Passive Thermal Analysis and Regulation for a Lightweight Lunar CubeRover

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3: NASA (Retired)

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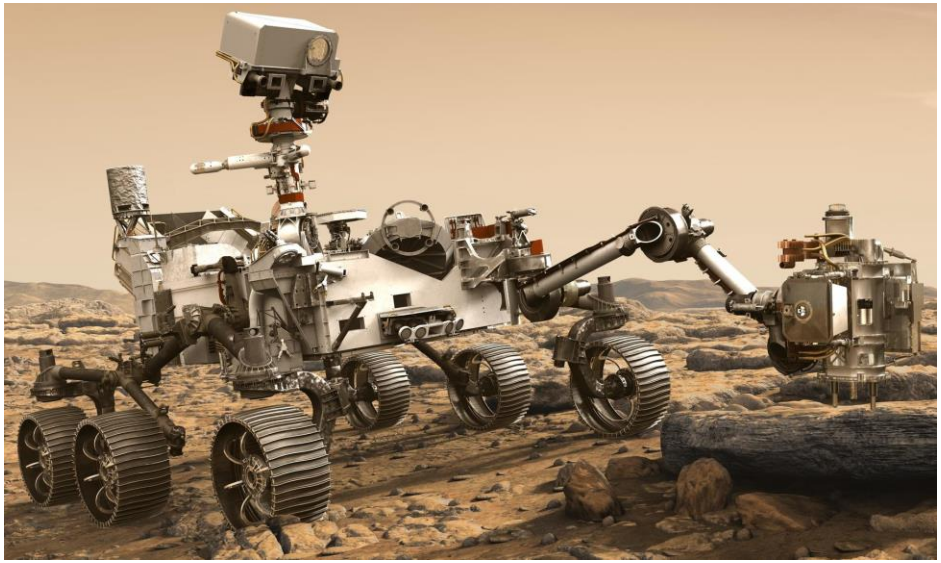
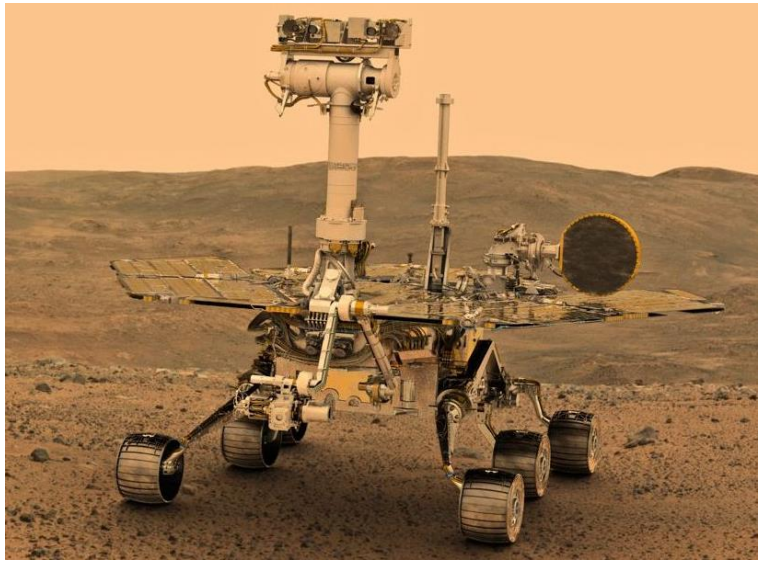
Outline

- Motivation
- Analysis: Spaceflight
  - Optimization: Insulation
- Analysis: Surface Operation
  - Optimization: Insulation
  - Optimization: Radiator
- TRASYS/SINDA Comparison

Motivation

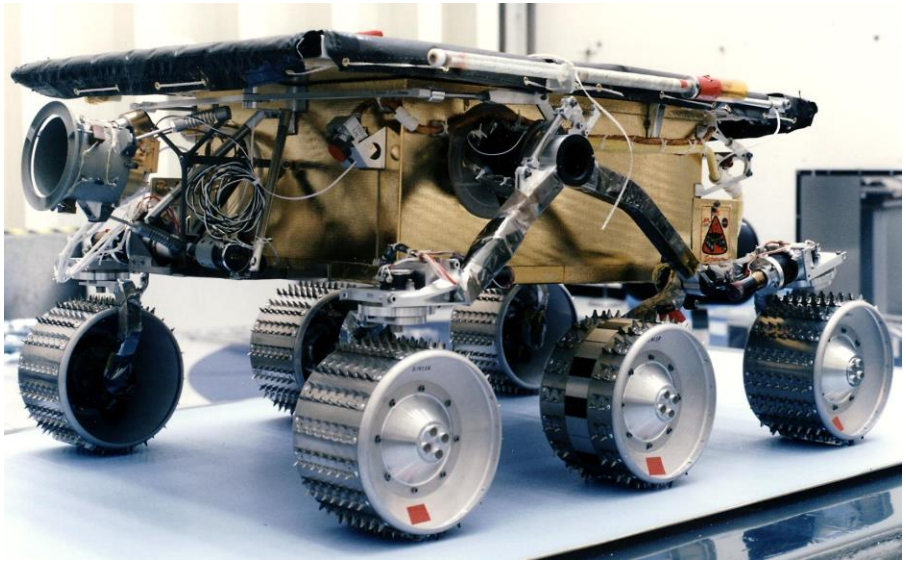
- Heavy and Medium Rovers: Legacy of Success
  - Weight: 100 – 1000 [kg] range
  - Advantages:
    - Longevity / Abundant Power / Equipment Capacity
  - Disadvantages:
    - High Cost / Low Mission Frequency / Limited Mission Flexibility

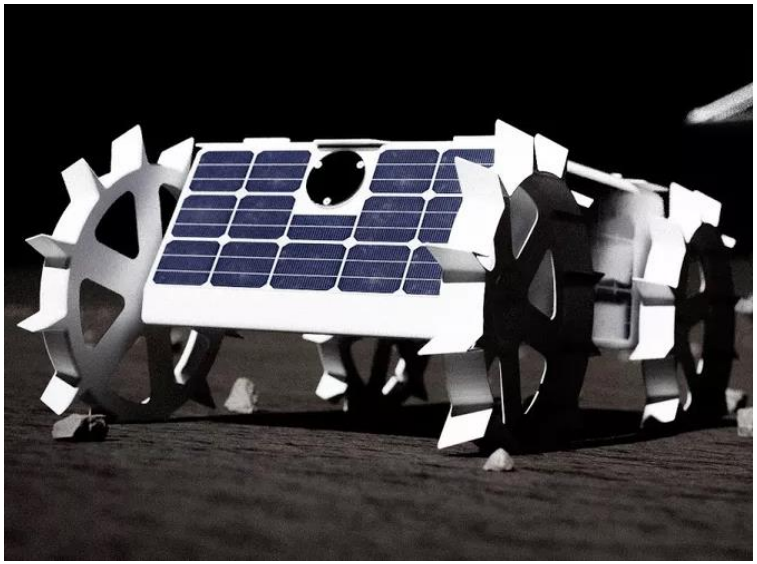




Motivation

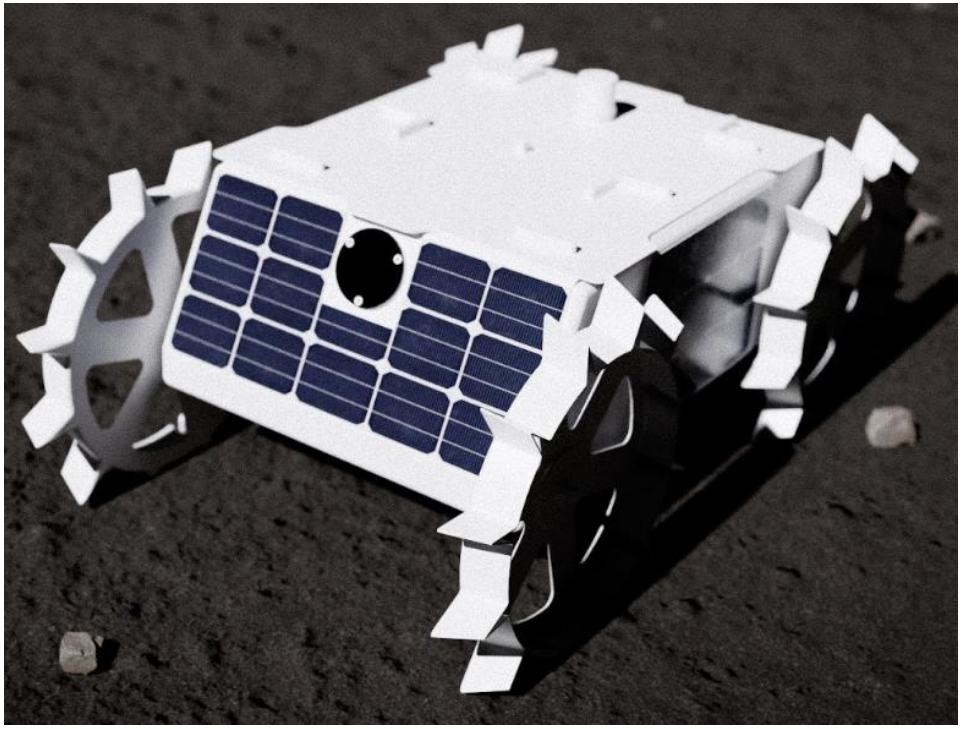
- Light and Ultralight Rovers: Future Vision
  - Weight: 1 – 10 [kg] range
  - Advantages:
    - Low Cost / High Mission Frequency / Modular Design
  - Disadvantages:
    - Short Lifespan / Low Power / Equipment Capacity



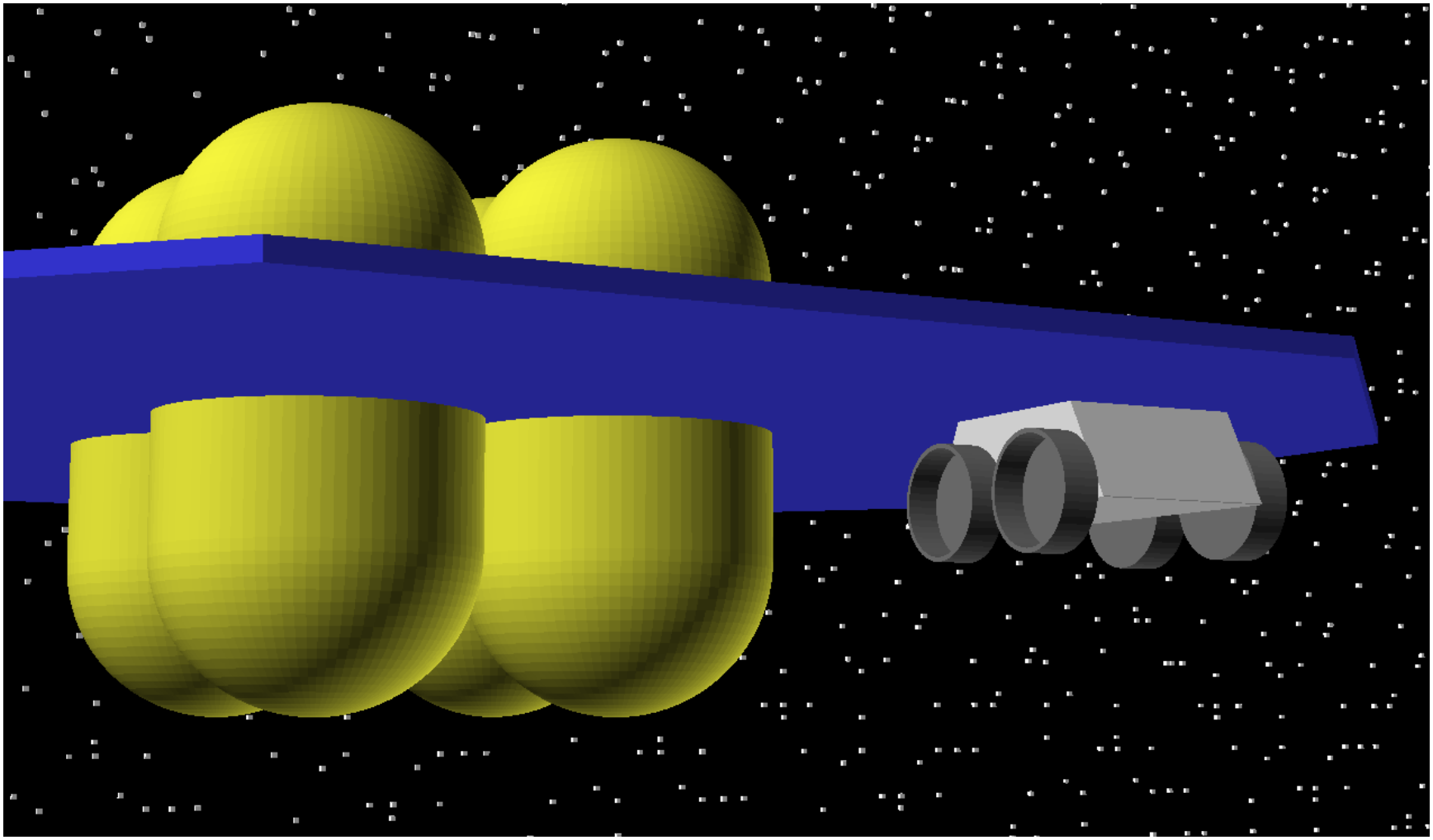


Motivation

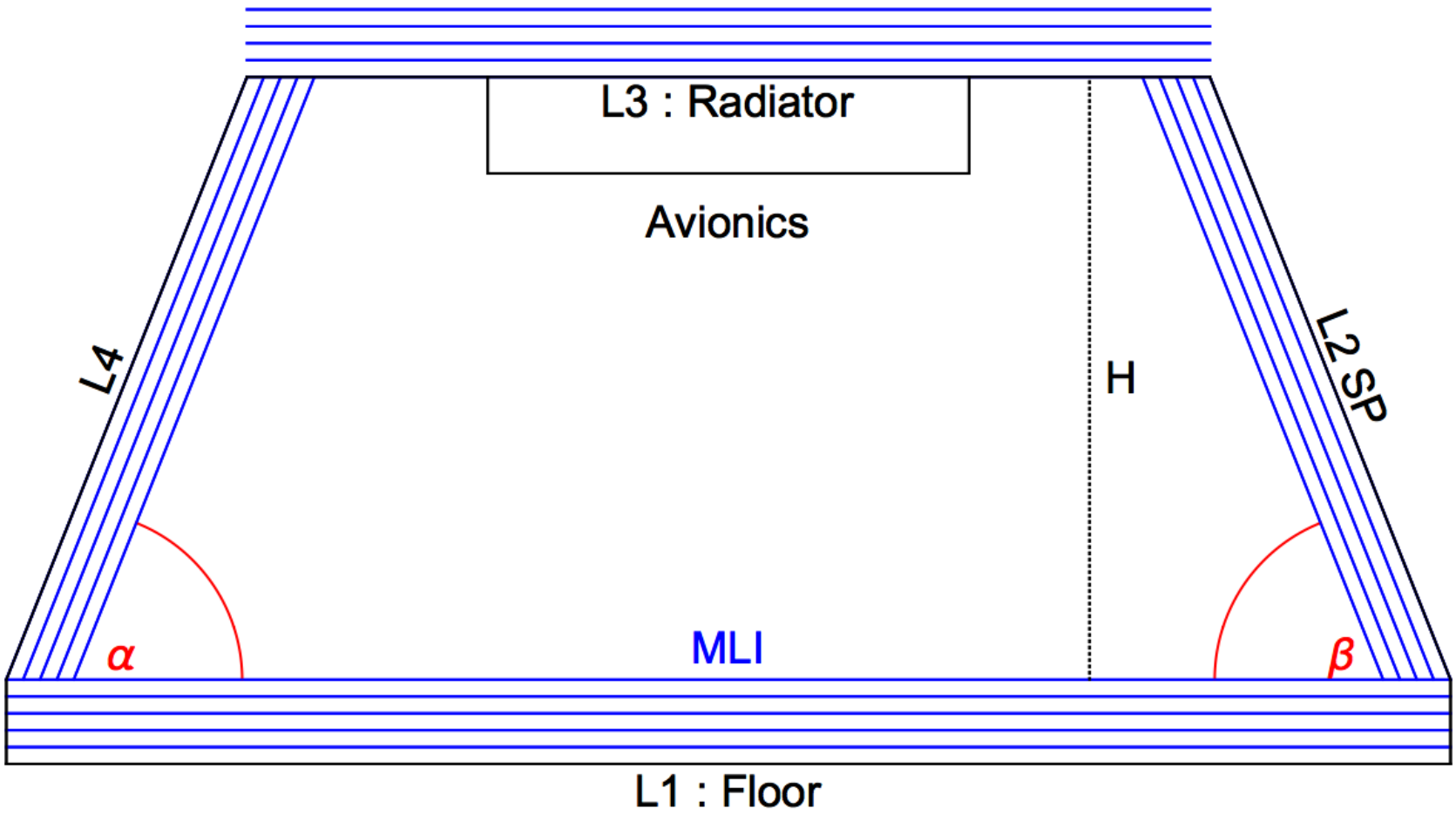
- CubeRover: Modular Ultralight Lunar Rover
  - Developed by Astrobotic and Carnegie Mellon University
  - Target weight: 2 [kg]
  - Hull bounding box: 30 [cm] x 20 [cm] x 10 [cm]
  - Average power consumption: 1.1 [W]



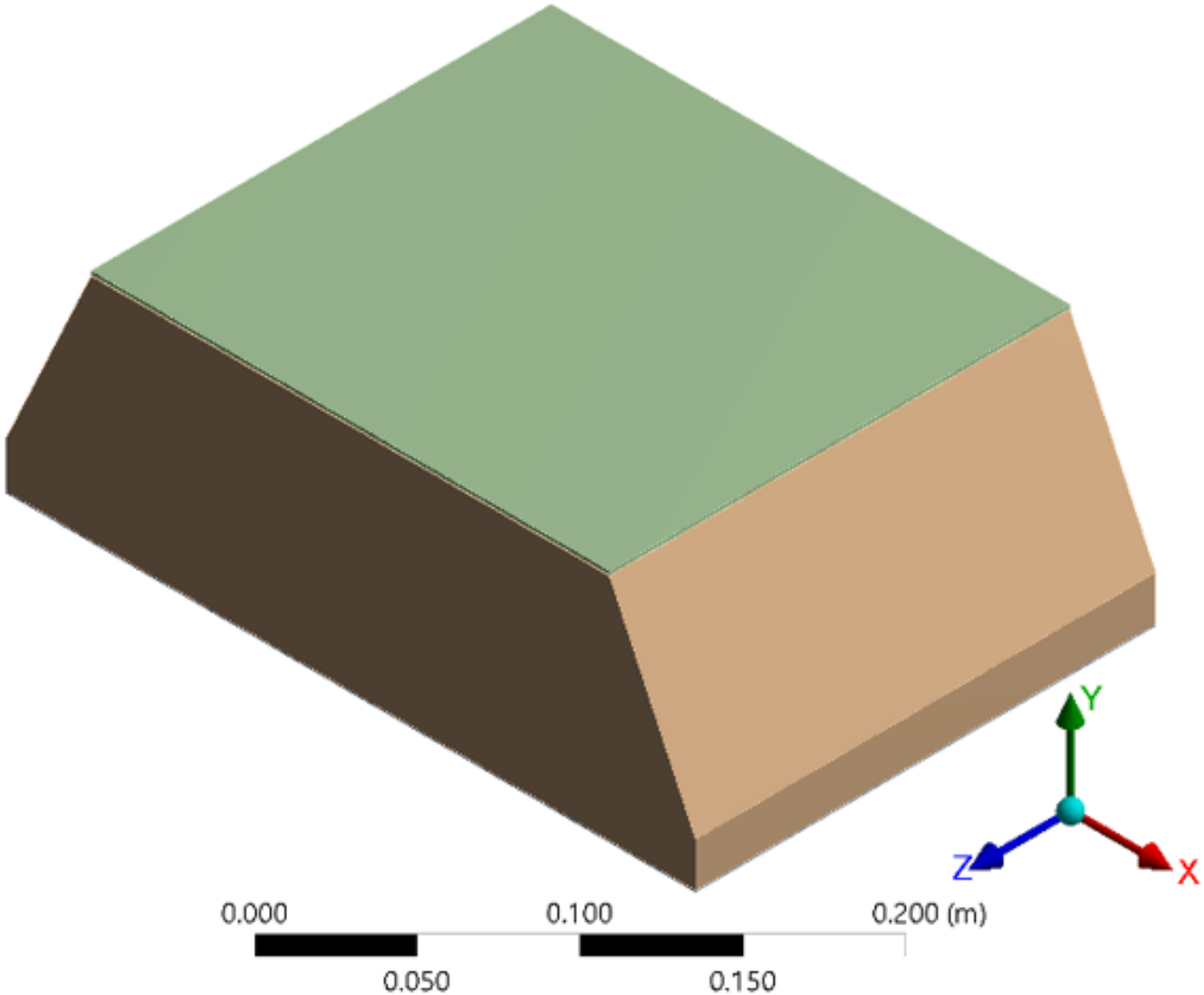
Spaceflight



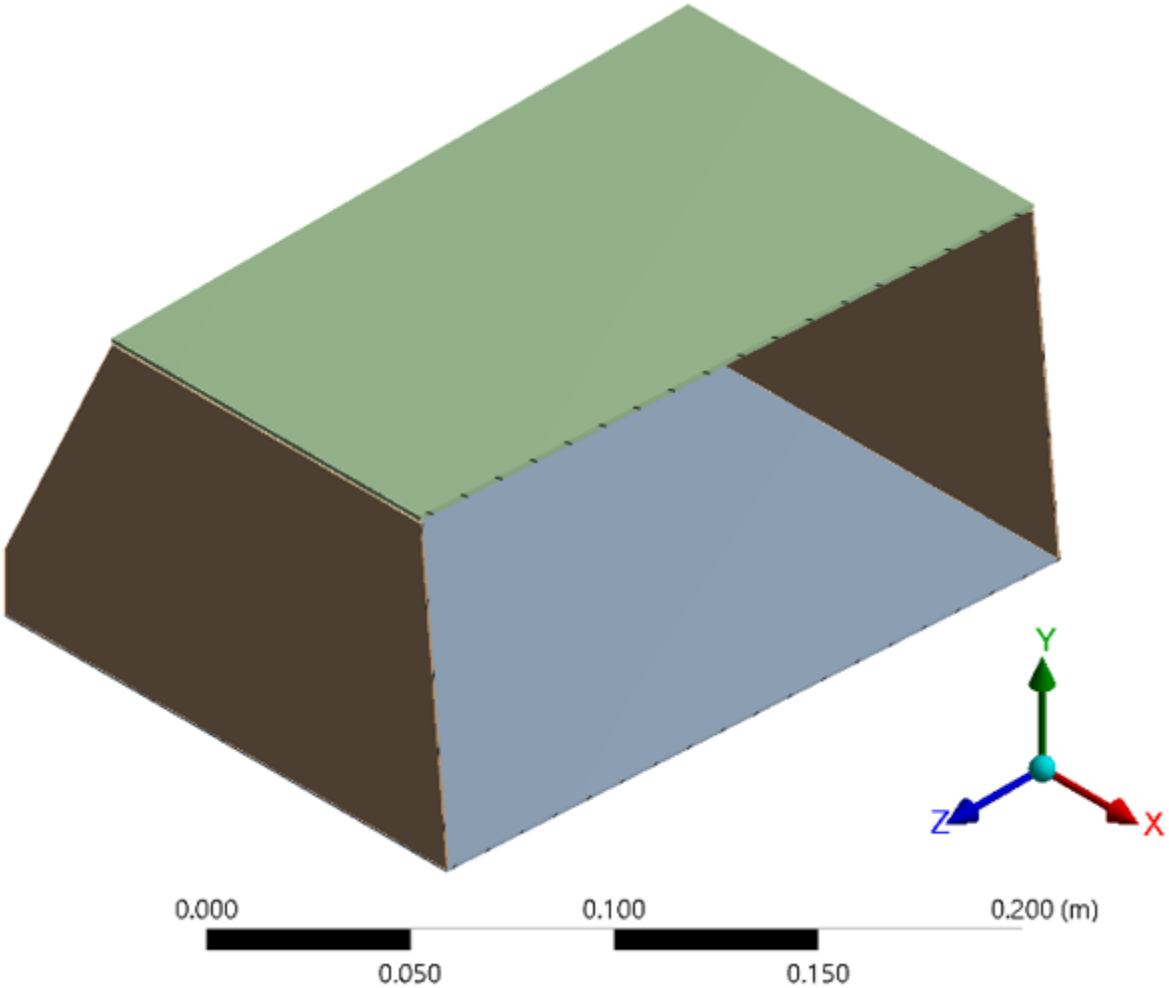
Method (Theory): Spaceflight



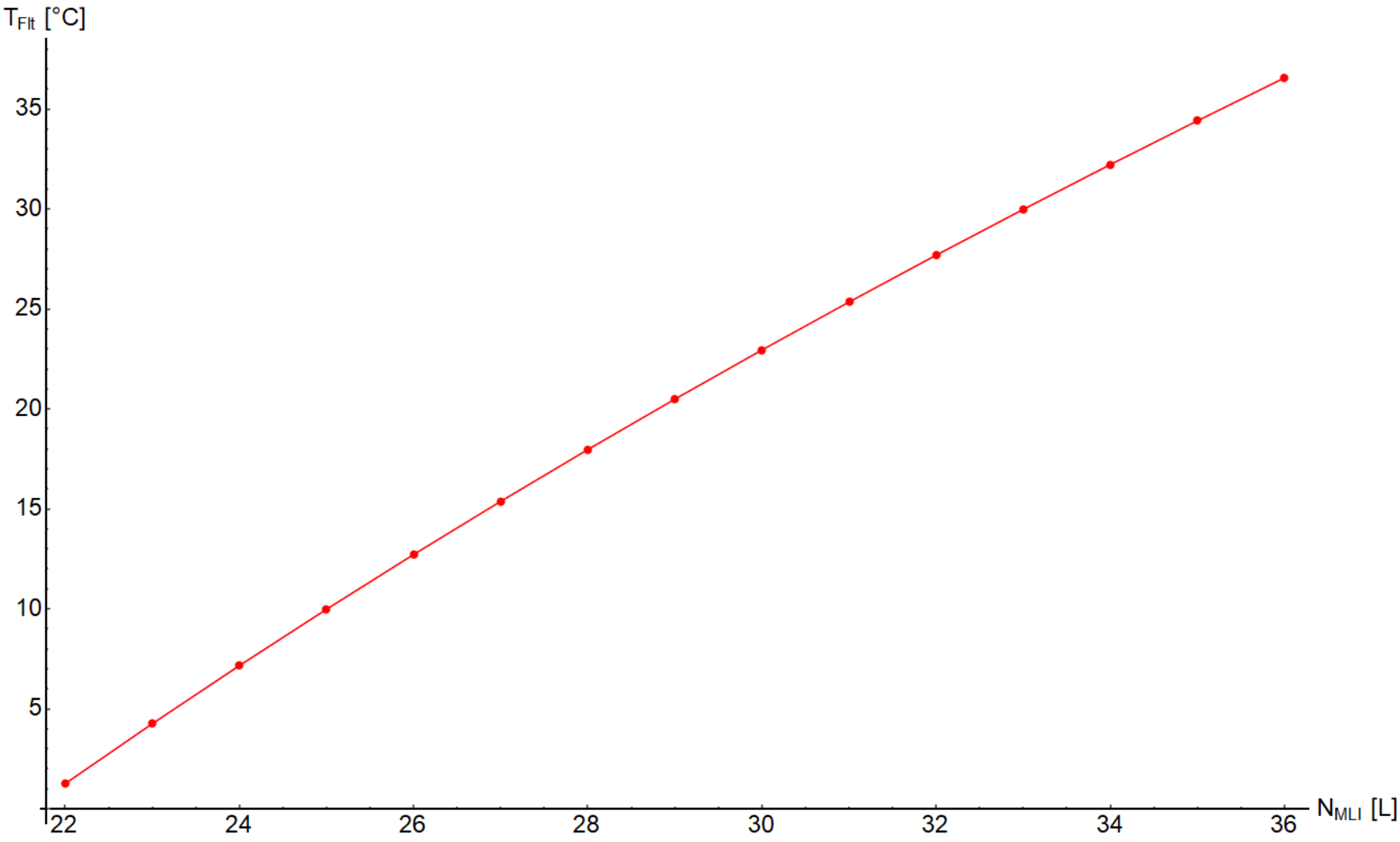
Method (FEA): Spaceflight



Method (FEA): Spaceflight

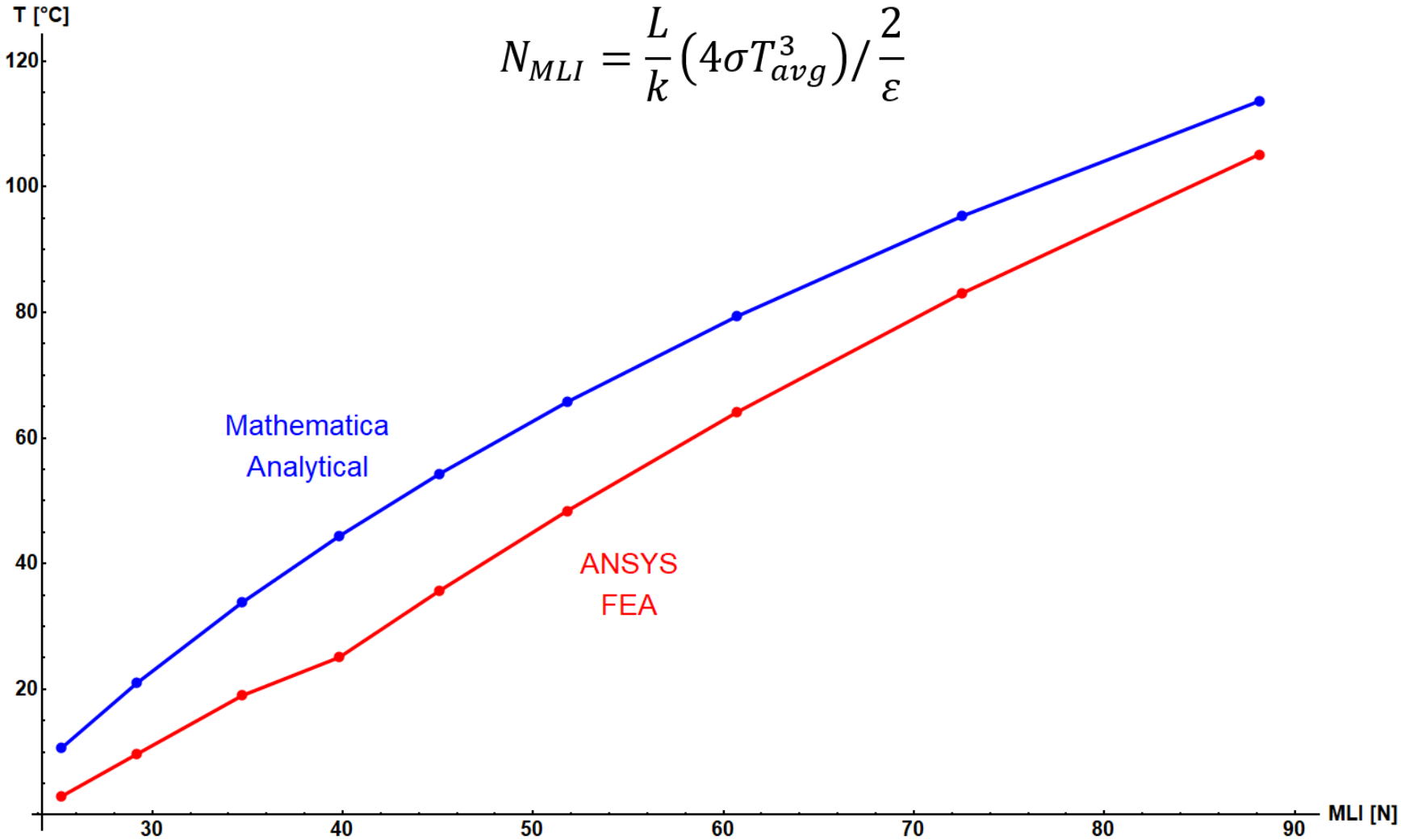


Results (Theory): Spaceflight

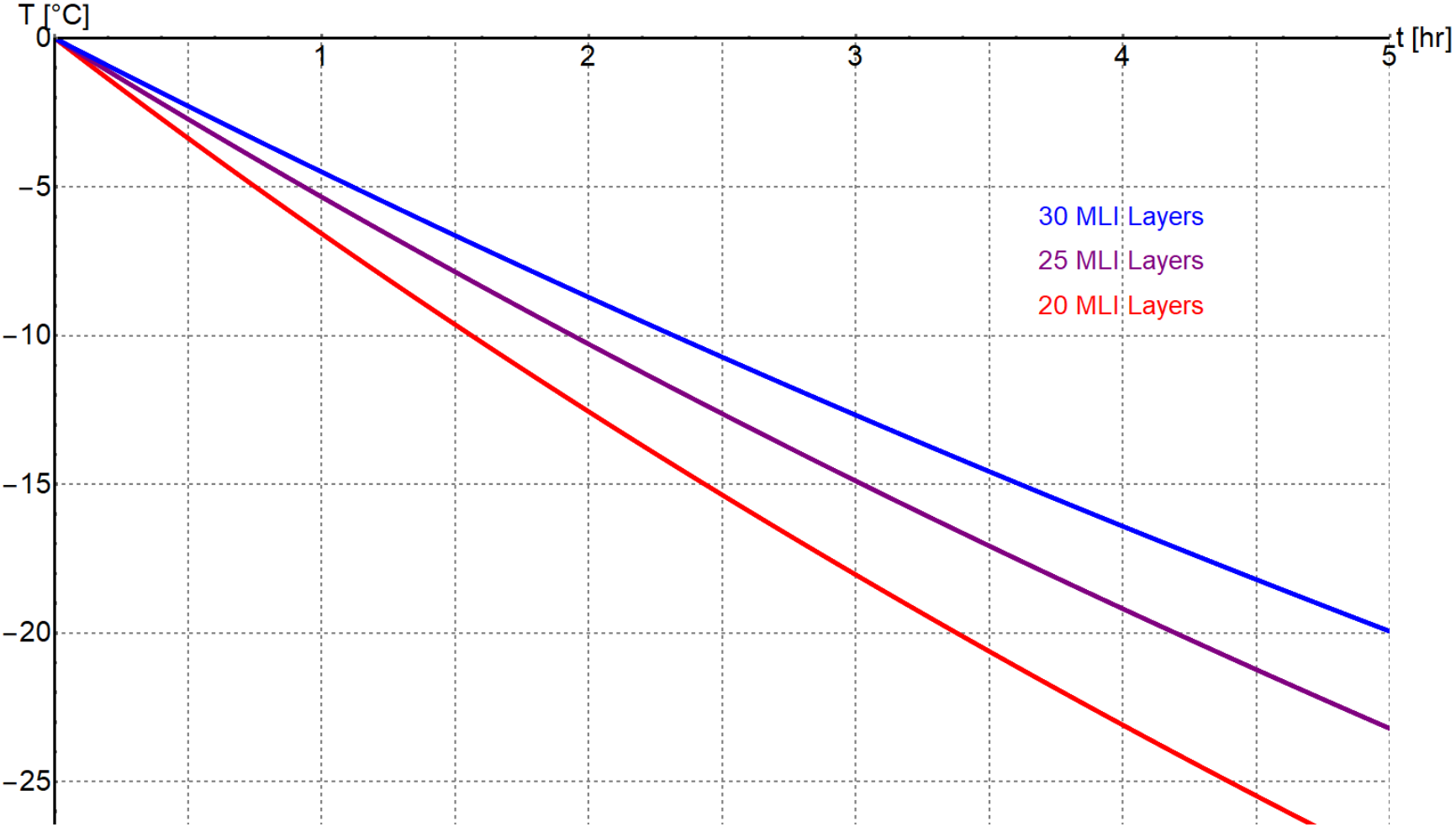


Results (FEA): Spaceflight

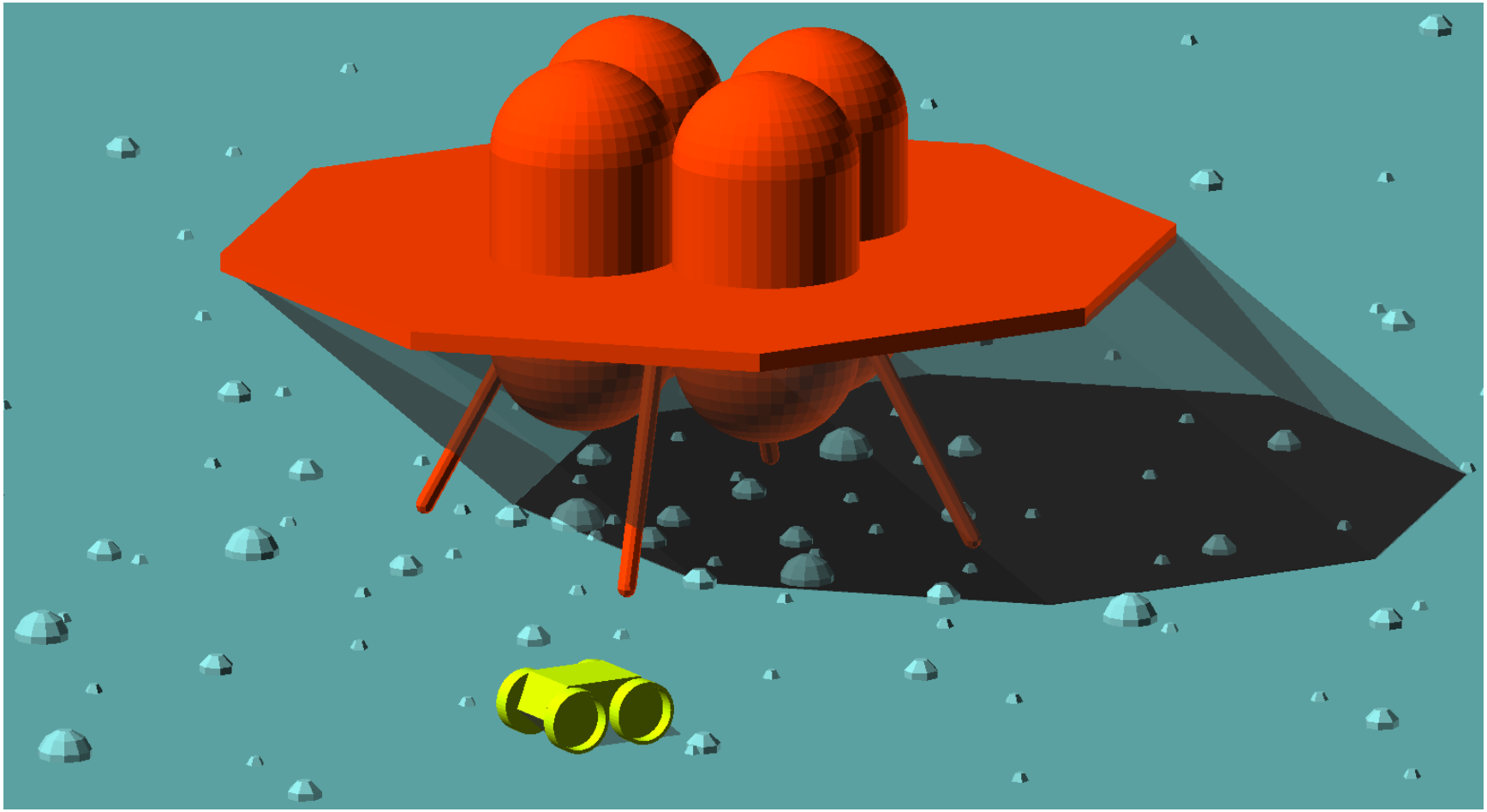
$$N_{MLI} = \frac{L}{k}\left(4\sigma T_{avg}^{3}\right) / \frac{2}{\varepsilon}$$



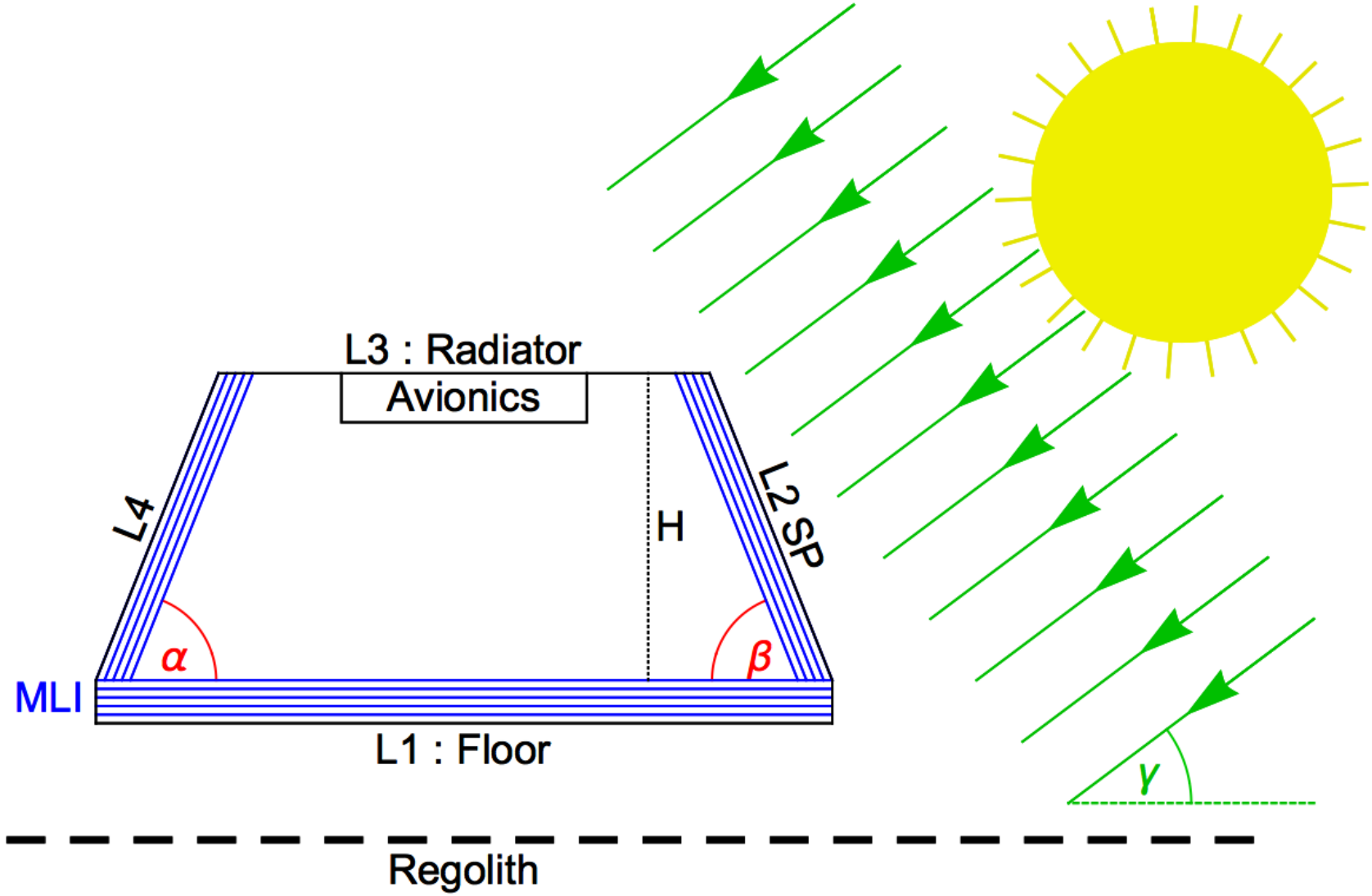
Results (Theory): Transient Spaceflight



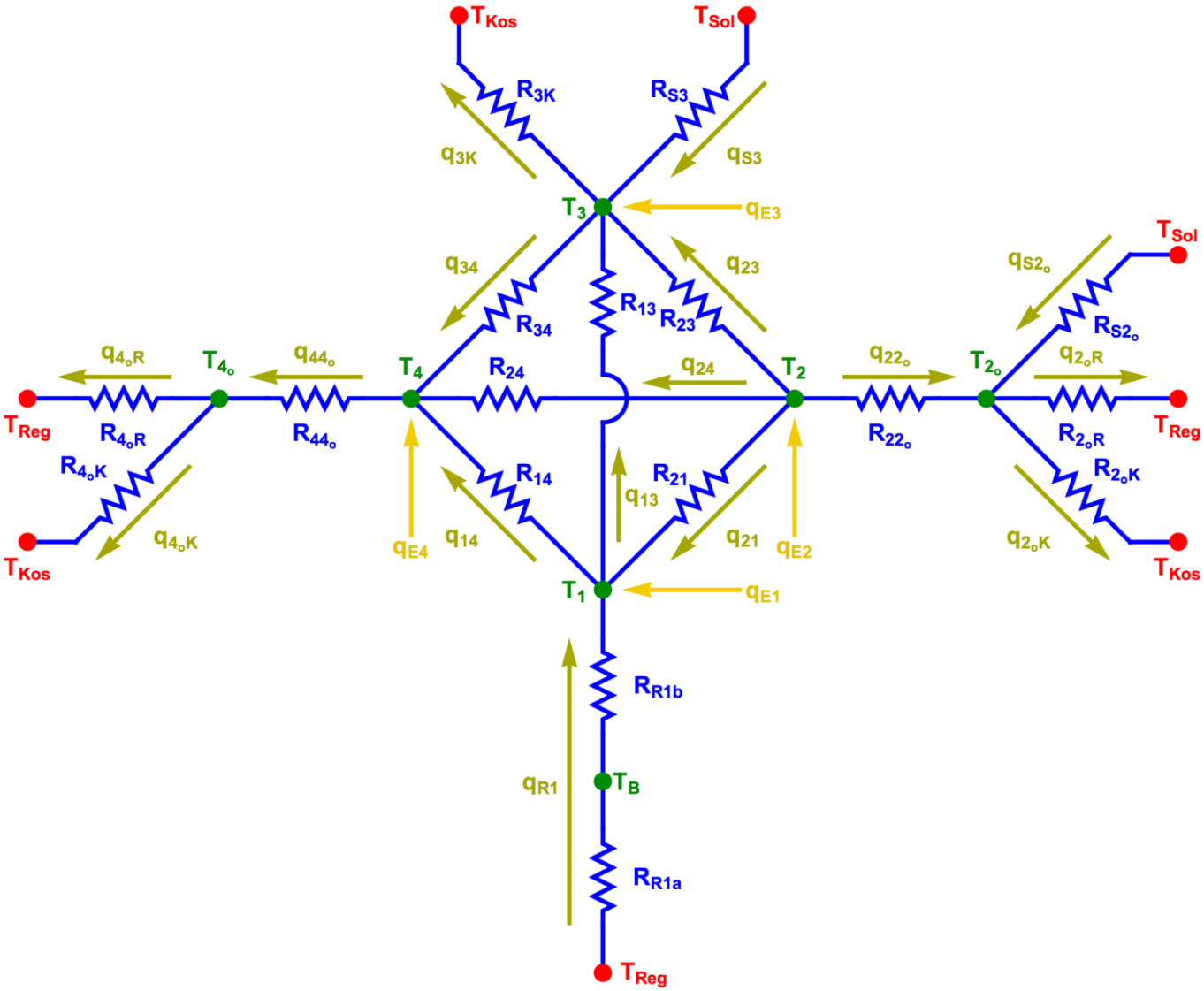
Surface Operation



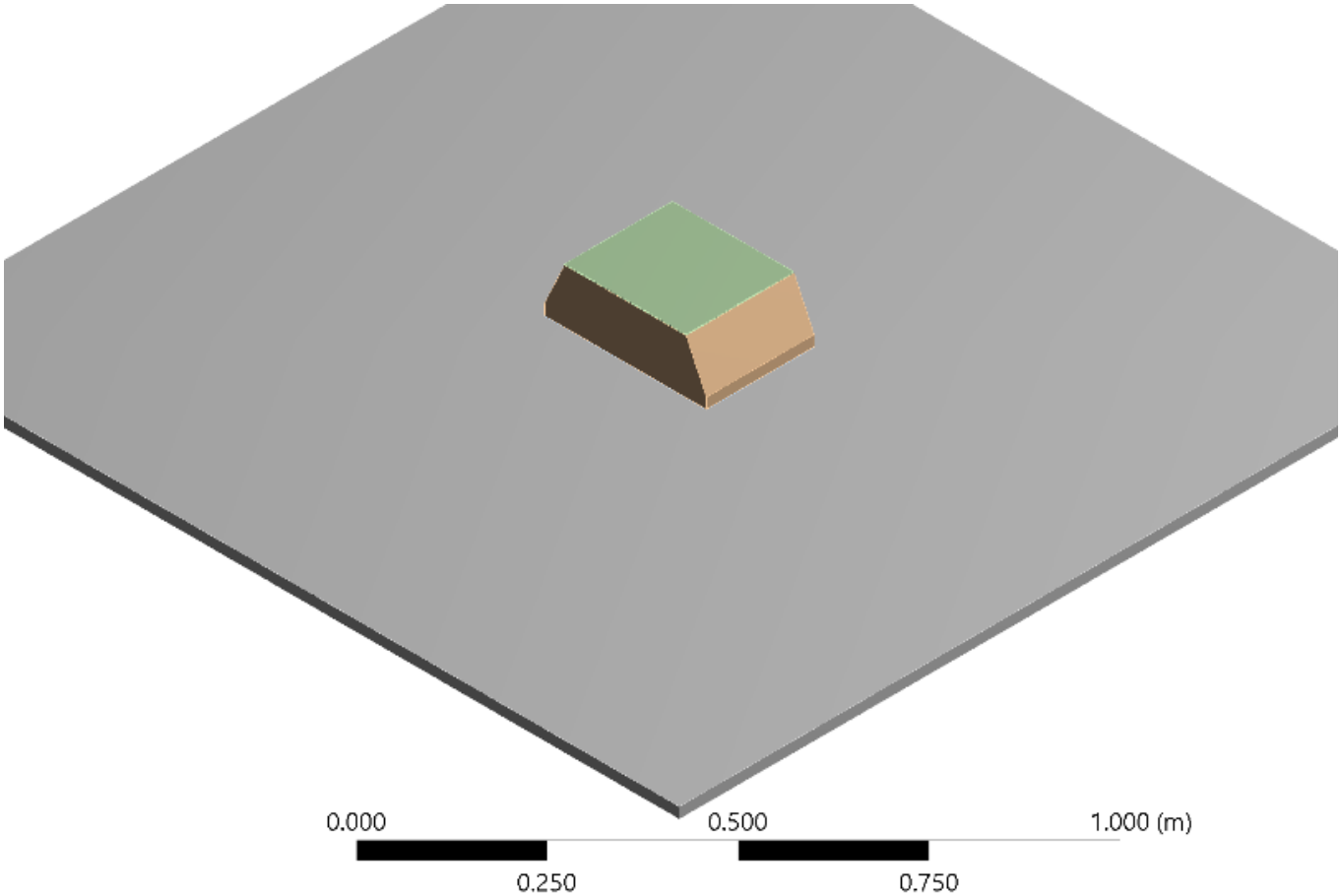
Method (Theory): Surface Operation



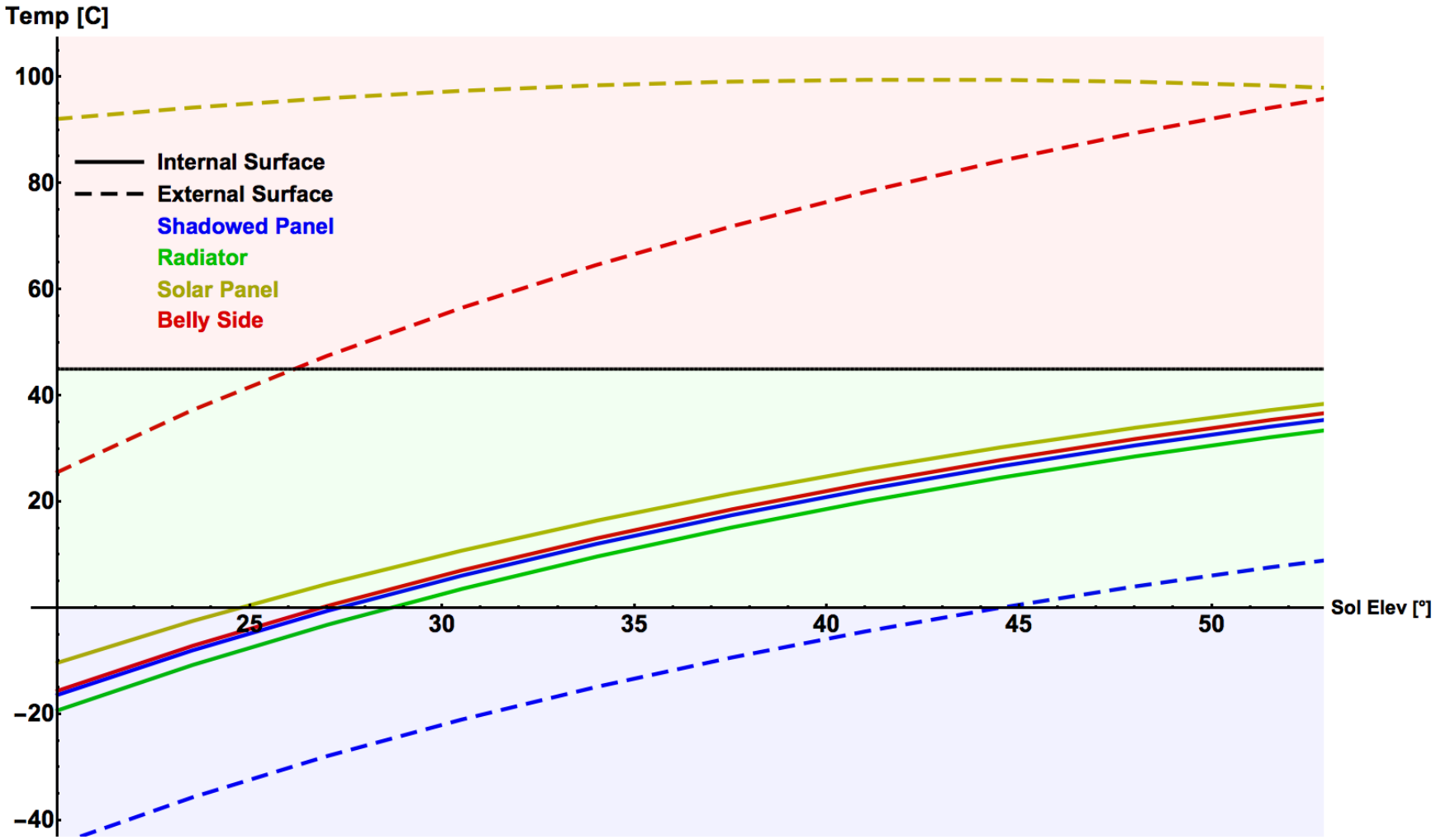
Method (Theory): Surface Operation



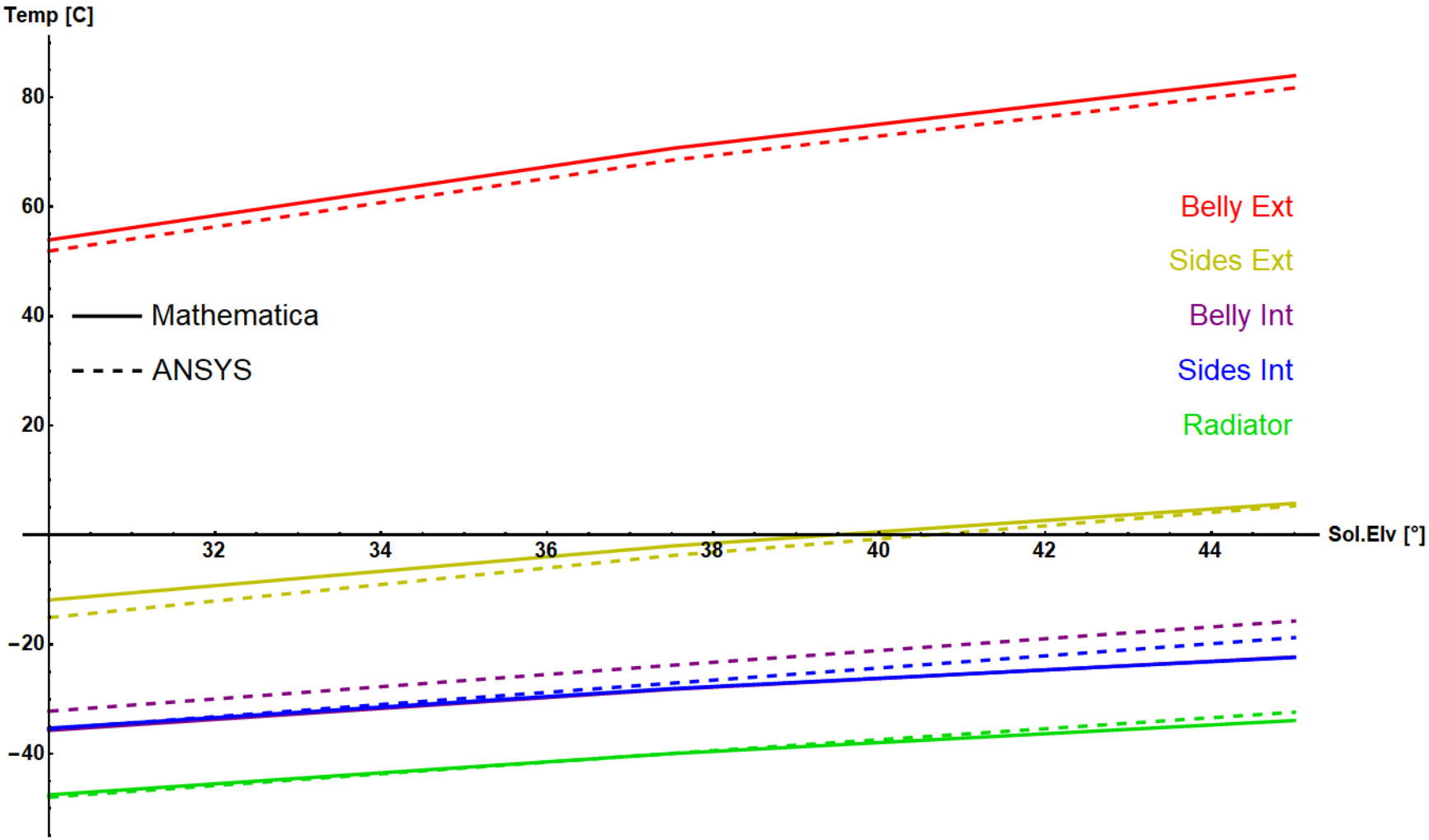
Method (FEA): Surface Operation



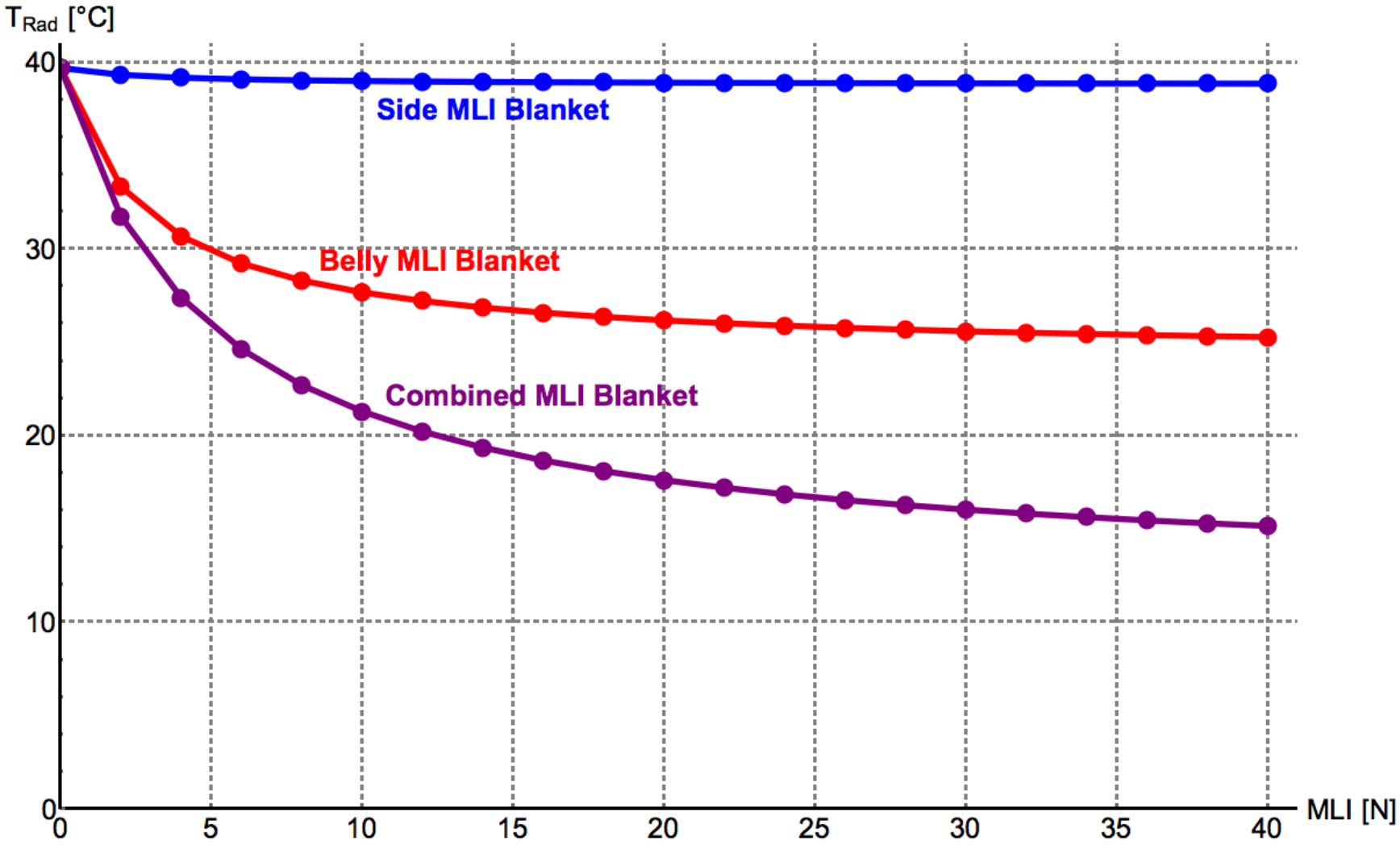
Results (Theory): Surface Operation



Results (FEA): Surface Operation

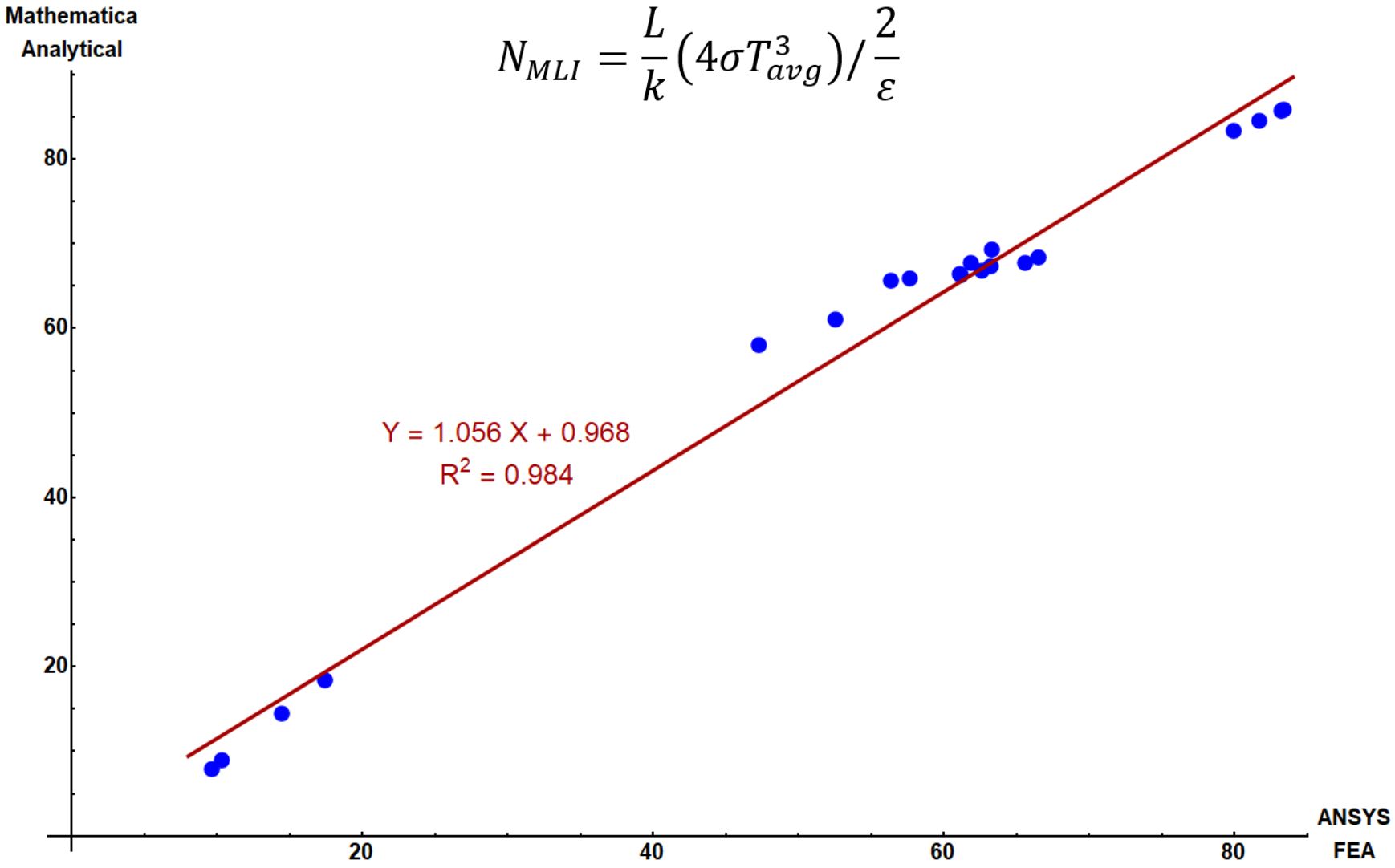


Results (Theory): MLI Blanket

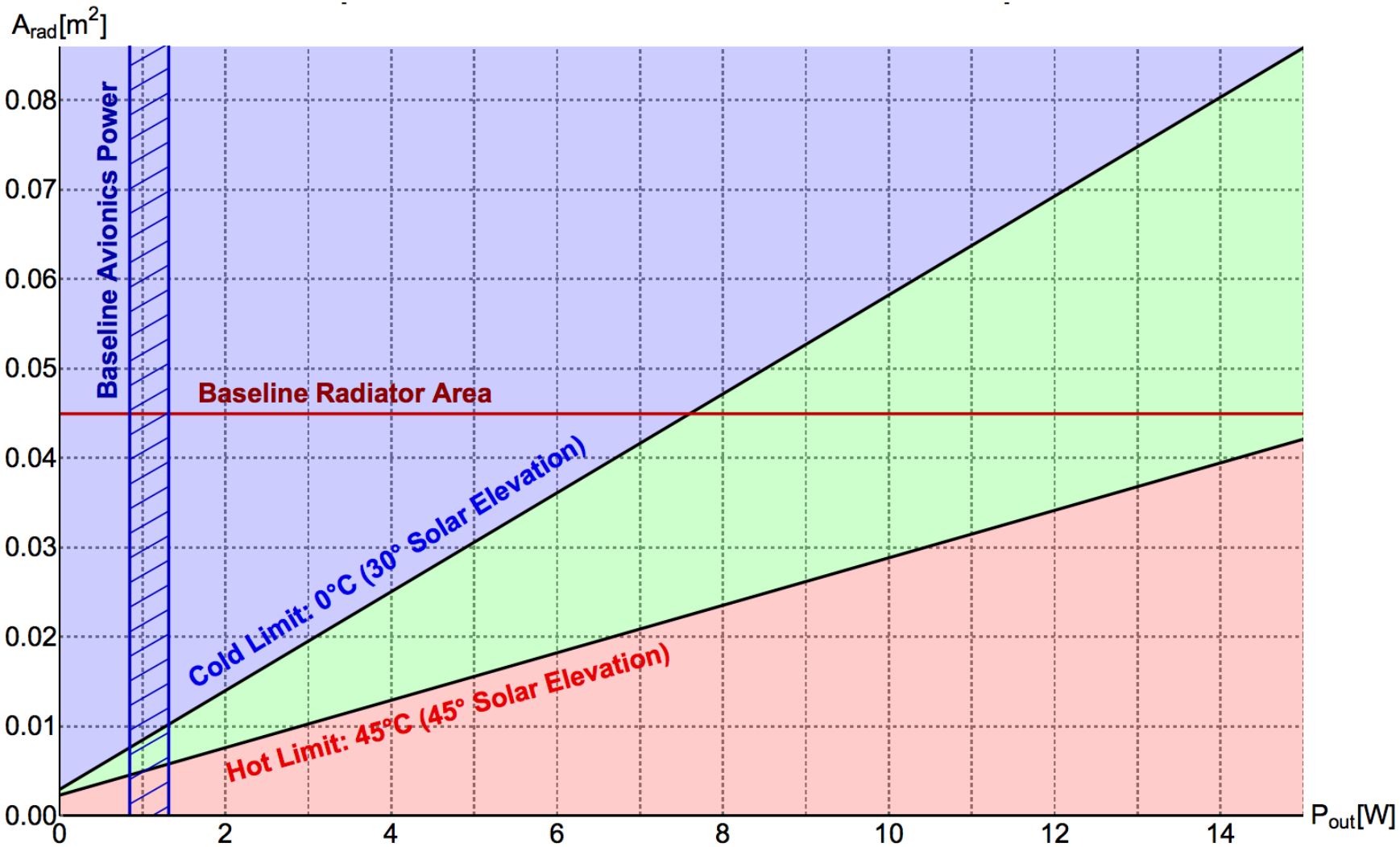


Results (FEA): MLI Blanket

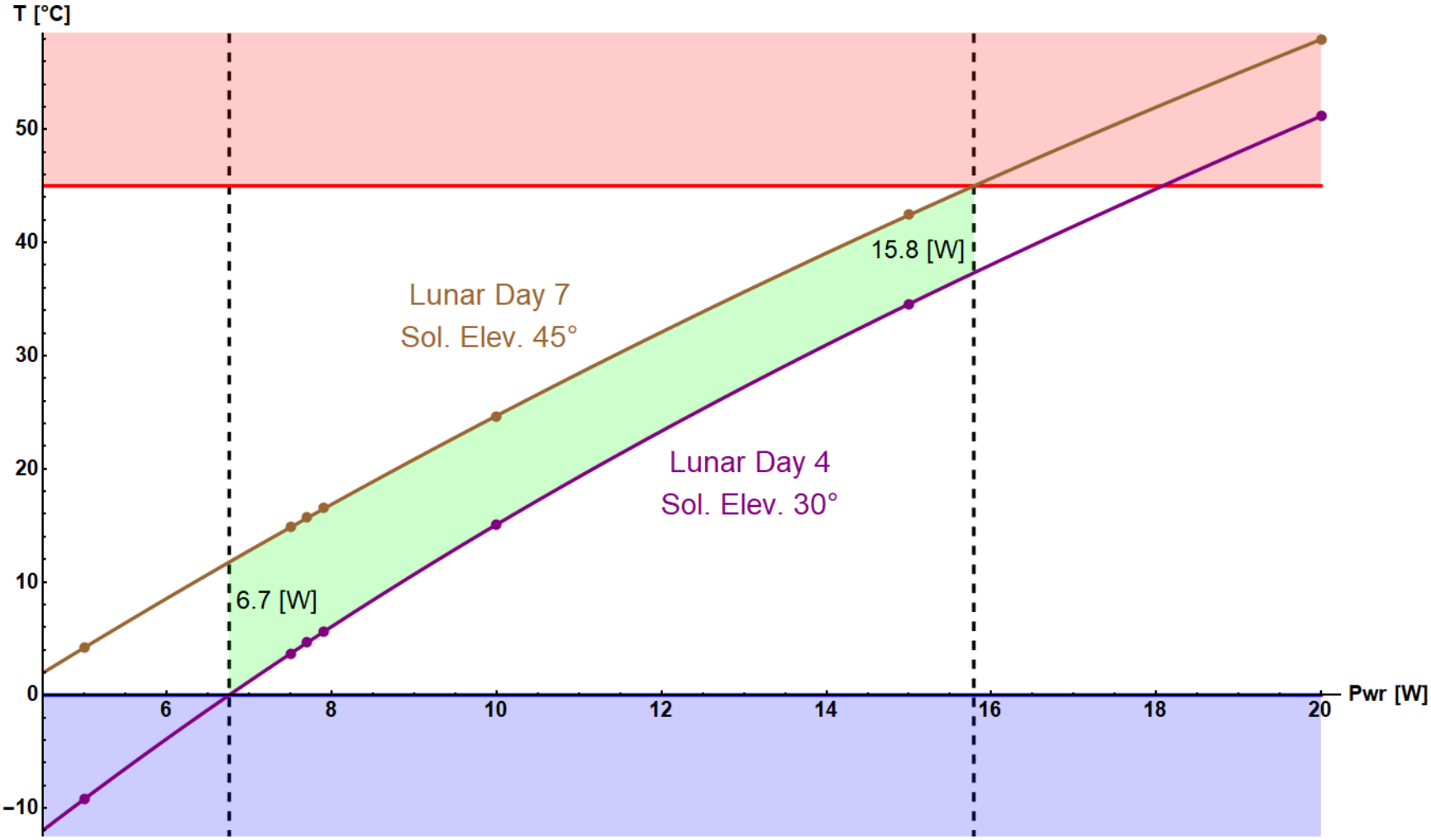
$$N_{MLI} = \frac{L}{k}\left(4\sigma T_{avg}^{3}\right) / \frac{2}{\varepsilon}$$



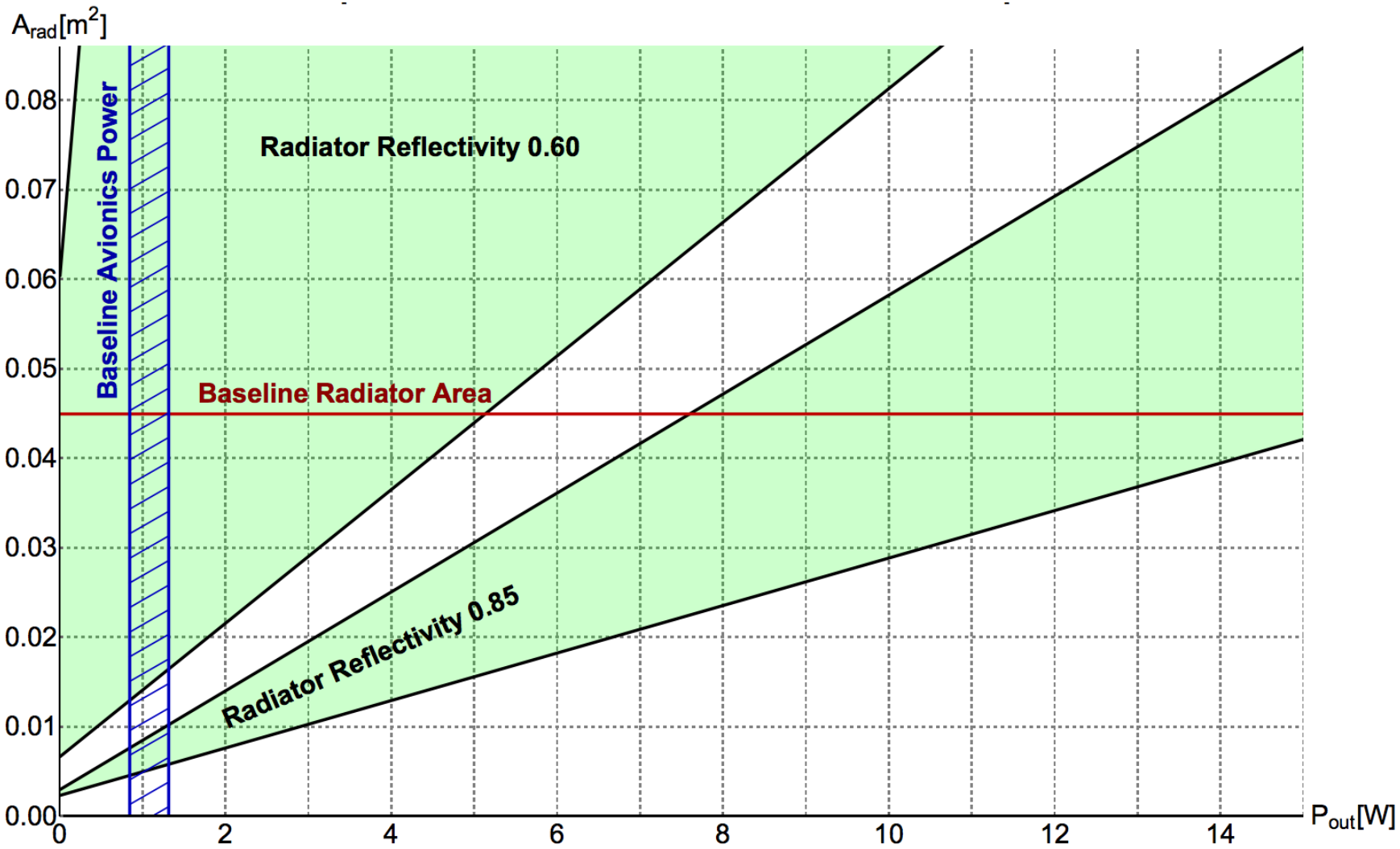
Results (Theory): Radiator Design



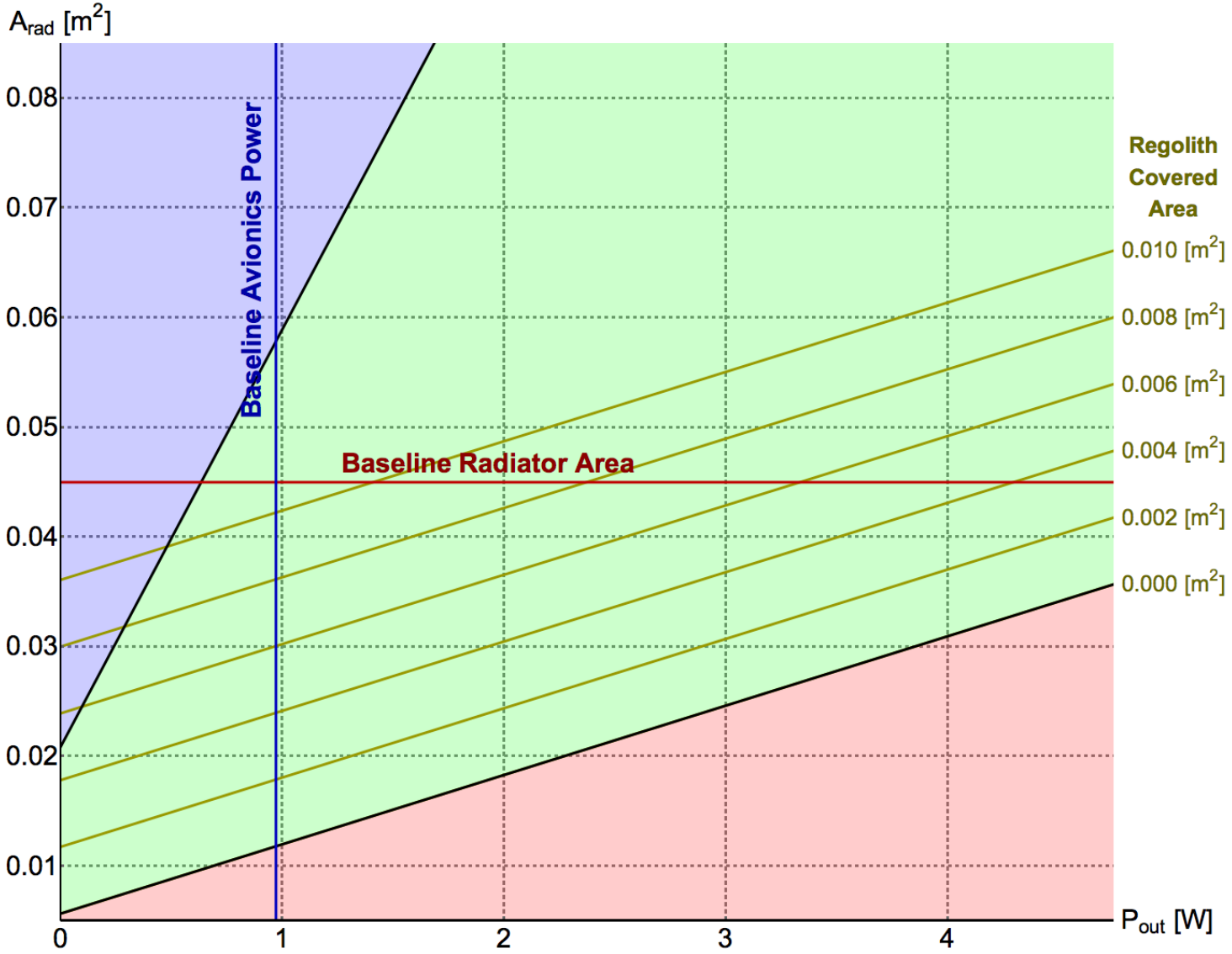
Results (FEA): Radiator Design



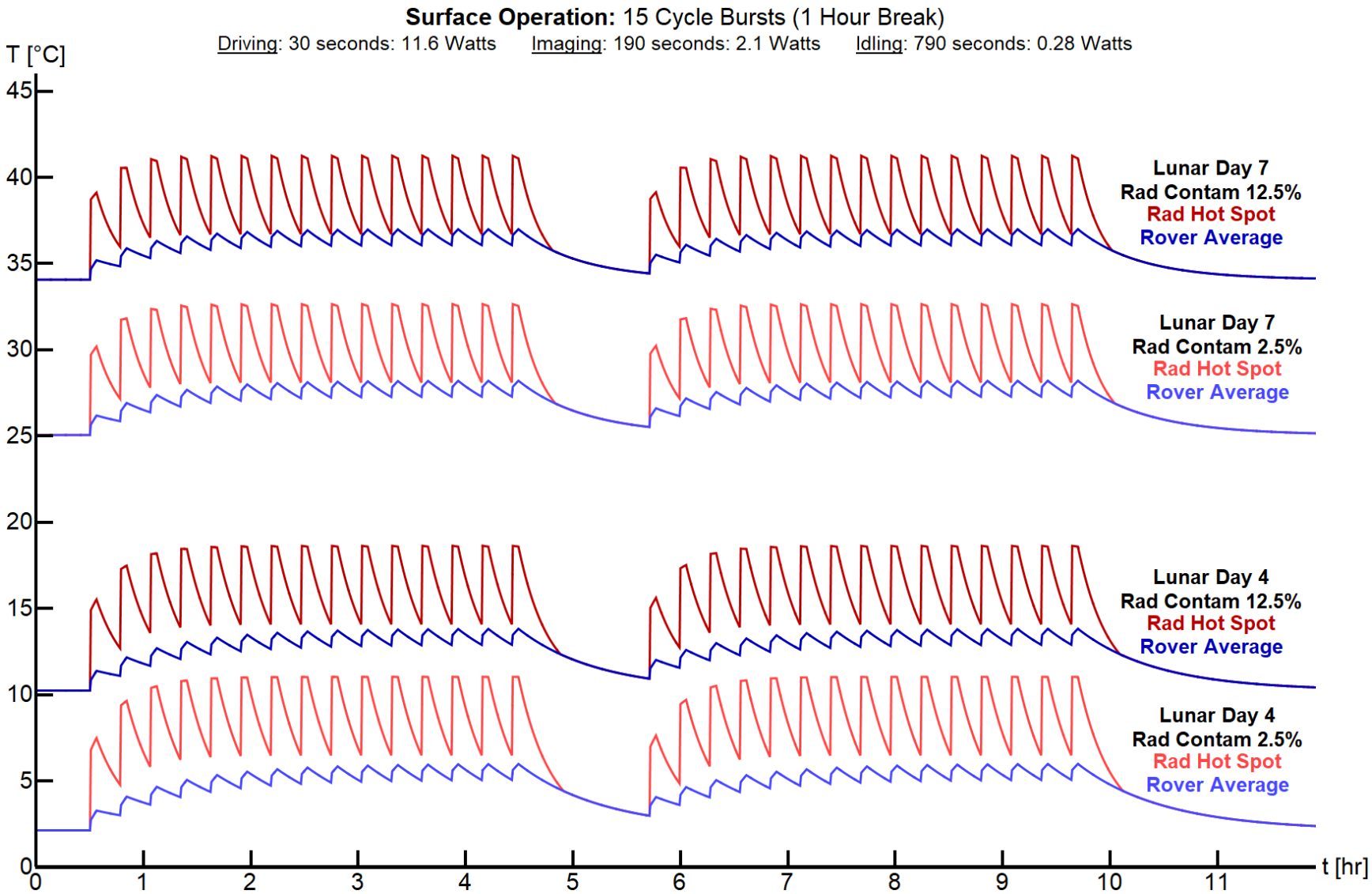
Results (Theory): Radiator Design



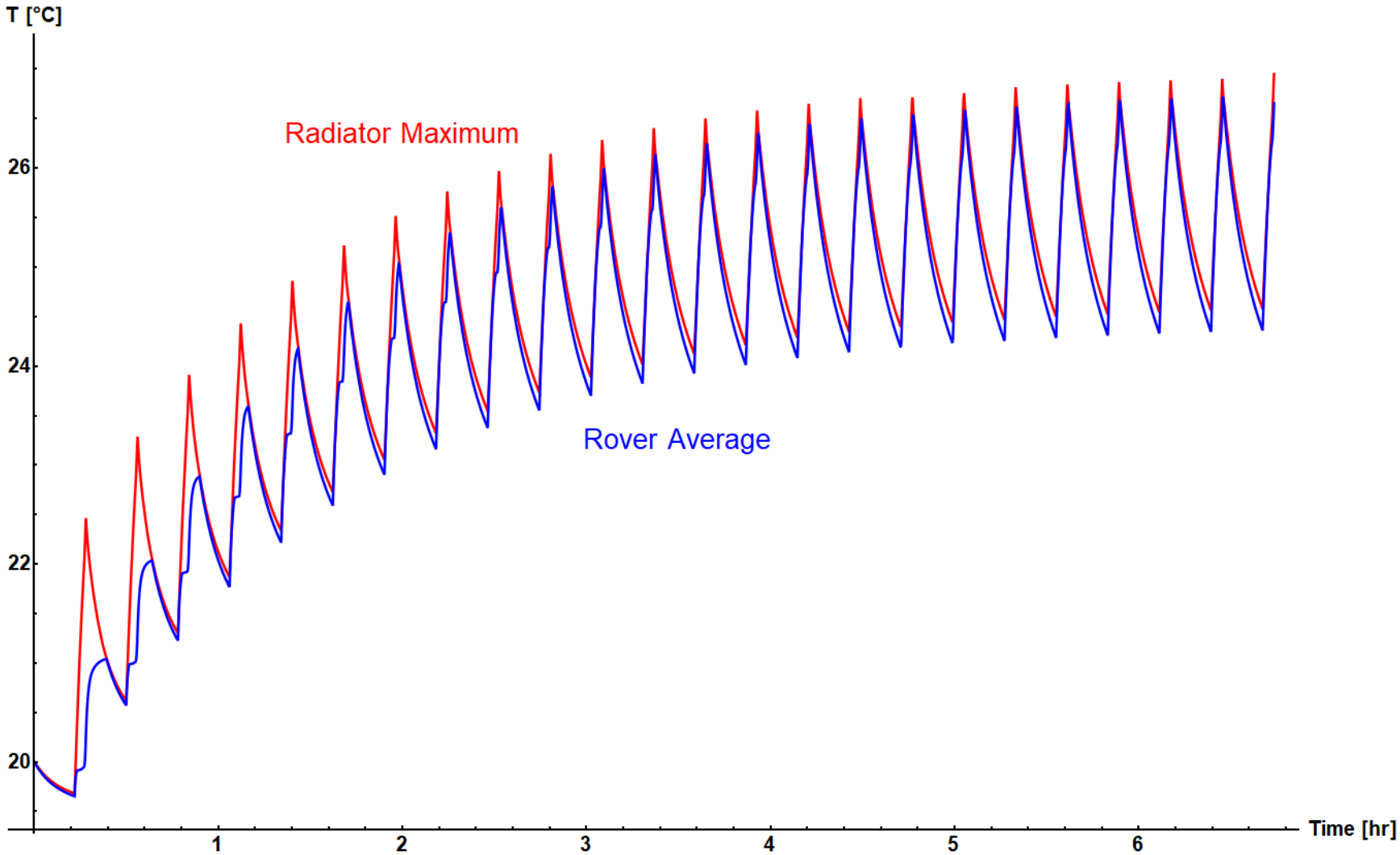
Results (Theory): Radiator Design



Results (Theory): Transient Operation

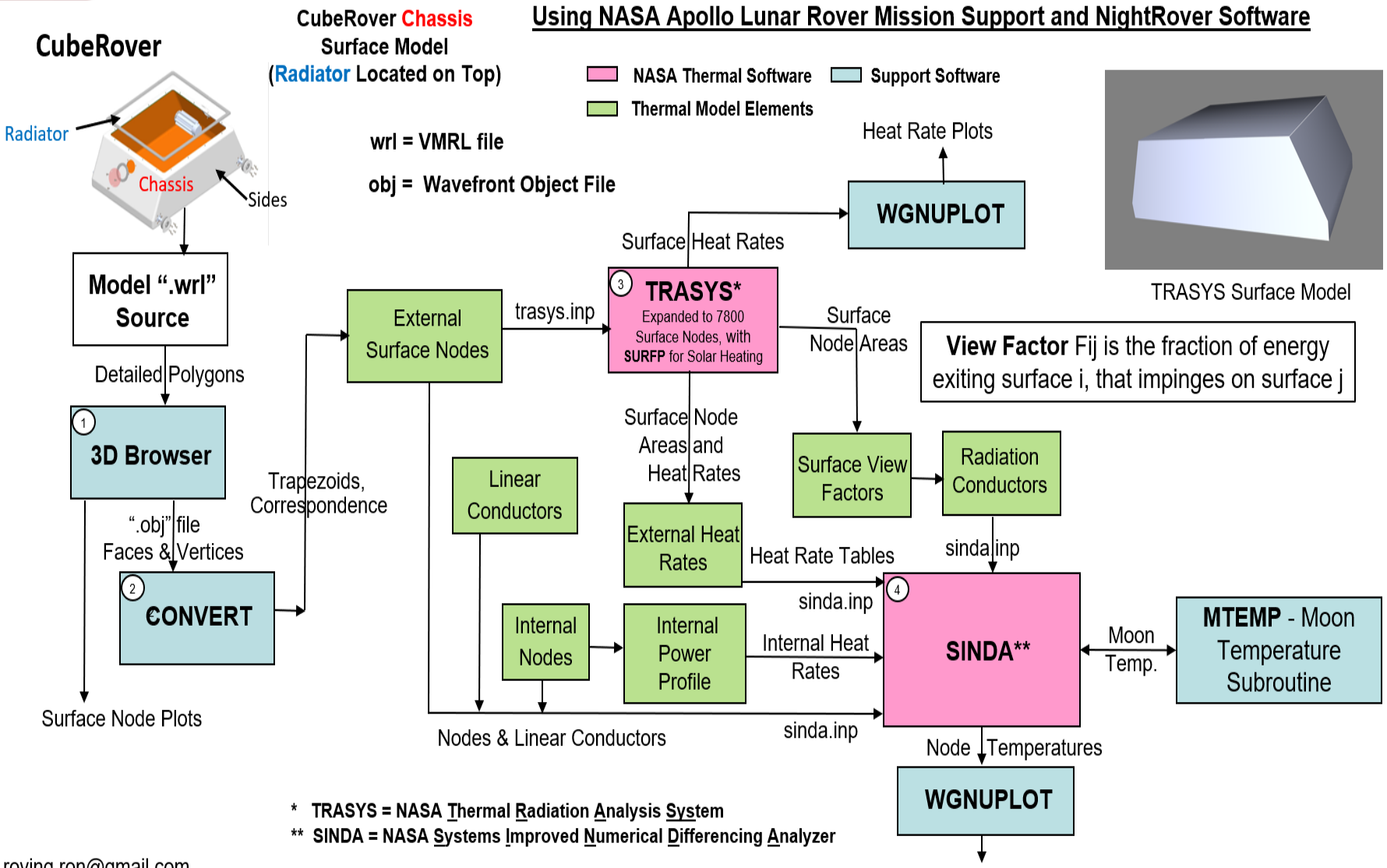


Results (FEA): Transient Operation



CubeRover Thermal Analysis Process for Comparison with Carnegie Mellon Method

Using NASA Apollo Lunar Rover Mission Support and NightRover Software



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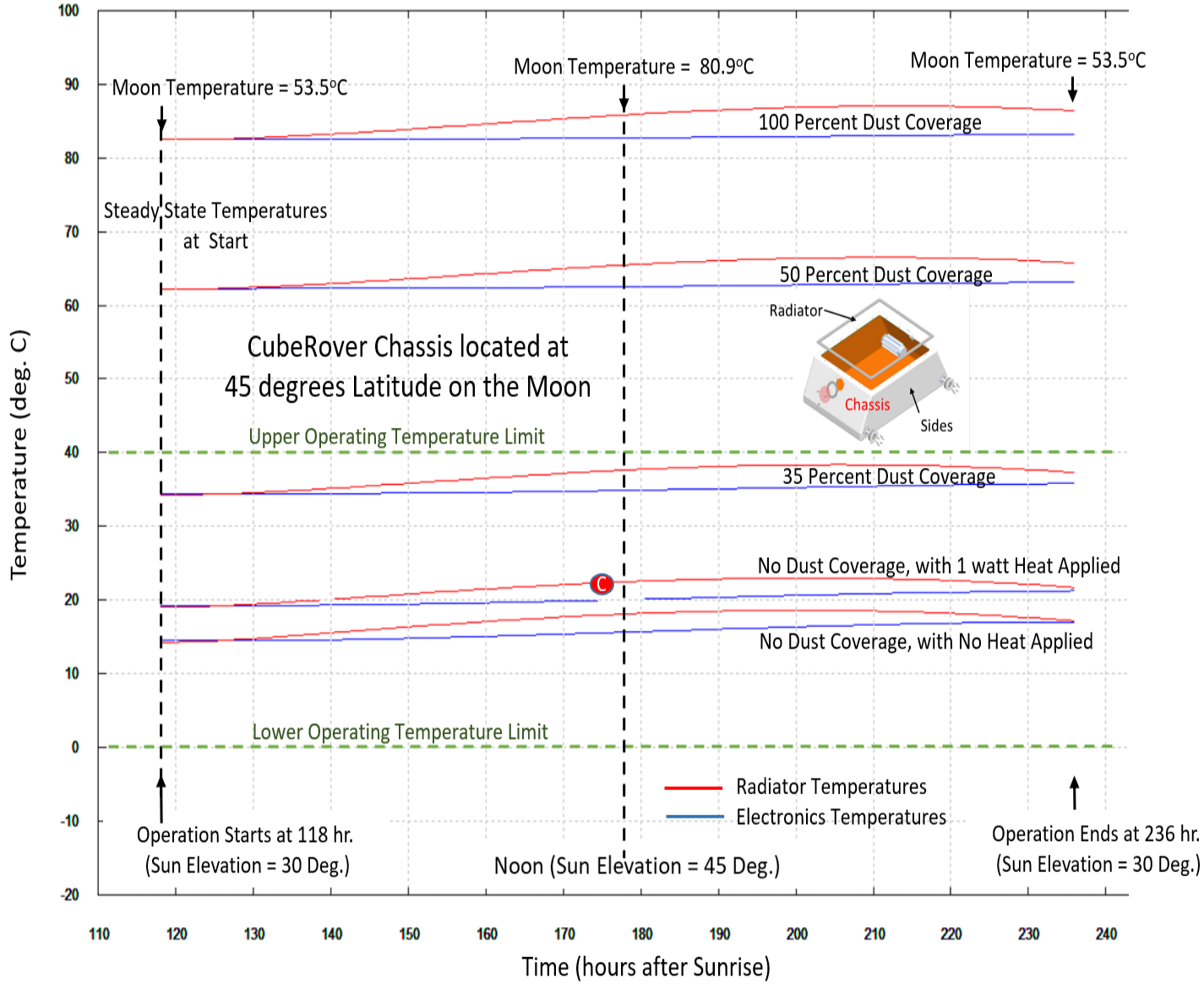
TRASYS/SINDA CubeRover Analysis Results Correlate Well with Carnegie Mellon Method

C Good Correlation with CMU Analysis

Radiator is Well Sized

35 Percent Dust Coverage on Radiator Can Be Tolerated

Radiator Dust Coverage Effects also Studied



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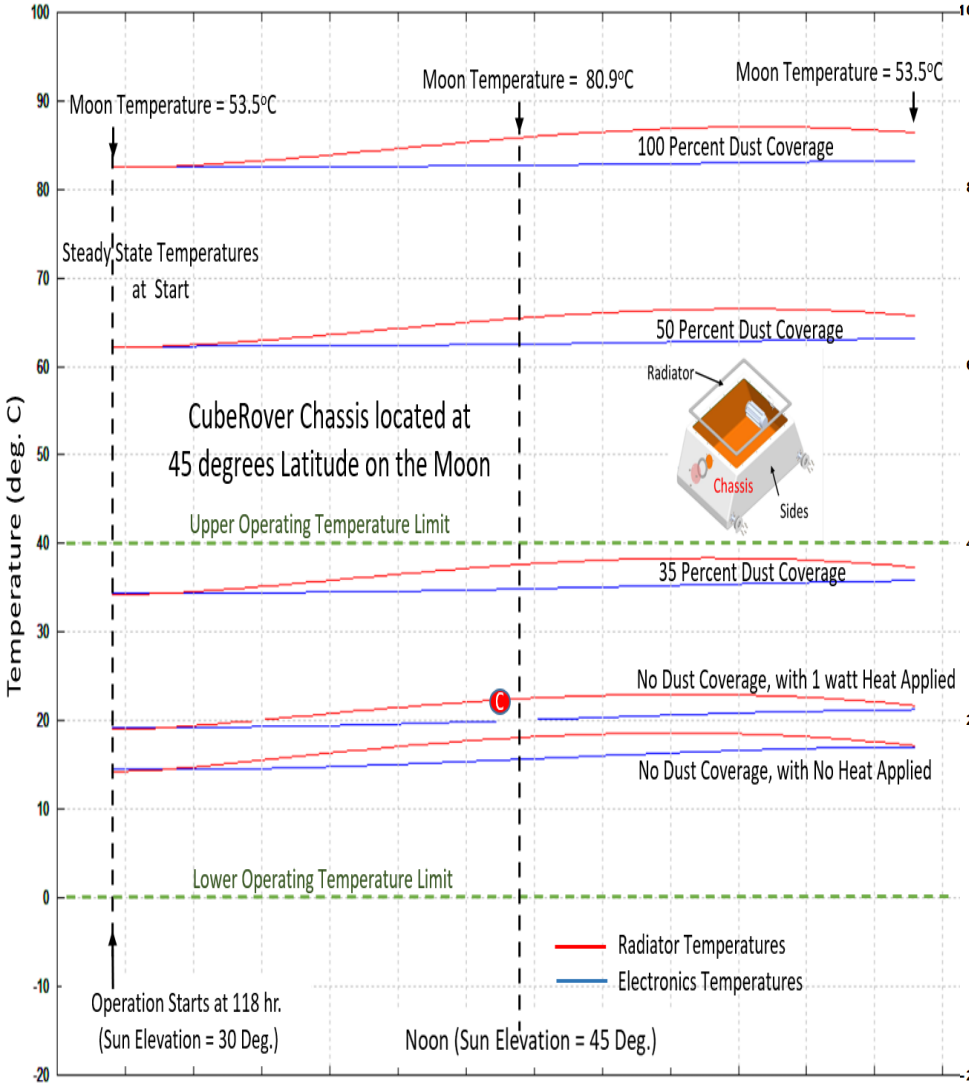
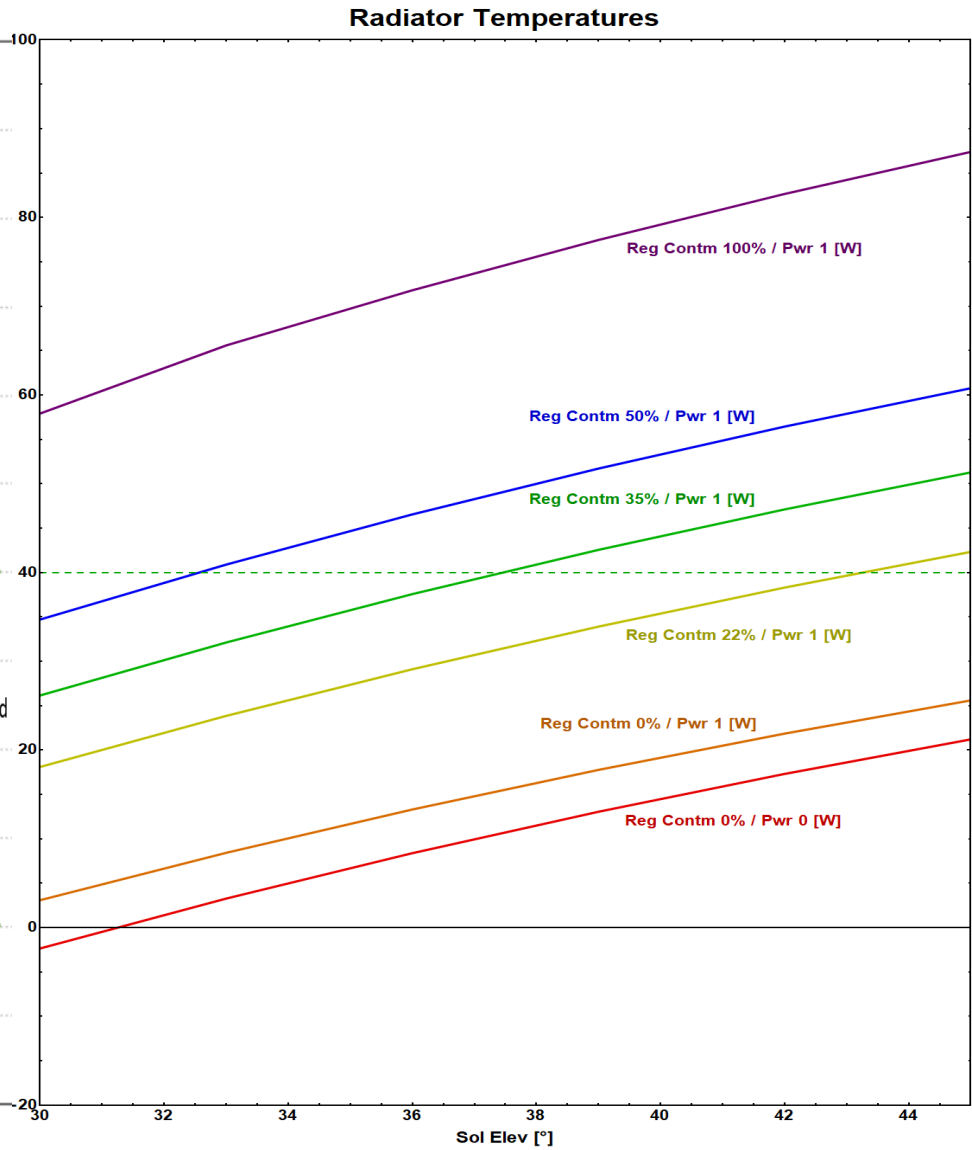
TRASYS/SINDA – Theory Comparison





Summary

- Resistance Network Modeling:
  - Effective approximation for CubeRover thermal performance
  - Allows rapid optimization of key design parameters
  - Capable of explicit MLI Modeling
- Finite-Element Modeling:
  - Enables higher model fidelity
  - Permits modeling of specific components
  - Requires lengthy optimization to match MLI specifications
- TRASYS/SINDA Modeling:
  - Improves accuracy of environment modeling
  - Requires high-detail structural model
  - Requires explicit calculation of internal thermal resistances

BACKUP SLIDES

Method (Theory): Surface Operation

- Primary Model Assumptions:
  - Rover is exploring perfectly flat Lunar terrain
  - Heat conduction through wheels is negligible
  - Heat conduction between rover surfaces is negligible
    - Rover surfaces are uniform in temperature
  - MLI insulation has no conduction leakage
  - Onboard electronics heat uniformly distributed across radiator

Method (Theory): Surface Operation

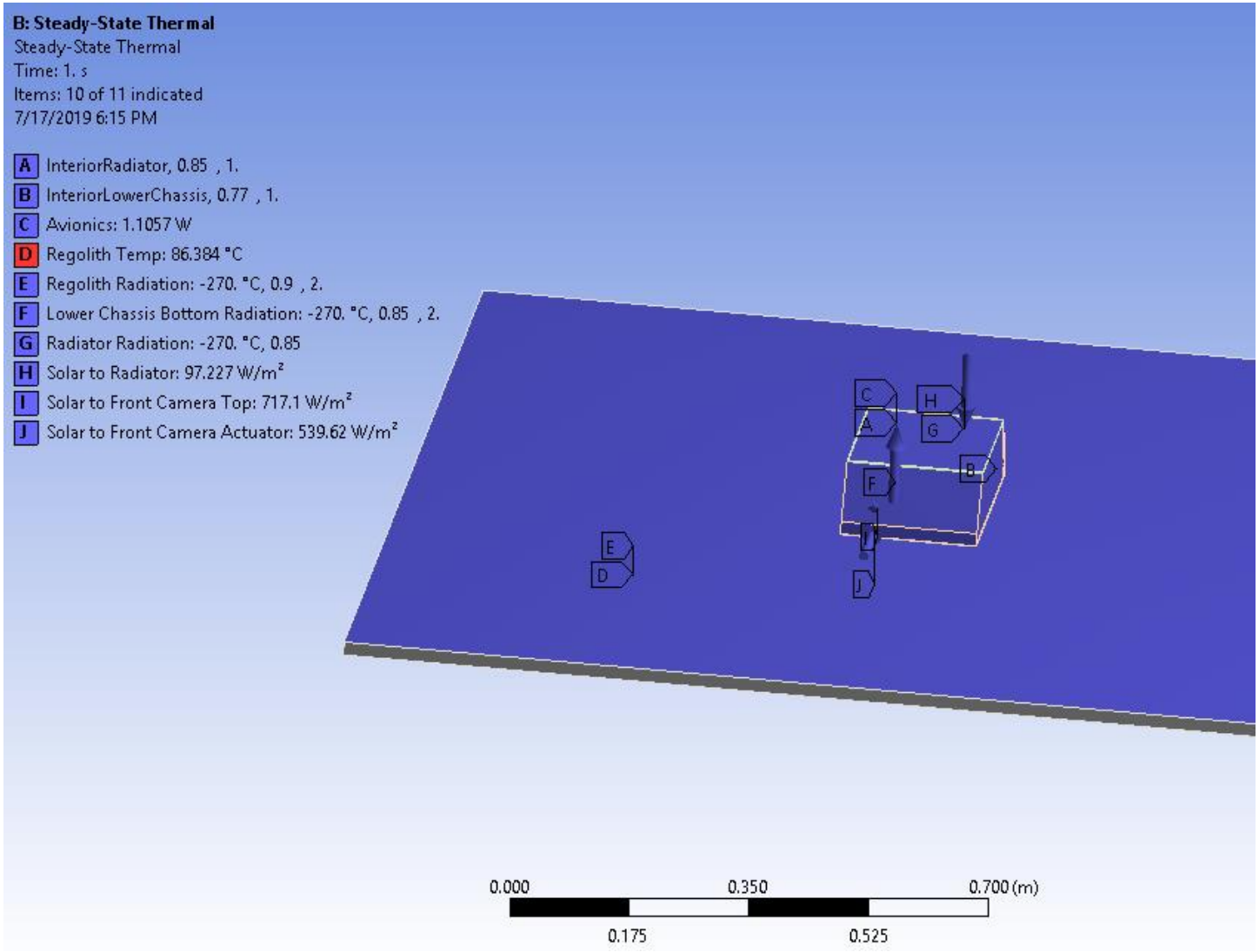
$$
\begin{array}{cccccccc}
T_1 & T_2 & T_3 & T_4 & T_{2o} & T_{4o} & T_B & = \\
\end{array}
$$

$$
\begin{pmatrix}
-\frac{1}{R_{13}}-\frac{1}{R_{14}}-\frac{1}{R_{21}}-\frac{1}{R_{R1a}+R_{R1b}} & \frac{1}{R_{21}} & \frac{1}{R_{13}} & \frac{1}{R_{14}} & 0 & 0 & 0 & -\frac{T_R}{R_{R1a}+R_{R1b}}-q_{E1} \\
-\frac{1}{R_{21}} & \frac{1}{R_{21}}+\frac{1}{R_{23}}+\frac{1}{R_{24}}+\frac{1}{R_{22o}} & -\frac{1}{R_{23}} & -\frac{1}{R_{24}} & -\frac{1}{R_{22o}} & 0 & 0 & q_{E2} \\
\frac{1}{R_{13}} & \frac{1}{R_{23}} & -\frac{1}{R_{13}}-\frac{1}{R_{23}}-\frac{1}{R_{34}}-\frac{1}{R_{3K}}-\frac{1}{R_{S3}} & \frac{1}{R_{34}} & 0 & 0 & 0 & -\frac{T_K}{R_{3K}}-\frac{T_S}{R_{S3}}-q_{E3} \\
\frac{1}{R_{14}} & \frac{1}{R_{24}} & \frac{1}{R_{34}} & -\frac{1}{R_{14}}-\frac{1}{R_{24}}-\frac{1}{R_{34}}-\frac{1}{R_{44o}} & 0 & \frac{1}{R_{44o}} & 0 & -q_{E4} \\
0 & \frac{1}{R_{22o}} & 0 & 0 & -\frac{1}{R_{22o}}-\frac{1}{R_{2oK}}-\frac{1}{R_{2oR}}-\frac{1}{R_{S2o}} & 0 & 0 & -\frac{T_K}{R_{2oK}}-\frac{T_R}{R_{2oR}}-\frac{T_S}{R_{S2o}} \\
0 & 0 & 0 & \frac{1}{R_{44o}} & 0 & -\frac{1}{R_{44o}}-\frac{1}{R_{4oK}}-\frac{1}{R_{4oR}} & 0 & -\frac{T_K}{R_{4oK}}-\frac{T_R}{R_{4oR}} \\
-\frac{1}{R_{R1a}+R_{R1b}} & 0 & 0 & 0 & 0 & 0 & \frac{1}{R_{R1a}} & \frac{T_R}{R_{R1a}}-\frac{T_R}{R_{R1a}+R_{R1b}}
\end{pmatrix}
$$

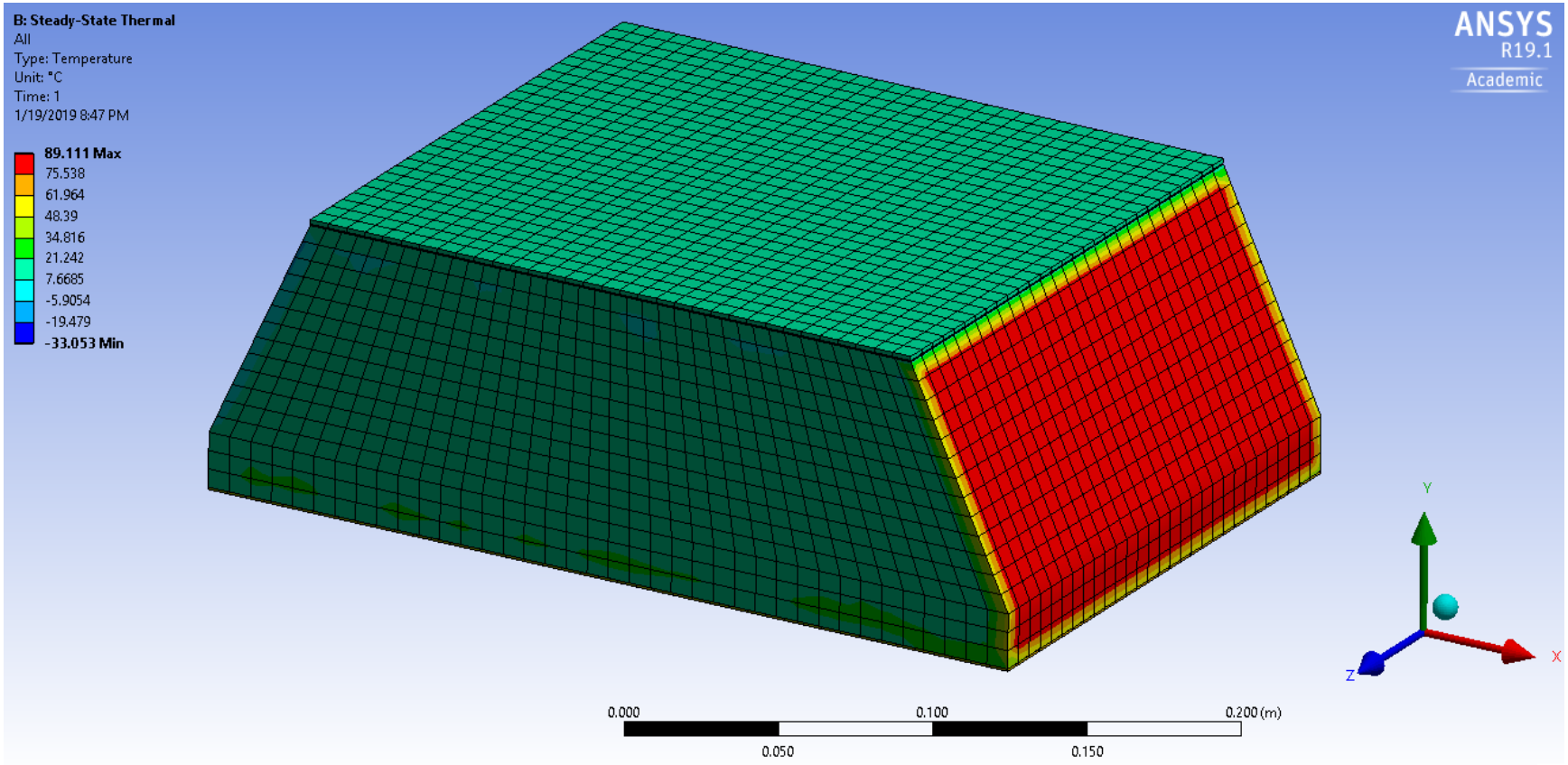
$$
R_{rad} = \frac{1}{\mathcal{F}_{12}\varepsilon_1 A_1 \sigma (1-\alpha_2)\left((T_1+T_2)(T_1^2+T_2^2)\right)}
$$

$$
R_{MLI} = \frac{N\left(\frac{2}{\varepsilon}-1\right)+1}{4\sigma T_{avg}^3 * A}
$$

Method (FEA): Surface Operation



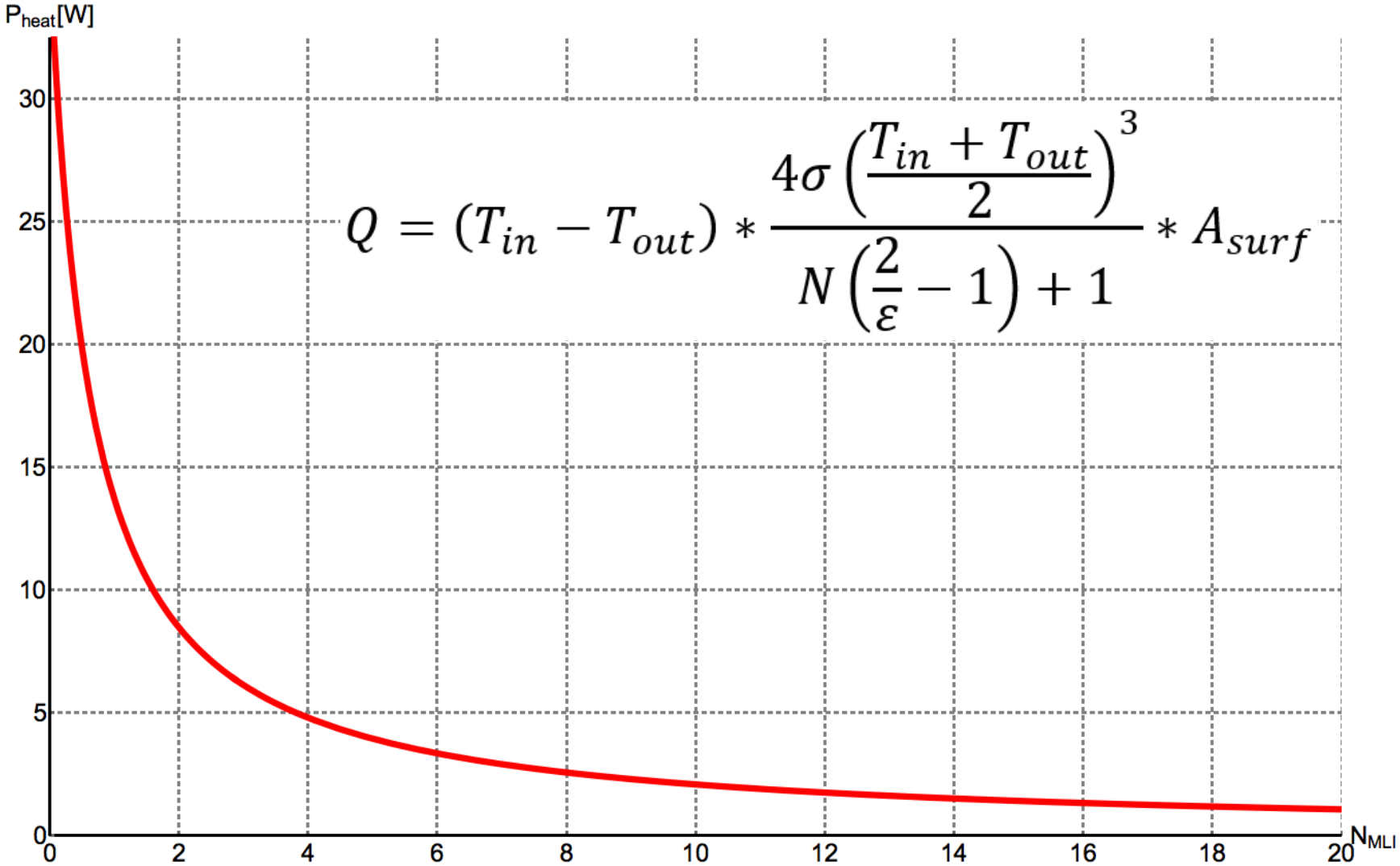
Results (FEA): Surface Operation



Method (Theory): Spaceflight

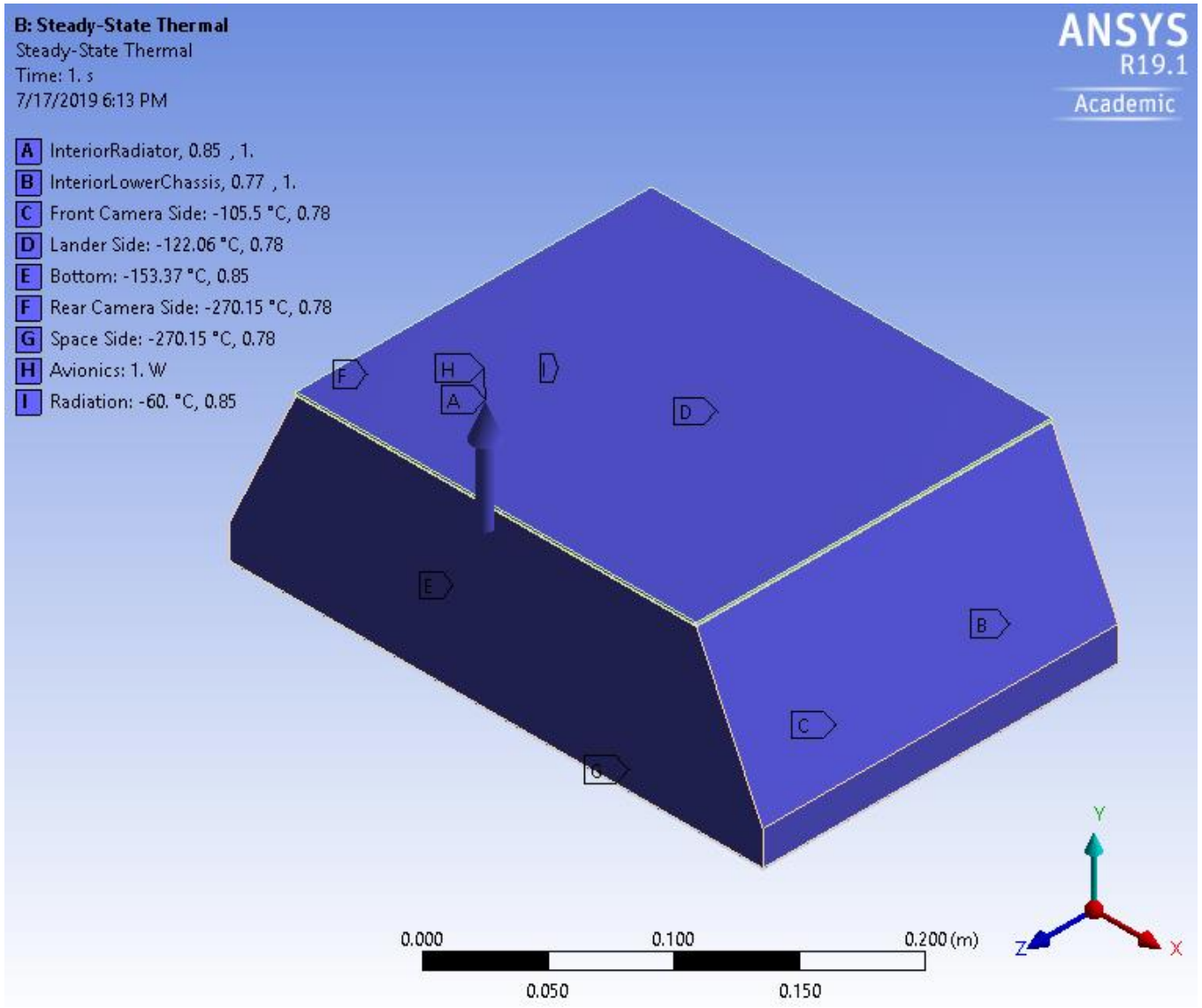
- Primary Model Assumptions:
  - Rover is stranded in open space
  - All surfaces leak heat out to 3 [K]
  - Rover internals are to be kept at 0 [C]
  - Rover covered with uniform insulation blanket

Results (Theory): Spaceflight



$$Q = (T_{in} - T_{out}) * \frac{4\sigma\left(\frac{T_{in} + T_{out}}{2}\right)^3}{N\left(\frac{2}{\varepsilon} - 1\right) + 1} * A_{surf}$$

Method (FEA): Spaceflight



Method (Theory): Radiator Design

- Primary Model Assumptions:
  - Radiator remains parallel to the surface
  - Radiator thermal properties are uniform throughout
  - Radiator evenly heated by electronics
  - Regolith contaminant properties are uniform
  - Rover operates between solar elevation of 30 and 45 degrees

Method (Theory): Radiator Design

- Uncontaminated Radiator: Power Balance

$$P_{in} = P_{av} + P_{leak} + \left(\left(1375\left[\frac{W}{m^2}\right]\right) * (sin\,\theta) * (0.15) * A_{rad}\right)$$

$$P_{out} = \sigma * 0.9 * 0.045 * (T_{rad}^4 - 3^4)$$

Method (Theory): Radiator Design

- Uncontaminated Radiator: Area Bounds

$$A_{Max} = \frac{P_{av} + 0.55}{(0.9 * \sigma * (273.15)^4) - (1375 * sin\, 30 * 0.15)}$$

$$A_{Min} = \frac{P_{av} + 0.9}{(0.9 * \sigma * (273.15 + 40)^4) - (1375 * sin\, 45 * 0.15)}$$

Method (Theory): Radiator Design

- Contaminated Radiator: Power Balance

$$P_{in} = P_{av} + P_{leak} + \left(1375\left[\frac{W}{m^2}\right]\right) * (sin\,\theta) * \left((1-\alpha_{rad}) * \left(A_{rad} - A_{reg}\right) + (1-0.12) * \left(A_{reg}\right)\right)$$

$$P_{out} = \sigma * 0.9 * 0.045 * (T_{rad}^4 - 3^4)$$

Method (Theory): Transient Simulation

- Model Assumptions (Spaceflight):
  - Rover can be treated as a uniform-temperature body
    - Full rover heat capacity: 560 [J/K]
    - Rover initial temperature: 0 [C]
    - Rover covered by uniform MLI blanket
    - Rover exposed to open space on all sides

Method (Theory): Transient Simulation

- Model Assumptions (Surface Operation):
  - Rover can (mostly) be treated as a uniform-temperature body
    - Full rover heat capacity: 560 [J/K]
    - Radiator heat capacity: 220 [J/K]
    - High-temperature zones occupy 1/3 of the radiator
  - Rover operational cycle continuously repeated:
    - Driving: 11.6 [W] (3%)
    - Imaging: 2.1 [W] (19%)
    - Idling: 0.28 [W] (78%)