Variable Emittance Coating Systems Thermal Modeling for a 3U CubeSat

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THERMAL & FLUIDS ANALYSIS WORKSHOP

TFAWS

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NASA Marshall Space Flight Center
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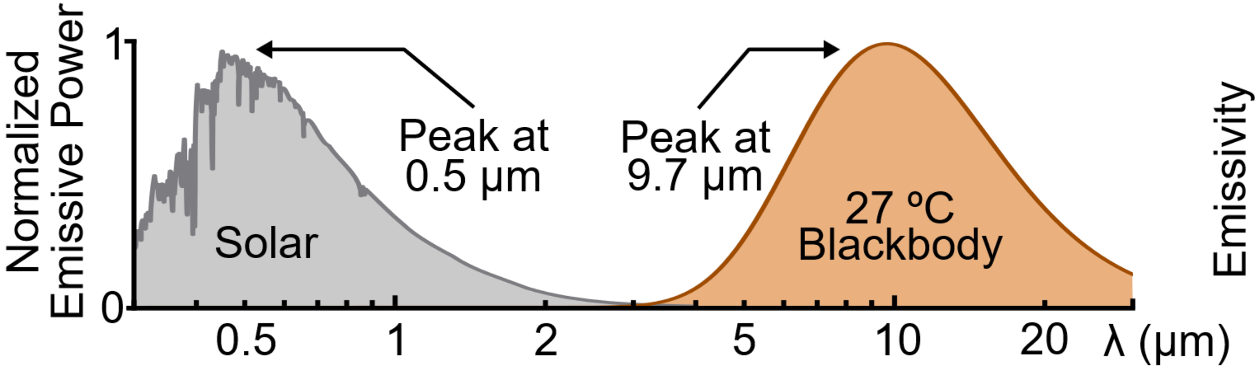
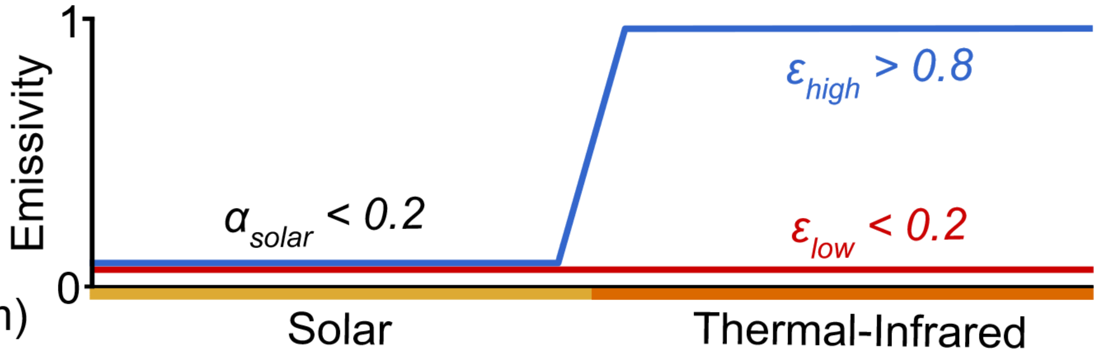
Variable Emissivity Coatings (VECs)

Variable emissivity coatings are a novel approach to adjustable heat rejection, offering low mass, reduced complexity, and net-zero power consumption.

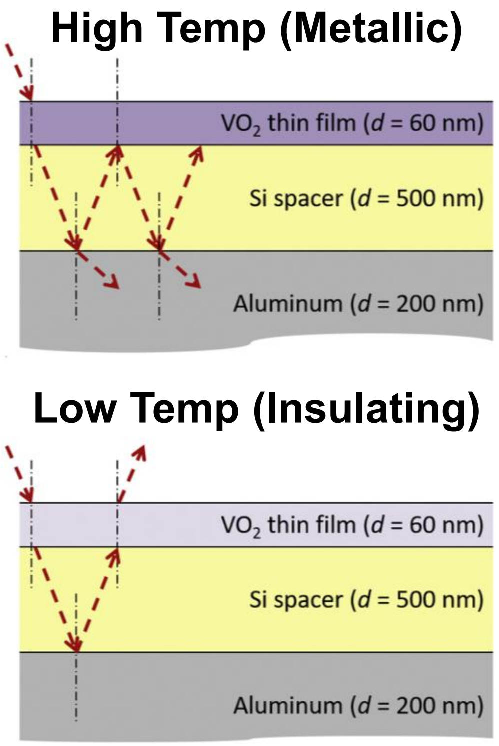


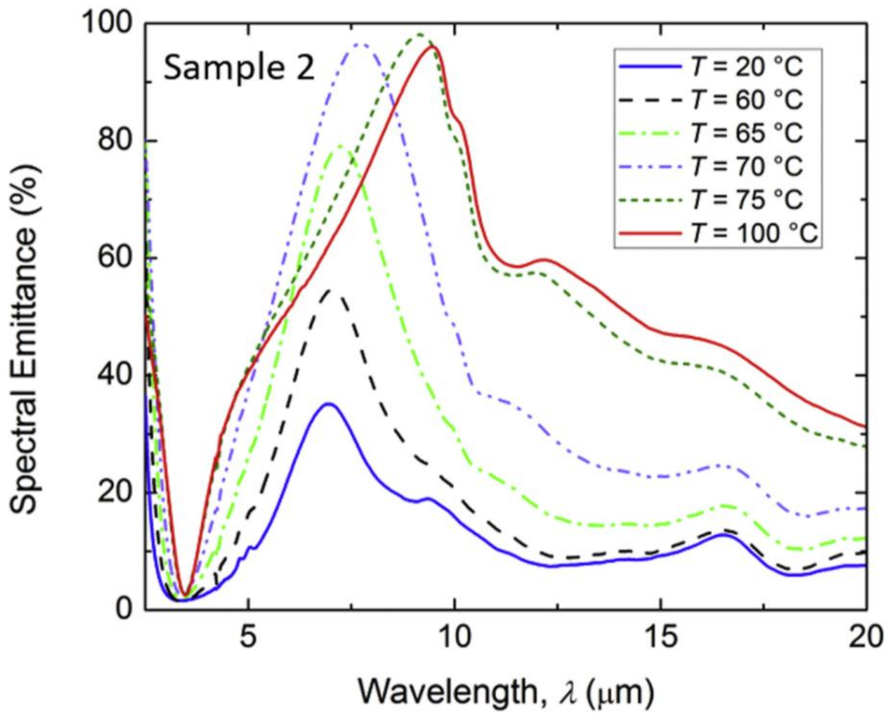


Technical Objective	KPP	Target	Rationale
Maintain High Emittance Contrast	$\Delta\varepsilon$	0.6	A greater emittance contrast improves thermal stability and decreases heater loads.
Maintain High Emittance at High Temperatures	ε_h	0.8	High emittance at high temperatures is required to minimize radiator area.
Maintain Low Solar Absorptance	α	0.2	VECs must have low solar absorptance to minimize solar heating in cases where orientation cannot be controlled.
Determine Transition and Set Point Temperatures	T_L, T_H, T_{set}	Mission Specific	Ideal transition temperatures are mission and spacecraft-dependent.

Passive Variable Emissivity Coatings

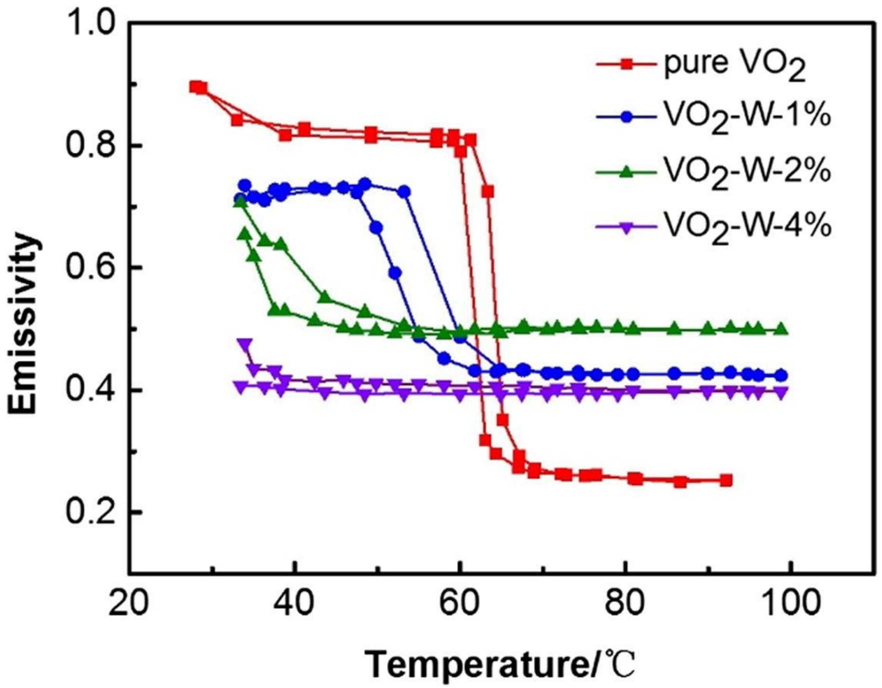
State-of-the-art passive VECs are comprised of thermochromic vanadium oxides which can be doped to change emittance contrast and transition temperature.





Taylor et al., Sol Energy Mater Sol Cells, 217, 2020

Tungsten-Doped VO_2 Emissivity for IR Stealth



Liu et al., Infrared Phsy. Technol., 77, 2016

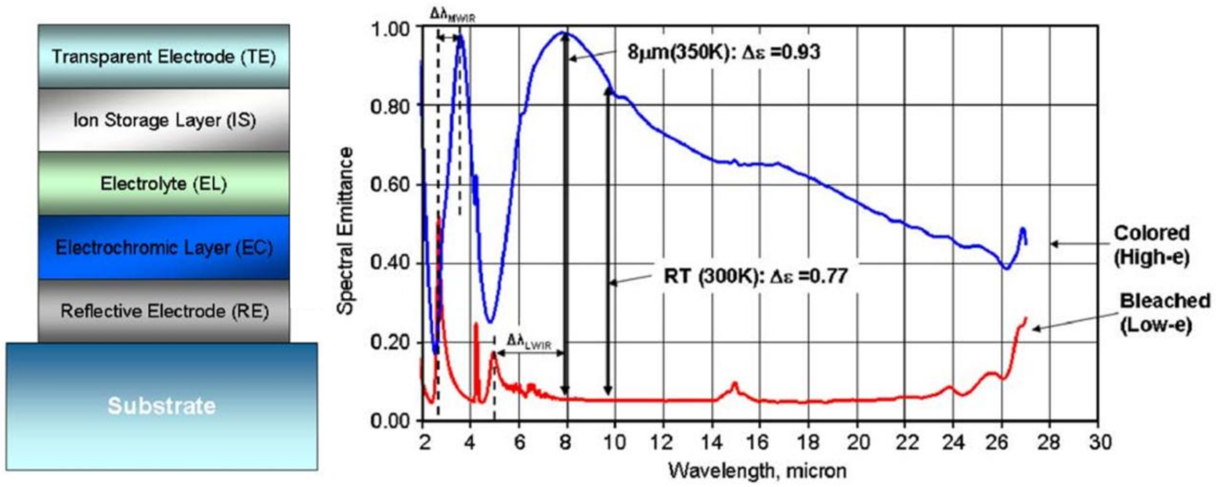
Decreasing the transition temperature often decreases emissivity contrast, resulting in poor passive VEC performance at exceedingly low temperatures.

Active Variable Emissivity Coatings

Active VECs operate independently of radiator temperature and require applied power to change the emittance.

Electrochromics

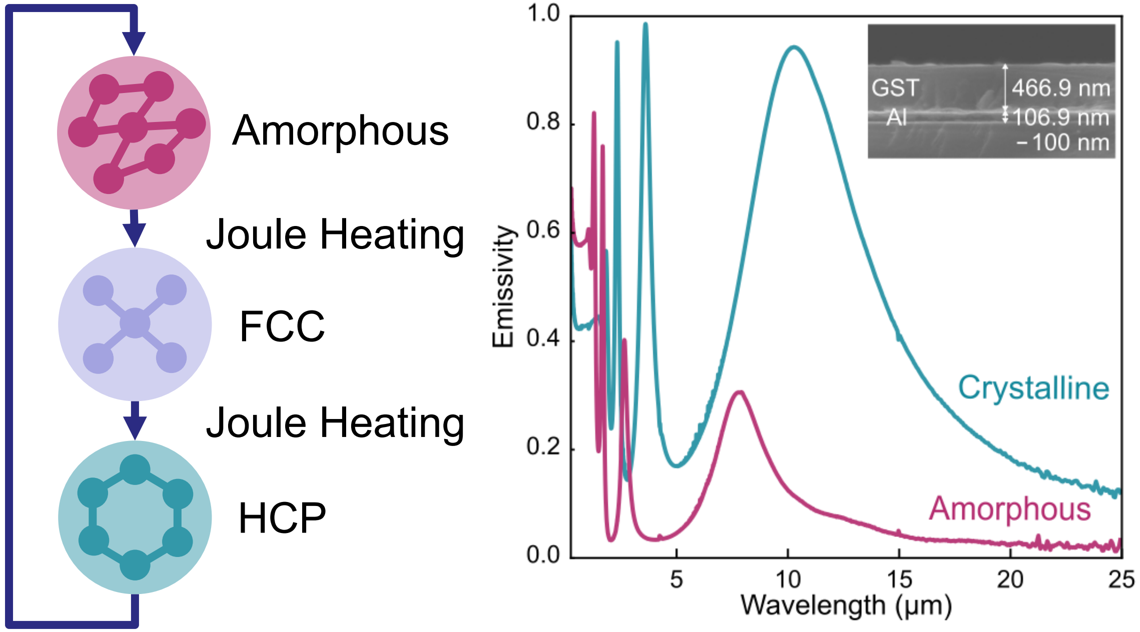
Emittance is varied using a constant low voltage to regulate ion transport and electrochemical reactions in a material.



Demiryont et al., Sol Energy Mater Sol Cells, 93, 2009

Chalcogenide Glasses

Emittance is varied using brief pulsed joule heating.



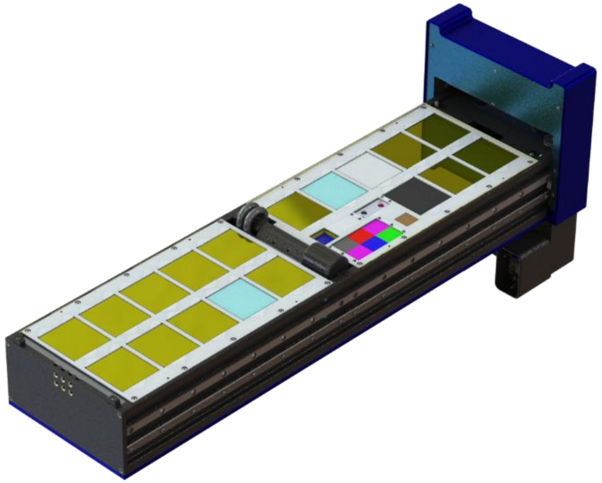
Kindem et al., ArXiv, 2605.21619, 2026

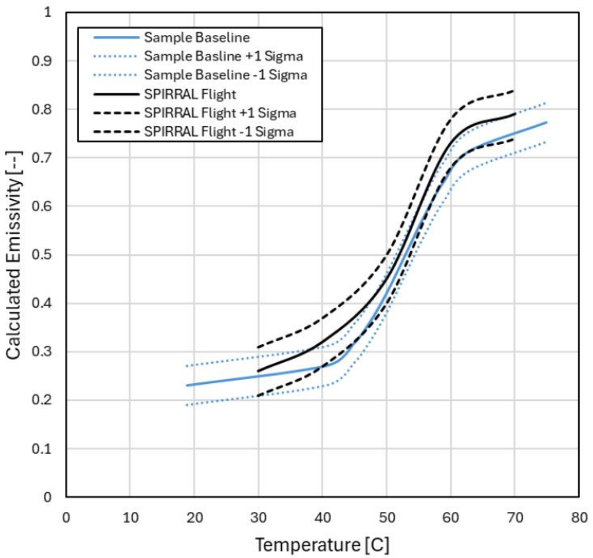
Electrochromics and chalcogenide glasses are expected to be more suitable for very high and low temperature applications.

Recent Variable Emissivity Coatings in Low Earth Orbit (LEO)

SPIRRAL (2024 – 2026) [5]

Vanadium Oxides, TRL 6-7



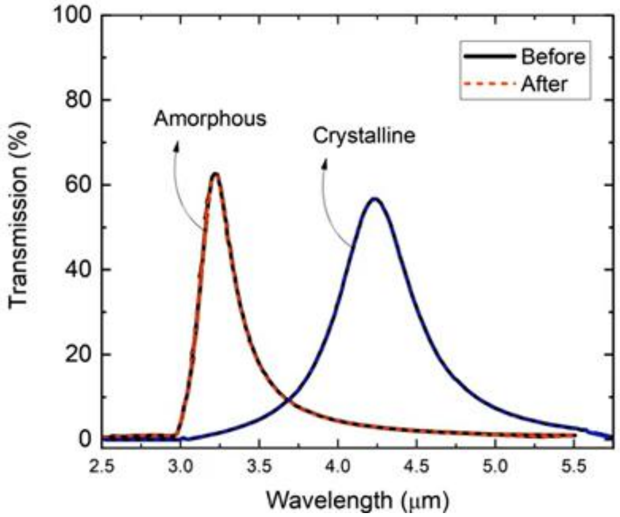


Goal: Measure emissivity (ε) and absorptivity (α) and estimate optical degradation.

Outcome: VEC samples will undergo testing using thermal vacuum chamber (TVAC) calorimetry and optical characterization to estimate end-of-life (EOL) properties.

MISSE-14 (2021) [6]

Chalcogenide Glasses, TRL 3-4

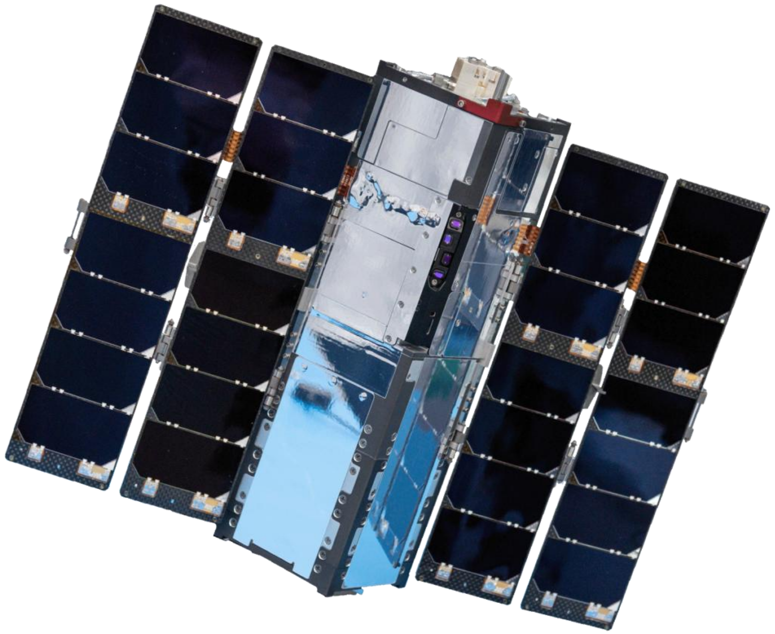


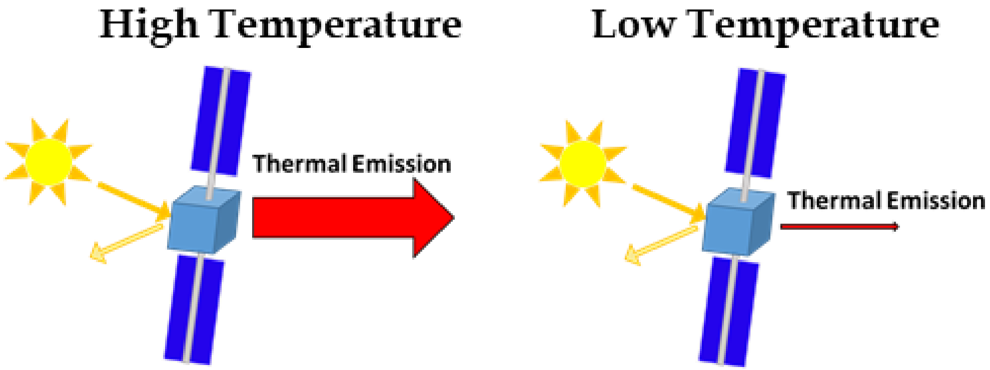
Goal: Estimate optical filtering degradation when exposed to a LEO environment.

Outcome: Various chalcogenide glasses including GST-225, GSST, and SbS demonstrated <5% decrease in transmission over ~330 days.

VECs for CubeSats

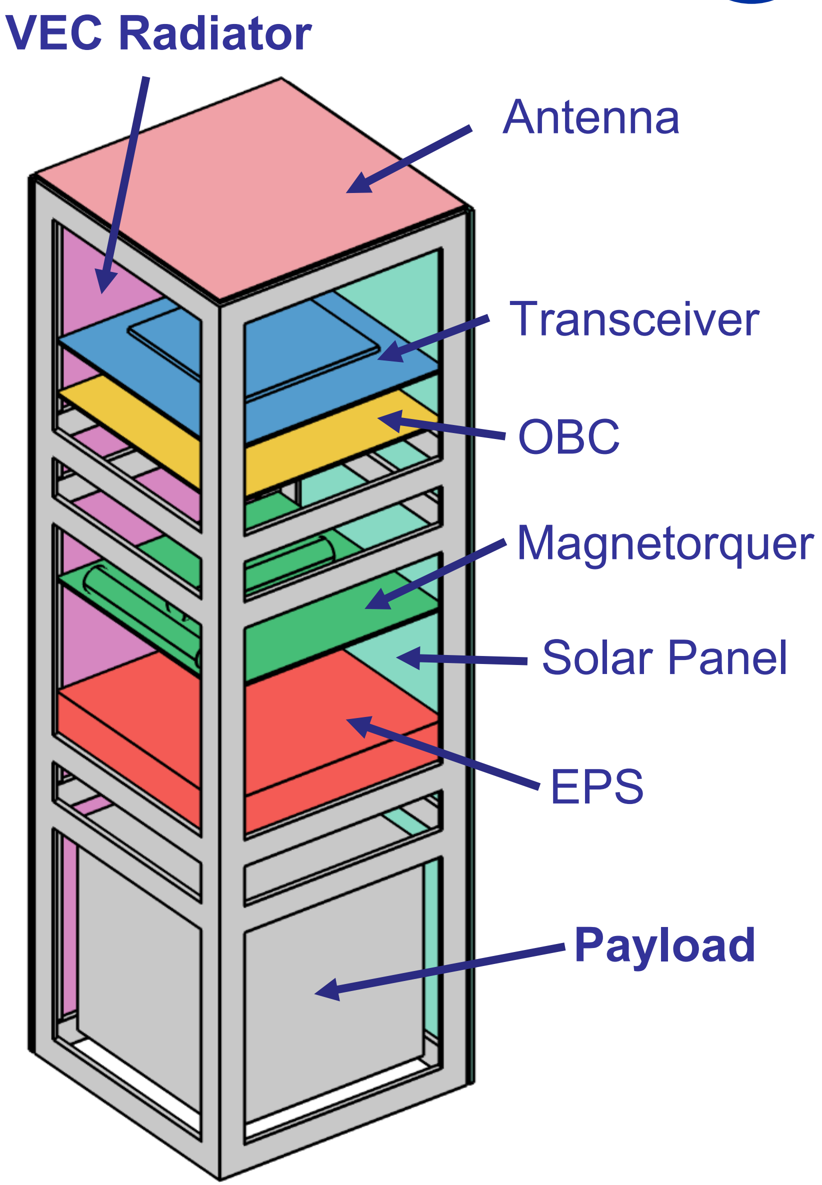
- Small satellites will serve as the next proving ground for VEC radiators in LEO
  - VECs are especially attractive for small satellite thermal control where power and mass are at a premium
- Next technology milestone would be fully integrating a VEC into a satellite's thermal control system instead of as an experimental payload
- On-going work within the community to characterize and catalog available VECs offered by vendors with full details on emittance contrast and transition regimes
- When designing a satellite, the thermal engineer would select from available list based on best match with thermal modeling study and/or tune satellite design to make ideal use of a chosen VEC
  - Balance of trade-offs regarding differences in VEC parameters (emissivity contrast, solar absorptance, transition regime, etc.)
  - Not cost-efficient to design a new VEC from scratch for a small satellite





3U CubeSat VEC Systems Modeling

- 3U CubeSat model constructed in Thermal Desktop (TD) and COMSOL Multiphysics (CM) to show benefit of VECs for a small satellite in LEO
  - Both programs are used in order to highlight their unique VEC modeling approaches
- Model used to examine the impacts of varying transition temperature, transition range, and emissivity contrast on heat rejection and survival heater power savings
- Demonstration of determining optimal VEC properties for a specific mission and understanding the impact of trade-offs to aid VEC selection

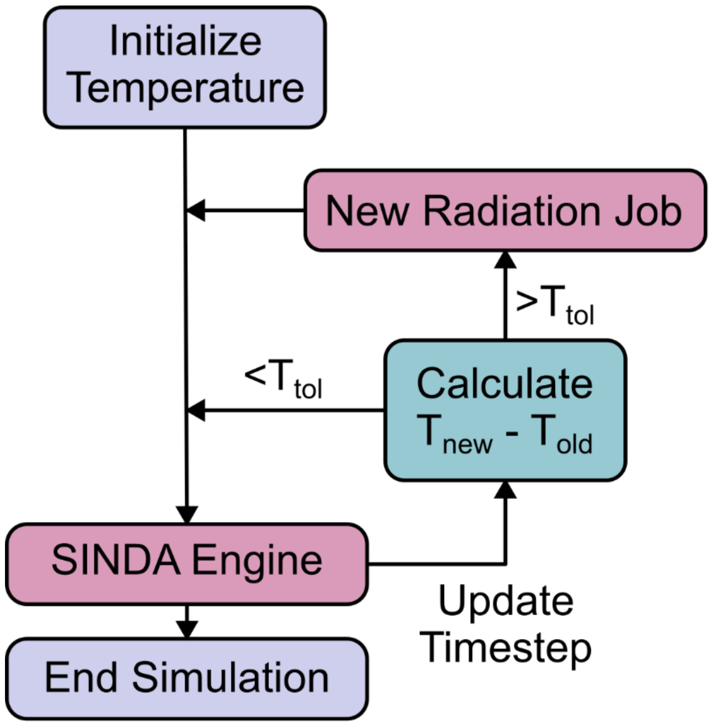


**3U CubeSat adapted from Foster/AFRL "Small Satellite Thermal Modeling Guide"*

Modeling VECs in TD & COMSOL

In VEC thermal models, the simulation must be paused when a given condition (radiator temperature change) is met to update the surface emissivity and recalculate radiosity when provided a temperature-dependent radiator optical property.

Thermal Desktop



D. Hengeveld et al., ICES, 129, 2023

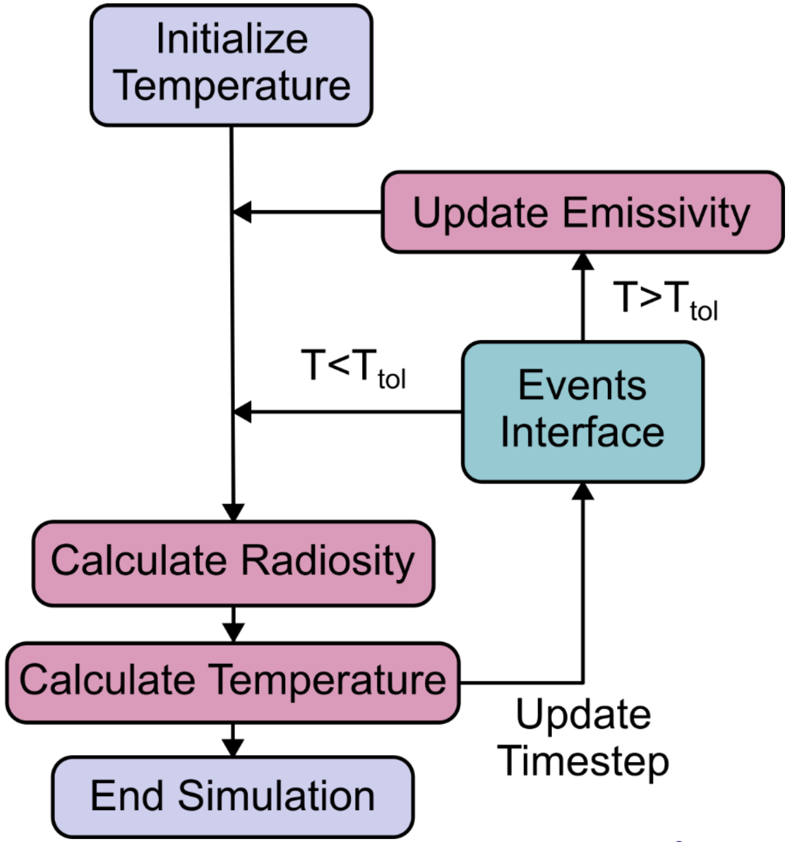
Thermal Desktop - Dynamic SINDA

T_{new} = VEC temperatures
IF ($|T_{new} - T_{old}| > T_{tol}$) THEN
    CALL DUMPT('dynamicTemps.dat', 0)
    CALL TDUPDATE
    CALL TD CASE
    T_{old} = VEC temperatures
ENDIF

COMSOL - Events Interface

Name	g(v,vt,vtt,t)	Initial value (u0)
T_high	T_vem- 295.0[K]	0
T_low	T_vem - 290.0[K]	0
T_set	T_vem - 292.5[K]	0
	0	0

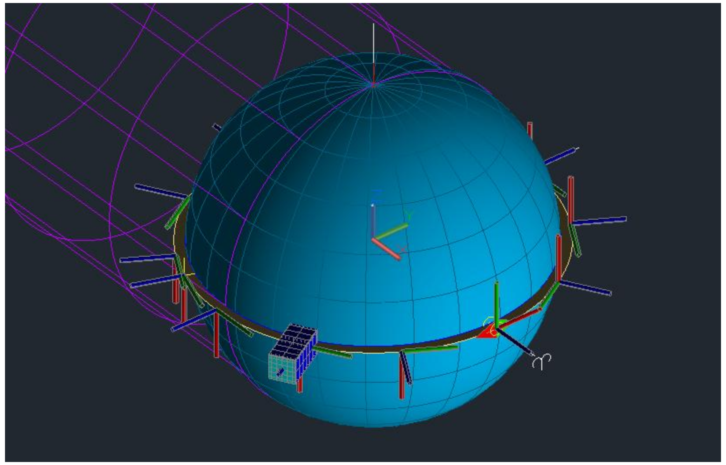
COMSOL Multiphysics

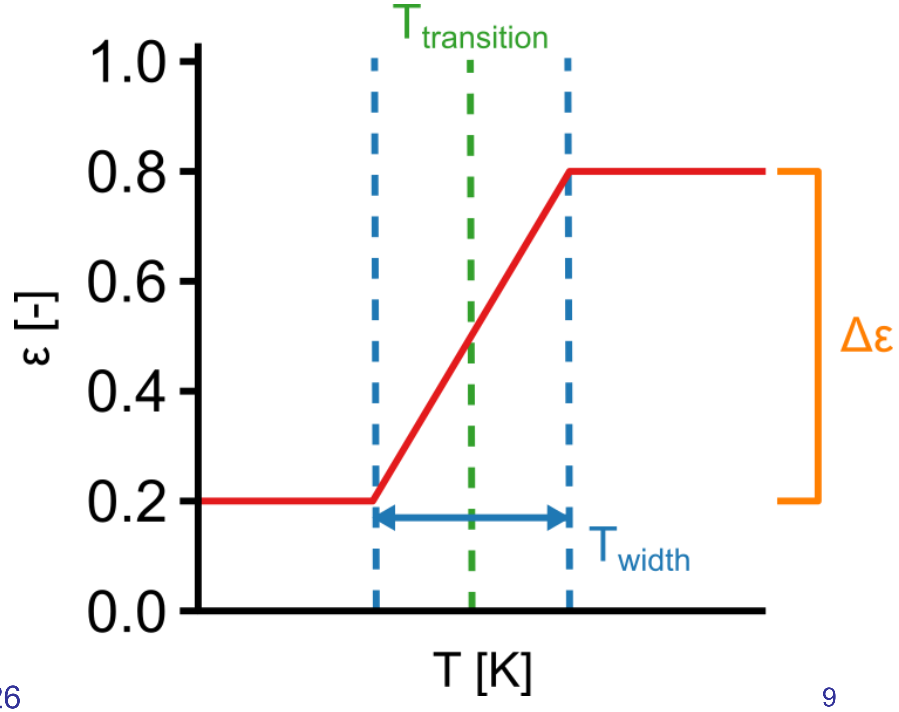


Case Setup & Matrix

- 400km, $\beta = 0^\circ$, circular orbit with nadir-facing payload and radiator pointed away from Sun
- 8W payload heat load with 2W survival heater

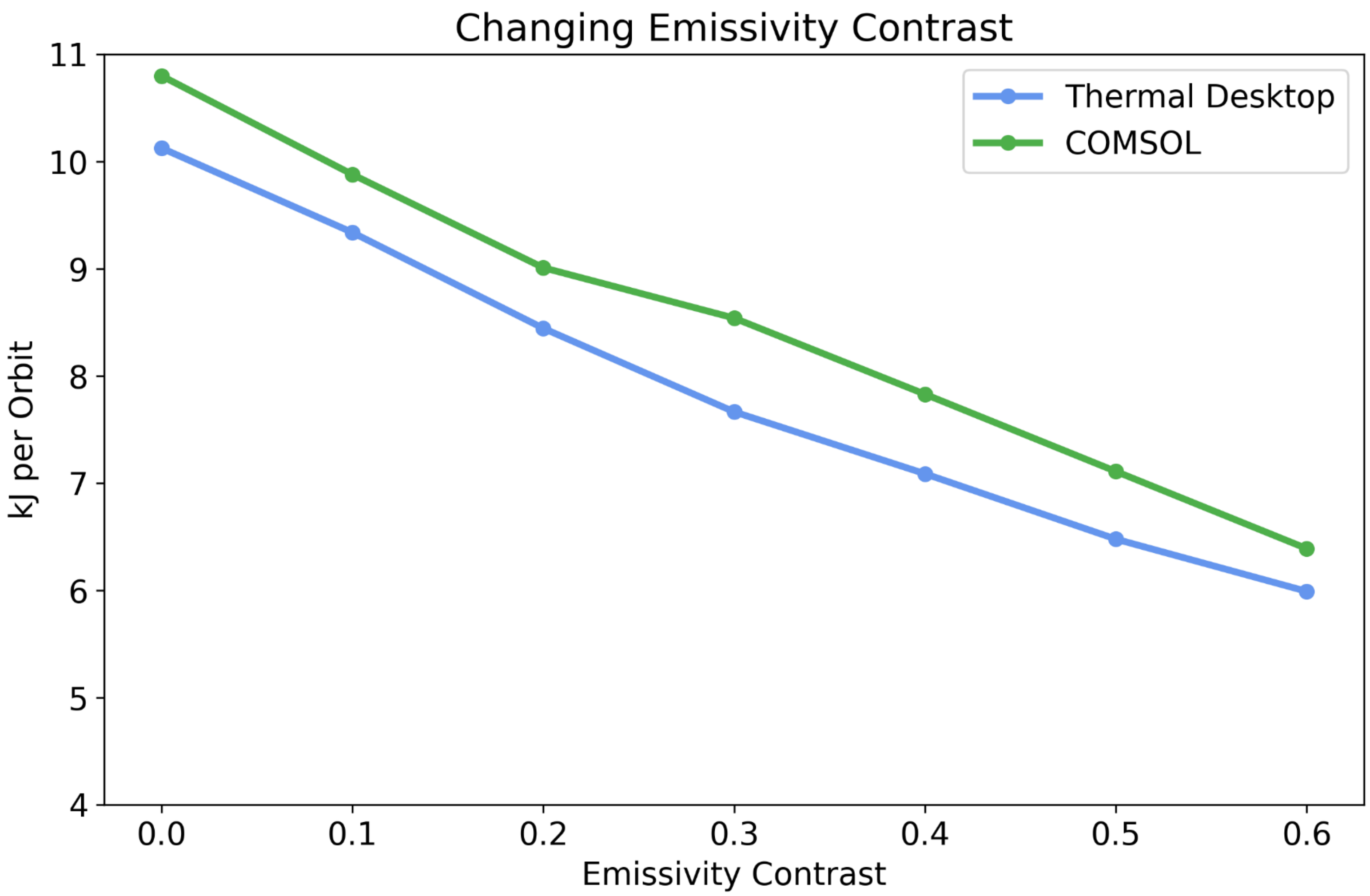
Case ID	ε_{low}	ε_{high}	$\Delta\varepsilon$	T_{low} (K)	T_{high} (K)	T_{width} (K)	Section
1a	0.2	0.8	0.6	280	285	5	Changing emissivity contrast
2a	0.3	0.8	0.5	280	285	5	
3a	0.4	0.8	0.4	280	285	5	
4a	0.5	0.8	0.3	280	285	5	
5a	0.6	0.8	0.2	280	285	5	
6a	0.7	0.8	0.1	280	285	5	
7a	0.8	0.8	0.0	280	285	5	
1b	0.8	0.8	0.0	N/A	N/A	N/A	Changing transition temps
2b	0.2	0.8	0.6	270	275	5	
3b	0.2	0.8	0.6	275	280	5	
4b	0.2	0.8	0.6	280	285	5	
5b	0.2	0.8	0.6	285	290	5	
6b	0.2	0.8	0.6	290	295	5	
7b	0.2	0.8	0.6	295	300	5	
8b	0.2	0.8	0.6	300	305	5	
9b	0.2	0.8	0.6	305	310	5	
1c	0.2	0.8	0.6	282.5	282.5	0	Changing transition width
2c	0.2	0.8	0.6	280	285	5	
3c	0.2	0.8	0.6	277.5	287.5	10	
4c	0.2	0.8	0.6	275	290	15	
5c	0.2	0.8	0.6	272.5	292.5	20	





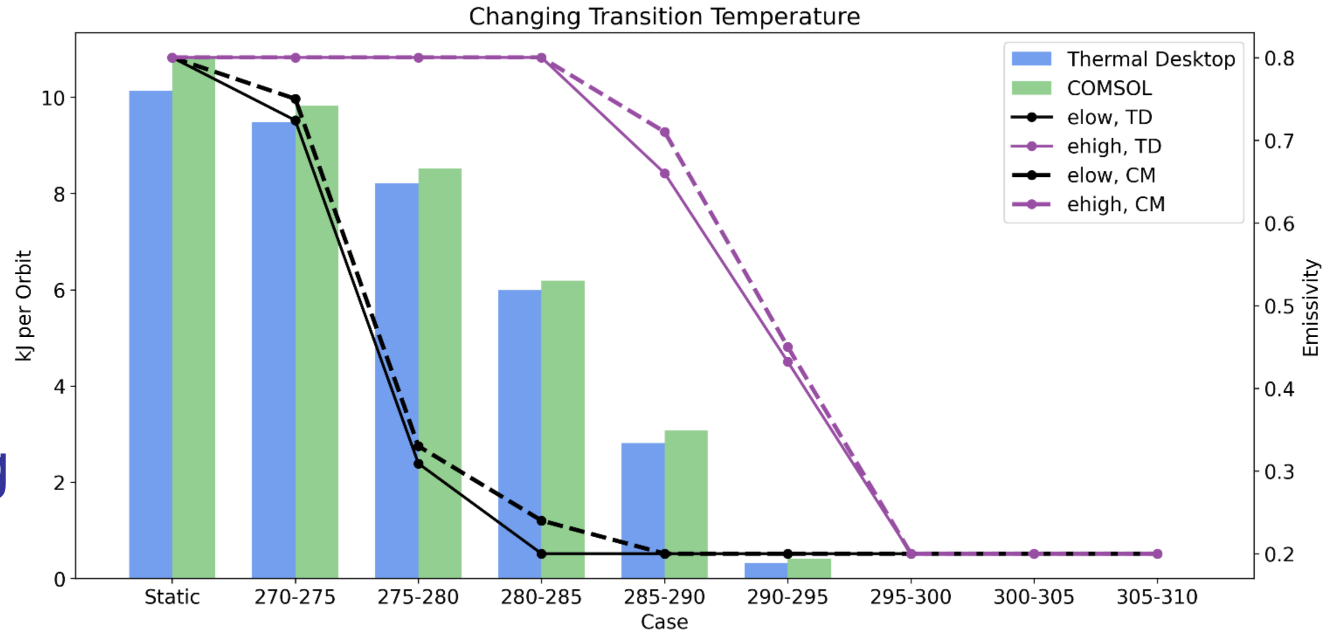
Changing Δε

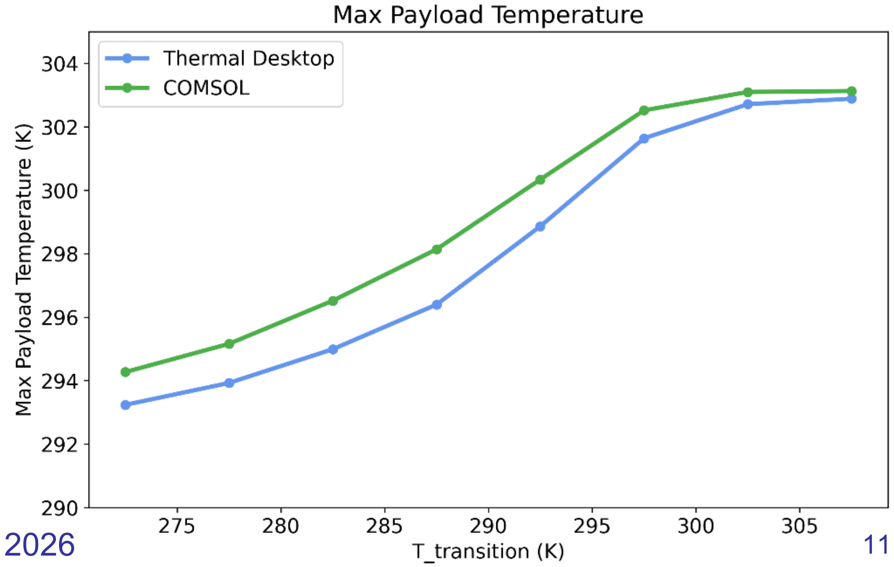
- A greater emissivity contrast results in lower minimum emissivity values which in turn reduce heat rejection and conserve heater power during eclipse
- High importance when selecting the appropriate VEC



Changing Transition Temperature (T*)

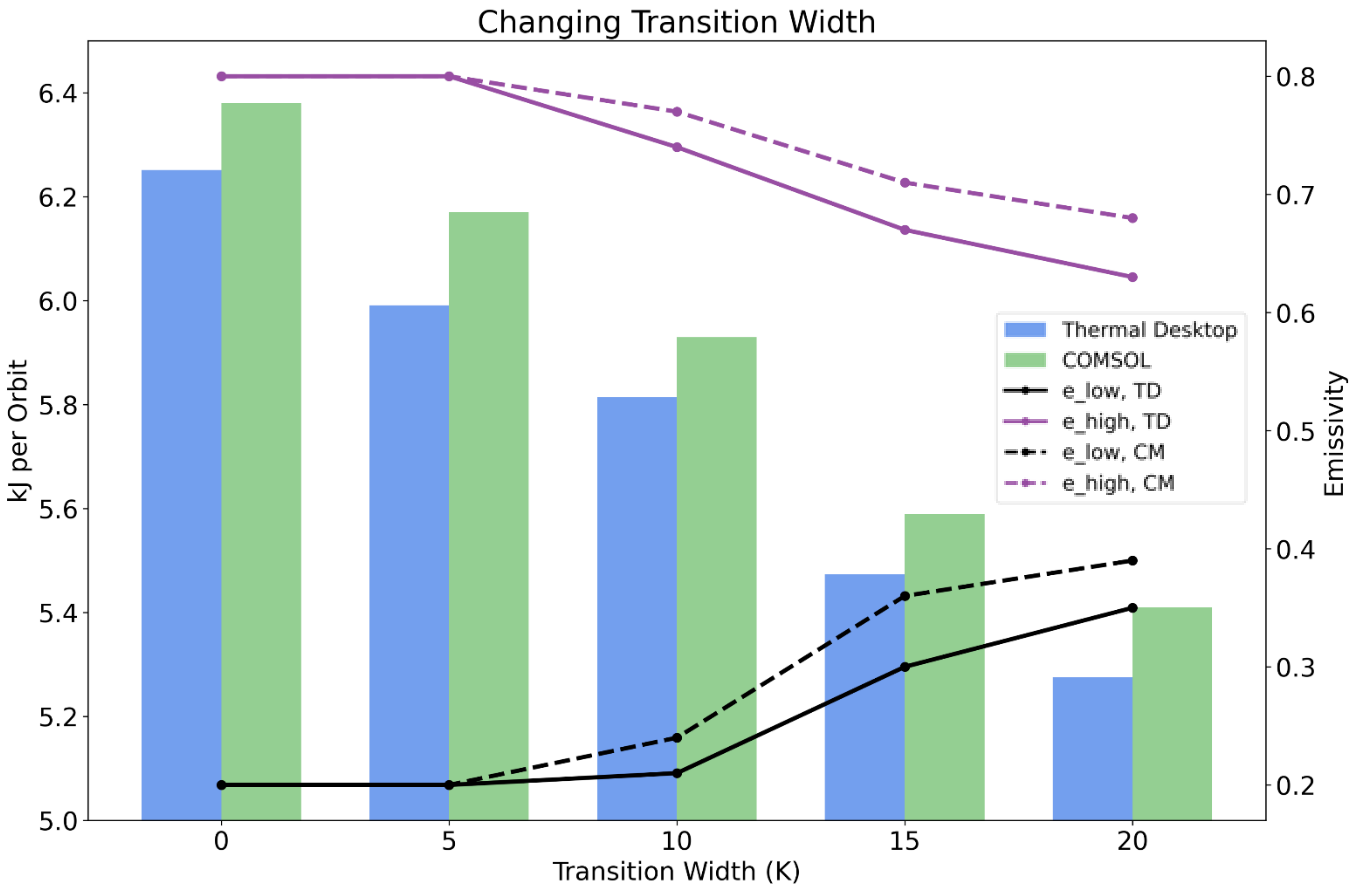
- As transition temperature increases, required heater power in eclipse decreases, but the payload will run hotter in the sun
- The 280-285K transition case covers the full emissivity range while reducing required heater power compared to the static radiator case
  - Saves energy while maintaining hot environment heat rejection capability
- Transition temperature also of high importance
  - Select a VEC with the greatest Δε for a given transition temp (based on radiator average operating temperature)





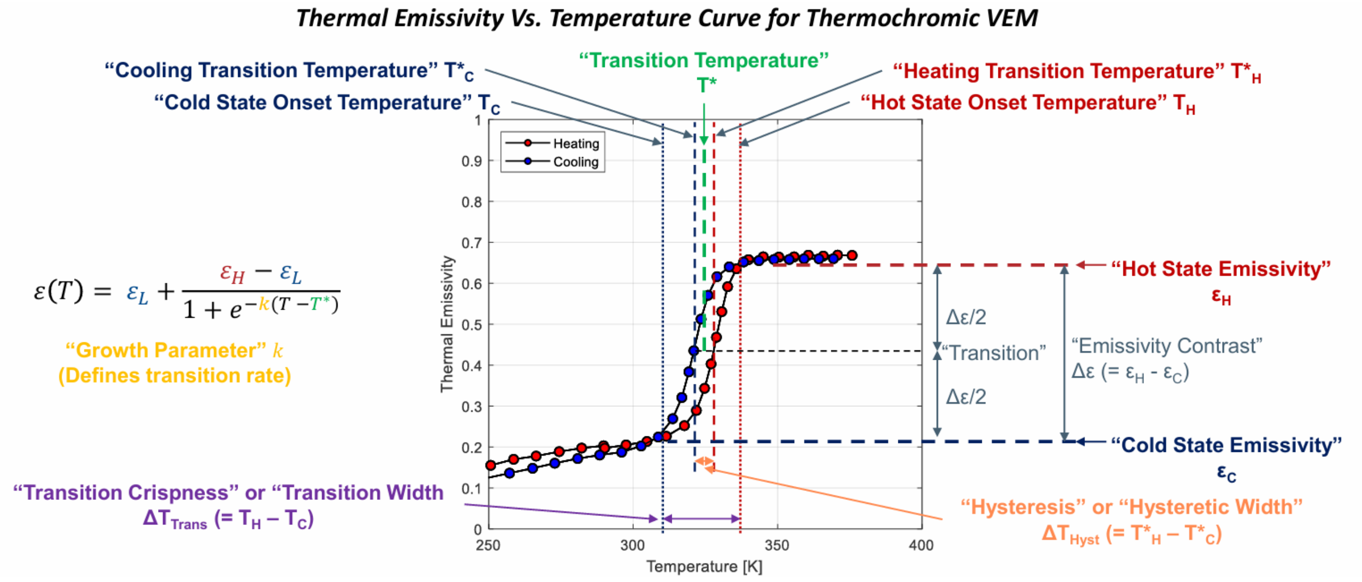
Changing Transition Width

- As transition width increases, effective emissivity contrast decreases for a given orbit
- Heater power and max payload temperature vary marginally with transition width – less importance in VEC selection
- In most cases, VEC developers aim to minimize transition width to produce the greatest emissivity contrast for a given T*



Modeling VEC Hysteresis

- VECs exhibit hysteresis behavior that should be accounted for in detailed thermal models for accurate temperature and power predictions
- To examine impact of more realistic VEC transitions, we include modeling logic to calculate temperature-dependent emissivity when different heating and cooling curves exist for the material of interest
  - This logic interpolates between two logistic curve functions that could be ideal or derived from test data
  - When inside the region between the heating and cooling curves, the model assumes a constant emissivity until a curve is reached



$$\boldsymbol{If\ T_{rad} > 0\ and\ T_{rad} \geq T_{heat}(\varepsilon)}$$
$$\boldsymbol{\varepsilon(t) = \varepsilon_{heat}(T)}$$

$$\boldsymbol{Else\ If\ T_{rad} < 0\ and\ T_{rad} \leq T_{cool}(\varepsilon)}$$
$$\boldsymbol{\varepsilon(t) = \varepsilon_{cool}(T)}$$

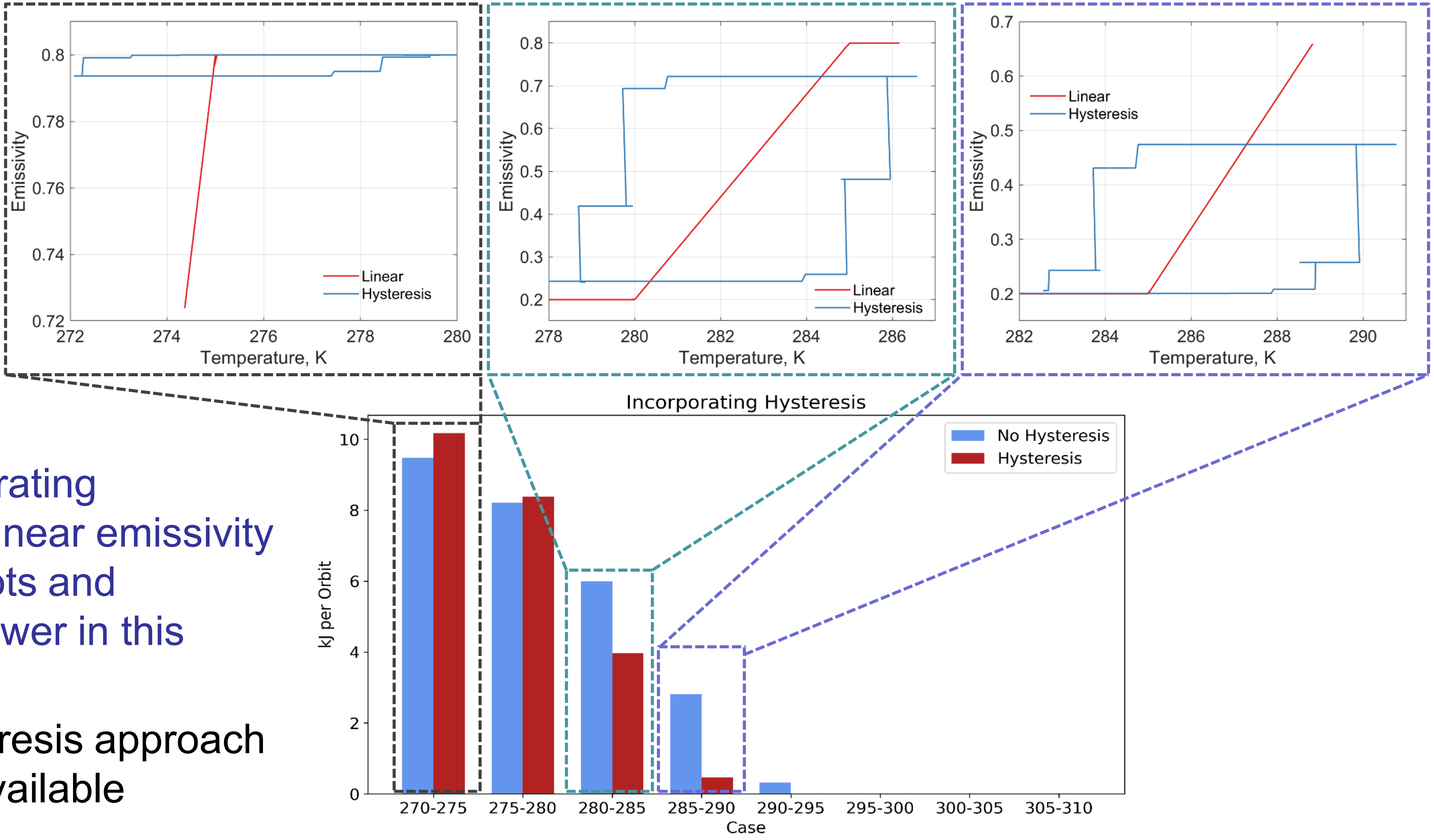
$$\boldsymbol{Else}$$
$$\boldsymbol{\varepsilon(t) = \varepsilon(t-1)}$$

Foster et al., NASA Thermal & Fluids Analysis Workshop, 2025

Modeling VEC Hysteresis

- Including hysteresis can significantly impact system-level parameters such as heater loads

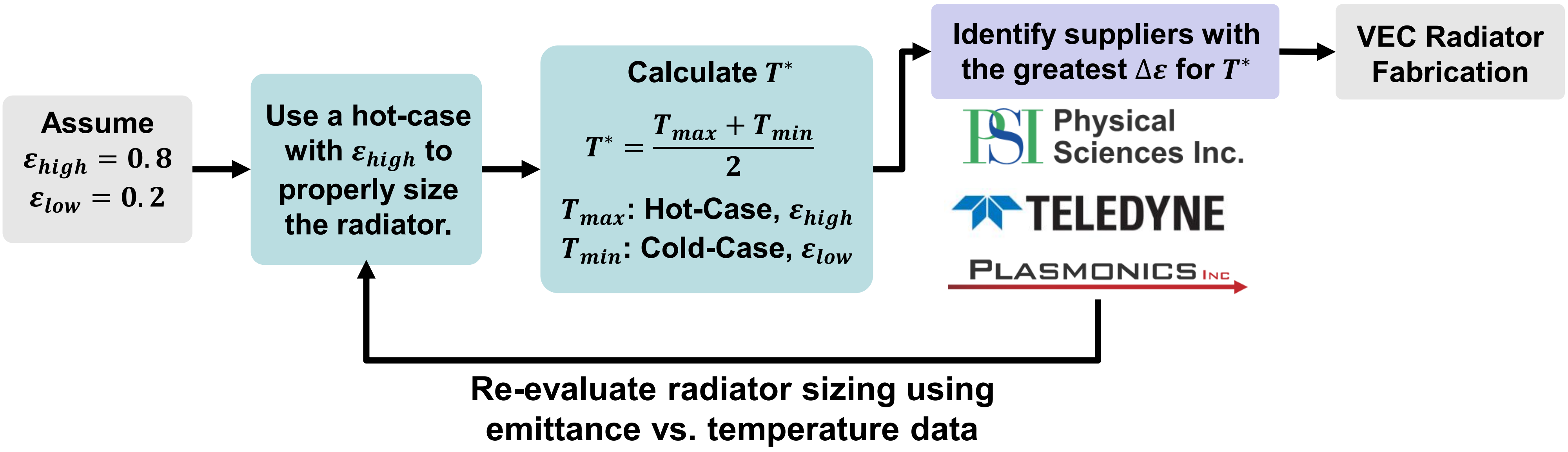
- Depending on the operating temperature range, a linear emissivity function both overshoots and undershoots heater power in this example
  - Better to use hysteresis approach unless data is unavailable

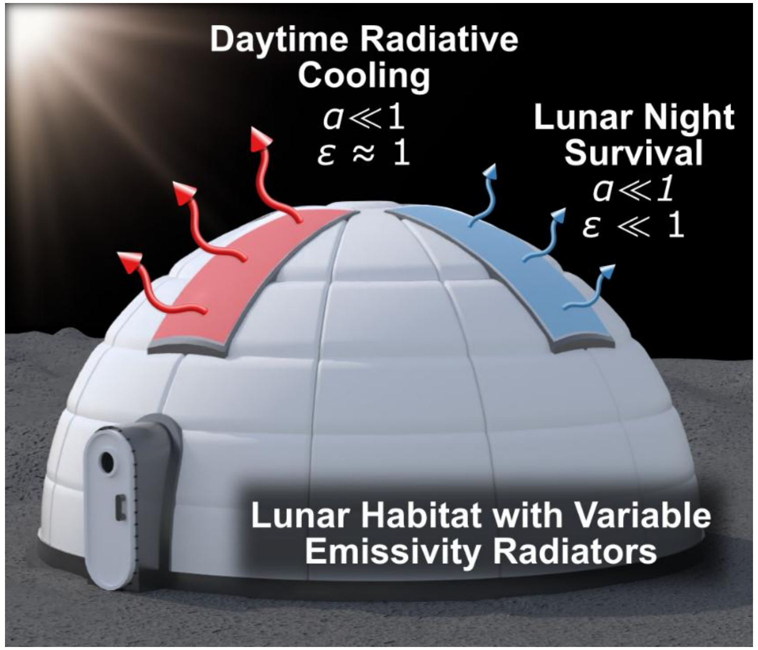


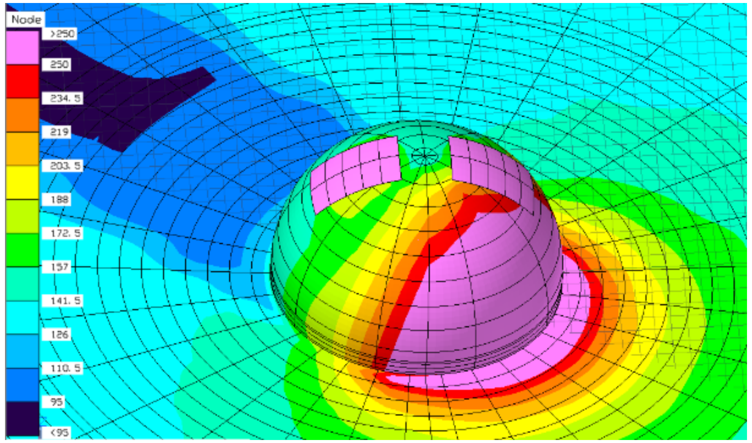
Conclusion

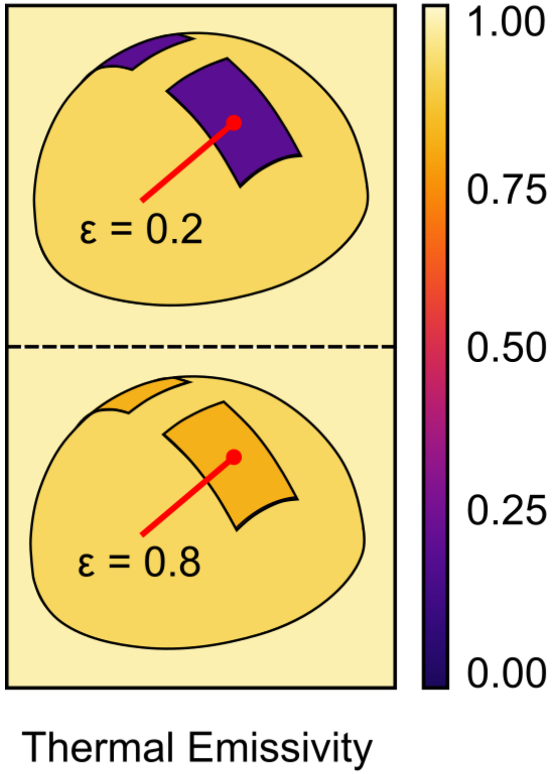
- Variable emissivity coatings are an efficient way to reduce heater power, battery mass, and mechanical actuation
- Thermochromic and Chalcogenide glass VECs have demonstrated minimal optical degradation in LEO with exposure lasting ~1 year
- Increasing VEC TRL to 8 will require these coatings to be integrated on a CubeSat as an essential thermal management solution

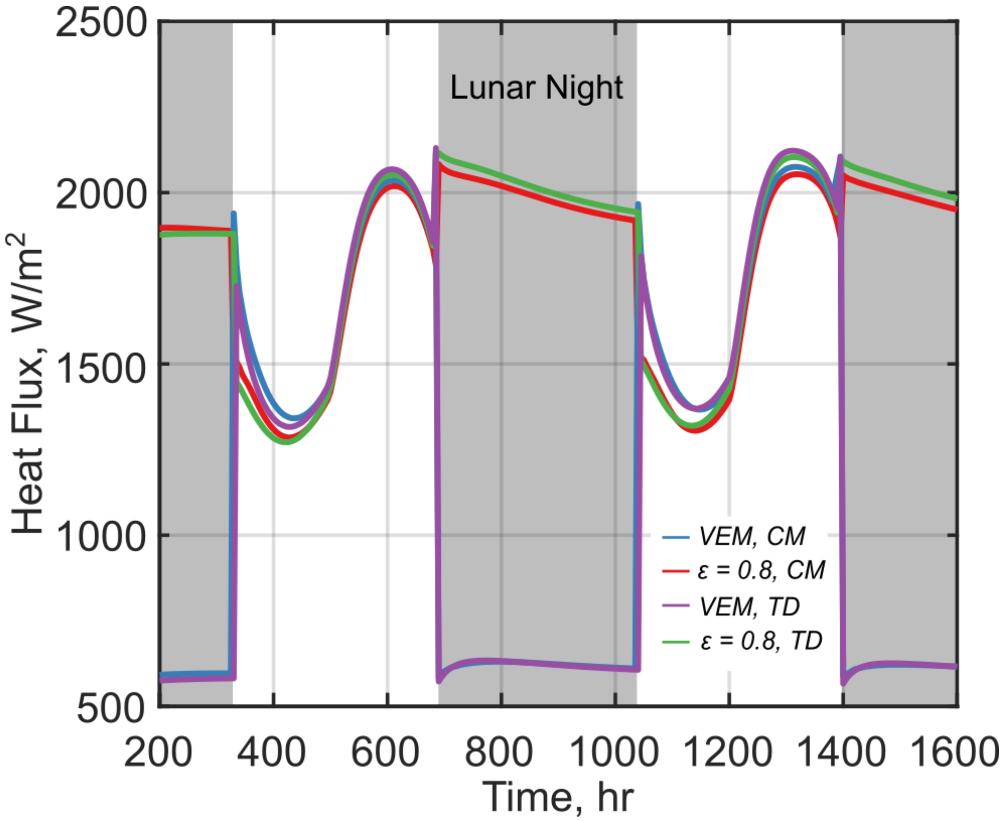
Recommended Path for VEC Inclusion at a System-Level







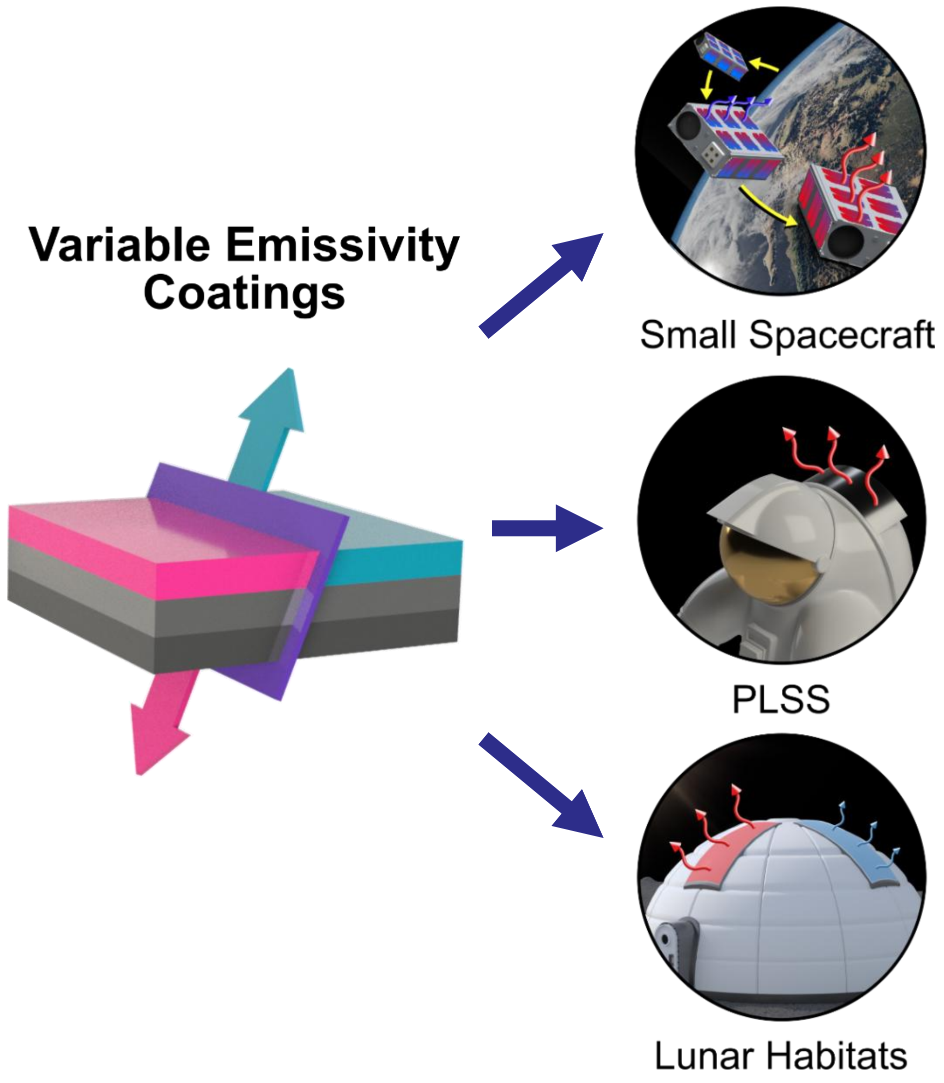




When using VEC radiators, we observe a **268 kWh** (*CM*) and **275 kWh** (*TD*) energy savings over single-state high-emissivity radiators for a single lunar night while maintaining an internal temperature of 300K.

Future Work

- Characterization and modeling of the effects of lunar dust on variable emissivity radiators
- Reducing the transition temperature and solar absorption of VECs for human spaceflight
- Combining VEC radiators with fluid loop systems using Thermal Desktop
- Improving the accuracy of VEC hysteresis behavior logic in thermal models
- Continued system-level thermal modeling for Earth orbit, lunar, and Martian applications



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