Novel Methods for Modeling Thermochromic Variable Emissivity Surfaces

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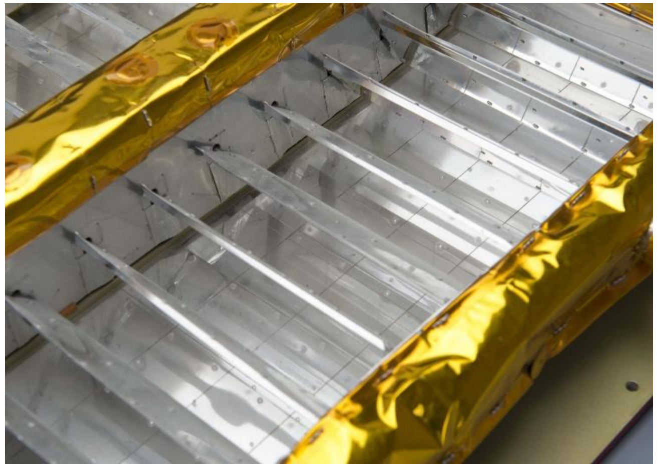
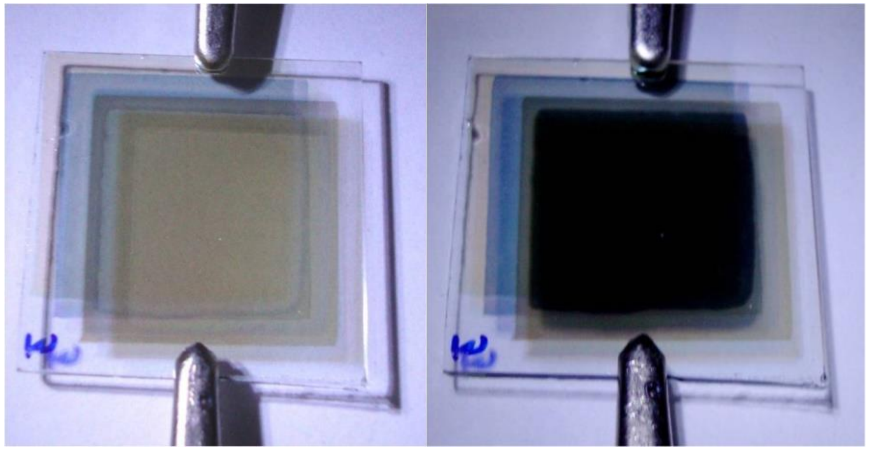
Variable Heat Rejection Surfaces

- Alter view factors, adjust heat conduction path near surface, change emissive properties of surface
- Provide adaptable heat rejection and temperature regulation for spacecraft thermal engineers
- Examples
  - Macro-louvers
  - Micro-electro-mechanical systems (MEMS)
  - Electrostatic switched radiators (ESRs)
  - Electrochromic devices (ECDs)
  - **Thermochromic Variable Emissivity Materials (VEMs)**



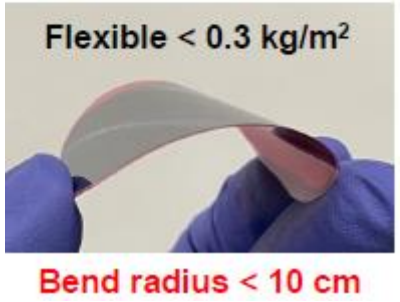
ESA's Rosetta macro louvers



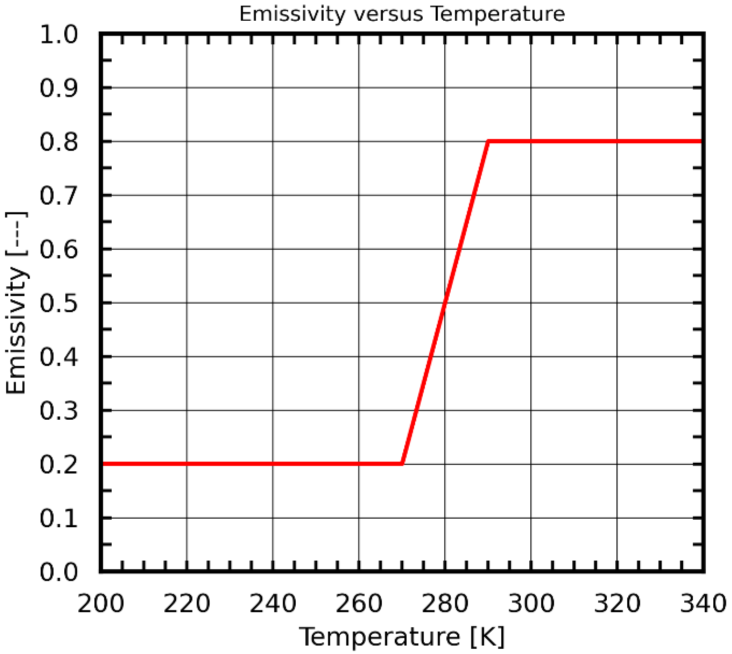
Electrochromic in bleached/colored states

Thermochromic Variable Emissivity Materials (VEMs)

- Thermochromic variable emissivity materials (Lawdensky)
  - Temperature dependent, passive, variable emissivity modulation
  - Commonly Vanadium dioxide (VO2) thin film; with a solid-solid phase transition at 67C (340K). Transition is customizable (Barako).
  - Provides passive regulation of variable thermal loads
  - Provides reduced size and weight (<1 kg/m2 areal density)
  - No moving parts; low complexity
  - Provides reliable, passive, and adaptable heat rejection and temperature regulation for spacecraft thermal engineers
- In the (near?) future, thermochromic VEMs will become more mainstream
  - To promote adoption, need to accurately model them using traditional tools (e.g., Thermal Desktop®)

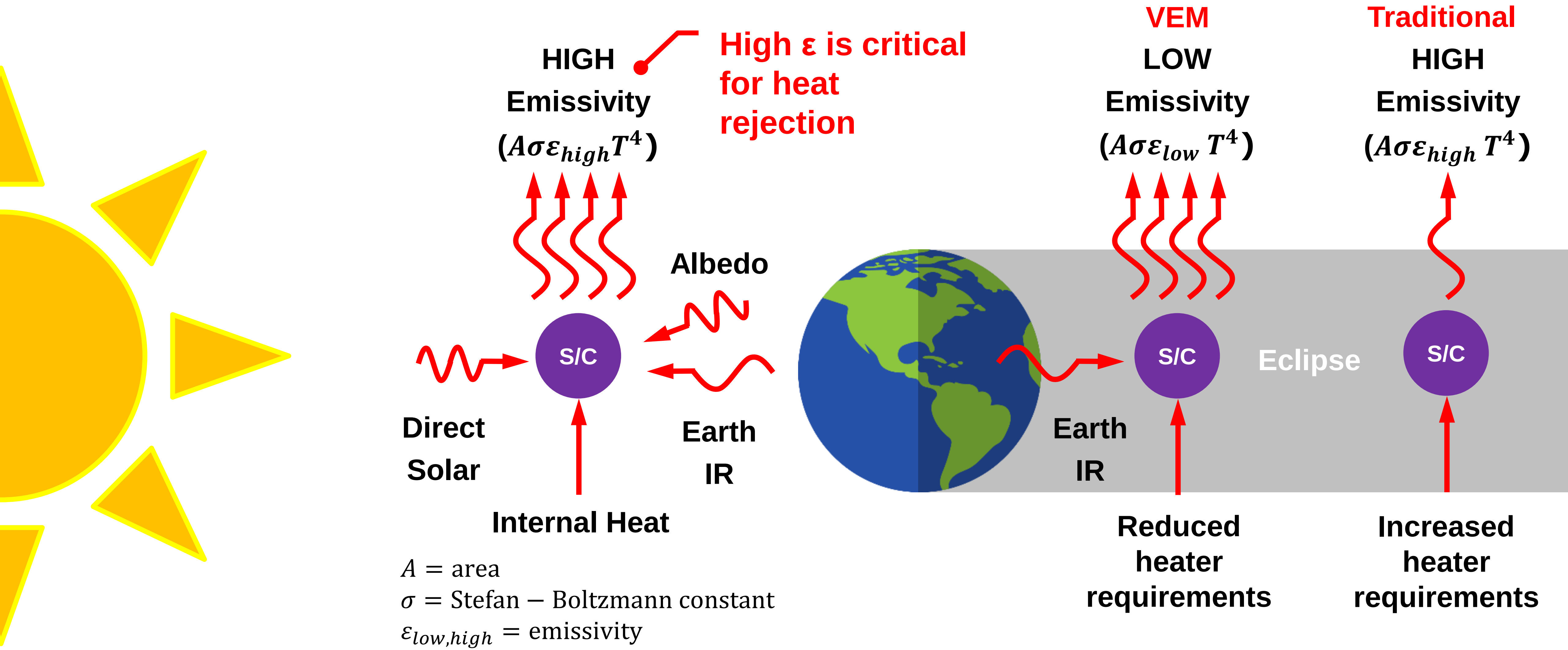


Example VEM (Lawdensky)



Nominal emissivity vs. temperature curve

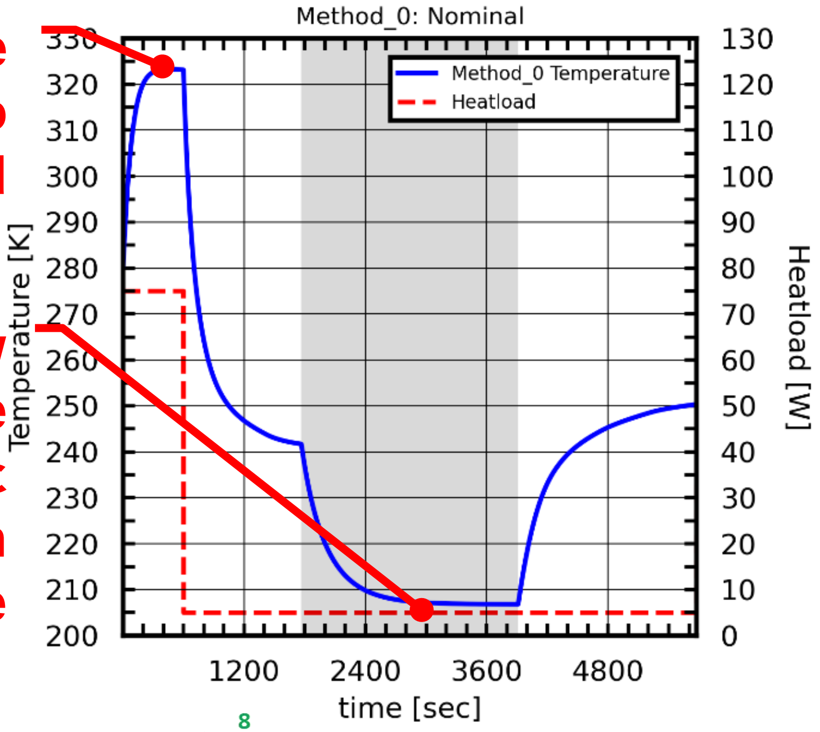
Thermochromic Variable Emissivity Materials (VEMs)



A = area
σ = Stefan – Boltzmann constant
$\varepsilon_{low,high}$ = emissivity
T = temperature

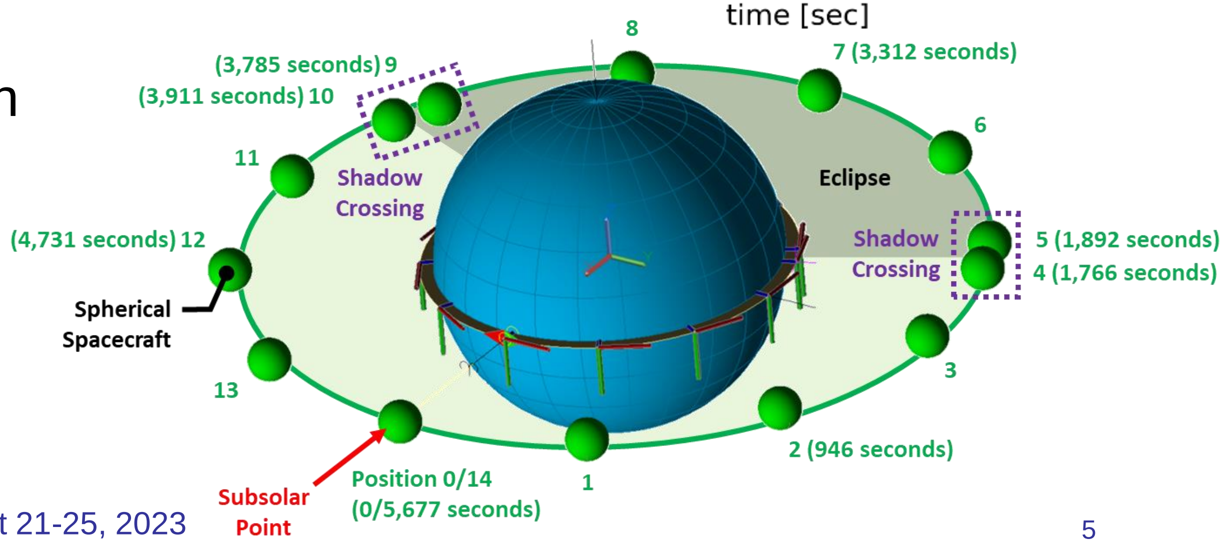
Method 0: Test Problem

- Used to compare modeling methods
- Spacecraft thermal model
  - Single-node sphere (100 J/K and radius of 0.132 m)
  - Non-uniform heat load. 75W for first 600 seconds; 5W thereafter.
  - Solar reflecting surface with (α=0.2;ε=0.8)
  - **Solar absorptivity assumed constant in this work!**
- Environment
  - 500 km, β = 0° , circular orbit (5,677s period) with 0K heat sink
  - Direct solar flux, albedo fraction, and Earth IR values were 1,414 W/m^2, 0.3, and 239.7 W/m^2
  - 14 orbital positions

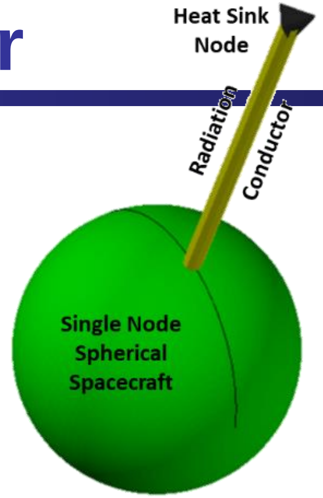


Temperature spike due to 75W heat load

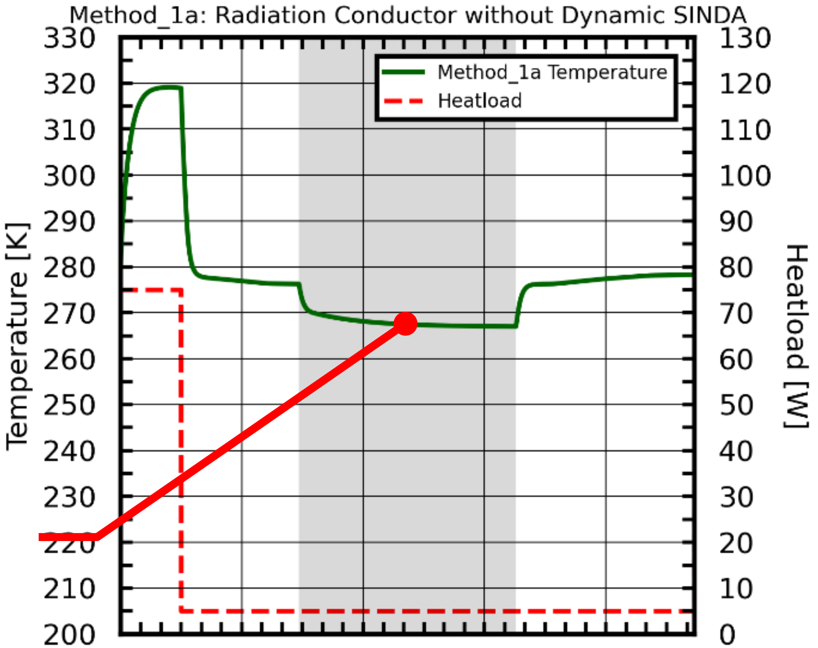
Low temperature due to high ε surface in eclipse



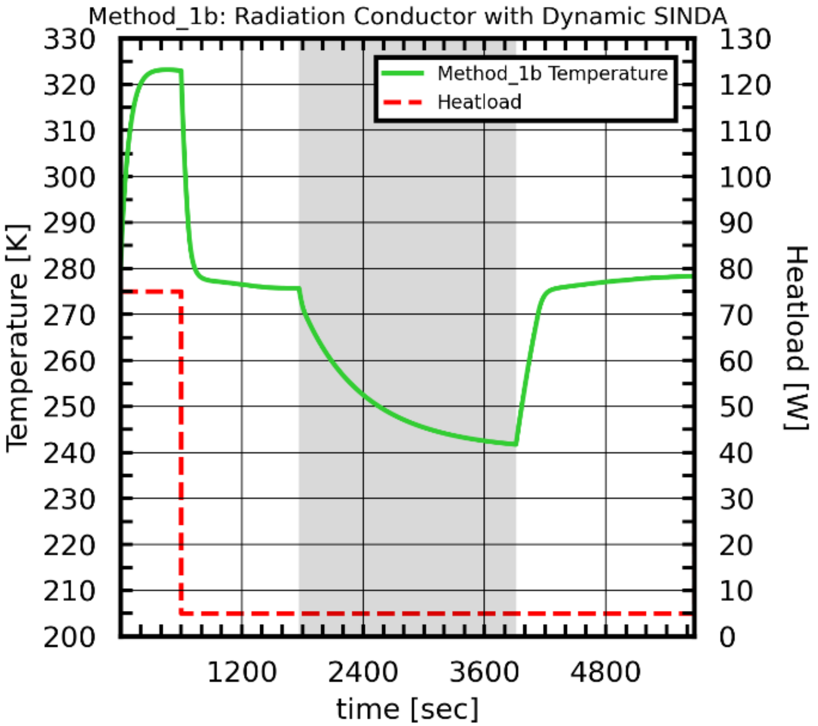
Method 1: Radiation Conductor



- Approach
  - Uses a node-to-surface conductor
  - Temperature-dependent optical property
  - Create emissivity-independent Heating Rate Radiation Tasks
- Restrictions
  - If radiation is to a sink only (e.g., deep space) and no other surfaces
  - There are no emissivity-dependent environmental heating sources (e.g., Earth IR). **Not true for our test problem!** Method 1b uses Dynamic SINDA to account for this.
- This is likely the least computationally expensive method but can only be used in select circumstances



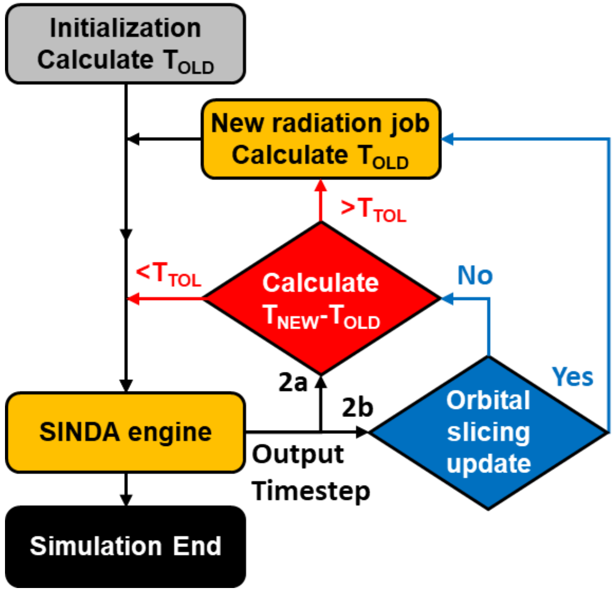
Earth IR overestimated; ε = 0.47 at beginning.



Earth IR corrected; ε varies.

Method 2: Dynamic SINDA

- Approach
  - Leverages Dynamic SINDA (a connection between SINDA and Thermal Desktop)
  - Temperature-dependent optical property
  - Periodically pause current SINDA solution, update radiation jobs (e.g., Radk and Heating Rates), then resume
    - Based on VEM temperatures



Initialization
Calculate T_{OLD}

New radiation job
Calculate T_{OLD}

Calculate
T_{NEW}-T_{OLD}

$>T_{TOL}$

$<T_{TOL}$

No

Yes

2a

2b

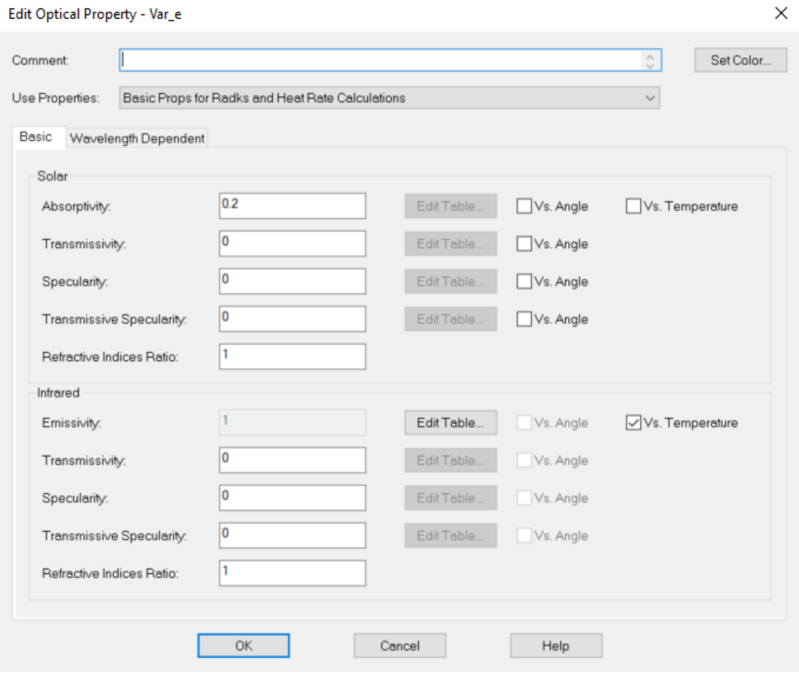
SINDA engine

Output
Timestep

Orbital slicing update

Simulation End

- This is the most versatile method and can be applied to nearly all situations but can be computationally expensive
- Includes 2 methods: With (Method 2b) and without (Method 2a) Orbital Slicing



Edit Optical Property - Var_e

Comment:

Use Properties: Basic Props for Radks and Heat Rate Calculations

Solar

Absorptivity: 0.2 ☐ Vs. Angle ☐ Vs. Temperature

Transmissivity: 0 ☐ Vs. Angle

Specularity: 0 ☐ Vs. Angle

Transmissive Specularity: 0 ☐ Vs. Angle

Refractive Indices Ratio: 1

Infrared

Emissivity: 1 ☐ Vs. Angle ☑ Vs. Temperature

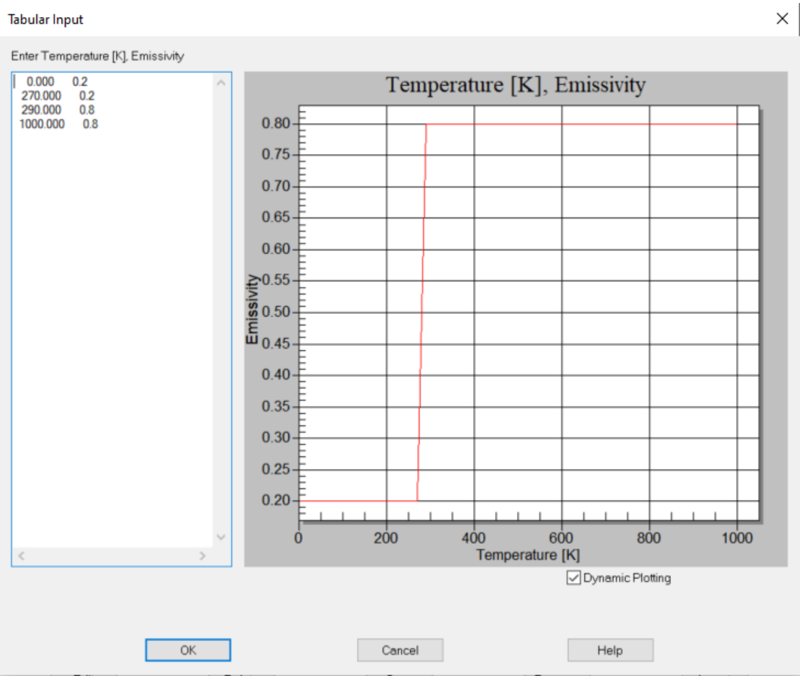
Transmissivity: 0 ☐ Vs. Angle

Specularity: 0 ☐ Vs. Angle

Transmissive Specularity: 0 ☐ Vs. Angle

Refractive Indices Ratio: 1

Sample Thermal Desktop inputs



Tabular Input

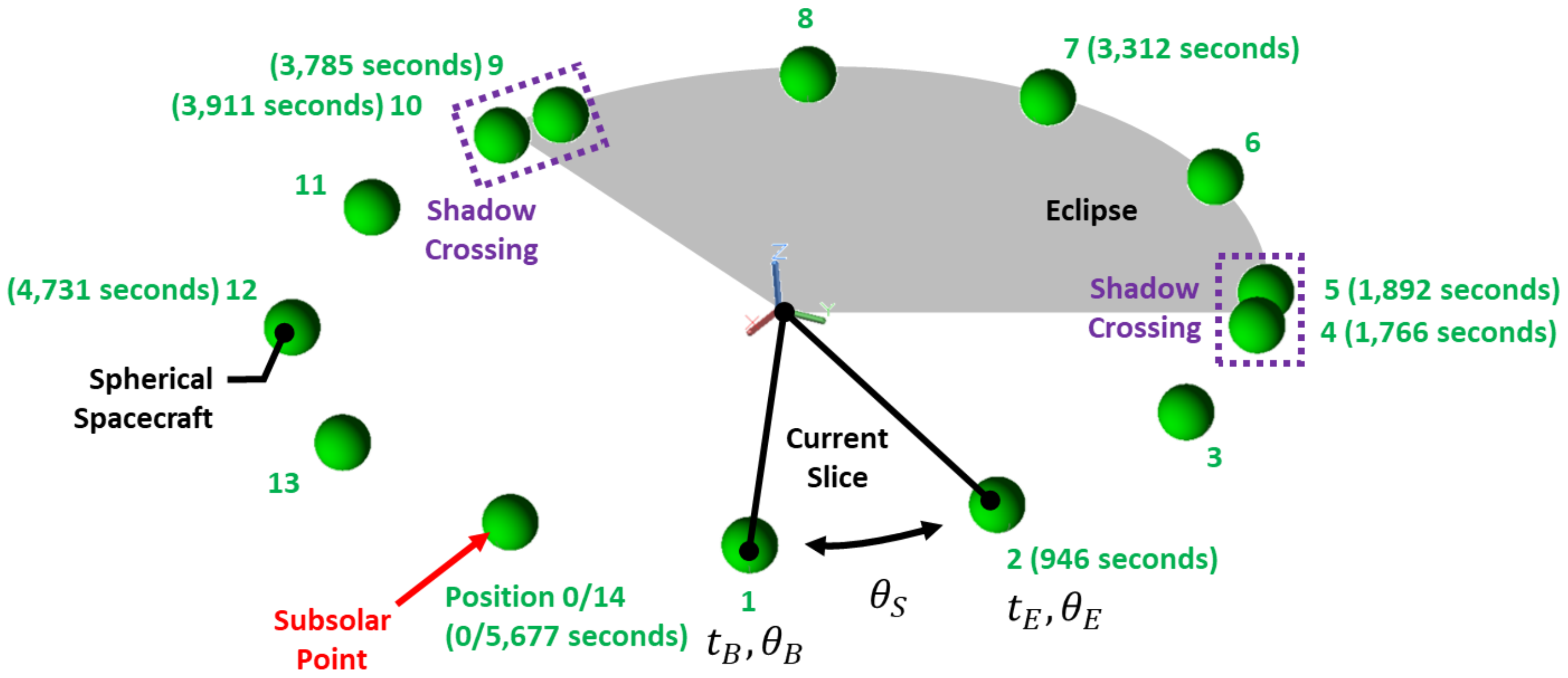
Enter Temperature [K], Emissivity

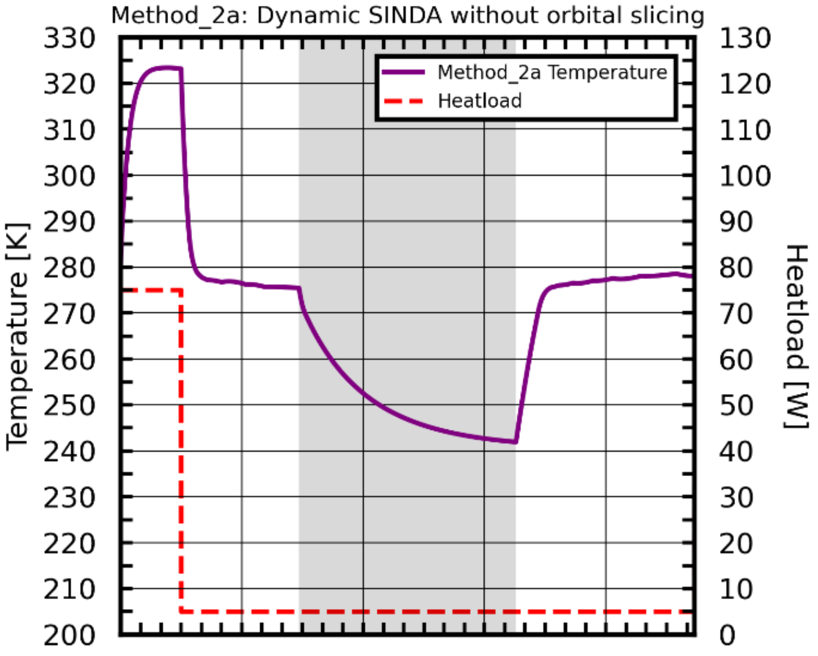
```
 0.000     0.2
270.000    0.2
290.000    0.8
1000.000   0.8
```

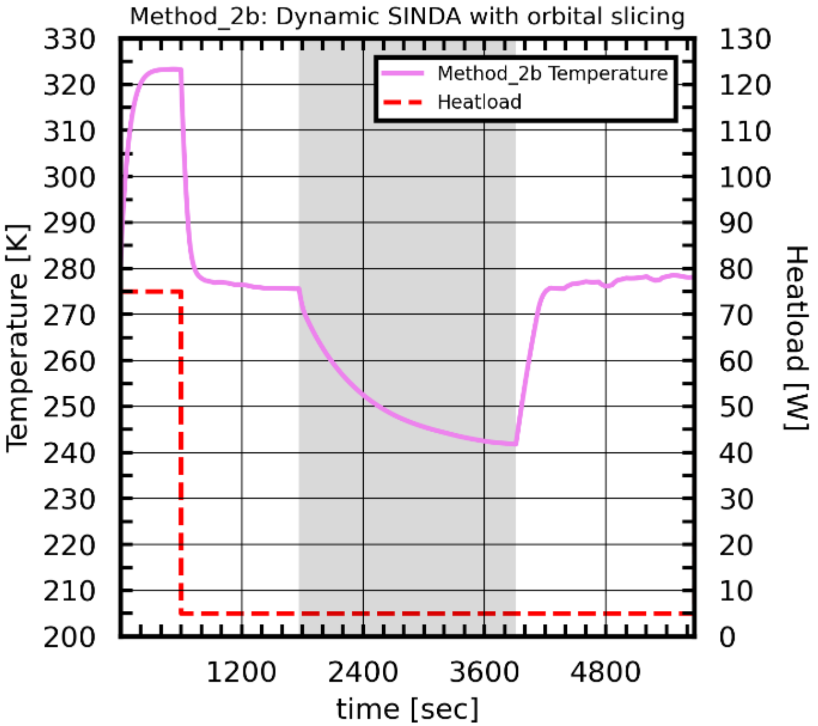
☑ Dynamic Plotting

Method 2: Dynamic SINDA (Orbital Slicing

- Dynamic SINDA
  - Computationally expensive. When radiation jobs are updated ALL orbital positions (i.e., 14 in our example) are recalculated)
  - Only local orbital positions are needed (i.e., 2 instead of 14)
  - More complex code



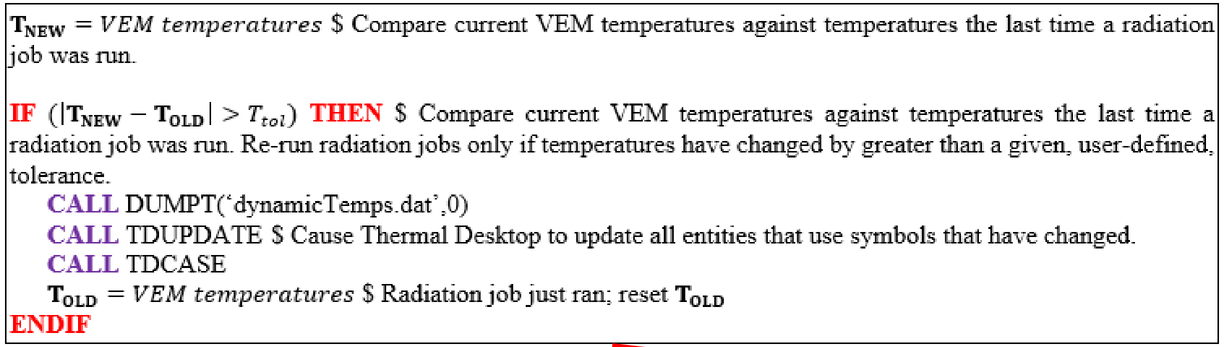

Method_2a: Dynamic SINDA without orbital slicing


Method_2b: Dynamic SINDA with orbital slicing

Method 2: Dynamic SINDA

- Dynamic SINDA
  - Requires additional variables/initialization and code in Output Calls
  - Details in paper

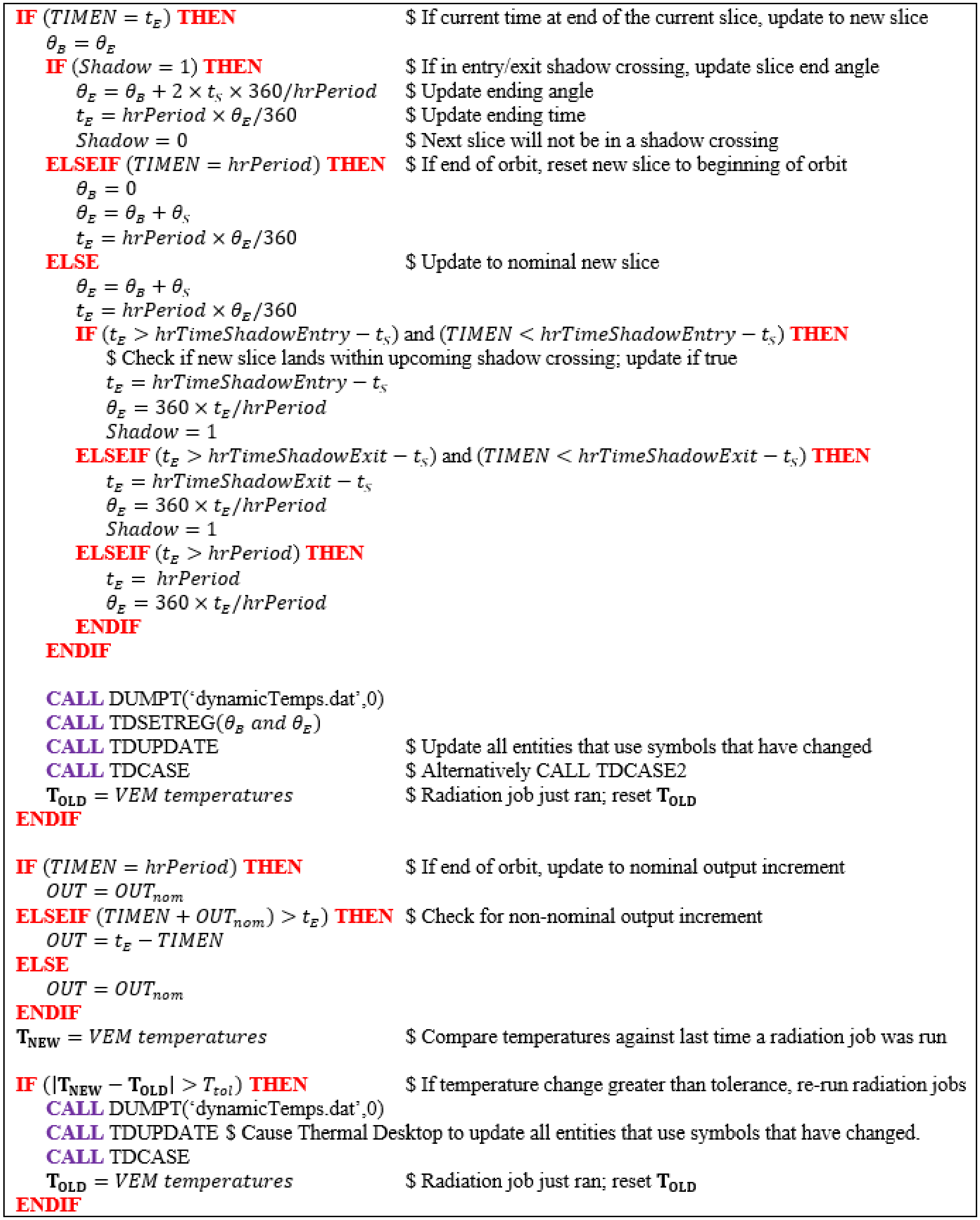
Dynamic SINDA pseudocode (Temperature evaluation)



```
$\mathbf{T_{NEW}} = VEM\ temperatures$ $ Compare current VEM temperatures against temperatures the last time a radiation job was run.

IF $(|\mathbf{T_{NEW}} - \mathbf{T_{OLD}}| > T_{tol})$ THEN $ Compare current VEM temperatures against temperatures the last time a radiation job was run. Re-run radiation jobs only if temperatures have changed by greater than a given, user-defined, tolerance.
    CALL DUMPT('dynamicTemps.dat',0)
    CALL TDUPDATE $ Cause Thermal Desktop to update all entities that use symbols that have changed.
    CALL TDCASE
    $\mathbf{T_{OLD}} = VEM\ temperatures$ $ Radiation job just ran; reset $\mathbf{T_{OLD}}$
ENDIF
```

Account for shadow crossings

Account for end of orbit

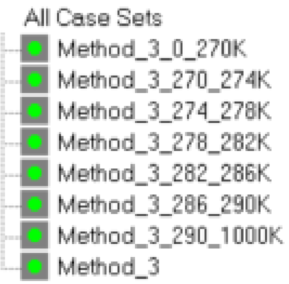


```
IF $(TIMEN = t_E)$ THEN                                  $ If current time at end of the current slice, update to new slice
    $\theta_B = \theta_E$
    IF $(Shadow = 1)$ THEN                               $ If in entry/exit shadow crossing, update slice end angle
        $\theta_E = \theta_B + 2 \times t_S \times 360/hrPeriod$   $ Update ending angle
        $t_E = hrPeriod \times \theta_E/360$                       $ Update ending time
        $Shadow = 0$                                               $ Next slice will not be in a shadow crossing
    ELSEIF $(TIMEN = hrPeriod)$ THEN                     $ If end of orbit, reset new slice to beginning of orbit
        $\theta_B = 0$
        $\theta_E = \theta_B + \theta_S$
        $t_E = hrPeriod \times \theta_E/360$
    ELSE                                                 $ Update to nominal new slice
        $\theta_E = \theta_B + \theta_S$
        $t_E = hrPeriod \times \theta_E/360$
        IF $(t_E > hrTimeShadowEntry - t_S)$ and $(TIMEN < hrTimeShadowEntry - t_S)$ THEN
            $ Check if new slice lands within upcoming shadow crossing; update if true
            $t_E = hrTimeShadowEntry - t_S$
            $\theta_E = 360 \times t_E/hrPeriod$
            $Shadow = 1$
        ELSEIF $(t_E > hrTimeShadowExit - t_S)$ and $(TIMEN < hrTimeShadowExit - t_S)$ THEN
            $t_E = hrTimeShadowExit - t_S$
            $\theta_E = 360 \times t_E/hrPeriod$
            $Shadow = 1$
        ELSEIF $(t_E > hrPeriod)$ THEN
            $t_E = hrPeriod$
            $\theta_E = 360 \times t_E/hrPeriod$
        ENDIF
    ENDIF

    CALL DUMPT('dynamicTemps.dat',0)
    CALL TDSETREG($\theta_B$ and $\theta_E$)
    CALL TDUPDATE                                        $ Update all entities that use symbols that have changed
    CALL TDCASE                                          $ Alternatively CALL TDCASE2
    $\mathbf{T_{OLD}} = VEM\ temperatures$               $ Radiation job just ran; reset $\mathbf{T_{OLD}}$
ENDIF

IF $(TIMEN = hrPeriod)$ THEN                             $ If end of orbit, update to nominal output increment
    $OUT = OUT_{nom}$
ELSEIF $((TIMEN + OUT_{nom}) > t_E)$ THEN                $ Check for non-nominal output increment
    $OUT = t_E - TIMEN$
ELSE
    $OUT = OUT_{nom}$
ENDIF
$\mathbf{T_{NEW}} = VEM\ temperatures$                   $ Compare temperatures against last time a radiation job was run

IF $(|\mathbf{T_{NEW}} - \mathbf{T_{OLD}}| > T_{tol})$ THEN       $ If temperature change greater than tolerance, re-run radiation jobs
    CALL DUMPT('dynamicTemps.dat',0)
    CALL TDUPDATE $ Cause Thermal Desktop to update all entities that use symbols that have changed.
    CALL TDCASE
    $\mathbf{T_{OLD}} = VEM\ temperatures$               $ Radiation job just ran; reset $\mathbf{T_{OLD}}$
ENDIF
```

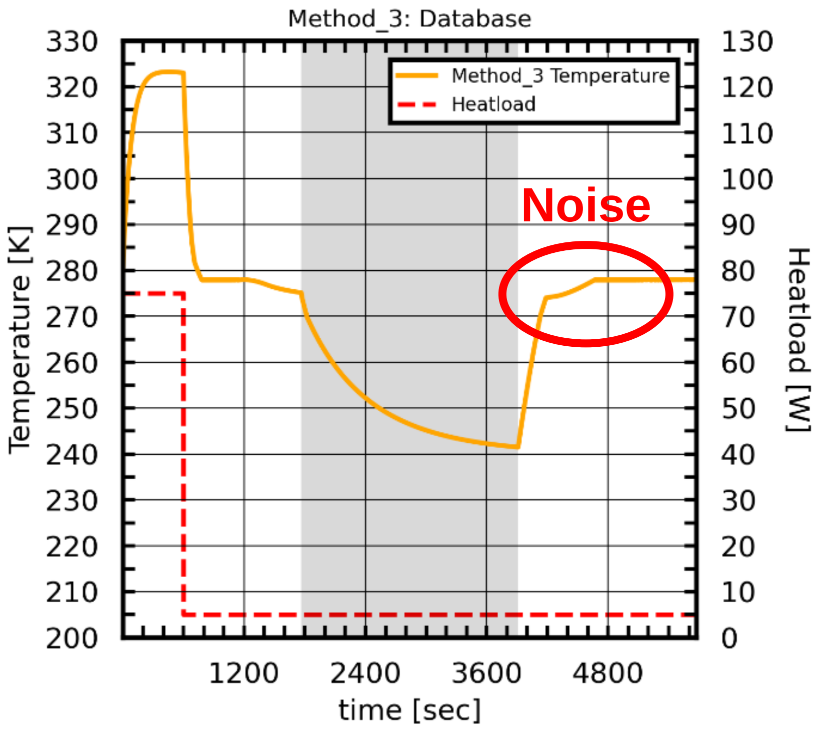
Method 3: Radiation Database

- Approach
  - Create pre-run Radks and Heating Rates across multiple temperature bands that capture the VEM properties
  - For each band: Create constant optical properties; Create Radiation Analysis groups; Create unique Case Sets
  - Control temperature bands with logic and insert files
- Do all the computationally expensive ray tracing ahead of time
- Not as versatile as Dynamic SINDA method (e.g., difficult to handle multiple VEM surfaces facing each other). However, less computationally expensive.

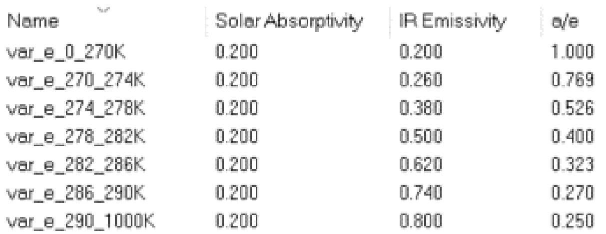
Example Case Sets



All Case Sets
- 🟩 Method_3_0_270K
- 🟩 Method_3_270_274K
- 🟩 Method_3_274_278K
- 🟩 Method_3_278_282K
- 🟩 Method_3_282_286K
- 🟩 Method_3_286_290K
- 🟩 Method_3_290_1000K
- 🟩 Method_3

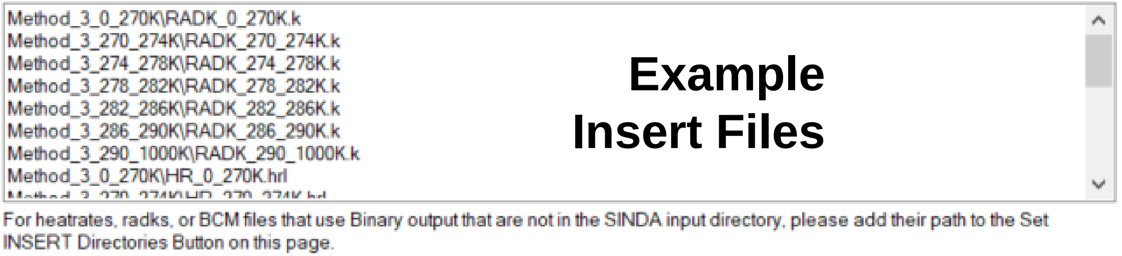


Example Optical Properties



Name	Solar Absorptivity	IR Emissivity	a/e
var_e_0_270K	0.200	0.200	1.000
var_e_270_274K	0.200	0.260	0.769
var_e_274_278K	0.200	0.380	0.526
var_e_278_282K	0.200	0.500	0.400
var_e_282_286K	0.200	0.620	0.323
var_e_286_290K	0.200	0.740	0.270
var_e_290_1000K	0.200	0.800	0.250

Example Insert Files



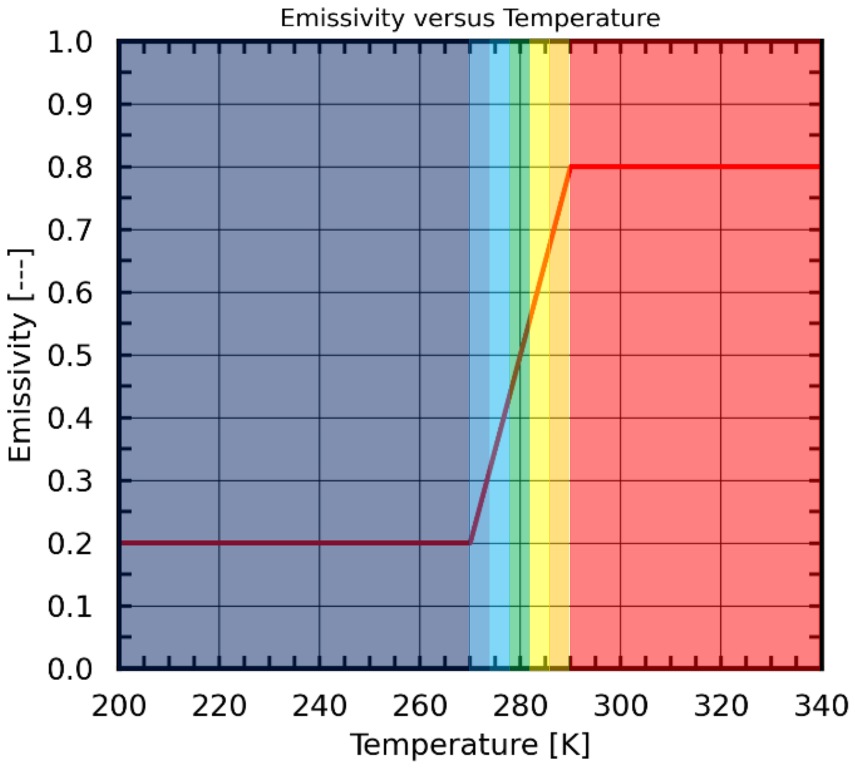
```
Method_3_0_270K\RADK_0_270K.k
Method_3_270_274K\RADK_270_274K.k
Method_3_274_278K\RADK_274_278K.k
Method_3_278_282K\RADK_278_282K.k
Method_3_282_286K\RADK_282_286K.k
Method_3_286_290K\RADK_286_290K.k
Method_3_290_1000K\RADK_290_1000K.k
Method_3_0_270K\HR_0_270K.hrl
```

For heatrates, radks, or BCM files that use Binary output that are not in the SINDA input directory, please add their path to the Set INSERT Directories Button on this page.

Method 3: Radiation Database

- Radiation Database
  - Requires additional variables/initialization and code in OPERATIONS block and User Logic
  - Details in paper

Illustration of temperature bands



Radiation Database pseudocode (OPERATIONS block)

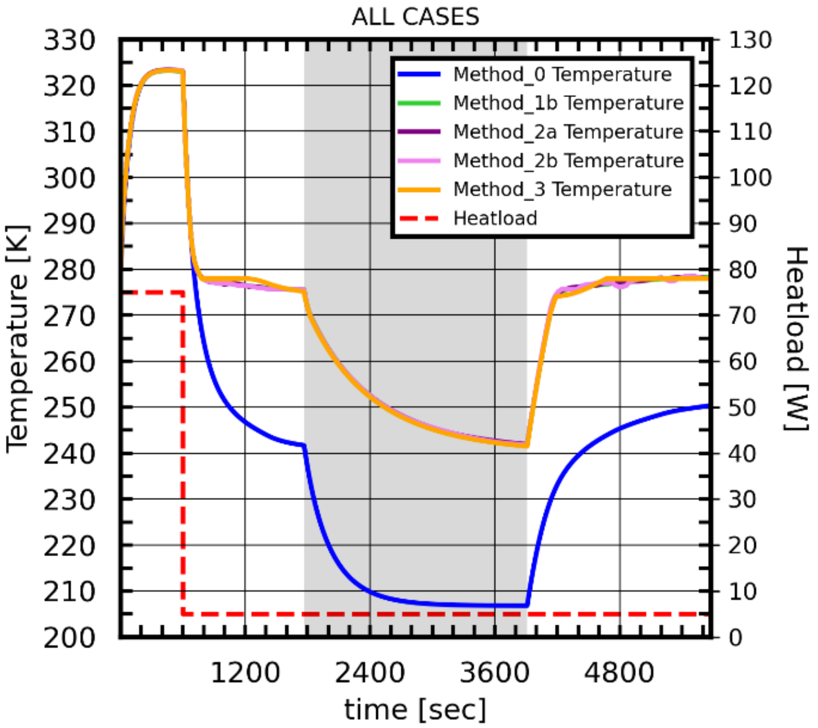
```
    ATEST = MAIN.T1
    BTEST = TIMEN
    TIMEND = HRPERIOD
    CTEST = TIMEND

F   DO WHILE (BTEST.LT.CTEST)
F   IF (ATEST .LE. 270.) THEN
BUILD BANDED, MAIN, HEAT, RADK_0_270K, HR_0_270K, SPACE
    TEMP_HIGH = 270.
    TEMP_LOW = 0.

F   ELSEIF ((ATEST .GT. 270.).AND.(ATEST .LE. 274.)) THEN
BUILD BANDED, MAIN, HEAT, RADK_270_274K, HR_270_274K, SPACE
    TEMP_HIGH = 274.
    TEMP_LOW = 270.
…
F   ELSEIF (ATEST .GT. 290.) THEN
BUILD BANDED, MAIN, HEAT, TDPROPS, RADK_290_1000K, HR_290_1000K, SPACE
    TEMP_HIGH = 1000.
    TEMP_LOW = 290.
F   ENDIF

    CALL TRANSIENT
    CALL TDHTOT $ Output Heater Summary

    ATEST = MAIN.T1
    BTEST = TIMEN
    TIMEND = HRPERIOD
    CTEST = TIMEND
F   END DO
```

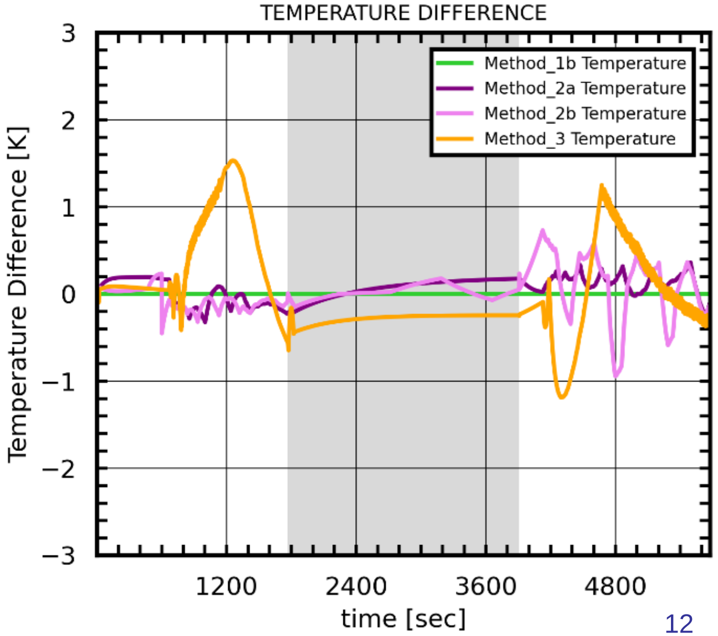
Radiation Database pseudocode (User Logic)

```
    FTEST = MAIN.T1
F   IF ((FTEST .LT. TEMP_LOW).OR.(FTEST .GT. TEMP_HIGH)) THEN
        TIMEND = TIMEN
F   ENDIF
```

Method Comparison

- Recall
  - Method 0: Nominal (constant ε)
  - Method 1b: Radiation conductor (with Dynamic SINDA)
  - Method 2a: Dynamic SINDA (without orbital slicing)
  - Method 2b: Dynamic SINDA (with orbital slicing)
  - Method 3: Radiation Database
- All methods above were compared
  - Method 1b used as control; good agreement with one another; +/-1.5° C
  - Some differences. Likely a result of temperature band resolution and differences in orbital positions





Conclusions and Future Work

- Thermochromic VEMs could provide temperature dependent, passive, and reliable heat modulation for future spacecraft
- Three novel modeling methods were developed for transient simulations in Thermal Desktop
  - Methods agreed within +/-1.5° C
  - No single ‘best’ method’; depends on application
- Future work
  - Improvements to algorithms
  - Extend to steady-state
  - Evaluate against more complex problems

Method	Description	Application	Computational Cost
0	Traditional	Fixed emissivity problems only	Low (10 seconds)
1a	Radiation Conductor (without Dynamic SINDA)	Single VEM surface without spacecraft IR (emissivity-dependent) environmental heating	Low (10 seconds)
1b	Radiation Conductor (with Dynamic SINDA every 2 seconds)	Single VEM surface with spacecraft IR (emissivity-dependent) environmental heating	Extremely High (2,196 seconds)
2a	Dynamic SINDA (using T_{tol} but not orbital slicing)	Any number of VEM surfaces; any heating environment	High (162 seconds)
2b	Dynamic SINDA (using T_{tol} and orbital slicing)	Any number of VEM surfaces; any heating environment	Medium-High (146 seconds)
3	Radiation Database	Single VEM surface with emissivity-dependent environmental heating	Medium-Low (20 seconds)

Acknowledgments and References

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- The authors would also like to thank Doug Bell and Ansys/C&R Technologies for their support in developing these methods.

- References

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