Thermochromic Variable Emittance Coatings for Spacecraft Thermal Control

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Outline

- Personal Background
- Research Introduction and Motivation
- Designing a Variable Emittance Coating
- Fabricating and Characterizing a Variable Emittance Coating
- Thermal Vacuum Experiments and Feasibility Studies
- On-going Projects at NASA
- Thermal Technology Gaps Overview

Background

2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

B.S. AAE '13

GE Combustion Intern Spring '12
GE PLM Intern Summer '13

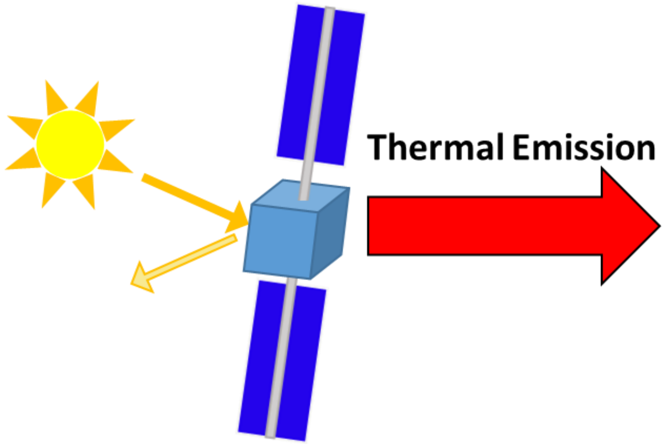
Ph.D. Aerospace Engineering '20

NASA Space Tech Research Fellow '16-'20
Pathways Intern Spring and Summer '20
Full-Time at NASA January '21

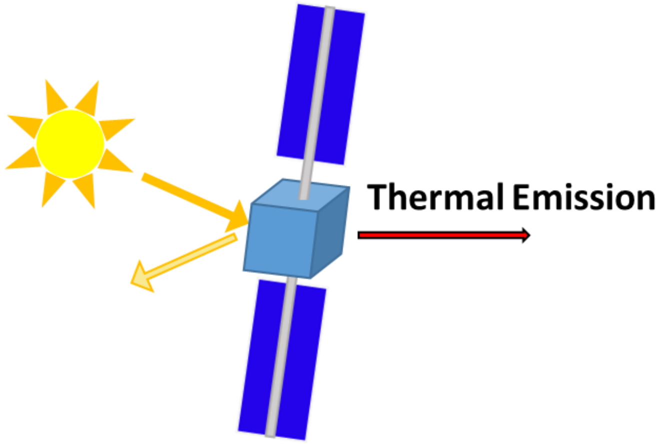
Research Introduction and Motivation

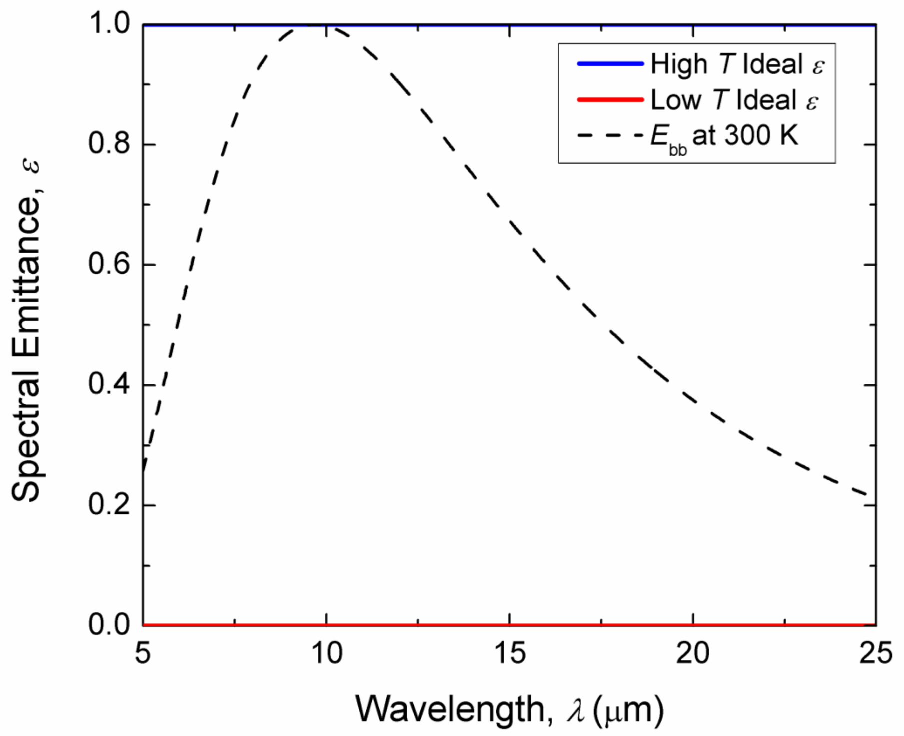
Variable Emittance Coatings

High Temperature (Cooling)



Low Temperature (Heating)





Ideal <u>Broadband</u> Emittance

- High Temp: ε ≈ 1
- Low Temp: ε ≈ 0

Thermochromic Coating Design

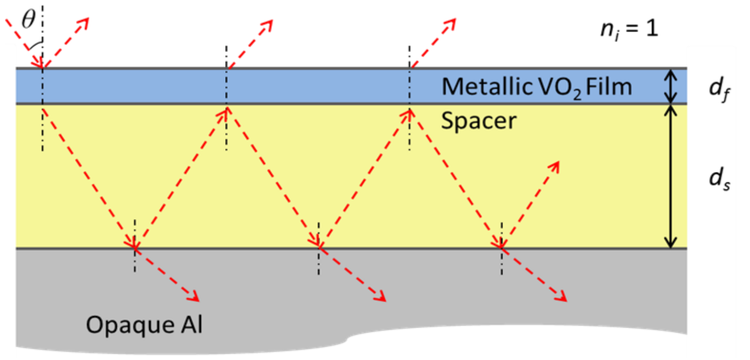
What is VO_2?

VO_2 is a thermochromic insulator to metal phase transition material

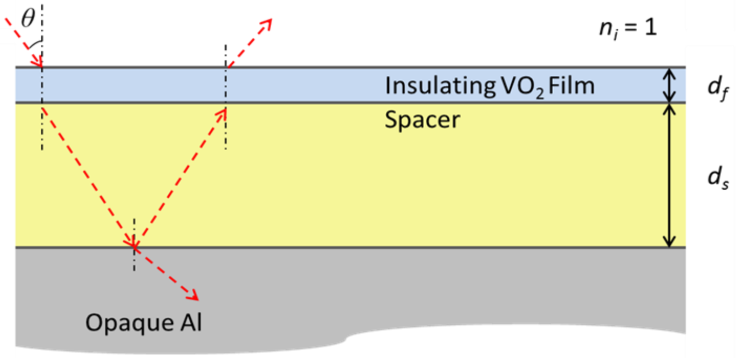
- At **high temperatures**, the Fabry-Perot resonance cavity is formed, leading to an emission enhancement near resonance wavelength of λ = 10 μm

- At **low temperatures**, the structure becomes highly reflective due to the high IR transmittance of the VO_2 and spacer material

Metallic VO_2 (T > 345 K)



Insulating VO_2 (T < 341 K)



Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, **197**, 76-83 (2017)

Designing a Variable Emittance Coating

Modeling Properties of VO_2

Dielectric Functions (ε):

Insulator (T = 341 K):

$$\varepsilon_d(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} S_j \frac{\omega_j{}^2}{\omega_j^2 - i\gamma_j\omega - \omega^2}$$

Metallic (T > 345 K):

$$\varepsilon_m = \frac{-\omega_p^2 \varepsilon_\infty}{\omega^2 - i\omega\omega_c}$$

In Transition (341 K< T < 345 K):

$$f \frac{\varepsilon_m - \varepsilon_{eff}}{\varepsilon_{eff} + q(\varepsilon_m - \varepsilon_{eff})} + (1 - f)\frac{\varepsilon_d - \varepsilon_{eff}}{\varepsilon_{eff} + q(\varepsilon_d - \varepsilon_{eff})} = 0$$

Where:

ε_∞ = High frequency dielectric constant

S_j = Phonon strength

ω_j = Phonon frequency

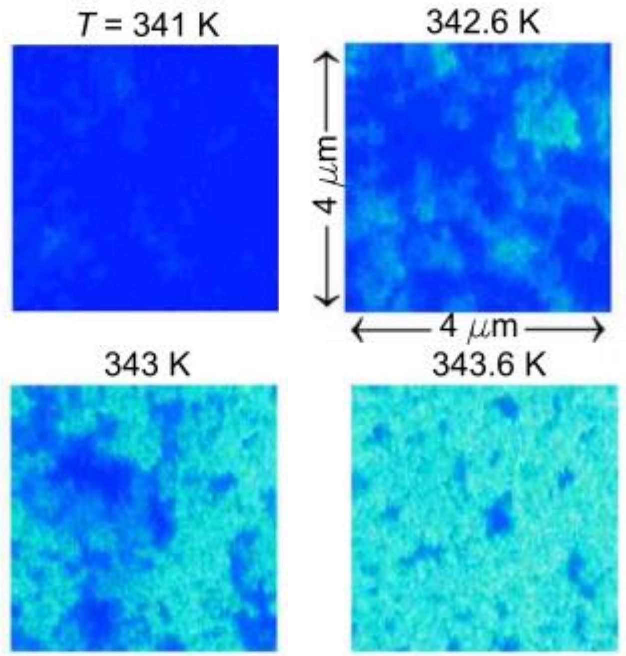
ω_p = Plasma frequency

ω_c = Collision frequency

q = Depolarization factor

f = Filling Fraction

γ_j = Damping Coefficient



T (K)	f	q_O	q_E
341	0	--	--
342	0.18	0.2	0.6
342.6	0.31	0.33	0.34
343	0.48	0.45	0.1
343.6	0.7	0.5	0
345	1.0	--	--

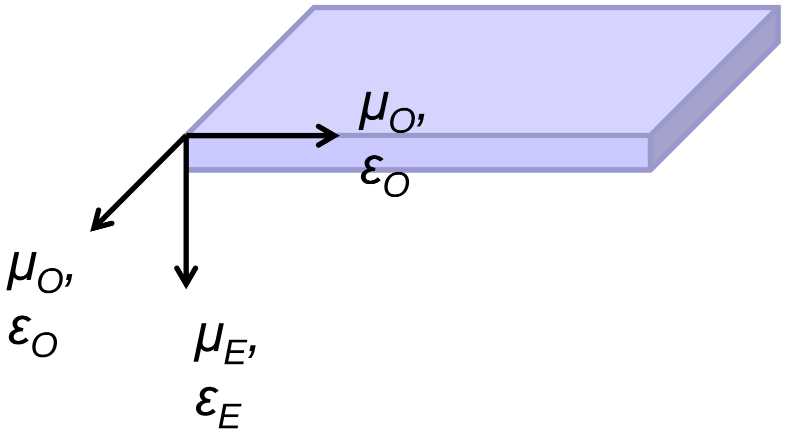
Qazilbash et al., Phys. Rev. B, **79**, 075107 (2007)

Barker et al., Phys. Rev. Lett., **17**, 1286 (1966)

Uniaxial Transfer Matrix Method

Indirect Calculation of Emittance:

$$\varepsilon'_\lambda = 1 - R'_\lambda - T'_\lambda$$



Transmittance:

$$T'^{,p}_\lambda = \frac{\mathrm{Re}(k^p_{z,N} / \varepsilon_{N,O})}{\mathrm{Re}(k^p_{z,1} / \varepsilon_{1,O})} \left| \frac{1}{M_{11}} \right|^2$$

$$T'^{,s}_\lambda = \frac{\mathrm{Re}(k^s_{z,N} / \mu_{N,O})}{\mathrm{Re}(k^s_{z,1} / \mu_{1,O})} \left| \frac{1}{M_{11}} \right|^2$$

Reflectance:

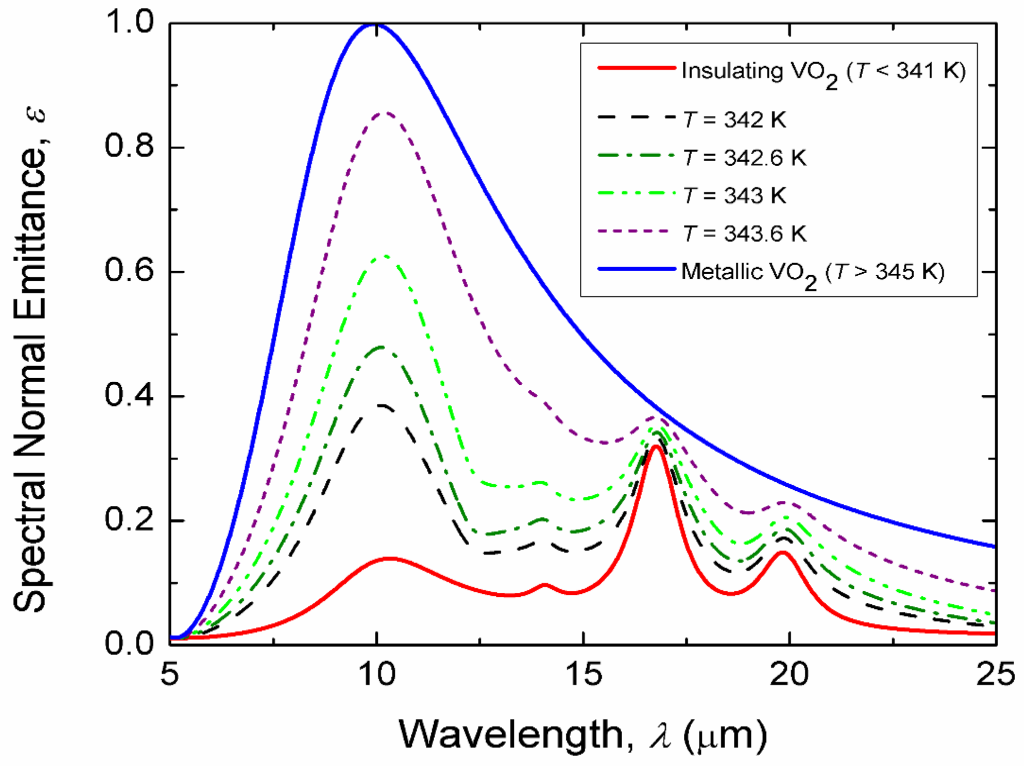
$$R'_\lambda = rr^* = \left| \frac{M_{21}}{M_{11}} \right|^2$$

Z-direction Wavevector:

$$k^s_{z,i} = \sqrt{k_0^2 \varepsilon_{iO} \mu_{iO} - \mu_{iO} k_x^2 / \mu_{iE}}$$

$$k^p_{z,i} = \sqrt{k_0^2 \varepsilon_{iO} \mu_{iO} - \varepsilon_{iO} k_x^2 / \varepsilon_{iE}}$$

Thermochromics Design



Temperature-dependent emittance via the VO_2 phase transition

- VO_2 Thickness:

$$d_f = 25 \text{ nm}$$

- Spacer Thickness:

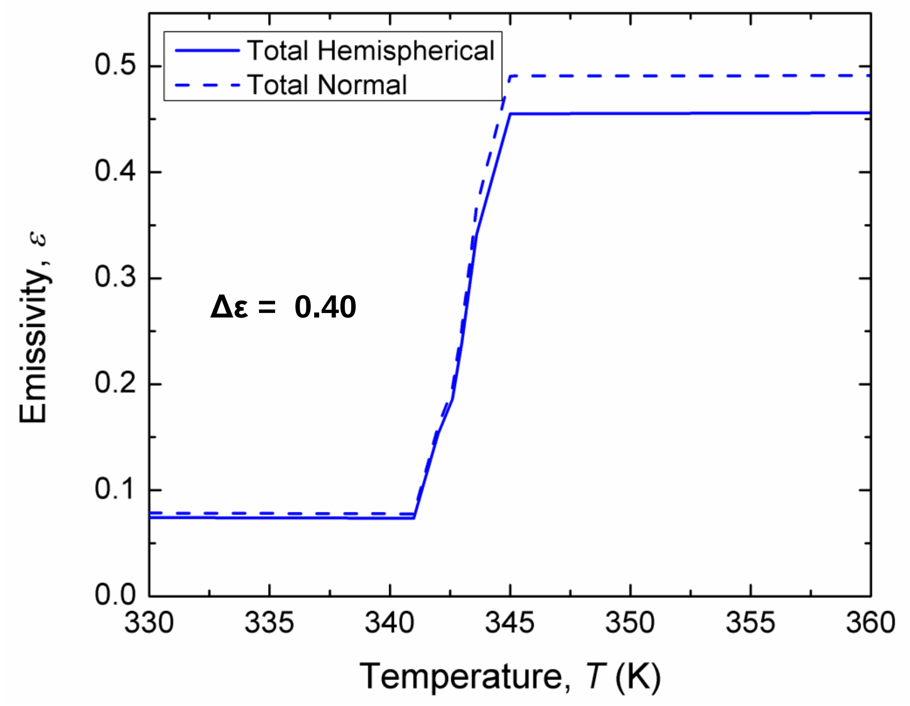
$$d_s = \lambda_{peak} / 4n \approx 730 \text{ nm}$$

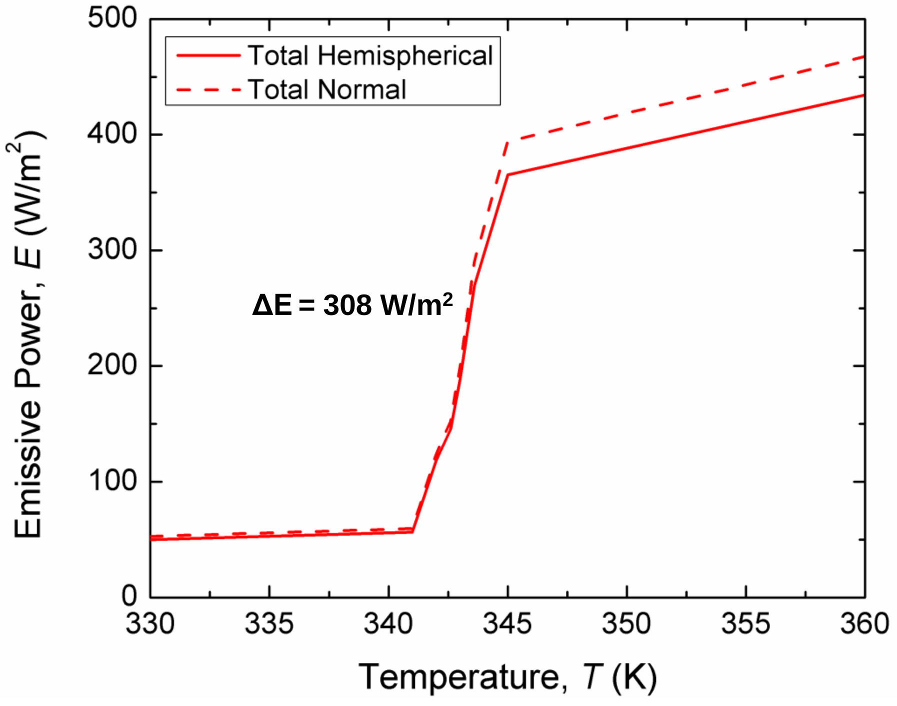
where $\lambda_{peak} = 10\ \mu\text{m}$

$$n = 3.4$$

Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, **197**, 76-83 (2017)

Variable Emitter Total Emittance





Total Hemispherical Emissivity:

$$\varepsilon = \frac{2\int_{0.3\mu m}^{40\mu m} E_{bb} \int_{0}^{\pi/2} \varepsilon_{\lambda}^{'}(T,\lambda,\theta)\cos\theta\sin\theta d\theta d\lambda}{\sigma T^4}$$

Total Hemispherical Emissive Power:

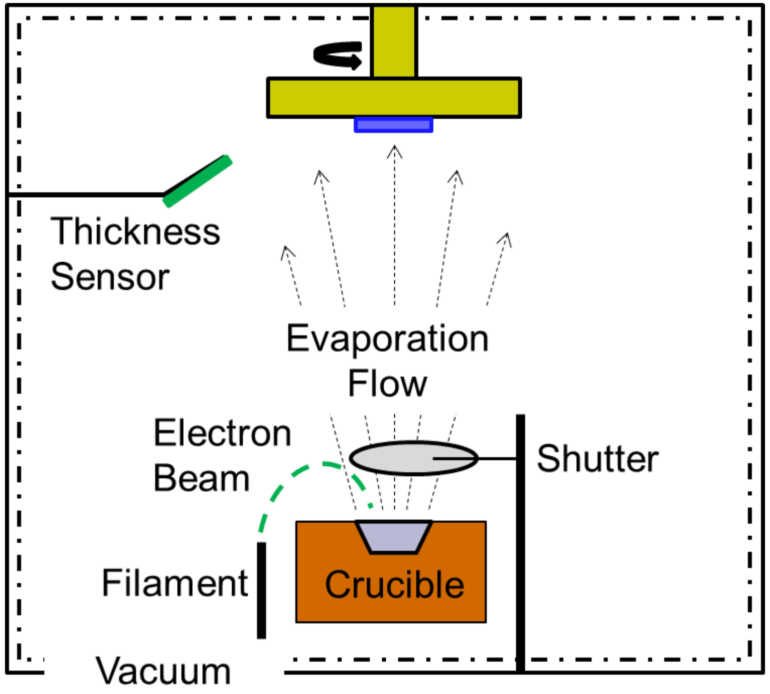
$$E_{\text{hem}} = \varepsilon\sigma T^4$$

Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, **197**, 76-83 (2017)

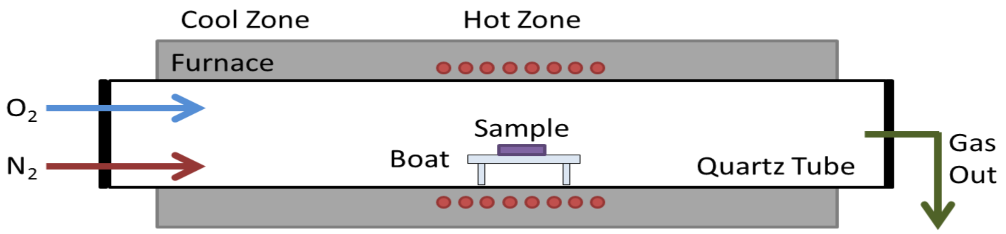
Fabricating and Characterizing a Variable Emittance Coating

VO_2 Thin Film Fabrication

Electron Beam Evaporation:
- Deposit V thin film



Tube Furnace Oxidation:
- Oxidize V thin film to VO_2

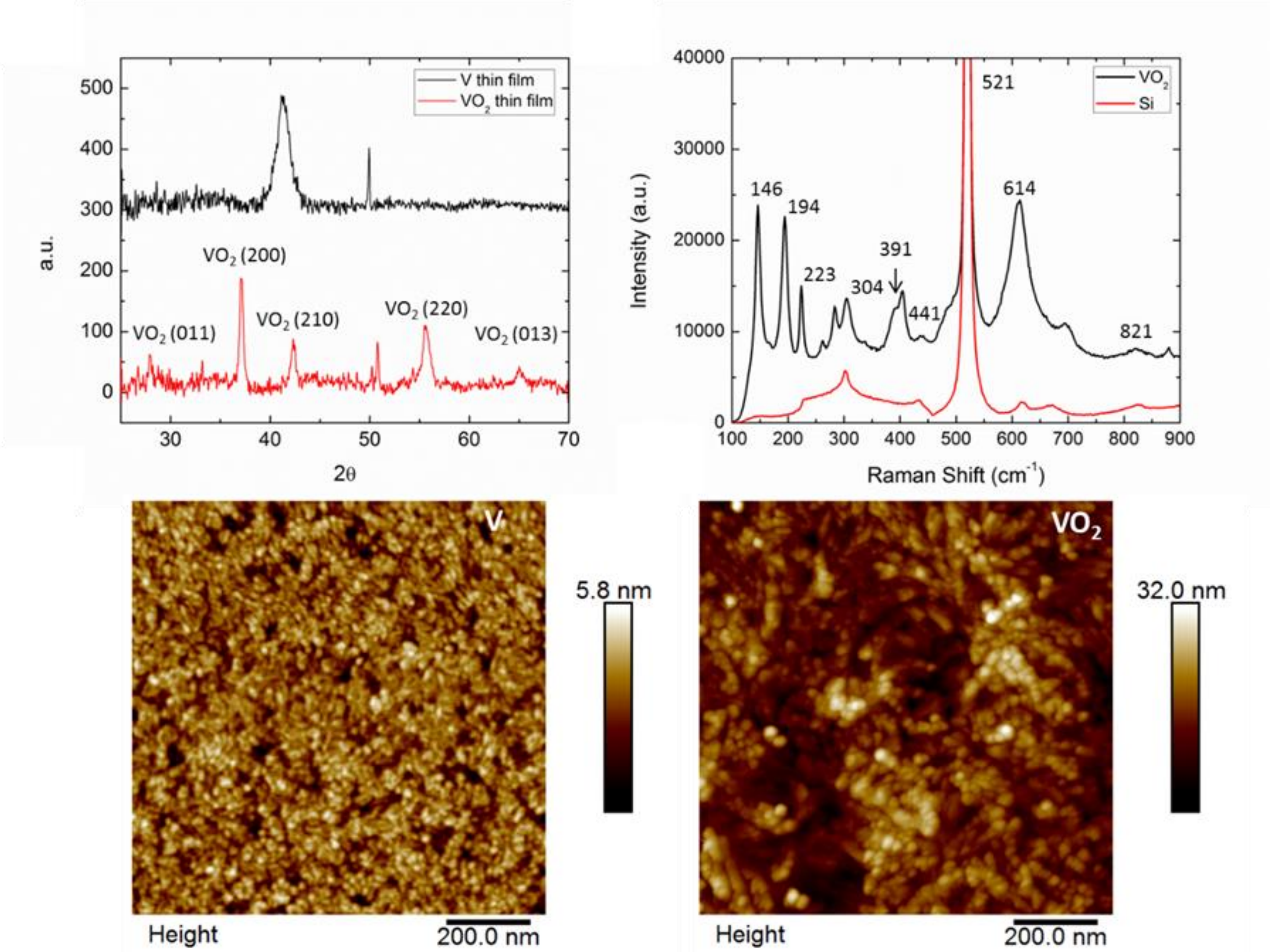


What furnace conditions do we need?
- Temperature
- Furnace Time
- O_2 flow rate
- N_2 flow rate

→ Conducted series of parametric studies to determine optimal conditions

Taylor et al., Thin Solid Films, **682**, 29-36 (2019)

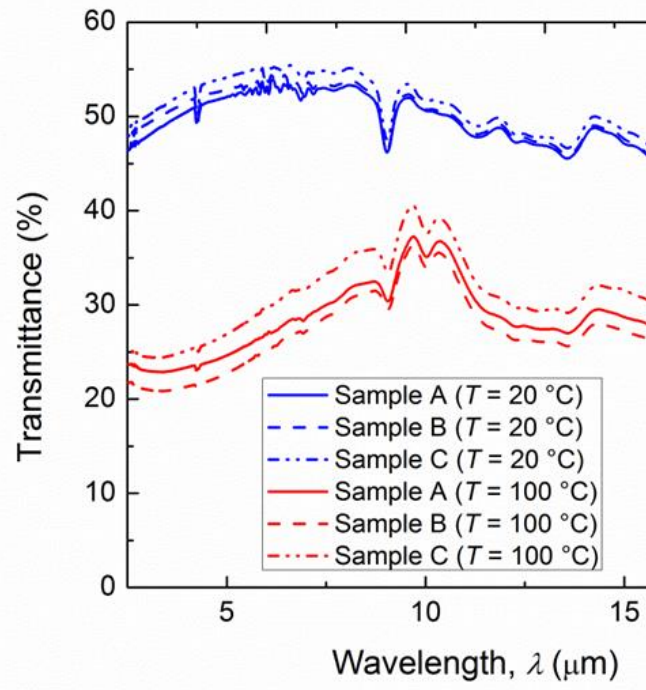
VO_2 Thin Film Characterization



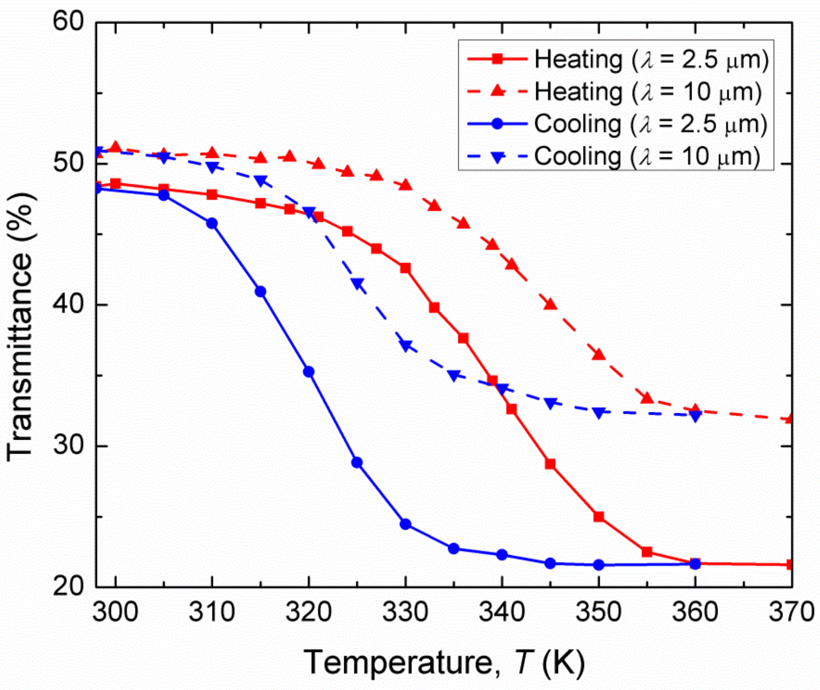
- XRD pattern and Raman spectrum consistent with published results for VO_2 thin films
- Roughness of V and VO_2 is 0.79 nm and 4.79 nm respectively

VO_2 Thin Film IR Characterization

Transmittance of VO_2 Films



Heating and Cooling Curves

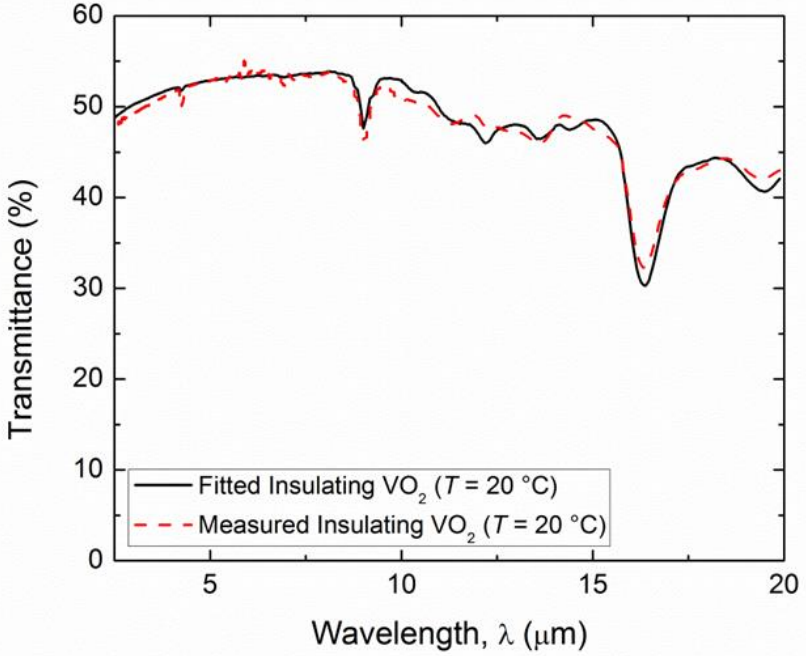


- Transmittance dips in fabricated films correspond to Si phonon modes
- All three fabricated VO_2 thin films had consistent transmittance
- Optical property models were developed for the VO_2 in IR range

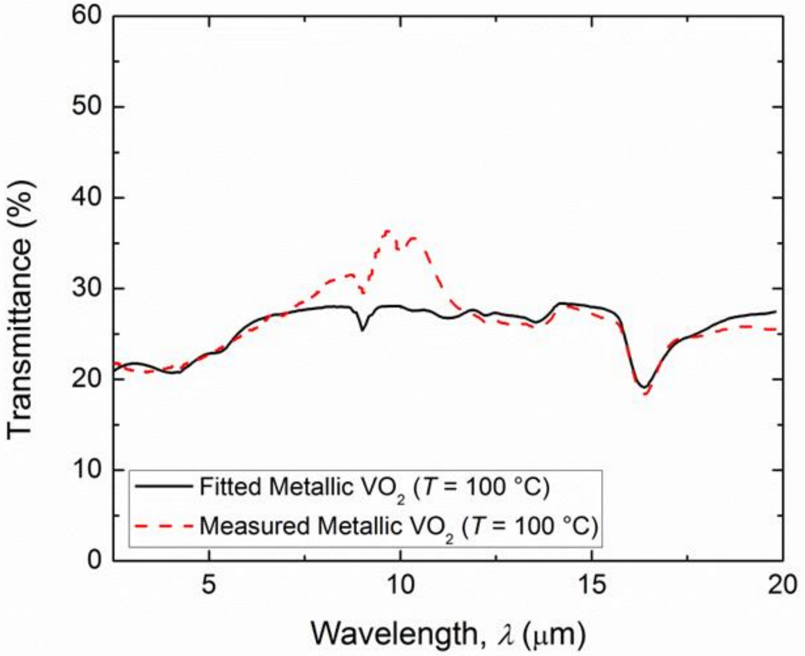
Taylor et al., Thin Solid Films, **682**, 29-36 (2019)

Optical Property Fitting

Insulating VO_2 Lorentz Fit



Metallic VO_2 Dispersion Fit



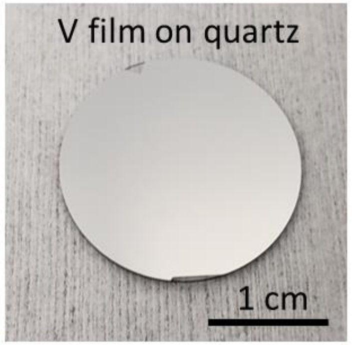
$$\varepsilon_d(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} \frac{S_j \omega_j^2}{\omega_j^2 - i\gamma_j \omega - \omega^2}$$

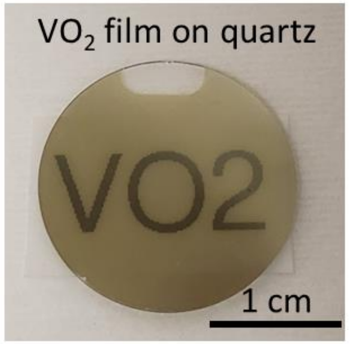
$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_n^2}{\omega^2 + i\omega_c \omega} + \sum_{j=1}^{N} \frac{S_j}{1 - \omega^2 / \omega_j^2 - i\gamma_j \, \omega / \omega_j}$$

Least Squares Fit: $F = \sum_{k=1}^{N} (T_{\text{exp}} - T_{\text{theo}})^2$

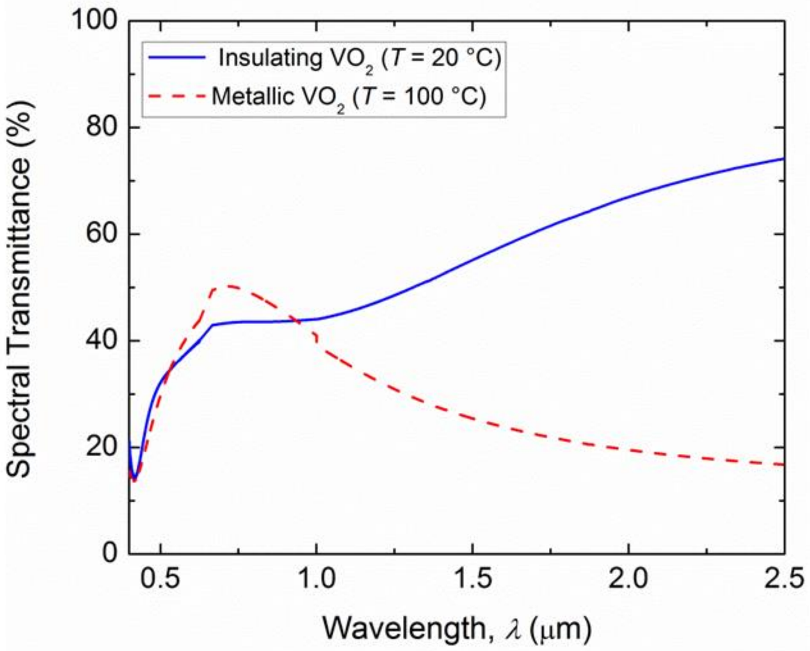
Ray Tracing: $T_{\text{theo}} = \dfrac{\tau_a \tau_s \tau}{1 - \rho_s \rho_b \tau^2}$

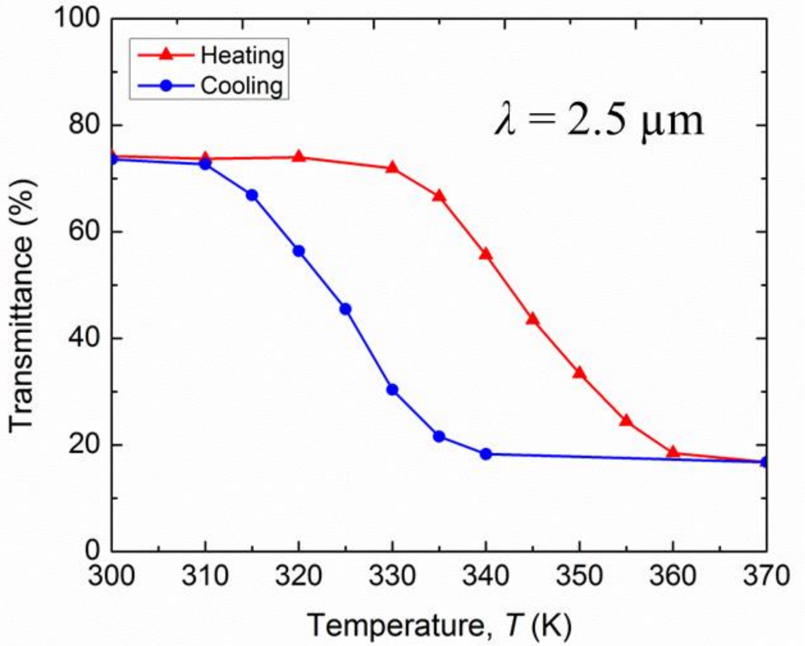
VO_2 VIS/NIR Characterization





Left: before oxidation Right: after oxidation

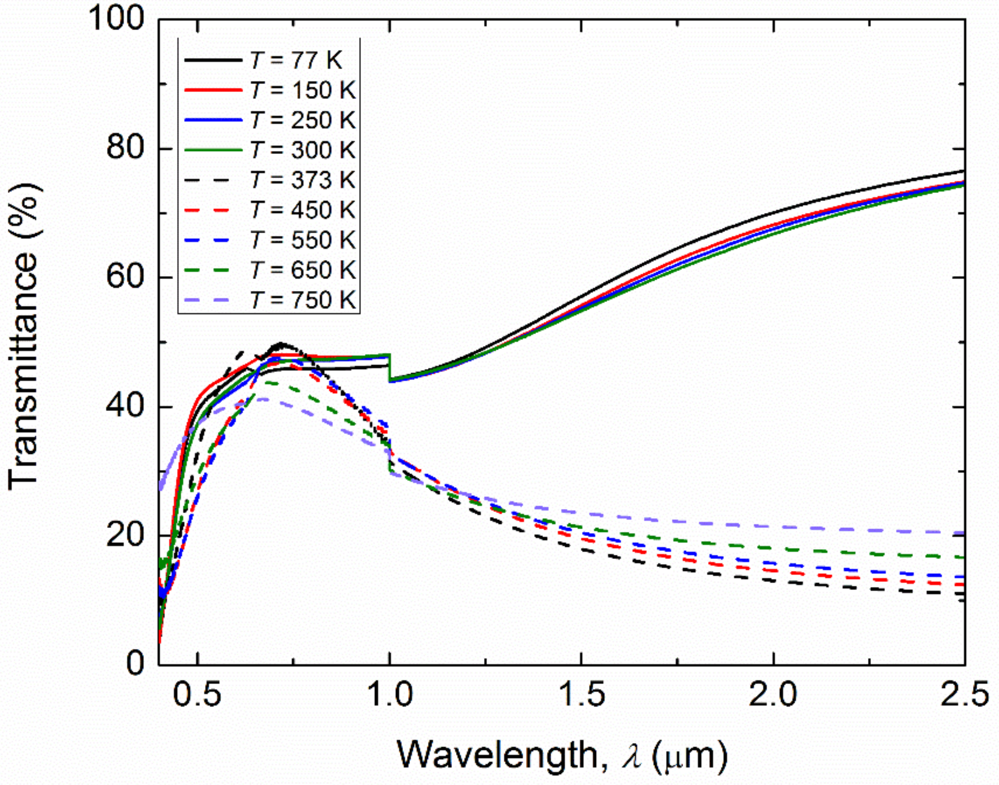




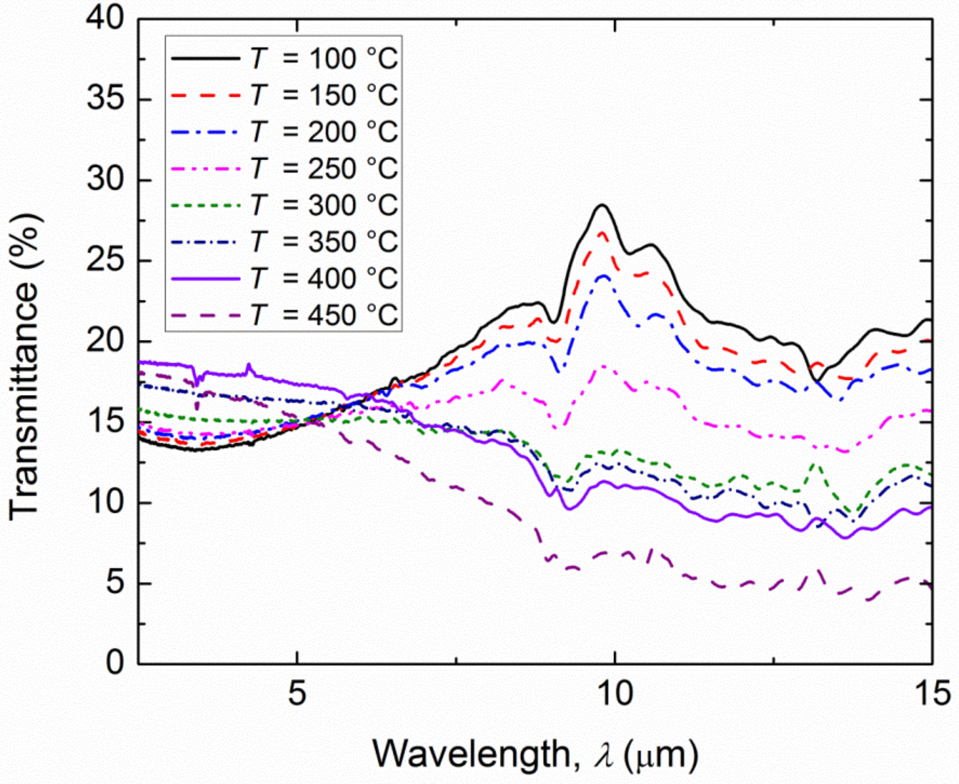
Taylor et al., ES Mater. Manuf., **6**, 62-67 (2019)

VO_2 Temperature Stability

VIS/NIR (VO$_2$ on SiO$_2$)



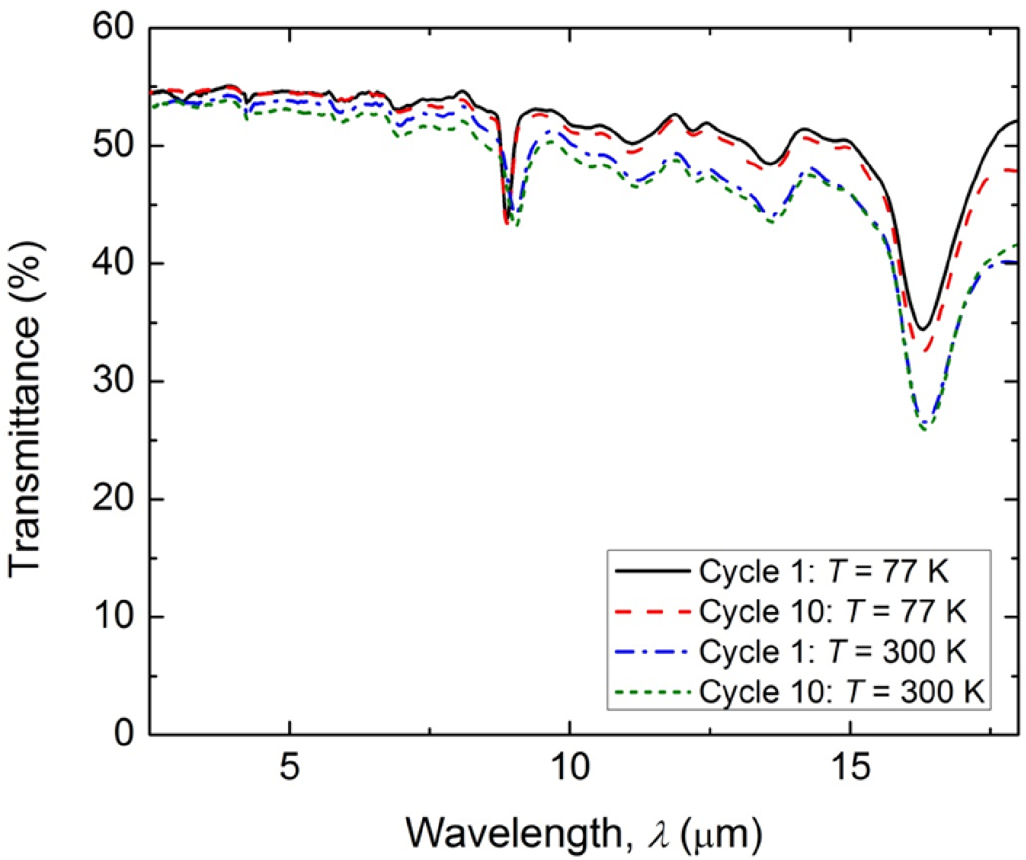
IR (VO$_2$ on Si)



- VO_2 is stable up until 200 °C
- VO_2 is not sensitive to cryogenic temperatures in the VIS/NIR range

Taylor et al., ES Mater. Manuf., **6**, 62-67 (2019)

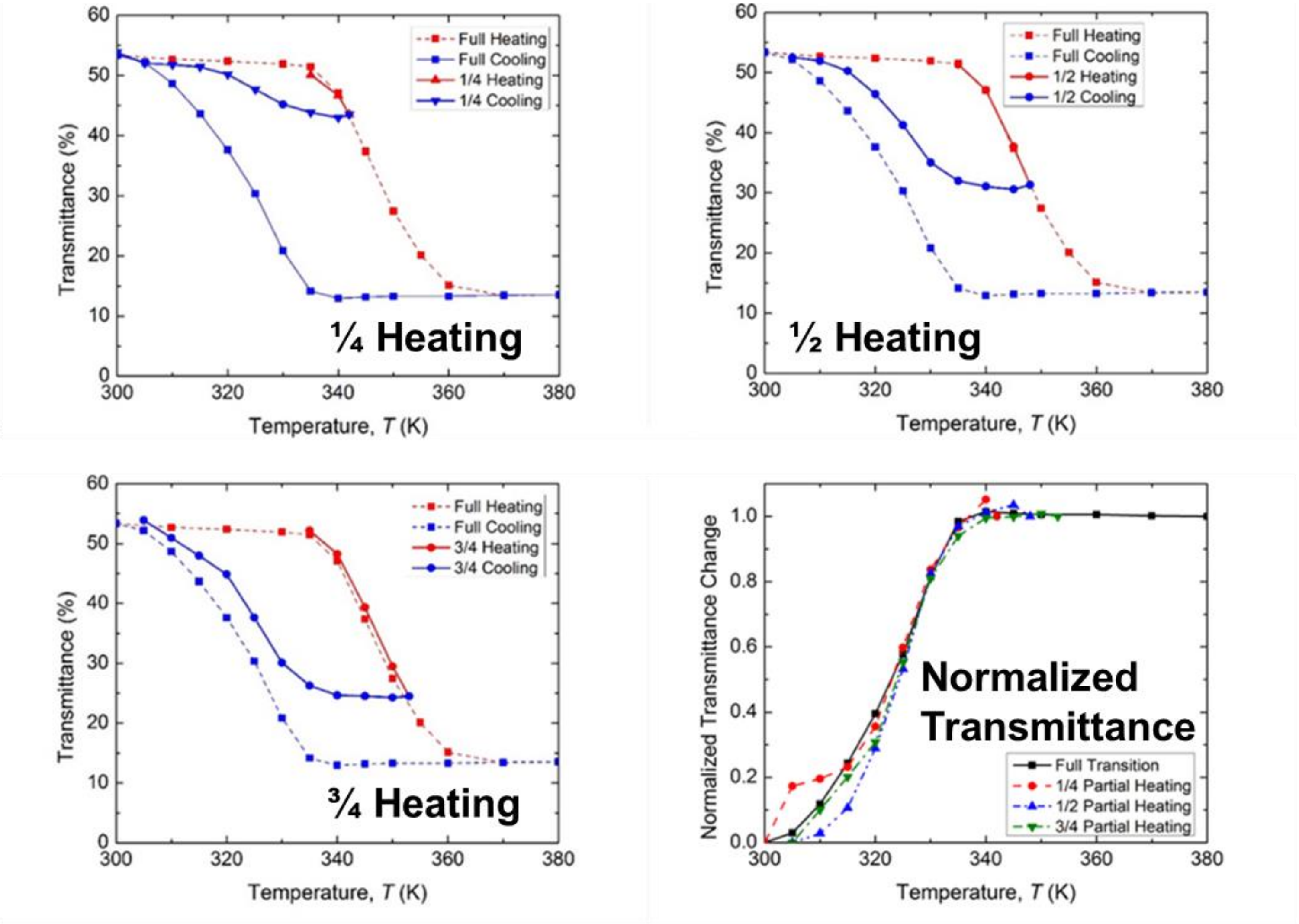
VO_2 Thermal Cycling Stability



- Thermochromic performance of VO_2 is not affected by cryogenic temperatures
- VO_2 did not degrade after being subjected to 10 thermal cycles

Taylor et al., Appl. Therm. Eng., under review

Partial Heating Hysteresis

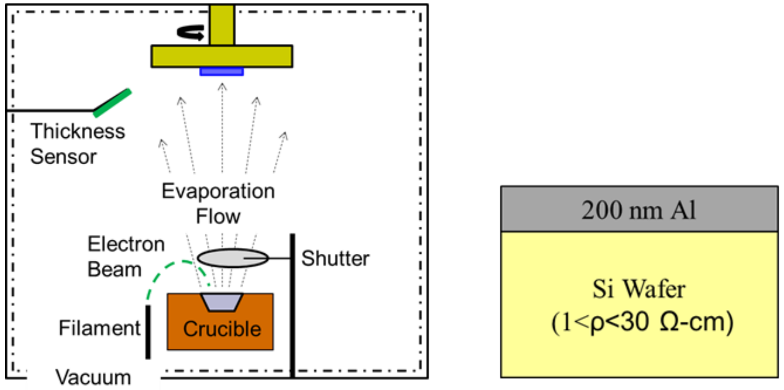


$\lambda = 2.5\ \mu m$

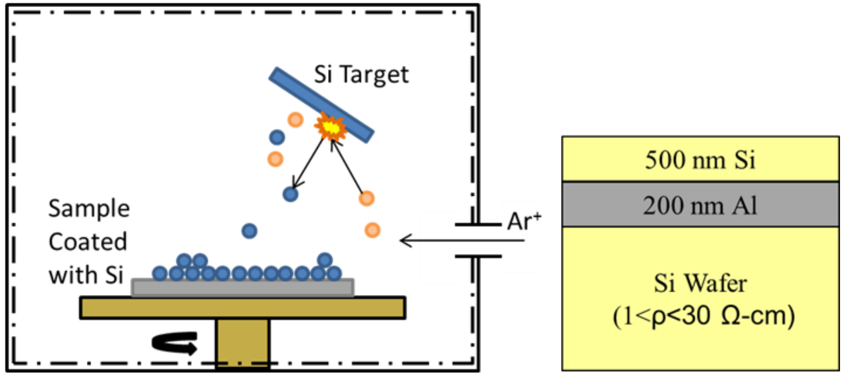
Taylor et al., Appl. Therm. Eng., under review

VO_2 FP Emitter Fabrication

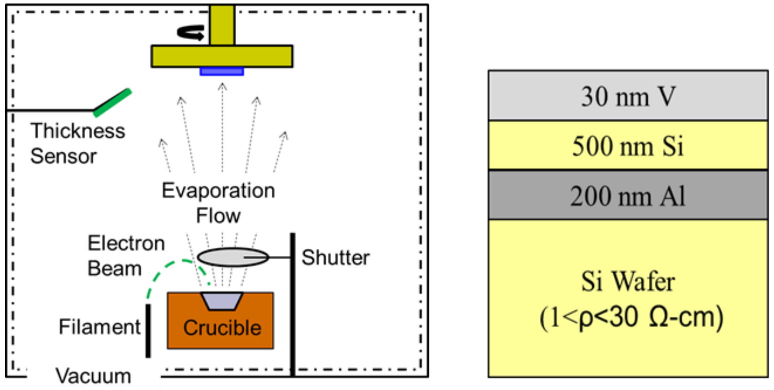
① 200 nm of Al with Electron Beam Evaporation (EBE)



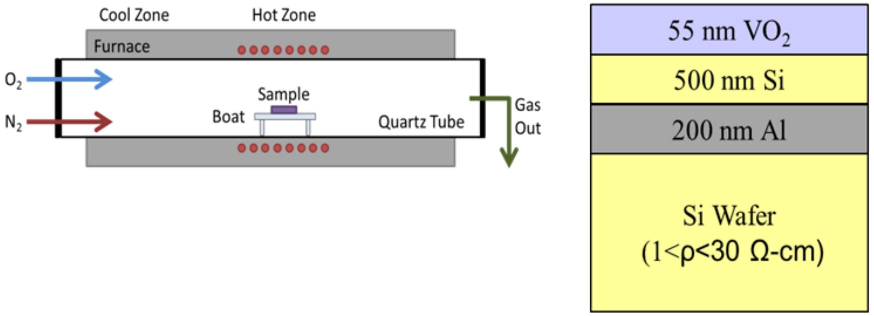
② 500 nm of Si with RF Magnetron Sputtering



③ 30 nm of V with EBE

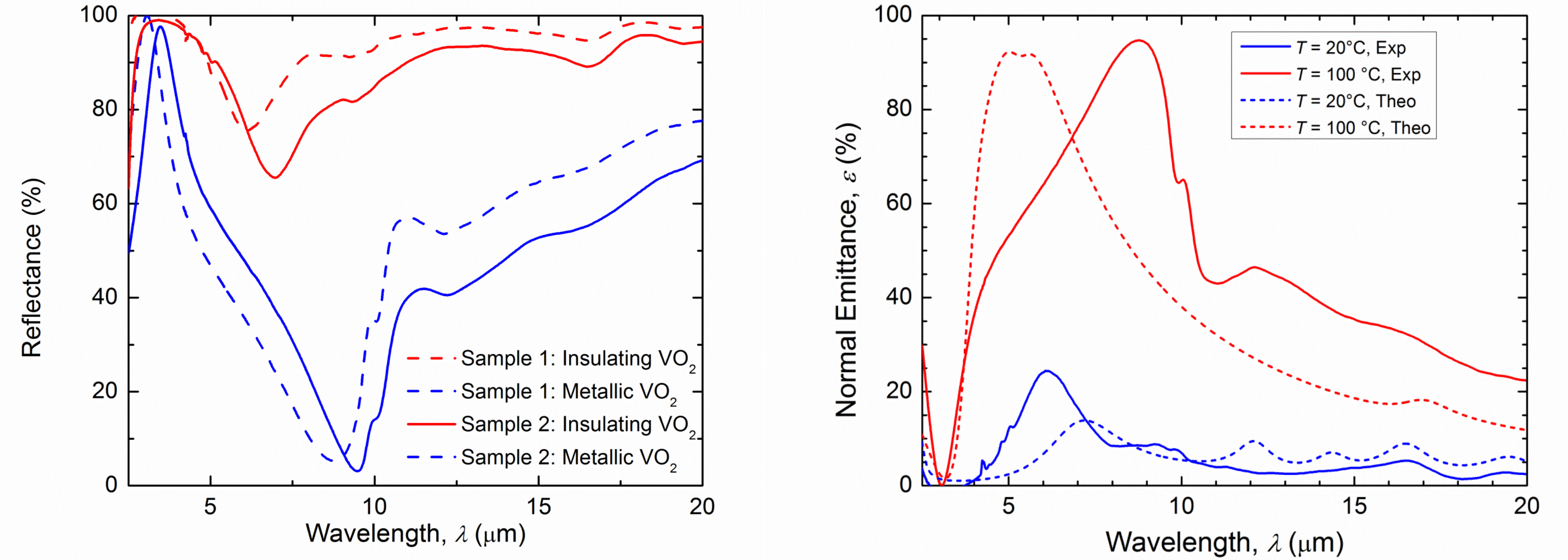


④ Oxidize in Tube Furnace



Taylor et al., Sol. Energy Mater. Sol. Cells, **217**, 110739 (2020)

VO_2 FP Emitter Characterization

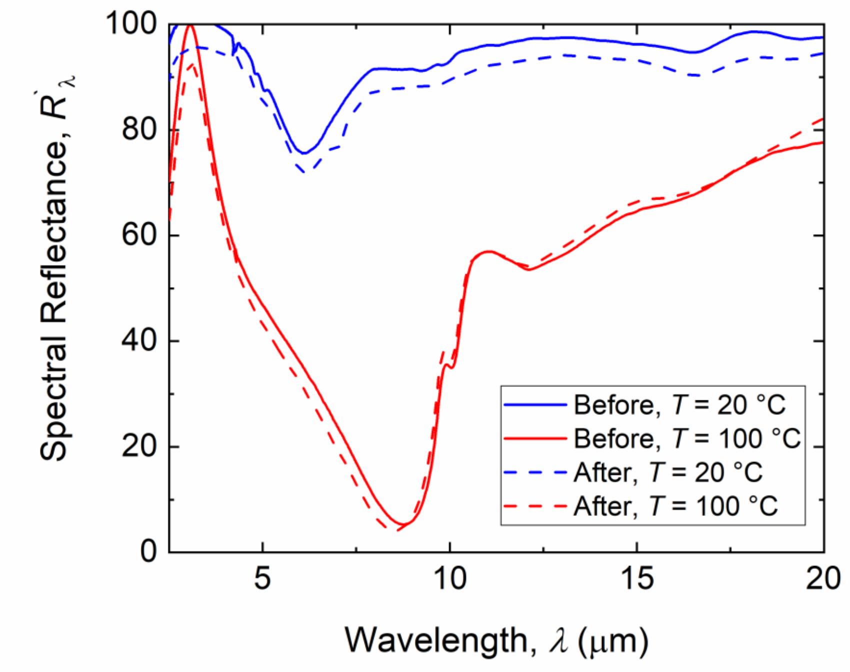


- Consistent behavior from both samples
- Significant change in mid-infrared reflectance upon phase transition
- Fabricated emitter demonstrates same behavior as the previously designed theoretical structure
- Disparity in experimental and theoretical performance could be explained by interface effects between VO_2 and Si, or by temperature-dependent optical properties for Si

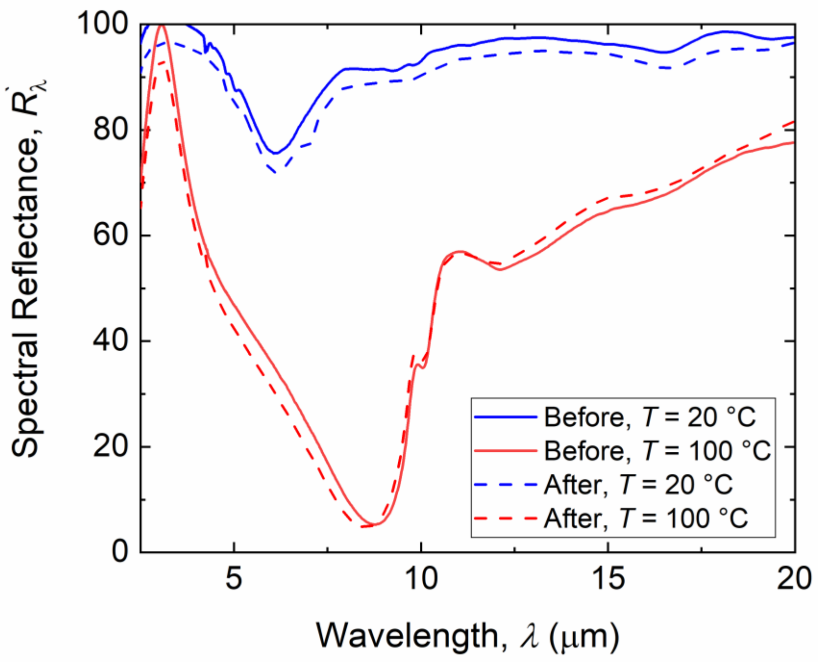
Taylor et al., Sol. Energy Mater. Sol. Cells, **217**, 110739 (2020)

FP Emitter Temperature Stability

Cryogenic (T = 77 K) Stability



High Temp (T = 200 C) Stability

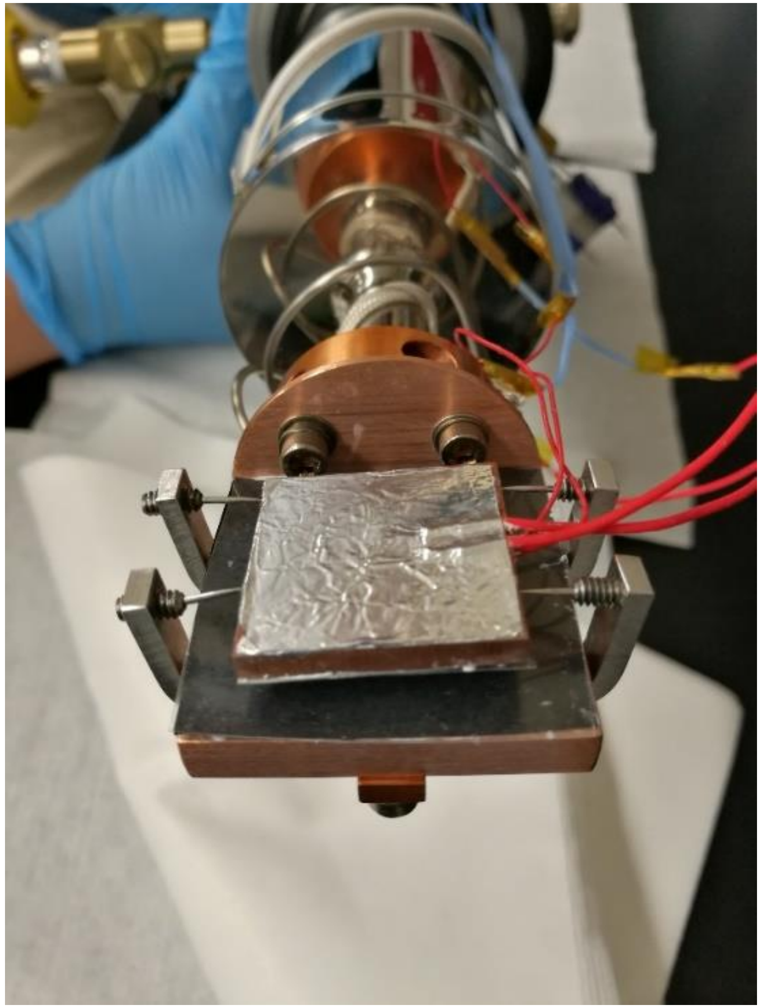


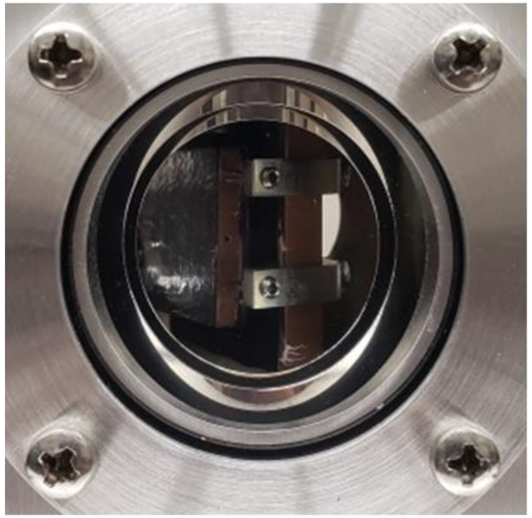
Before and after measurements for both samples are nearly identical, indicating good temperature stability for spacecraft thermal control applications

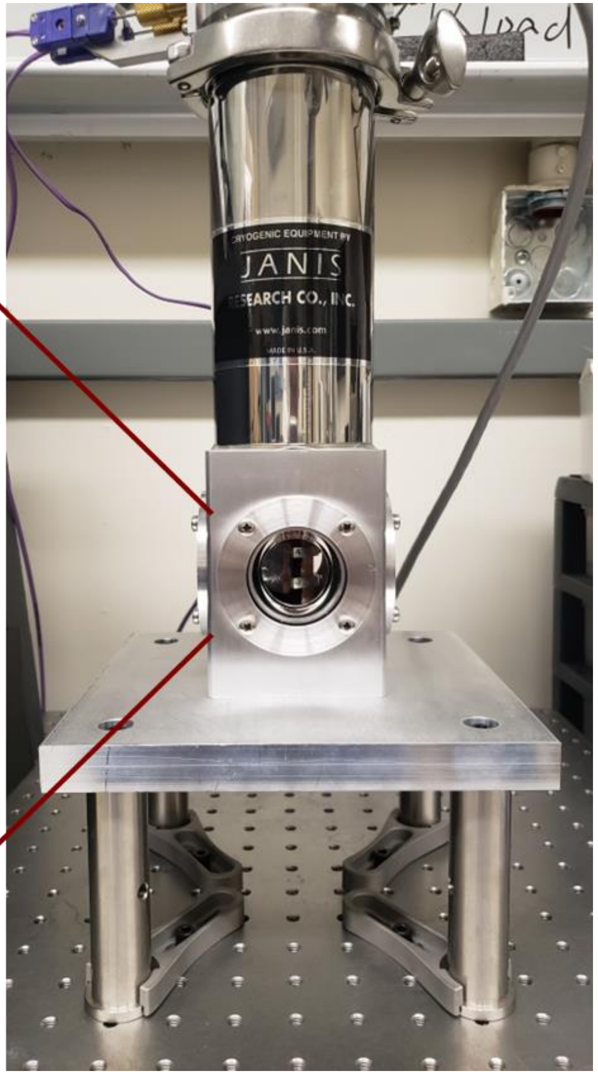
Taylor et al., Appl. Therm. Eng., under review

Thermal Vacuum Experiments and Feasibility Studies

Thermal Vacuum Experiment







Taylor et al., Appl. Therm. Eng., under review

Heat Transfer Model

$$\sum Q = 0 = Q_{heater} - Q_{rad} - Q_{sides} - Q_{bot} - Q_{cond}$$

Q_{loss}

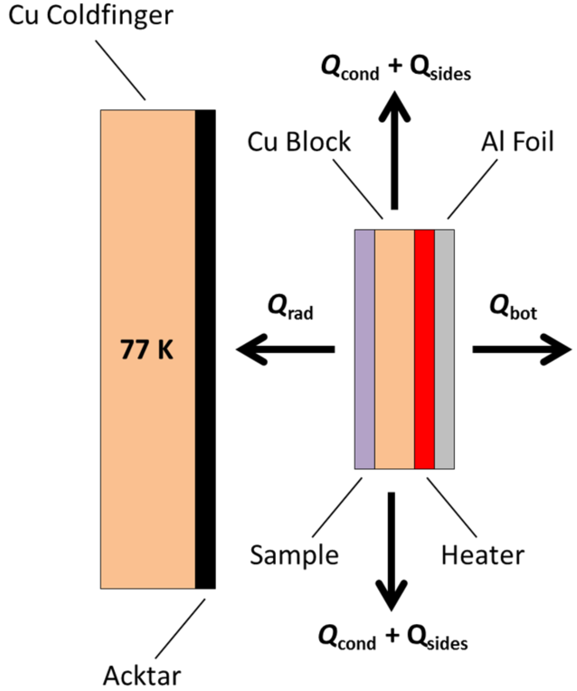
$$Q_{heater} = P_{heater} = I^2 R$$

$$Q_{emiss,theo} = \varepsilon\sigma(T^4_{sample} - T^4_{coldfinger})$$

$$Q_{emiss,exp} = Q_{heater} - Q_{loss}$$

→ $Q_{loss}(T)$ is determined from the aluminum measurements:

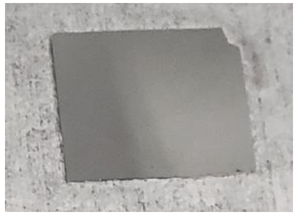
$\varepsilon_{Al} = 0.03$ → $Q_{loss}(T) = Q_{heater} - Q_{emiss,theo}$



Black (Acktar)

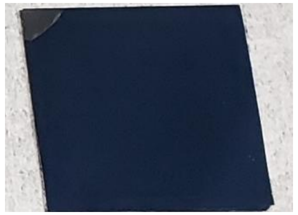
$\varepsilon_{IR} \approx 93\%$

Aluminum (200 nm on Si)



$\varepsilon_{IR} = 3\%$

VO_2 FP Emitter



ε_{IR} = Varies with T

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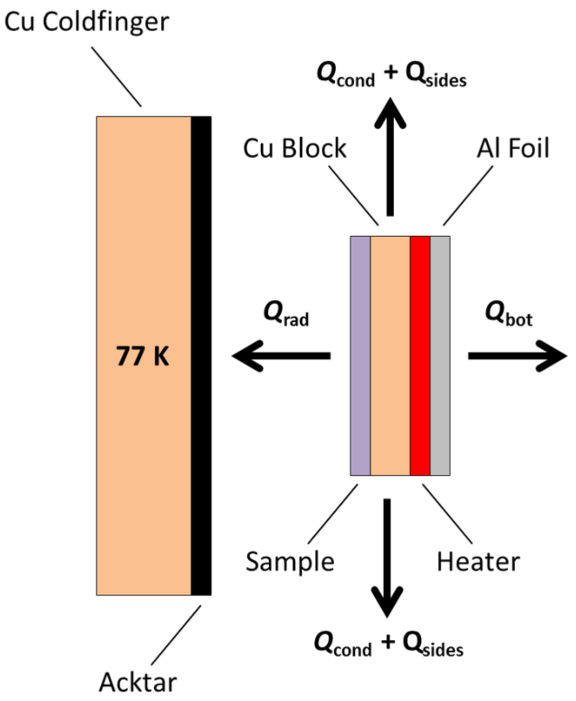
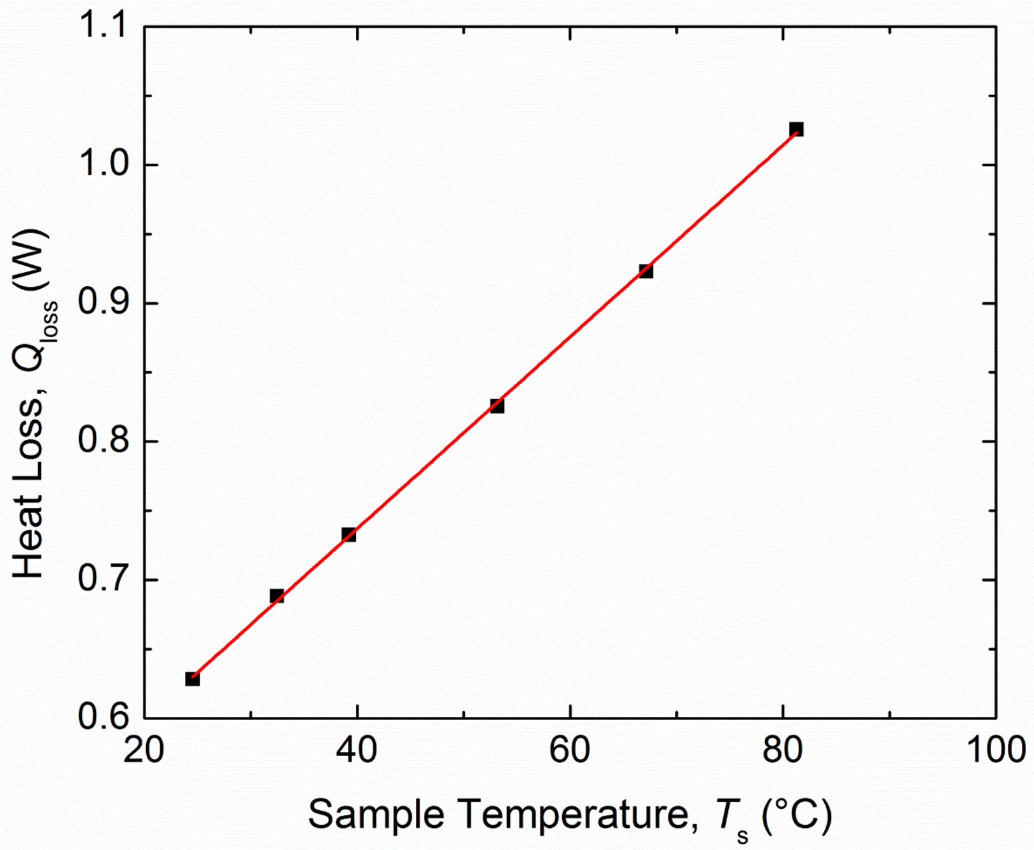
Thermal Vacuum Experiment



$Q_{loss}(T) = Q_{heater} - Q_{rad}$

$Q_{rad} = \varepsilon\sigma T^4_{sample}$



- Q_{loss} (T_s) is described by a linear fit
- Q_{loss} is independent of sample mounted

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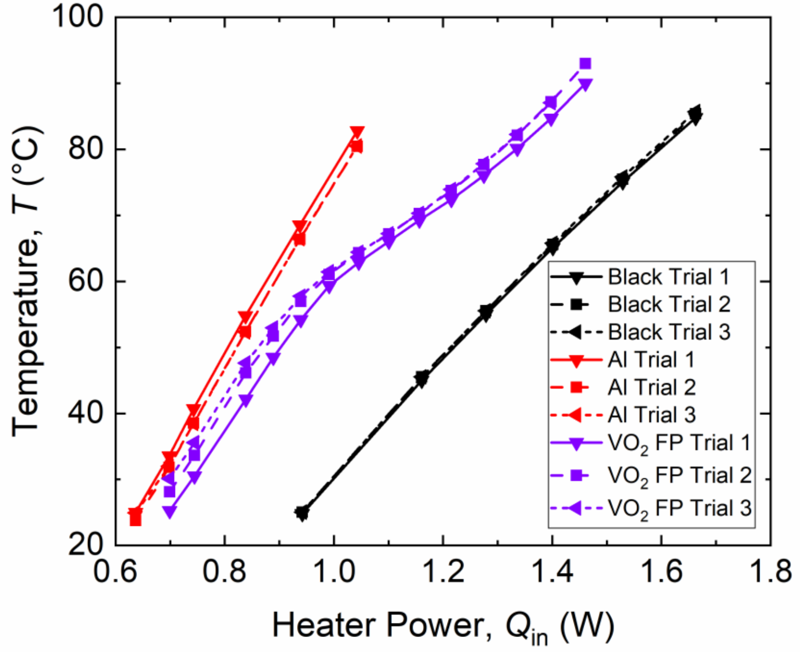
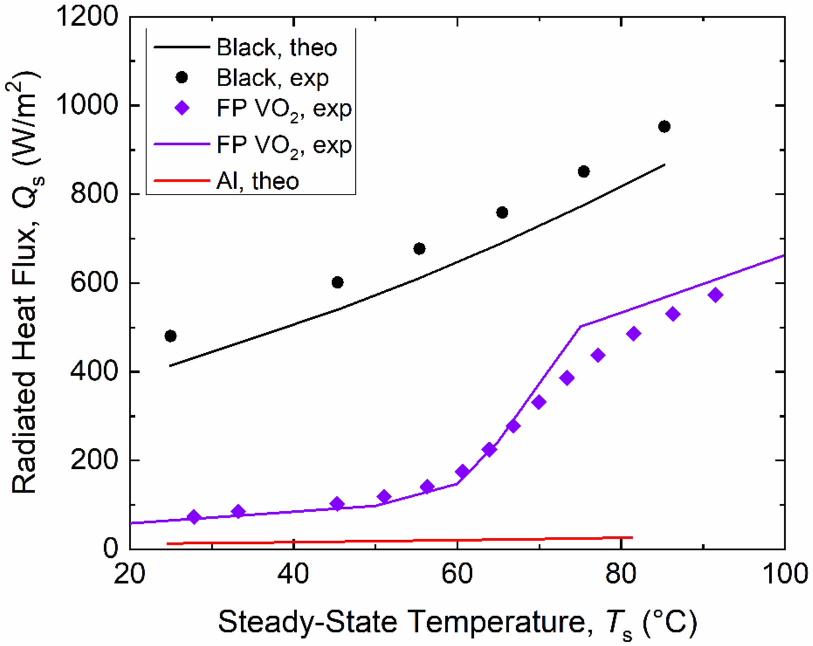
Thermal Vacuum Experiment



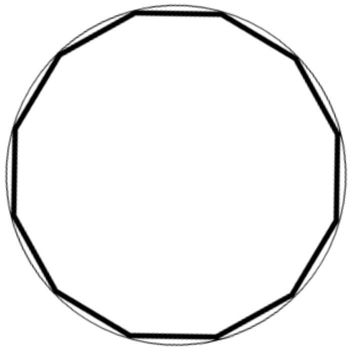


- Clear change in VO_2 FP behavior upon phase transition
- Good agreement between experiment and theoretical prediction
- VO_2 FP emitter varies heat from 72 W/m^2 at room temp to 570 W/m^2 at 90 °C

Taylor et al., Appl. Therm. Eng., under review

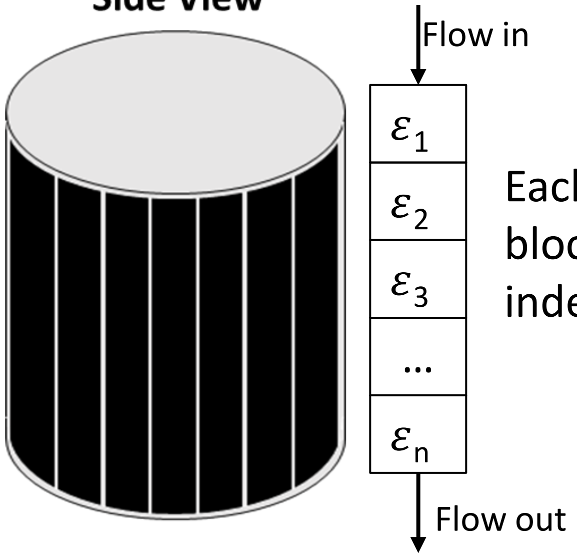
Spacecraft Thermal Systems Modeling

Top View

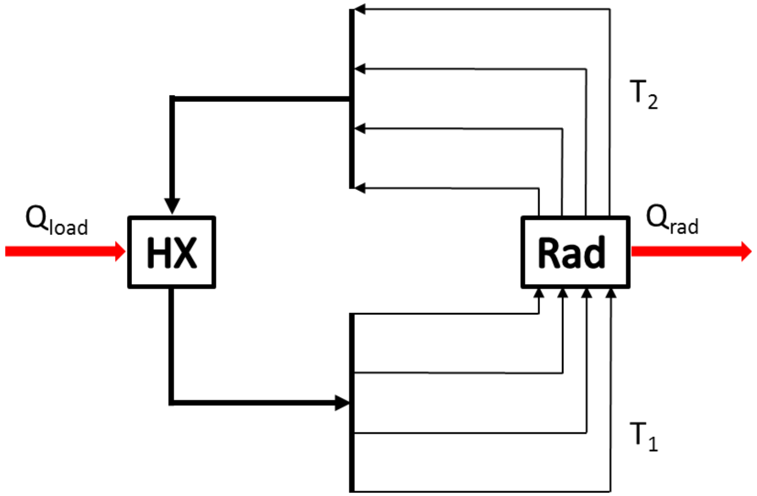


Body-mounted radiators that are discretized into N = 360 panels

Side View



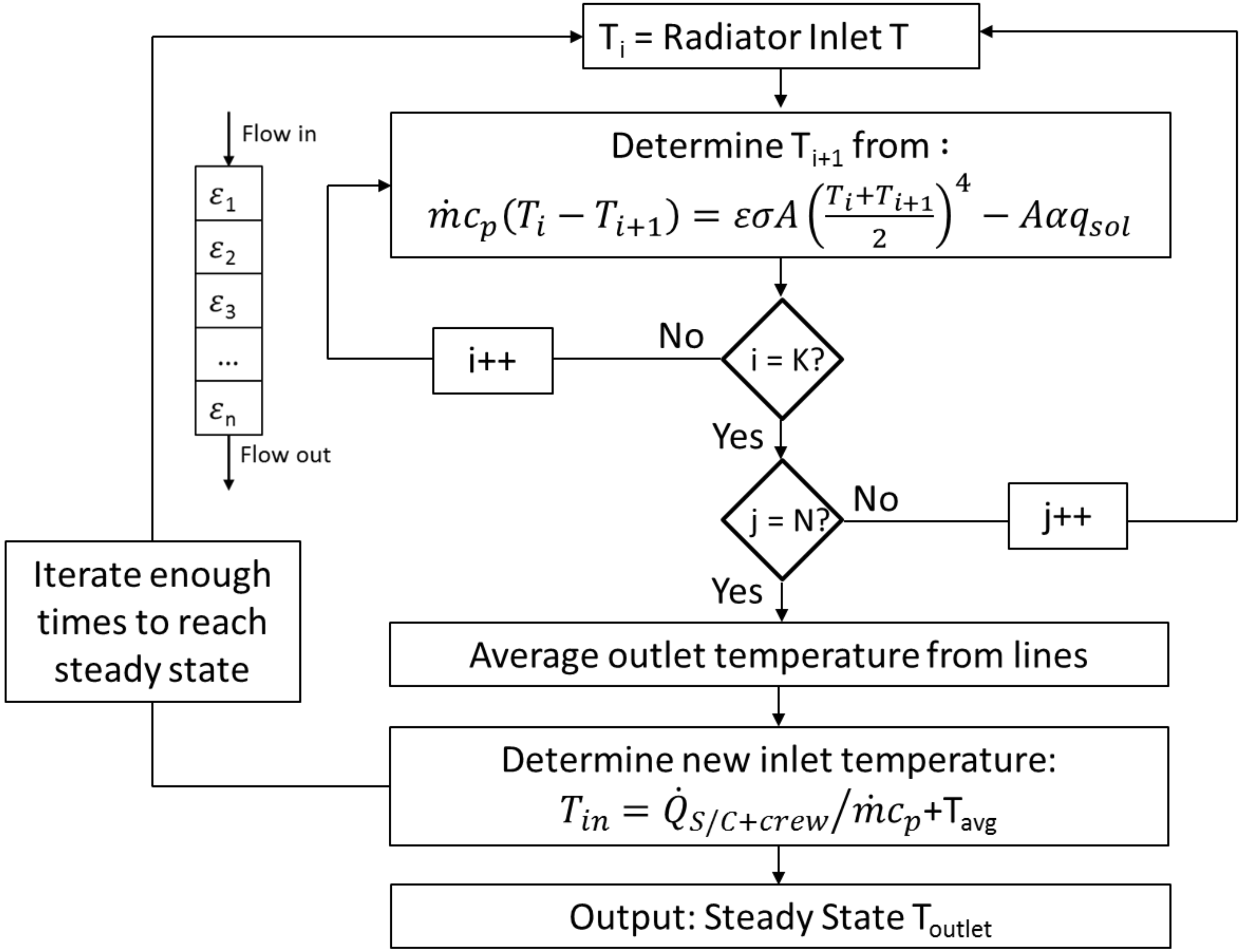
Each panel is discretized into K blocks, each with their own independent emissivity

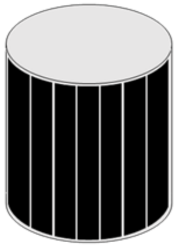


1. Fluid picks up heat from HX
2. Flow separates into 360 lines with equal flow rates
3. Heat is rejected by each separate fluid line/radiator panel
4. Flow is mixed to give average T_{outlet}

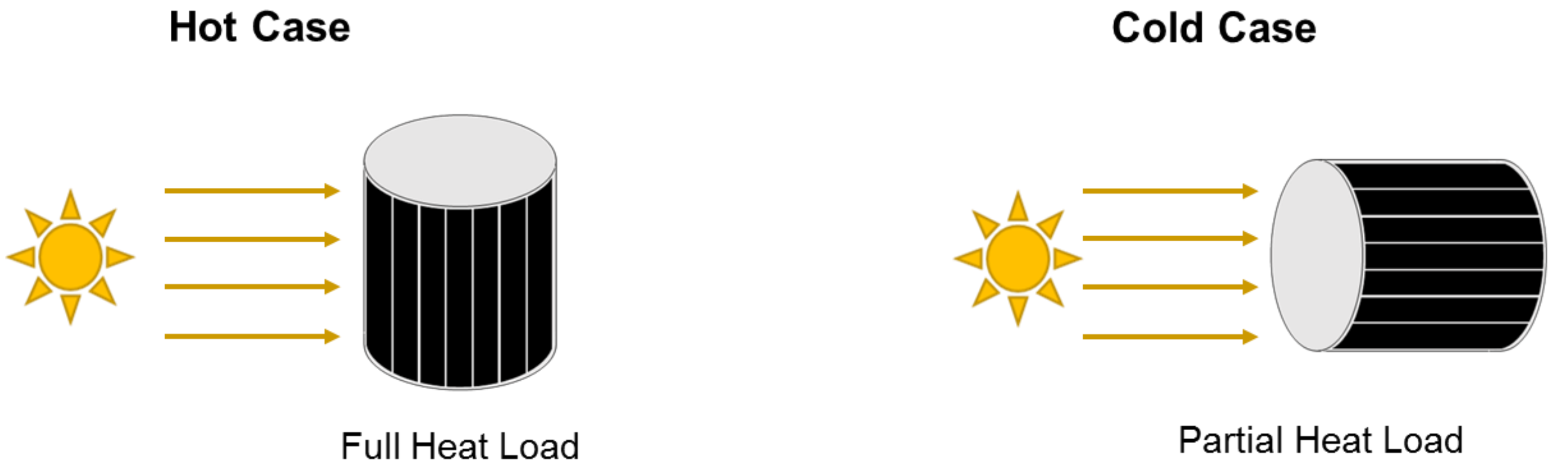
<u>Objective:</u> Determine Optimum Transition Temperature Range

Coding Approach





Steady-State Cases Considered

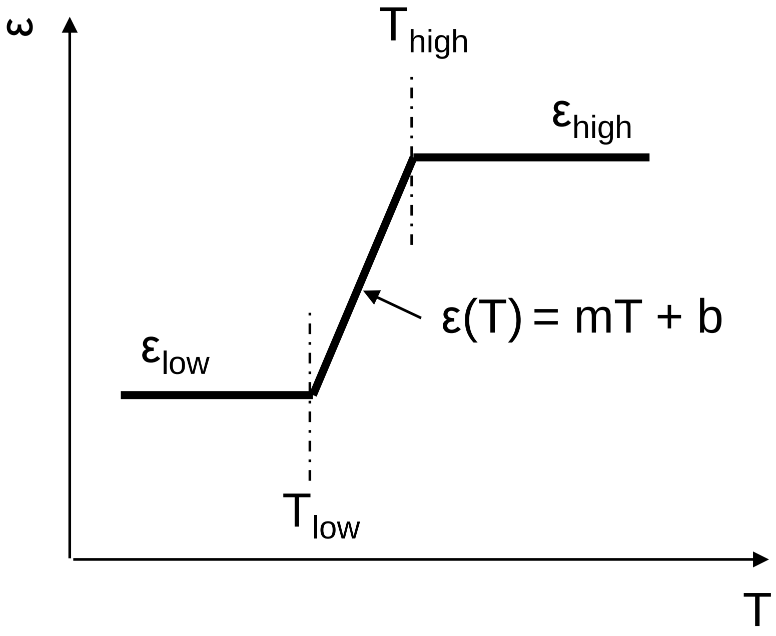


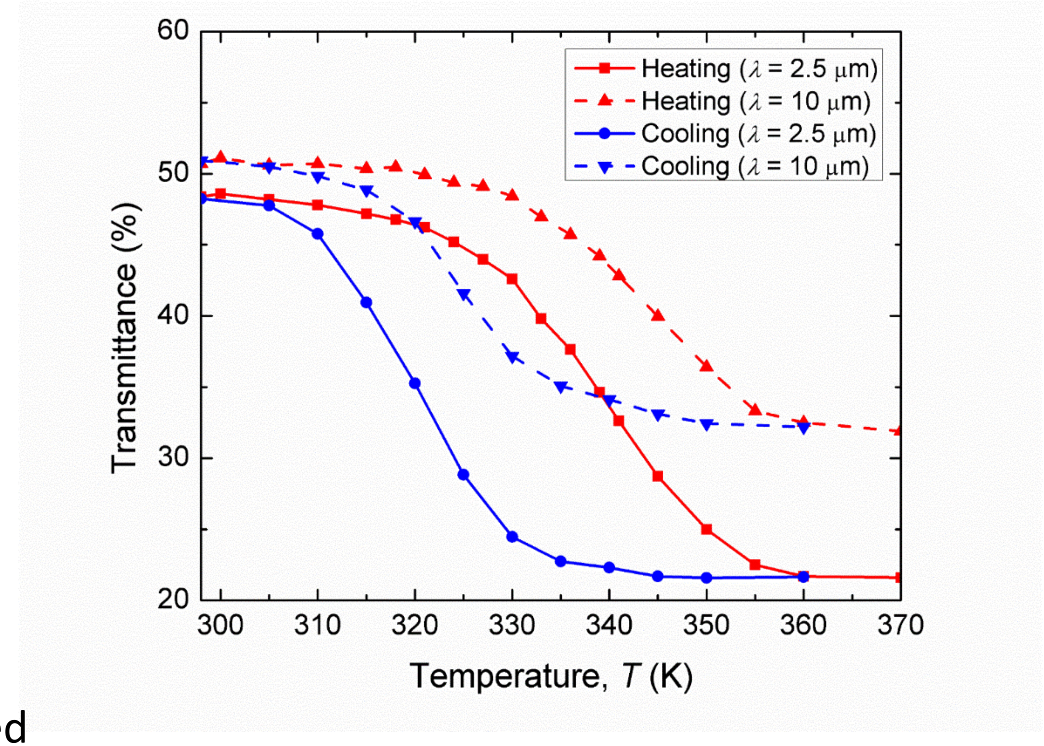
Q_{FHL} = 8500 W

- Requirement 1: Average outlet temperature must be between 0 ºC and 10 ºC
- Requirement 2: The temperature of each radiator panel must be above -10 ºC

- Turndown percentage TD = lowest percentage of full load that can be reduced to while still meeting requirements

Simplified VO_2 Variable Emittance

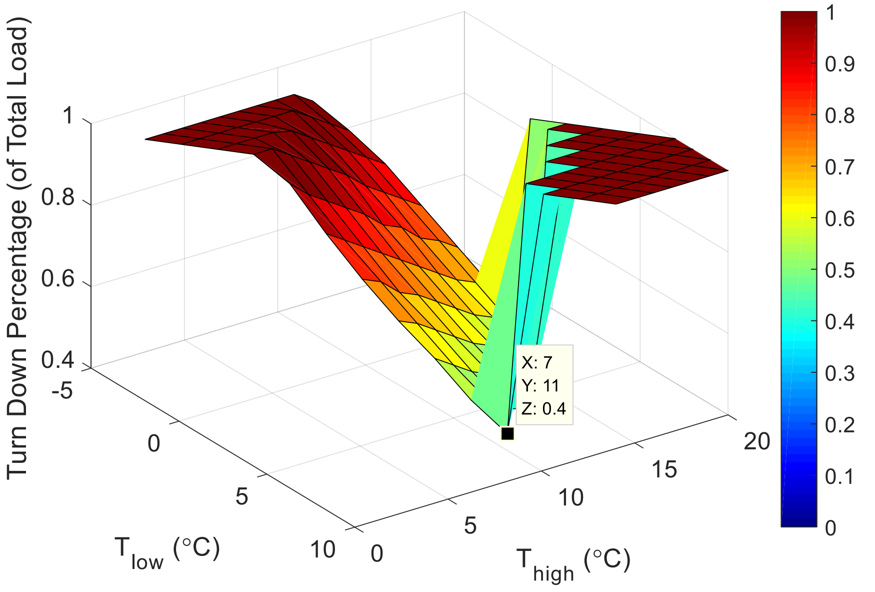


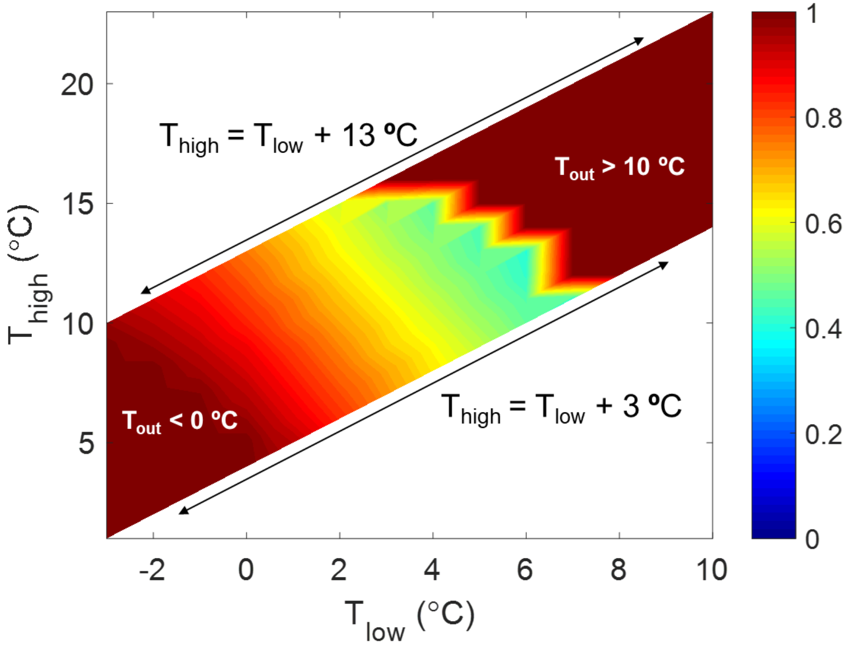


1. No hysteresis considered
2. ε_{low} can vary between 0.3 and 0.6
3. ε_{high} can vary between 0.6 and 0.9
4. T_{high} must be between 4 and 20 degrees higher than T_{low}

→ (2), (3), and (4) are based on fabrication limitations

Transition Range Optimization





Maximum turn down percentage of 40% occurs when T_{low}= 7 ºC and T_{high}= 11 ºC

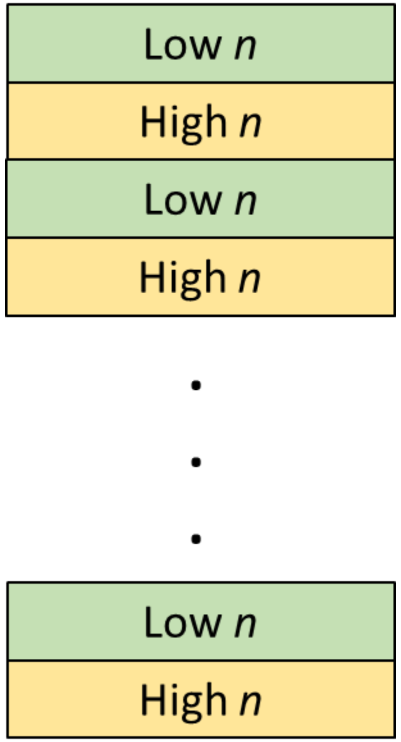
- Optimization ends due to T_{out} going out of bounds
- No cases with freezing as the exit condition

On-going Projects at NASA

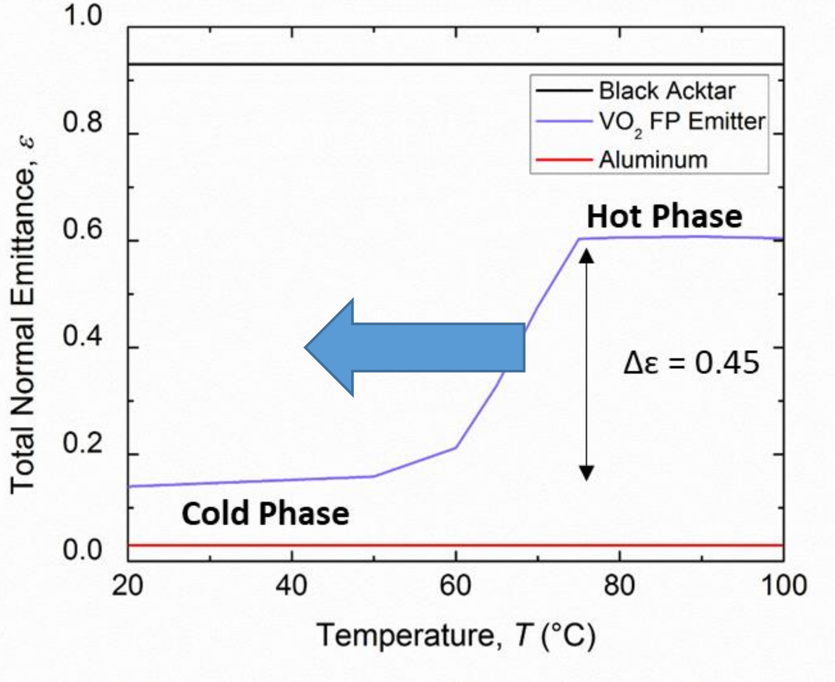
ASU VO_2 Variable Emittance

Tech Dev Project Objective:
Develop a thermochromic variable emittance coating based on W-doped VO_2 and a solar filtering layer

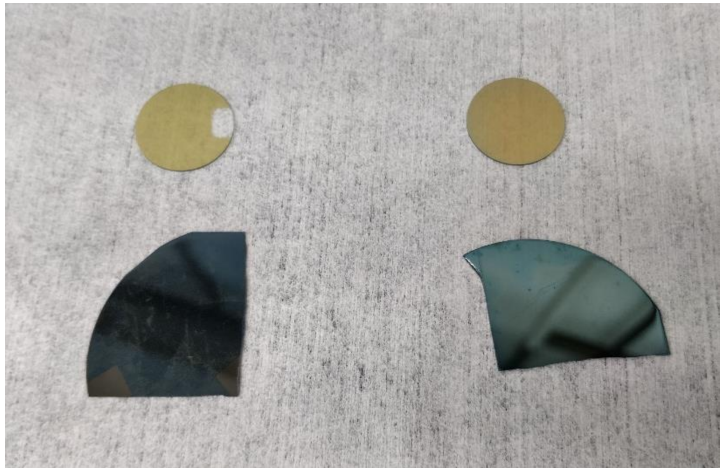
<u>1-D PhC Solar Filter</u>



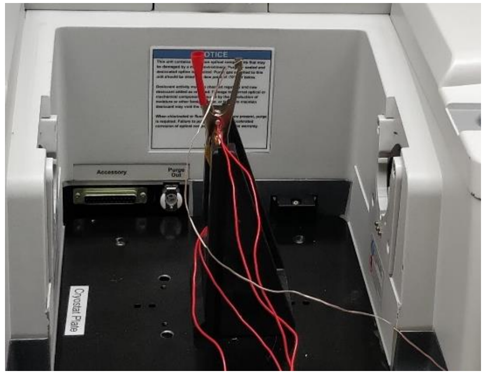
<u>Shift Emittance Change to Lower Transition Temperature</u>



<u>First round of sputtered VO_2 thin film samples</u>

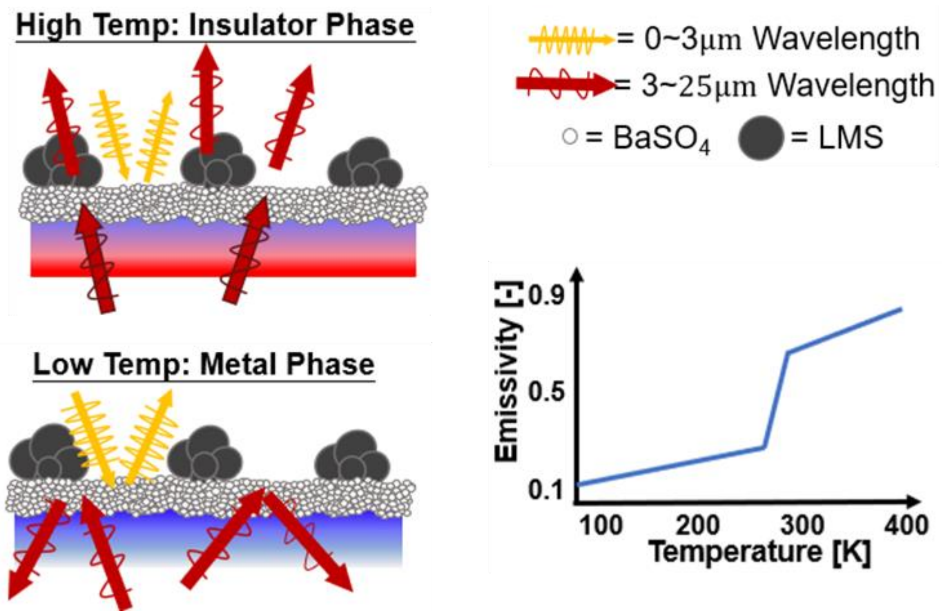


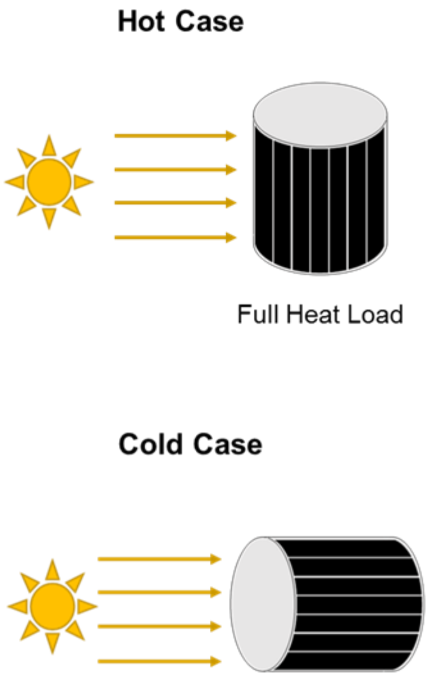
<u>Temperature-dependent Reflectance and Transmittance Measurements</u>

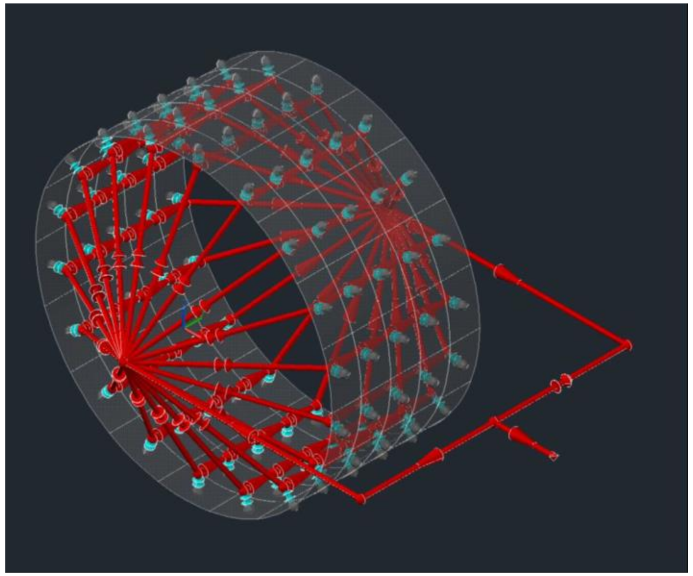


LSM Variable Emittance NSTGRO RC

NSTGRO Project Objective:
Develop a thermochromic variable emittance coating based on $BaSO_4$ white paint and LSM nanoparticles

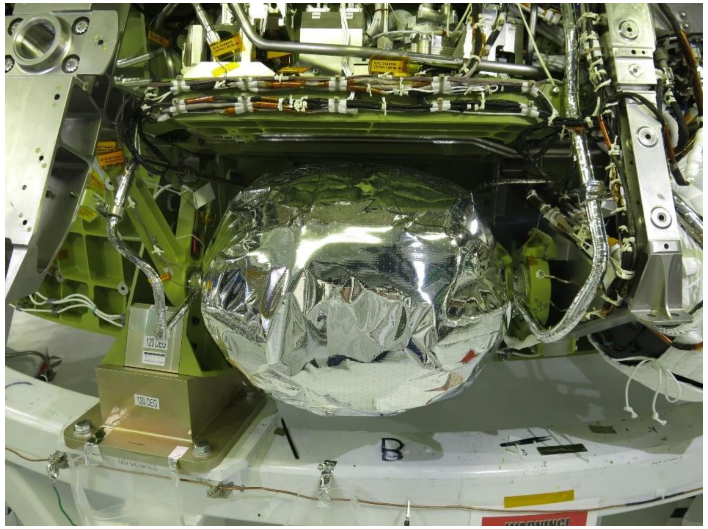


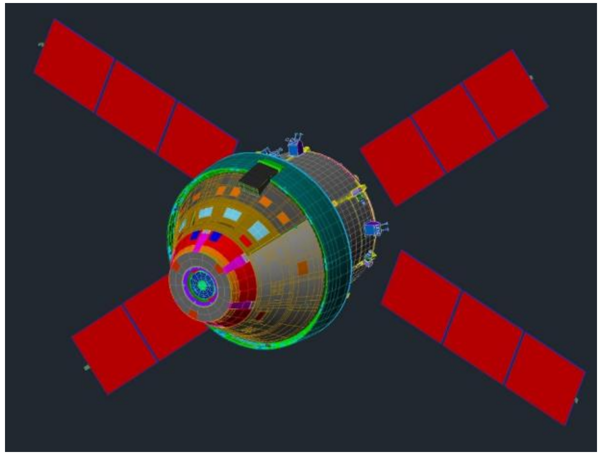


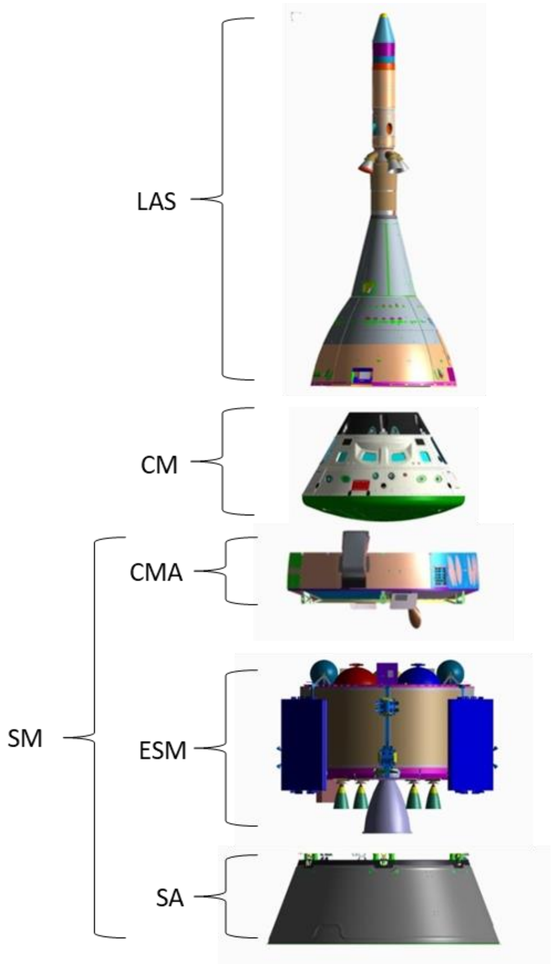


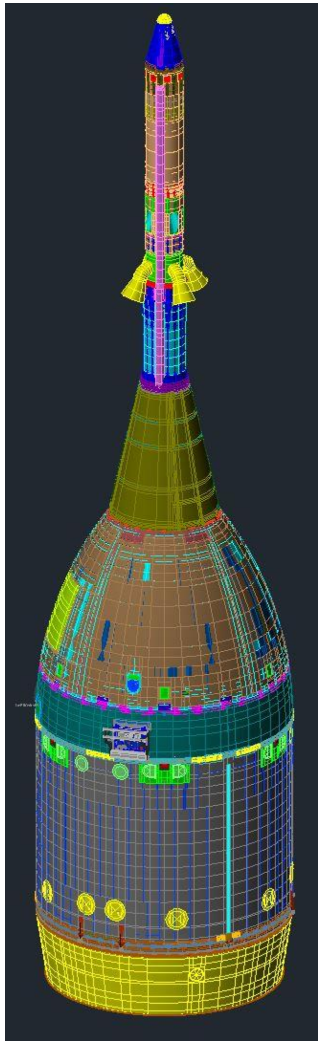
Variable Emittance Modeling Objective:
Determine transition temperature, emittance change, solar absorptance, etc. for the coating to be useful for spacecraft thermal control applications (both human and robotic)

Orion Passive Thermal Control

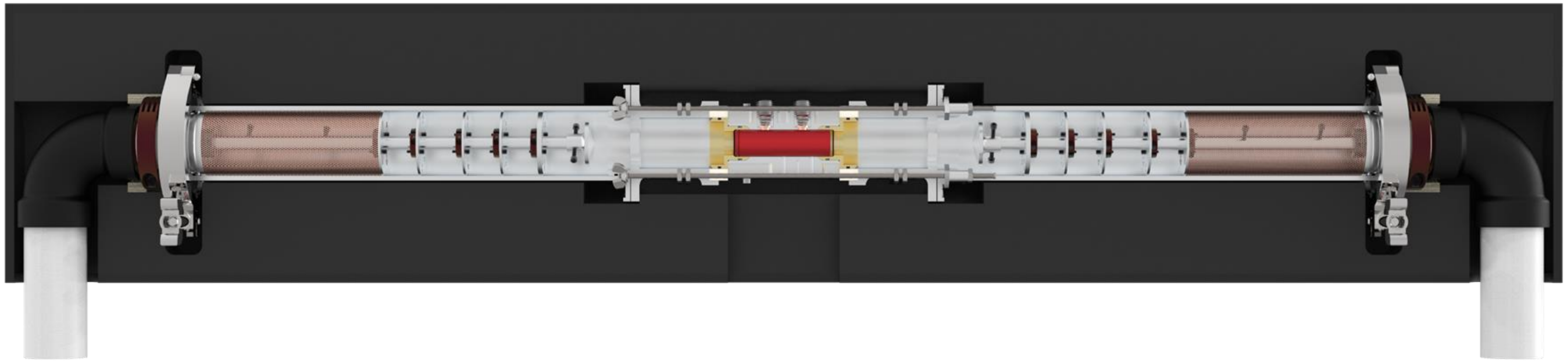


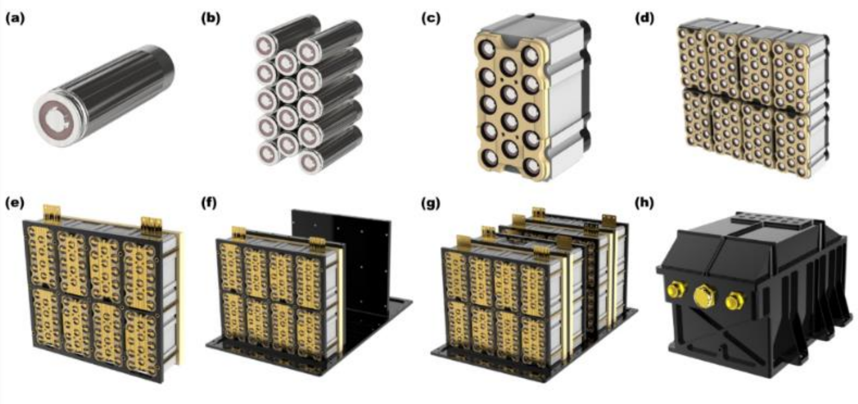


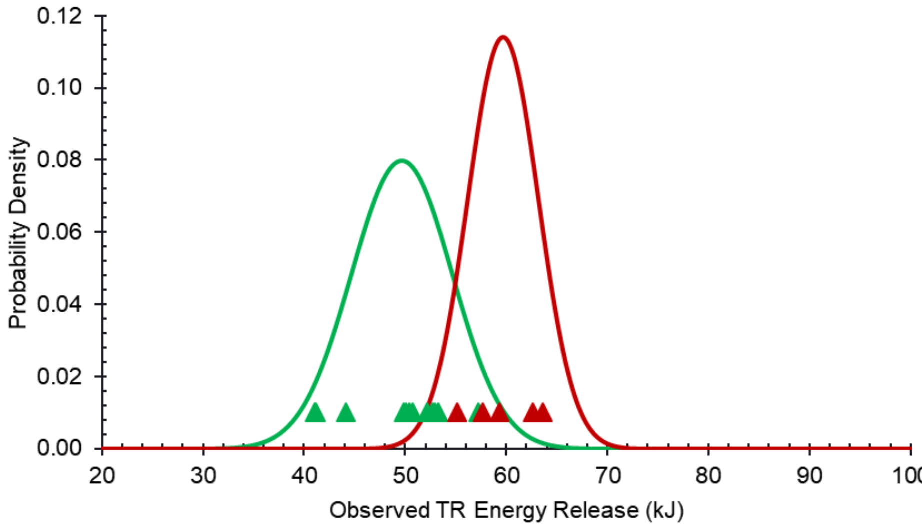




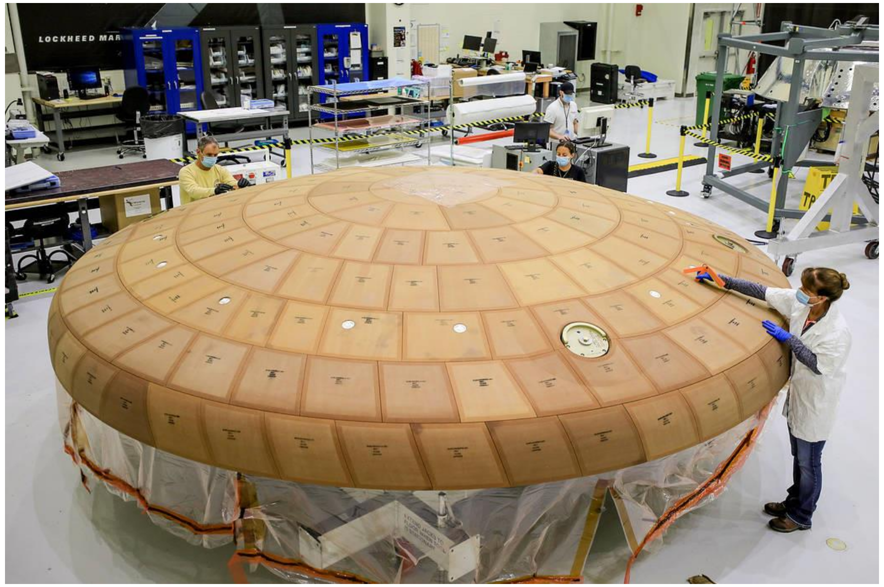
Battery Thermal Runaway Analysis and Testing

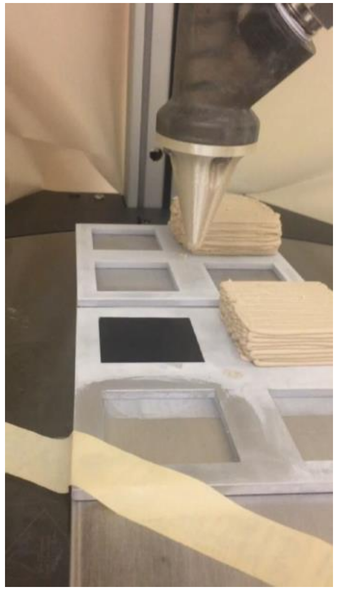


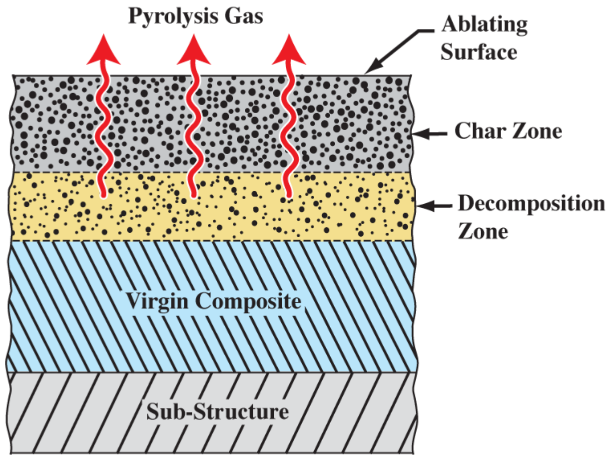


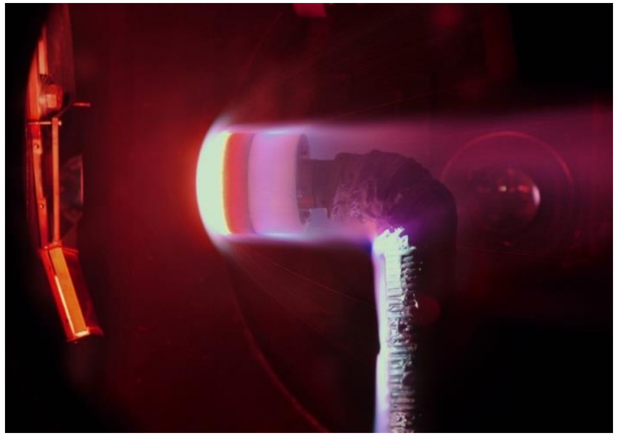


Orion and 3D Printed Thermal Protection Systems









Thermal Technology Gaps

2020 NASA Technology Taxonomy

→Great resource for understanding what capabilities NASA has identified as necessary to complete our missions

Technology Areas:
TX01: Propulsion Systems
TX02: Flight Computing and Avionics
TX03: Aerospace Power and Energy Storage
TX04: Robotic Systems
TX05: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
TX06: Human Health, Life Support, and Habitation Systems
TX07: Exploration Destination Systems
TX08: Sensors and Instruments
TX09: Entry, Descent, and Landing
TX10: Autonomous Systems
TX11: Software, Modeling, Simulation, and Information Processing
TX12: Materials, Structures, Mechanical Systems, and Manufacturing
TX13: Ground, Test, and Surface Systems
TX14: Thermal Management Systems
TX15: Flight Vehicle Systems
TX16: Air Traffic Management and Range Tracking Systems
TX17: Guidance, Navigation, and Control

TX14.2 Thermal Control Components and Systems

- **Thermal control phase change materials**

  → Need higher latent heat of fusion materials and PCM architectures that lead to high energy absorption per storage volume solutions on spacecraft.

- **High-performance, low contact pressure thermal interfaces**

  → Need thermal interfaces with predictable and repeatable interface conductances in different environments (lab versus spacecraft). Spacecraft application typically cannot apply high pressure.

- **High power density, long lifetime, space-qualified heater systems**

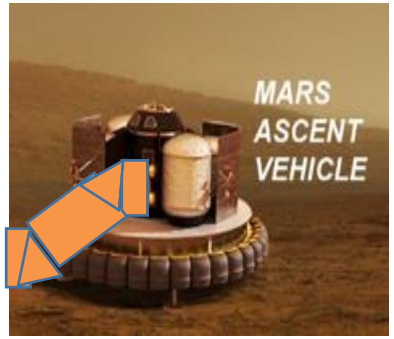
  → Need robust high watt density heaters, especially for non-planar surfaces.

- **Full-field, Full Structure Instrumentation**

  → Need instrumentation for stagnant fluid lines, high stress areas on structure, and high temperature structures.

TX14.2 Thermal Control Components and Systems

- **Fully-integrated Multiphysics modeling**
  → Need ability to simultaneously model thermal and mechanical behavior of spacecraft.
- **Dust Mitigation for thermal control surfaces**
  → Need a way to mitigate degradation of thermal control surfaces due to accumulation of dust.
- **Active/passive optical property control**
  → Need to tailor optical properties of thermal control coatings based on external environment or internal heat load.
- **Fully integrated thermal control systems**
  → Need to have thermal control components (heating elements, cold plates, heat pipes) embedded in structure.
- **High energy passive transport**
  → Need ability to move large amounts of heat to a needed location or heat rejection site.



TX14.X Other Thermal Management Systems

- EDL flight vehicle (aeroshell) flight performance data for human Mars entry and Earth return

  →Need instrumentation to obtain flight vehicle performance data such as:
  - Pressure
  - Temperature
  - Heat flux
  - Radiation
  - Spectra from mid-IR to VUV
  - Strain
  - TPS recession/in-depth response
- Efficient, rapid processing of ultra-large thermal/fluid/propulsion databases

  → Need efficient, rapid processing of >100 Gb up to 1 Tb thermal/fluid/propulsion databases to enhance autonomous control

Questions?

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