
  - Integrated device performance agnostic to angle of incidence

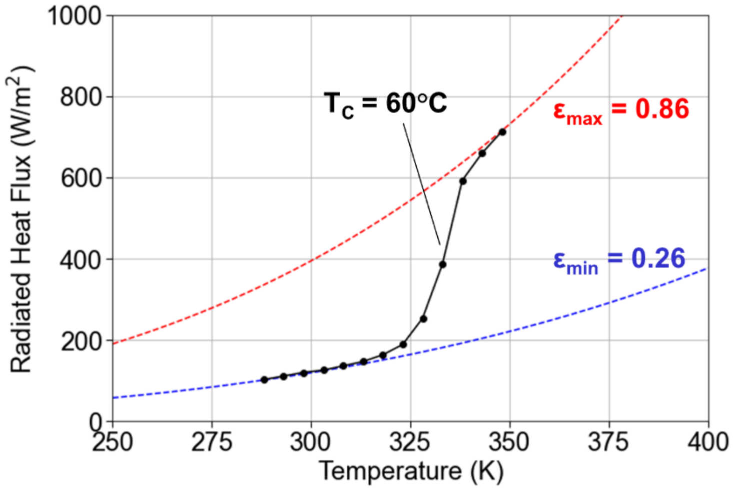


High & Constant Solar Rejection…

- Low α properties are integrated into the top coat
  - Working toward α =0.14.

LAVER top surface

…with Variable IR Emissivity



Feature 2: Controllable Set Point Temperature

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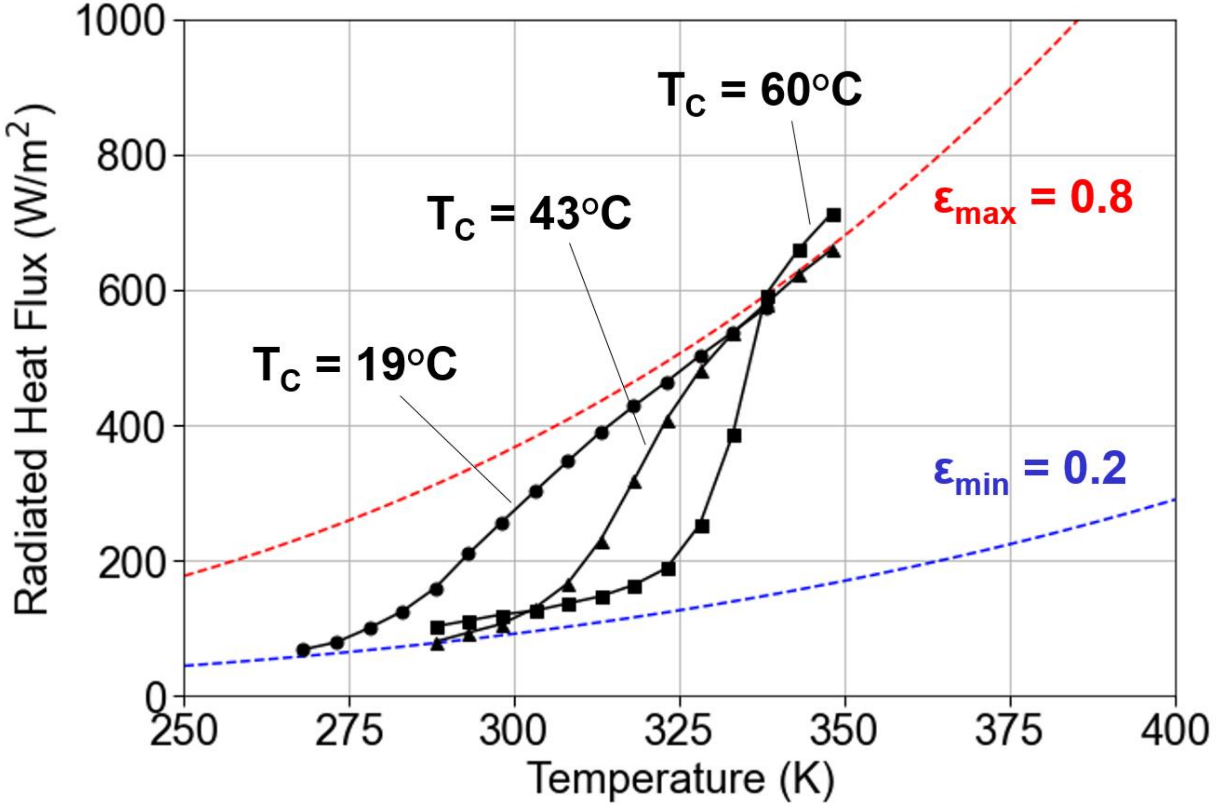
- Set point temperature of LAVER tiles can be modified without sacrificing emissivity contrast
  - PSI achieves this via tight process controls and a unique doping method

T_C (Critical Temperature)	Peak Normal Emissivity	Minimum Normal Emissivity	Δε	TDR
60°C	0.86	0.26	0.6	3.3
43°C	0.82	0.21	0.61	3.9
19°C	0.78	0.2	0.58	3.9

TDR = Turn Down Ratio

LAVER Devices with Varying Set-points



- **Phase change VO_2 passively modulates emissivity with contrast of >3.25:1 and peak >0.8**

Performance of LAVER Tiles: Space Environmental Testing

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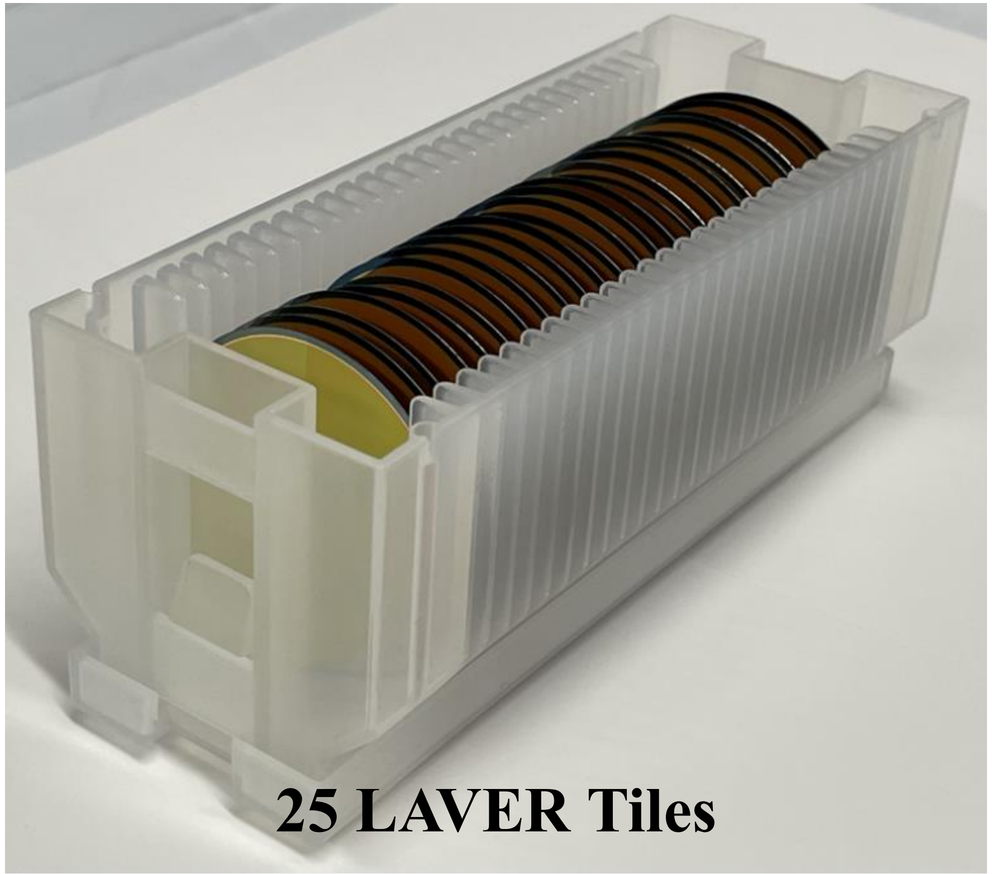
- LAVER tiles subjected to numerous space environmental tests for an initial evaluation of overall "space-worthiness" and an estimate of degradation through end-of-life, including combined effects
  - Tests performed by third-party aerospace contractor
- LAVER tiles survived space environmental testing and handling and testing for space qualification
- Near-term goal to flight test LAVER technology

Surface Resistivity	limit 100 GΩ/□	PASS
Outgassing	ASTM E595-15	PASS
Adhesion	MIL-F-48616	PASS
Humidity	MIL-F-48616 3.4.1.1/3.4.1.4	PASS
Solvent	MIL-F-48616 3.4.1.1/3.4.1.4	PASS
Contamination + UV	NA	PASS
Electron Radiation	$2x10^{16}$ e^-/cm^2 at 100 keV (1 year in LEO)	PASS
Proton Radiation	($1x10^{14}$ p^+/cm^2 at 1.8 MeV)	PASS
Thermal Cycling	(+90C to -90C,10x)	PASS

Continued Development: Volume Production

- LAVER technology currently at TRL 6 and MRL 4
  - Based on technology performance, manufacturing status, and device reproducibility
- PSI has fabricated and delivered batches of LAVER devices to customers in limited quantities (<25)
- Currently funded through NASA CCRPP program to enhance TRL 6 → 7 and MRL 4 → 5 by 2024
  - Cost reduction via scaled fabrication
  - Device uniformity and reproducibility



Continued Development: Extending LAVER Capabilities

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- Flexible substrates:
  - Conformal tiling over non-planar surfaces & increased retro-fitting
  - Lightweight for more robust application space

- Maximal performance:
  - Reduce absorption in layered structure contributing to higher ε_{min} in LWIR, with small reduction in ε_{max}
  - **Net effect:** Emissivity contrast (TDR) approaches theoretical limit (~10:1)

Current Performance

ϵ: .20 → .83

TDR ~ 4:1

$\alpha = 0.4$

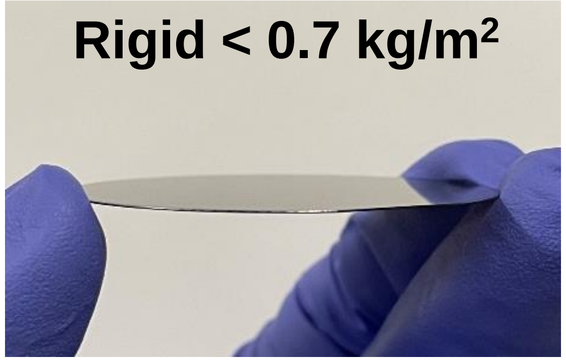
→

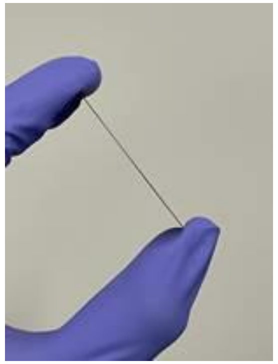
Anticipated Performance

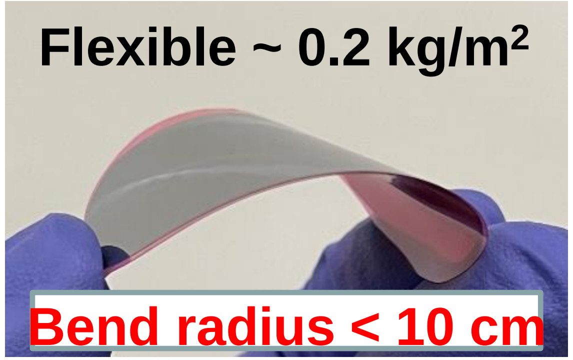
ϵ: .10 → .82

TDR ~ 8:1

$\alpha = 0.14$







Technology Summary

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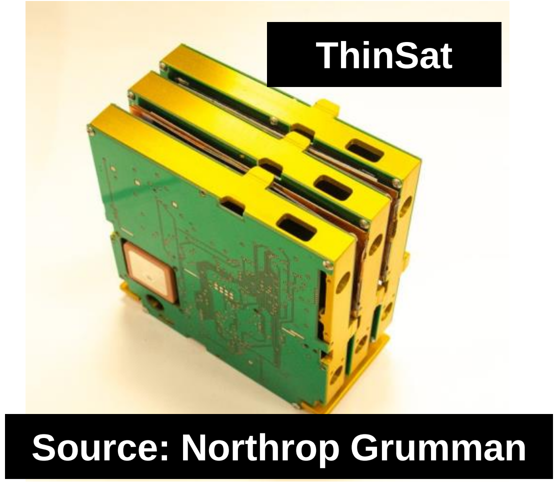
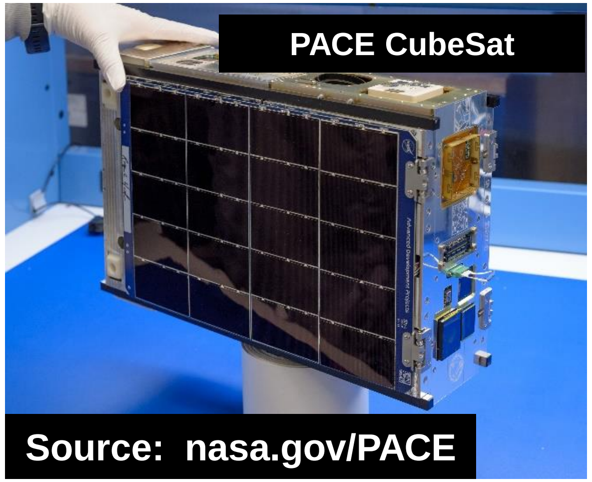
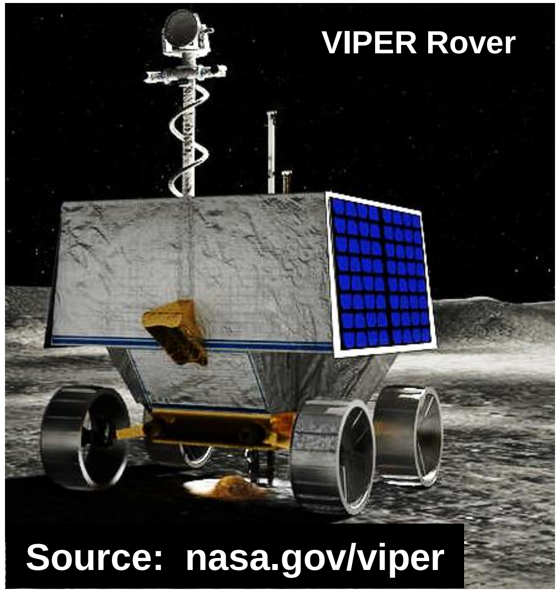
- PSI has developed a versatile technology for passive regulation of spacecraft in orbit, on the lunar surface, and beyond.
- With emissivity contrast ~ 4:1, peak emissivity of 0.8 and a critical temperature that can be set below 20° C, *Low-alpha, variable emissivity radiator (LAVER)* tiles are well suited for a variety of applications, including Lunar vehicles, ThinSats, and CubeSats







PSI Team

- PSI has received funding by numerous agencies to develop VO_2 variable emissive technologies.

- Acknowledgement to Prof. Mikhail Kats at the University of Wisconsin – Madison, for high fidelity optical characterization

- Questions?

Funding Sources

Key Contributors

David Woolf

Colin Hessel

AJ Wright

Joseph Andrade

Dung Quach

Joel Hensley

Jim Glynn

ADDITIONAL CONTENT

Dissipation of Heat in Space

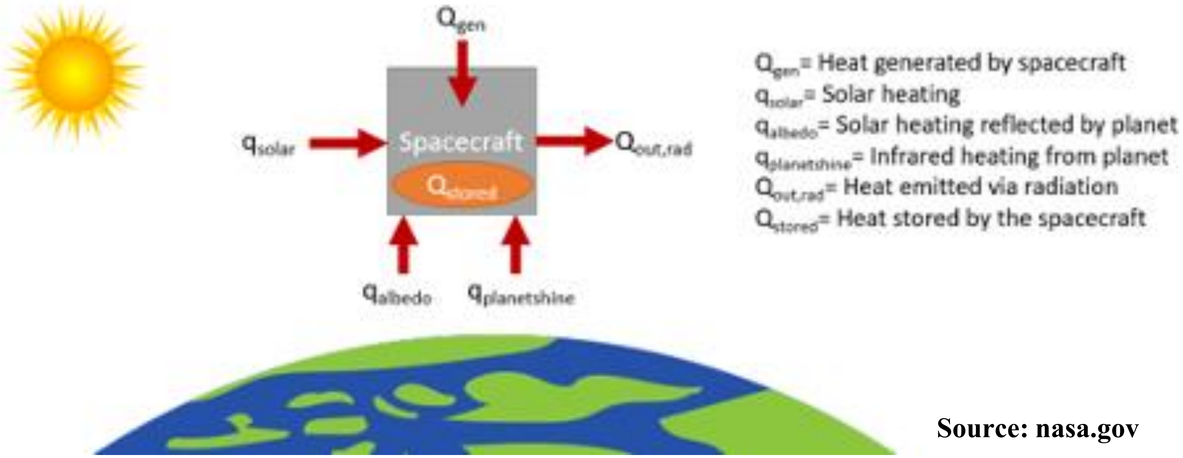
VG-2023-249

- Without an atmosphere (or a ground to stand on!), the only way to dissipate heat in space is via thermal radiation

- Any satellite must contend with the following thermal inputs
  - Waste heat generated by spacecraft payload functions (Q_{gen})
  - Heat absorbed from direct solar blackbody radiation (Q_{solar})
  - Heat absorbed from solar radiation reflected from a nearby celestial body (Q_{albedo})
  - Infrared emission from a nearby celestial body ($Q_{planetshine}$)

- The equilibrium temperature is set when the dissipated heat ($Q_{out,rad}$) is equal to the absorbed heat
  - $Q_{in} = Q_{gen} + Q_{solar} + Q_{albedo} + Q_{planetshine}$
  - $Q_{out,rad} = \epsilon \sigma T^4$

- For many satellites, equilibrium is constantly changing
  - When in eclipse (Q_{solar}, $Q_{planetshine}$)
  - Non-continuous payload operation (Q_{gen})



Source: nasa.gov

SWaP and Thermal Requirements for Satellites

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- With a constantly changing thermal environment, maintaining a spacecraft within its operating temperature range becomes a significant challenge

- For SmallSats (CubeSats, ThinSats, etc.), SWaP matters

Table 7-1: SmallSat Thermal Control Challenges	
SmallSat Property	**Challenge**
Low thermal mass	The spacecraft is more reactive to changing thermal environments.
Limited external surface area	There is less real estate to be allocated to solar cells, designated radiator area, and/or viewports required for science instruments.
Limited volume	There is less space for electronic components, science instruments, and thermal control hardware. Components can be more thermally coupled.
Limited power	There is less power available for powered thermal control technology.

Source: nasa.gov

Component/ System	Operating Temperature (C)	Survival Temperature (C)
Digital electronics	0 to 50	-20 to 70
Analog electronics	0 to 40	-20 to 70
Batteries	10 to 20	0 to 35
IR detectors	-269 to –173	-269 to 35
Solid-state particle detectors	-35 to 0	-35 to 35
Momentum wheels	0 to 50	-20 to 70
Solar panels	-100 to 125	-100 to 125

Given thermal control constraints, maintaining systems within specified temperature range is a challenge!

LAVER vs. VO2-based State-of-the-Art

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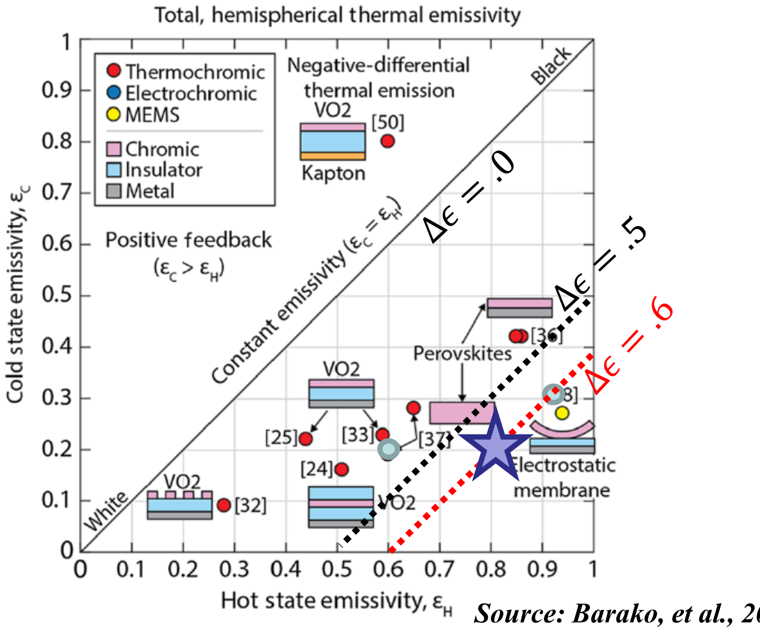
- Thermochromic materials change their optical properties as function of temperature
  - No external power is required

- Thermochromic activity in the LWIR can enable variable emissivity and passive space radiator technologies

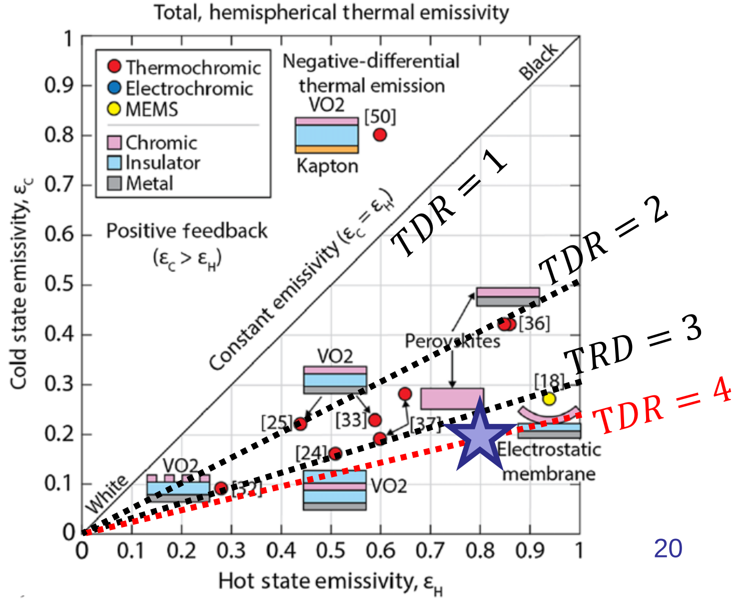
- Integrating thermochromics into a patterned or layered structure can further enhance the emissivity variation

- Published state of the art:
  - $\Delta\epsilon = \epsilon_{hot} - \epsilon_{cold} = 0.5$, $TDR = \epsilon_{hot}/\epsilon_{cold} = 3$
- Target:
  - $\Delta\epsilon = \epsilon_{hot} - \epsilon_{cold} > 0.6$, $TDR = \epsilon_{hot}/\epsilon_{cold} > 4$

- The LAVER technology harnesses thermochromic VO2 in passive radiator tiles
  - Achieves TDR up to 10:1 from 2-25 microns

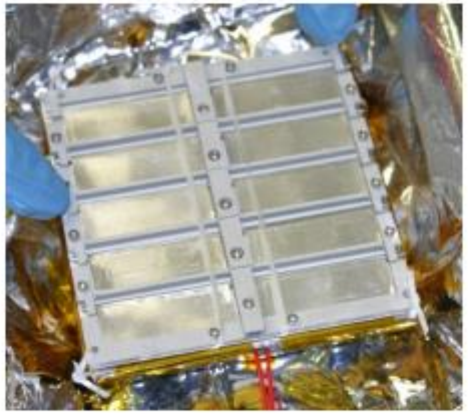


Source: Barako, et al., 2022

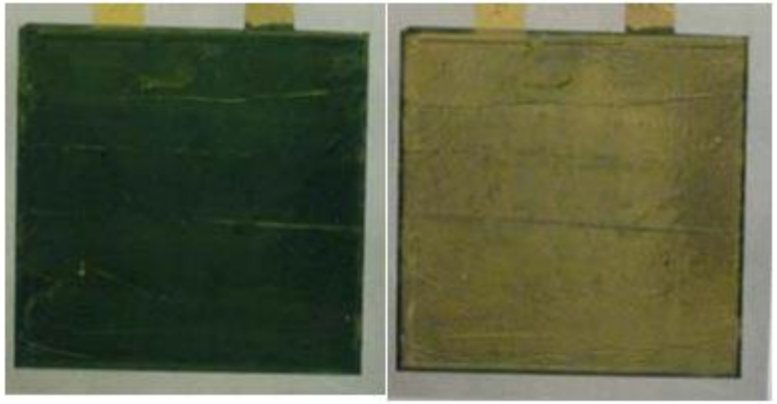


Advantages of Passive Thermal Regulation

- (Micro)louvers:
  - Advantages:
    - Low cost, high redundancy
  - Disadvantages:
    - Moving parts (risk of failure)
    - Heavy (areal density of 4-10 kg/m^2)
    - Limited emissivity contrast
- Electrochromics
  - Advantages:
    - Lightweight (~1 kg/m^2)
    - Good emissivity contrast (~0.15 – 0.7)
    - Low power consumption (40 uW/cm^2 transient)
  - Disadvantages:
    - Poorly scalable
- Thermochromics
  - Advantages:
    - No power consumption
    - Good emissivity contrast (~0.2 – 0.8)
  - Disadvantages:
    - Limited space heritage



Evans, A, "Design and Testing of the CubeSat Form Factor Thermal Control Louvers," AIAA/USU Conf. on Small Sats, 2019



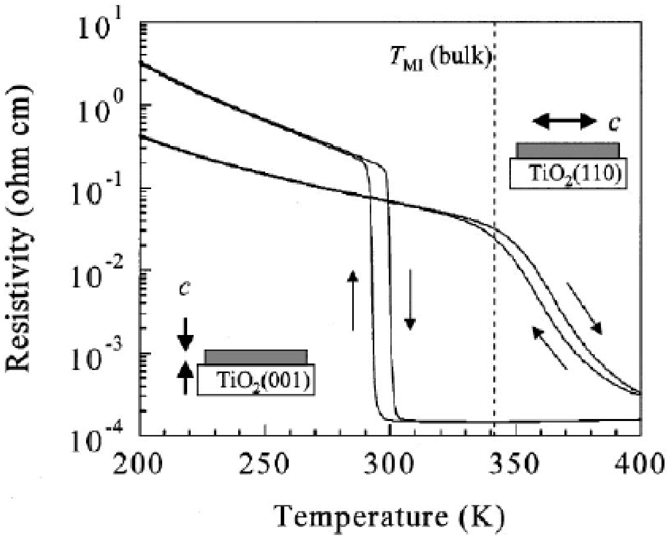
Dark State (+0.2 V) Light State (-1.0 V)

Paris, A., and Anderson, K., "Electrochromic Radiators for Microspacecraft Thermal Control," NASA, 2005,

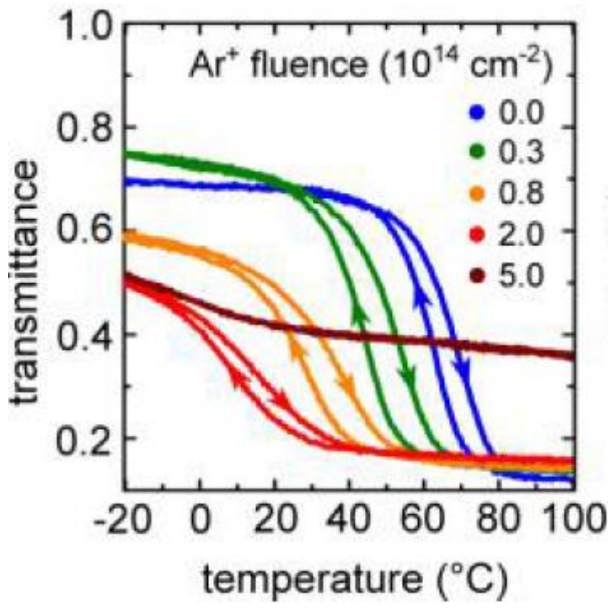
Feature 2: Controllable Set Point Temperature – Literature Comparison

VG-2023-249

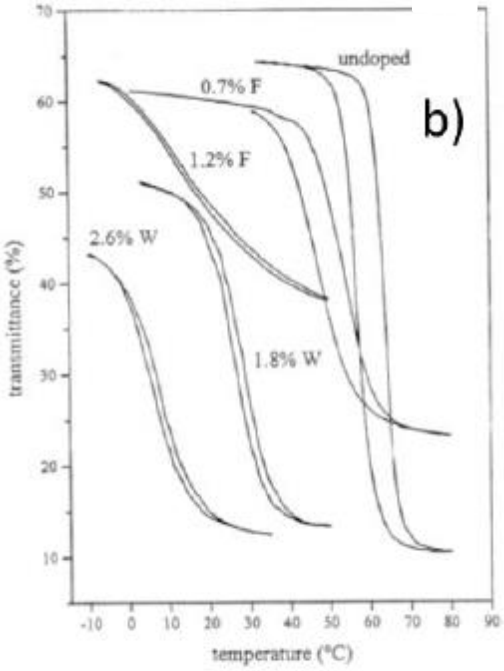
- Degradation of the phase contrast as a function of doping or defect density is a consistent feature of published deposition or synthesis approaches
  - Epitaxial growth on TiO2 Defect engineering Doping with atomic species



Muraoka, et al 2002



Rensberg, et al 2015



Burkhardt, et al 1999

dopant	limit (at. %)	effect on τ_c (°C/at. %)
Eu^{3+} [17]	4	−6.5
Mg^{2+} [18−20]	7	−3
W^{6+} [21]	2.5	−23
F^{-} [21]	2.1	−20
Mo^{6+} [22]	2.5	−12
Nb^{5+} [22]	4	−8
P^{3-} [23]	1	−13
Fe^{3+}[24]	1.4	−6
Sb^{3+} [25]	7	−1
Zr^{4+} [26]	11	unchanged

Wang, et al 2016

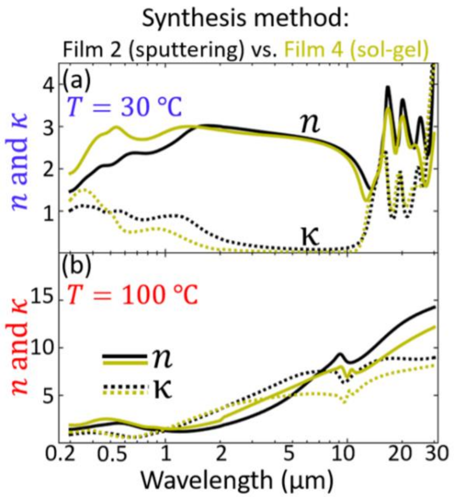
- PSI's synthesis approach for LAVER is able to reduce the phase transition temperature of VO_2 via doping *without* other kinds of material degradation that suppress the phase contrast.

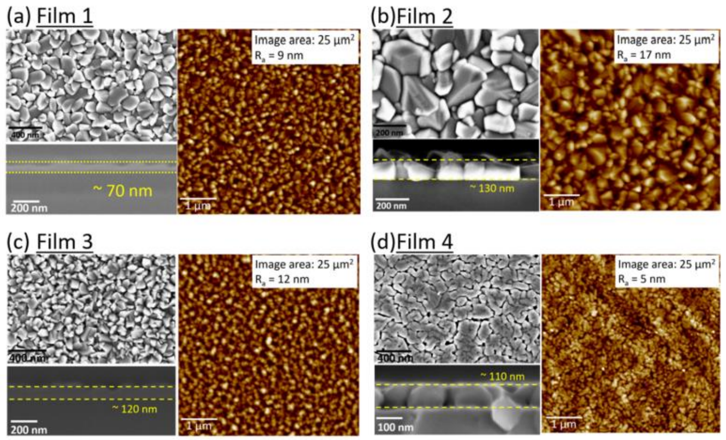
Feature 2: Controllable Set Point Temperature via Sol-gel Synthesis

- VO_2 films can be made using
  - Sputtering, Pulsed Laser Deposition, atomic layer deposition, epitaxial growth, and solution (sol-gel) based techniques have all been used to make VO_2 films
- Many of these approaches are not conducive to high volume production, or have significant costs associated with the deposition method.
- PSI has focused our development on the sol-gel method
  - V_2O_5 sol gel film annealed and reduced to VO_2

	Thickness (nm)	Substrate	Synthesis method
Film 1	70 ± 9	Si + native oxide	Magnetron sputtering
Film 2	130 ± 17	Si + native oxide	Magnetron sputtering
Film 3	120 ± 12	Sapphire	Magnetron sputtering
Film 4	110 ± 5	Si + native oxide	Sol-gel

- Advantages of sol-gel processing:
  - Scalable
  - Inexpensive
  - High quality VO_2 thin film
  - Versatility for aqueous doping
  - Yields same optical properties as sputtered films





Wan, et al., Annalen der Physik 2019