Jet Propulsion Laboratory
California Institute of Technology

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Thermal Design, Analysis, and Sensitivity of a Sample Tube on the Martian Surface

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Outline

- Introduction
- Temperature Requirements
- Environments
- Optical Property Measurements
- Assumptions
- Closed Form Model
- Sensitivity Studies
- Flight Tube Design
- Operational Considerations
- Conclusions

Mission Overview

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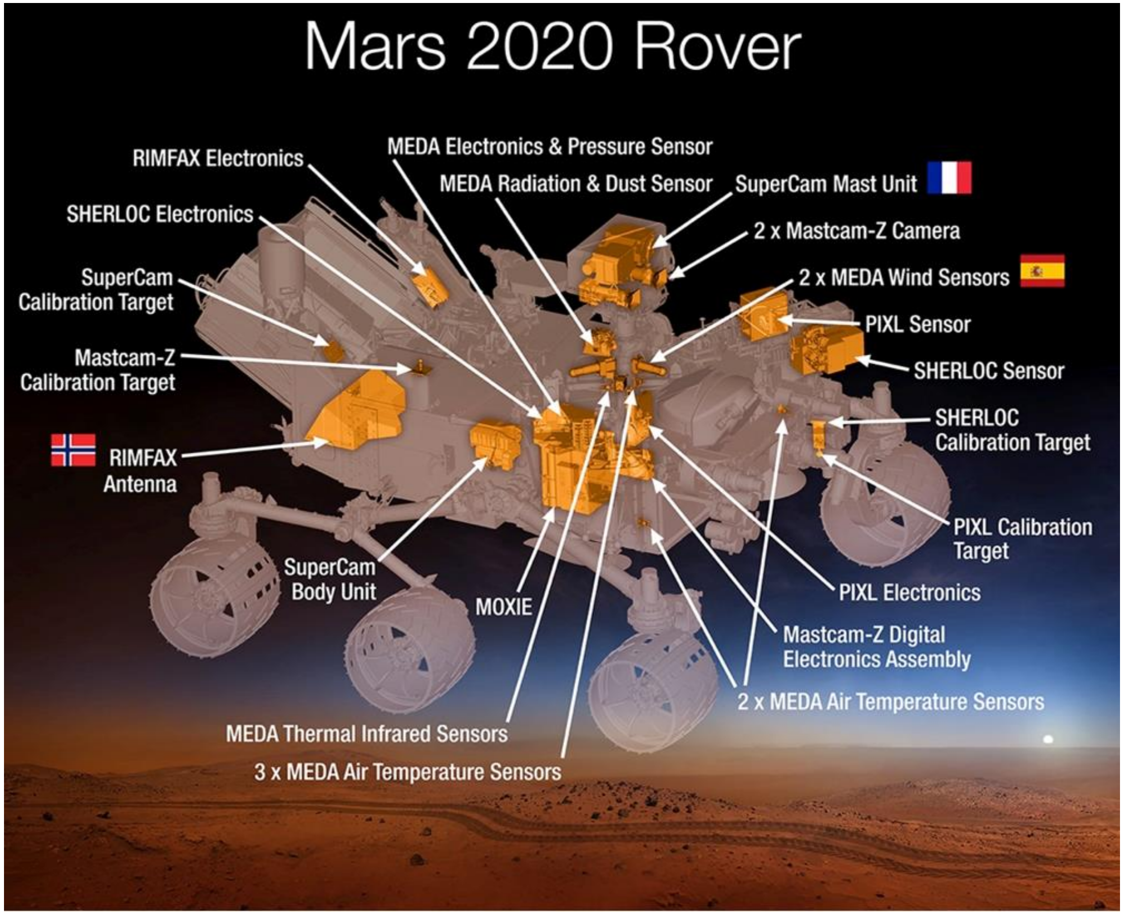
- The Mars 2020 Rover is planned for launch in 2020, and will carry a suite of instruments as well as a Sample Caching System (SCS).

Instrument Suite:

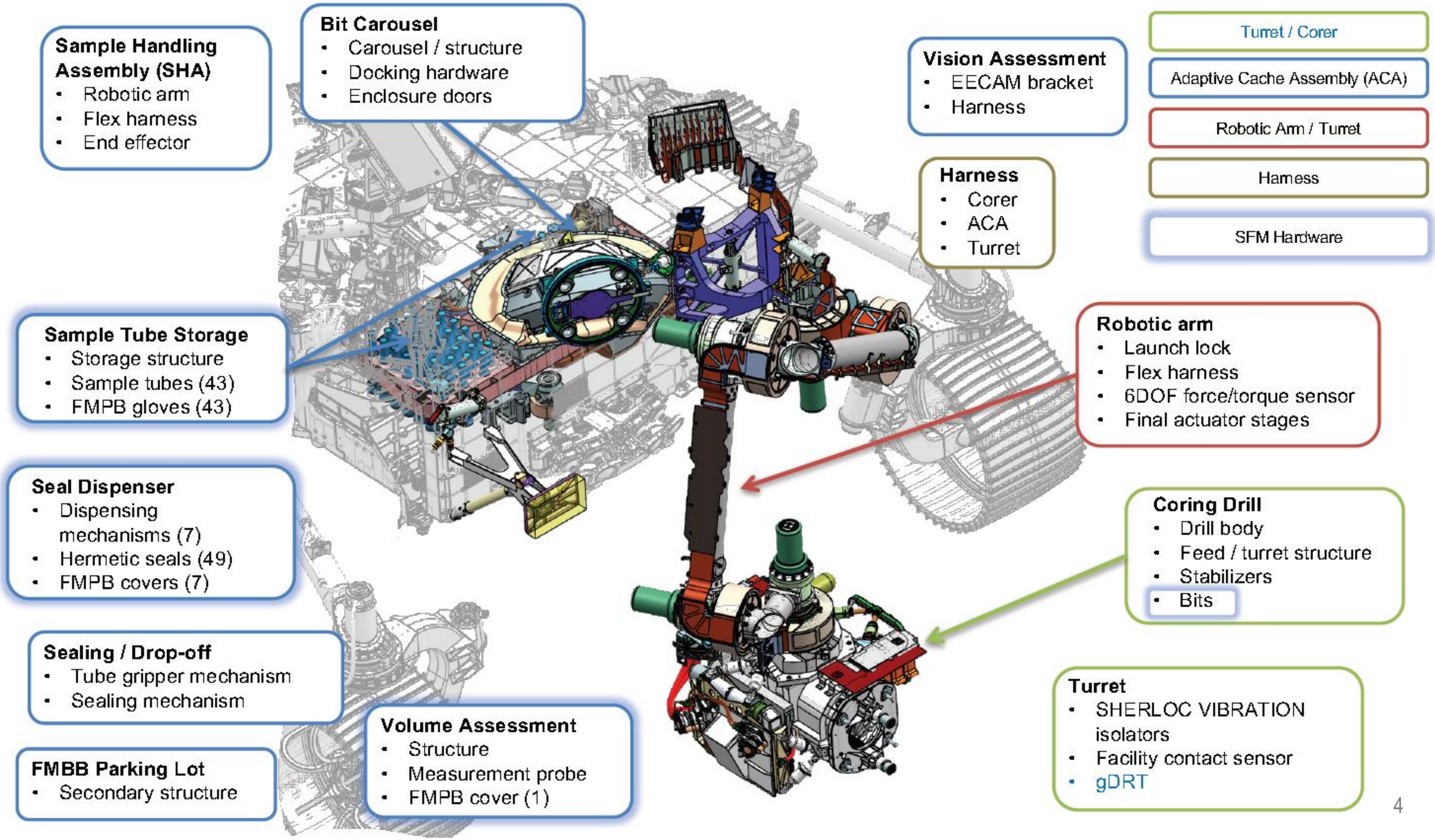
1. **Mastcam-Z** - stereo zoom camera
2. **Supercam** - remote elemental chemistry and mineralogy
3. **SHERLOC** - fine-scale organic geochemistry and mineralogy (mapping)
4. **PIXL** - fine-scale elemental chemistry (mapping)
5. **RIMFAX** - subsurface structure - ground penetrating radar (Norway)
6. **MEDA** - weather and atmospheric dust monitoring (Spain)
7. **MOXIE** - ISRU - conversion of atmospheric CO_2 to O_2



[1] Farley, K., "Mars 2020 Project Update," Committee on Astrobiology and Planetary Science, September 17, 2015. Accessed from http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_169425.pdf on 12/9/2016.

Sample Caching System (SCS)

- **The SCS performs sample collection, manipulation, sealing, storage, and caching.**



Adaptive Caching Assembly (ACA)

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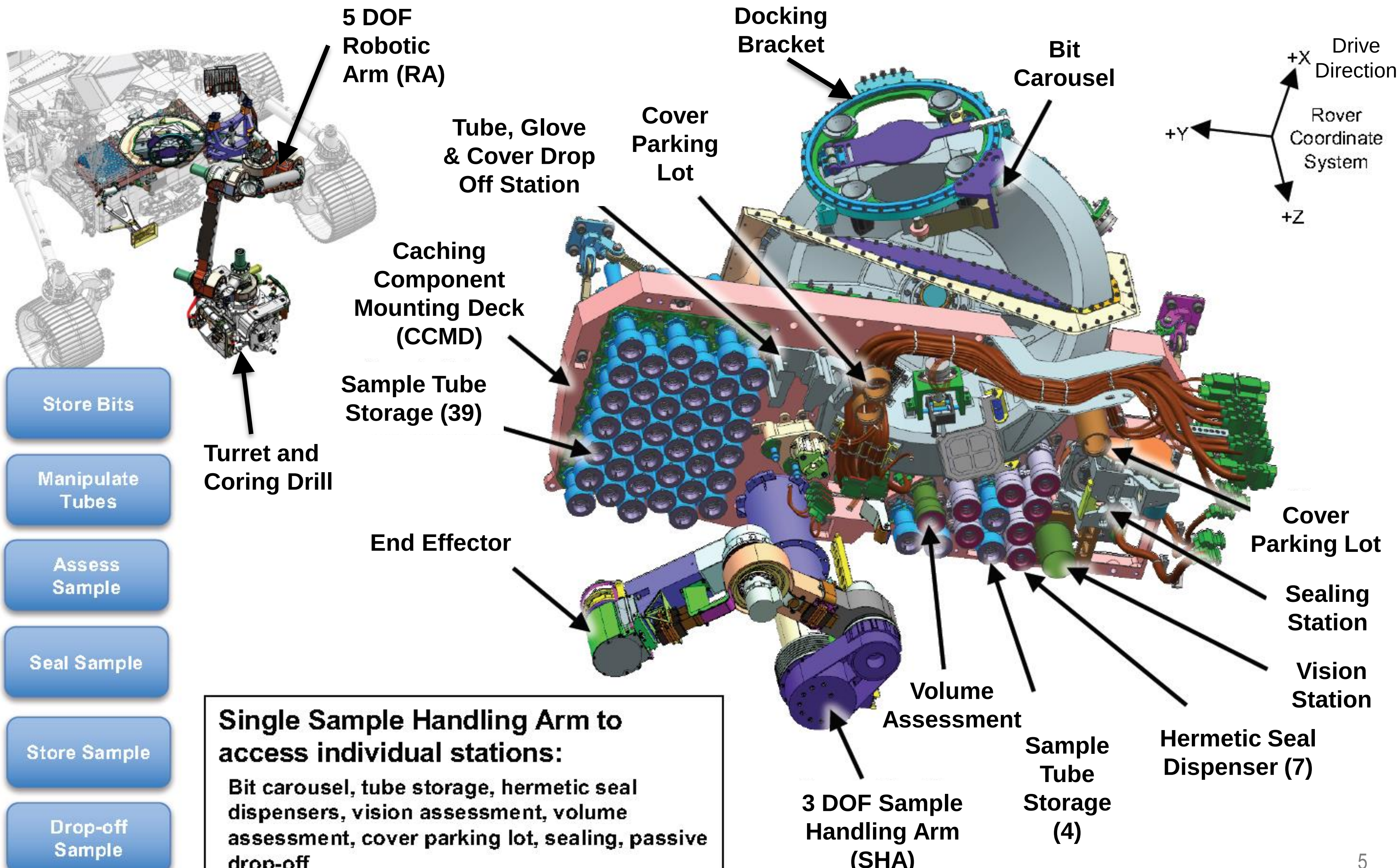

- Store Bits
- Manipulate Tubes
- Assess Sample
- Seal Sample
- Store Sample
- Drop-off Sample

Single Sample Handling Arm to access individual stations:

Bit carousel, tube storage, hermetic seal dispensers, vision assessment, volume assessment, cover parking lot, sealing, passive drop-off

Depot Caching Strategy

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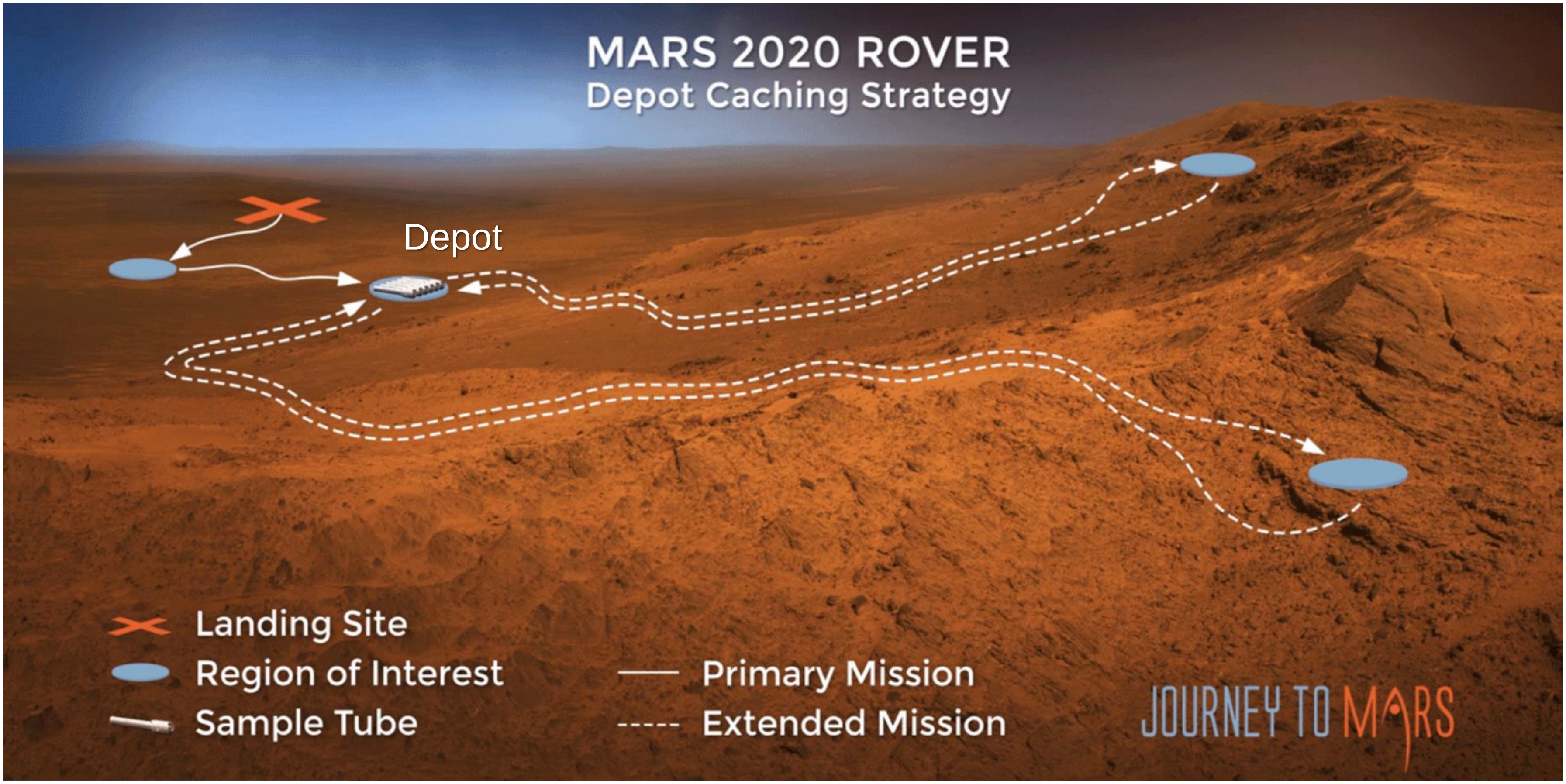
- Once samples are collected and sealed in tubes, they will be cached in a depot for possible future collection and return to Earth.

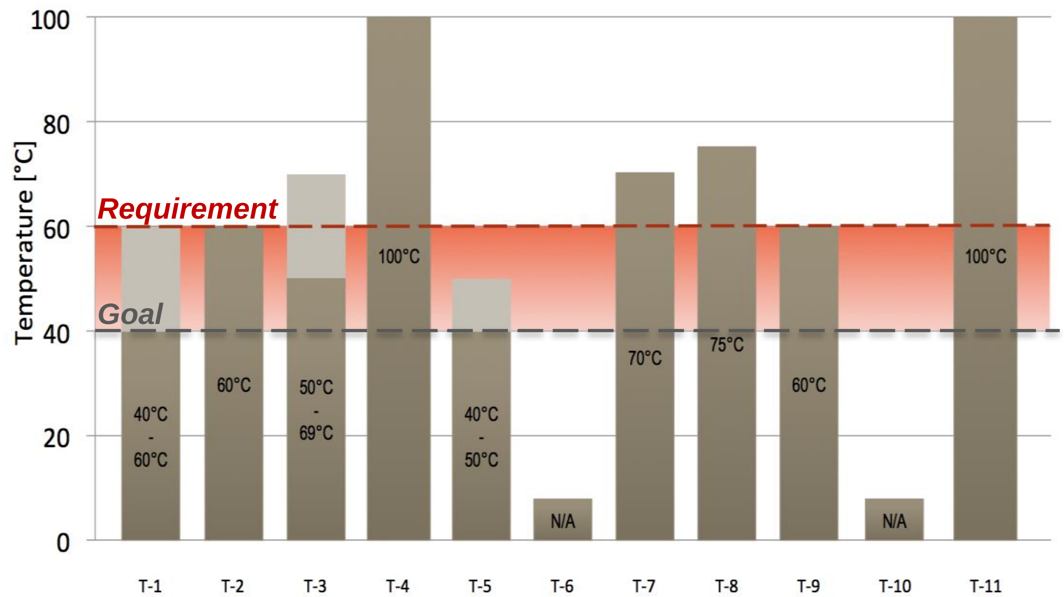


Sample Temperature Requirement

Short Text: Post-Sealing Sample Temperature

Object Text: The PS **shall** keep the **maximum** temperature of sealed samples **below 60C**…."

Rationale: "….**Engineering goal** to keep the maximum temperature of sealed samples **below 40C** …."



Maximum temperature for 11 temperature sensitive scientific investigations

From Beaty et al "The Effect of Sample Temperature on Mars Returned Sample Science." November 9, 2015.

Top Landing Site Candidates

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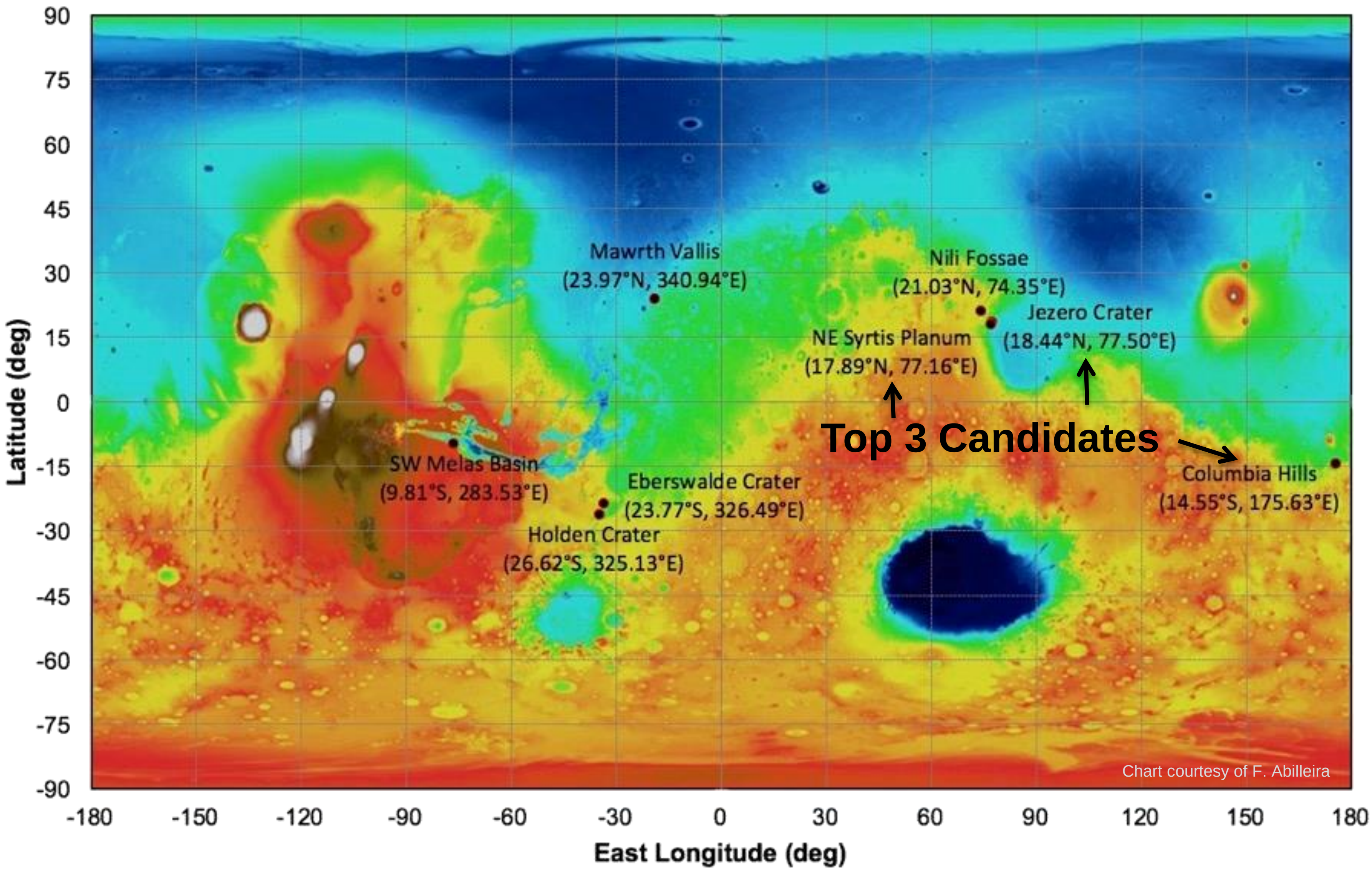
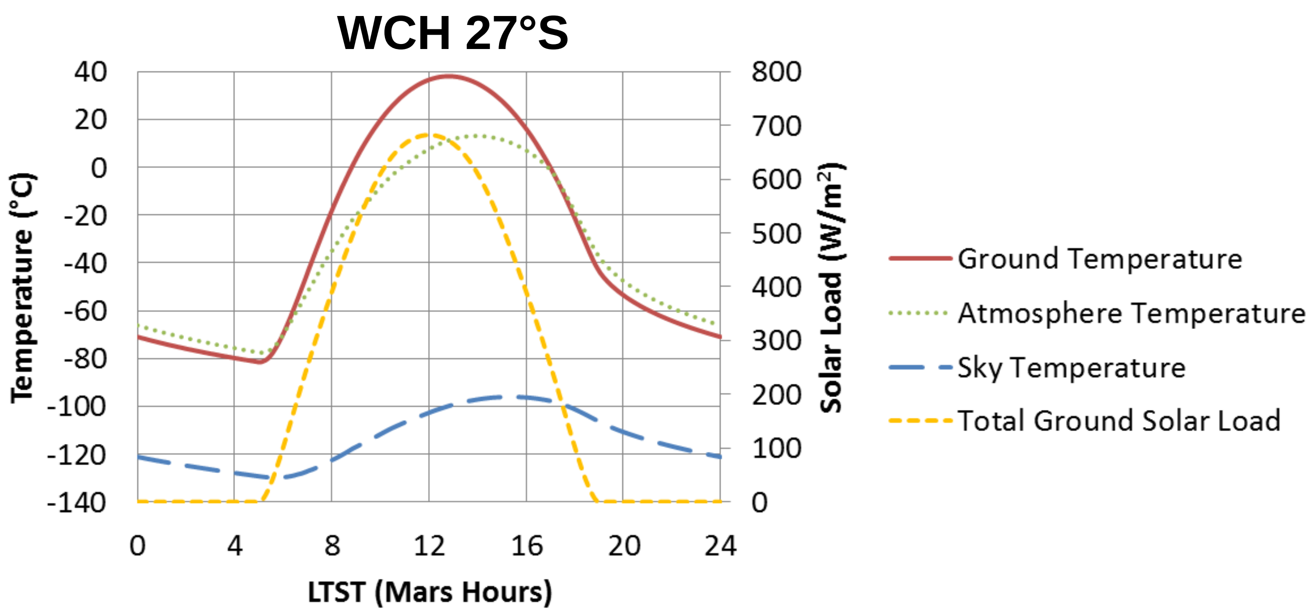


Thermal Environments



(27 °S, Tau = 0.2, Albedo = 0.12, TI = 220 $Jm^{-2}K^{-1}s^{-1/2}$)

Approximate Peak Diurnal Boundary Conditions:

Latitude	Ls (degrees)	T_G (°C)	T_A (°C)	T_S (°C)	$q''_{diffuse}$ (W/m^2)	q''_{direct} (W/m^2)	Θ (degrees)
WCH 27 °S	270	38	13	-96	103	582	88
15 °S	270	28	2	-104	103	572	80
0 °	270	17	7	-105	103	517	65
15 °N	90	1	-8	-105	72	402	80
30 °N	90	3	-8	-105	72	408	85

TES Temperature Data

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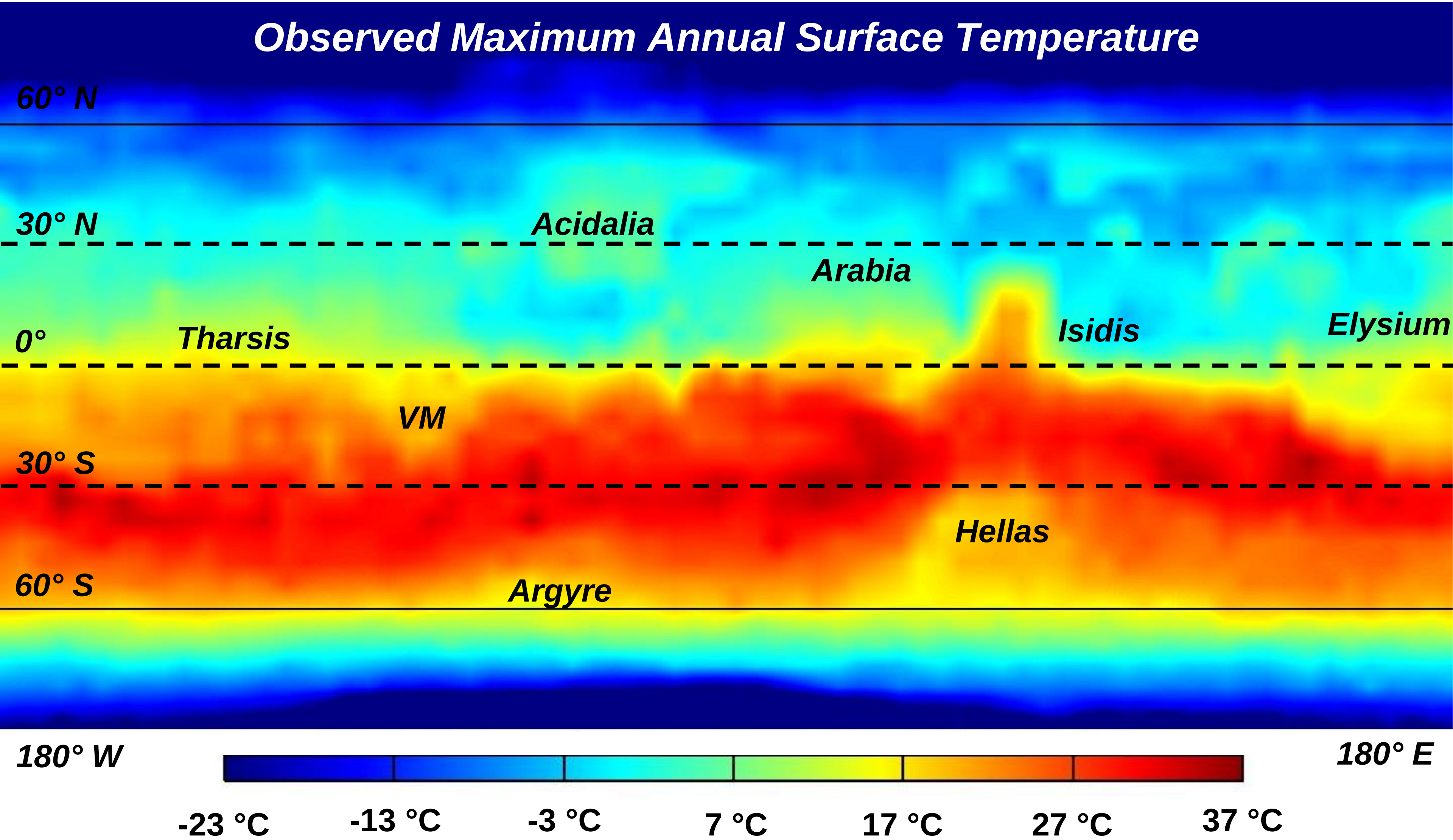


Observed Maximum Annual Surface Temperature

Optical Property Measurements

Surface Treatment or Coating	Solar Absorptivity	Thermal Emissivity
3 mil Flame Sprayed Aluminum Oxide (Al_2O_3), ABS	0.41 to 0.49	0.83 to 0.85
3 mil Flame Sprayed Aluminum Oxide (Al_2O_3), Surface Modification Systems	0.23 to 0.35	0.81 to 0.82
Polished Flame Sprayed Aluminum Oxide (Al2O3)	0.39 to 0.69	0.76 to 0.85
Grit Blasted Stainless Steel, Surface Optics Corp	0.58	0.38 to 0.49
Grit Blasted Aluminum, Peen Rite	0.24 to 0.48	0.13 to 0.29
Grit Blasted Titanium, Surface Optics Corp	0.80 to 0.88	0.46 to 0.60
Bare Titanium	0.48 to 0.66	0.16 to 0.20
Oxidized Titanium, After 500 C Bake Out	0.70 to 0.77	0.20 to 0.22
Titanium Nitride (TiN), Brycoat	0.36 to 0.38	0.07 to 0.11
Titanium Nitride (TiN), Solar Atmospheres	0.45 to 0.52	0.16 to 0.18
Titanium Anodize, Tiodize, Type II	0.82 to 0.84	0.45 to 0.51
Titanium Anodize, Danco, Type II	0.80 to 0.83	0.36 to 0.41
Titanium Anodize, Tiodize K2V	0.91	0.86
Titanium Anodize, Tiodize Type IV (Type II + X40 PTFE “Teflon Infused”)	0.85	0.45

Green = Surface Treatments and Coatings selected for use on the Mars 2020 Sample Tube

Assumptions

- Assumptions:
  - Free convection only (h = 0.4 W/m^2-K)
  - Tube is not in contact with the ground (minor effect in sensitivity studies)
  - Tube is empty (maximum local temps and tube gradients)
  - Tube is placed on flat ground
  - Worst case dust coverage assumption

Three Stages of Dust Coverage:

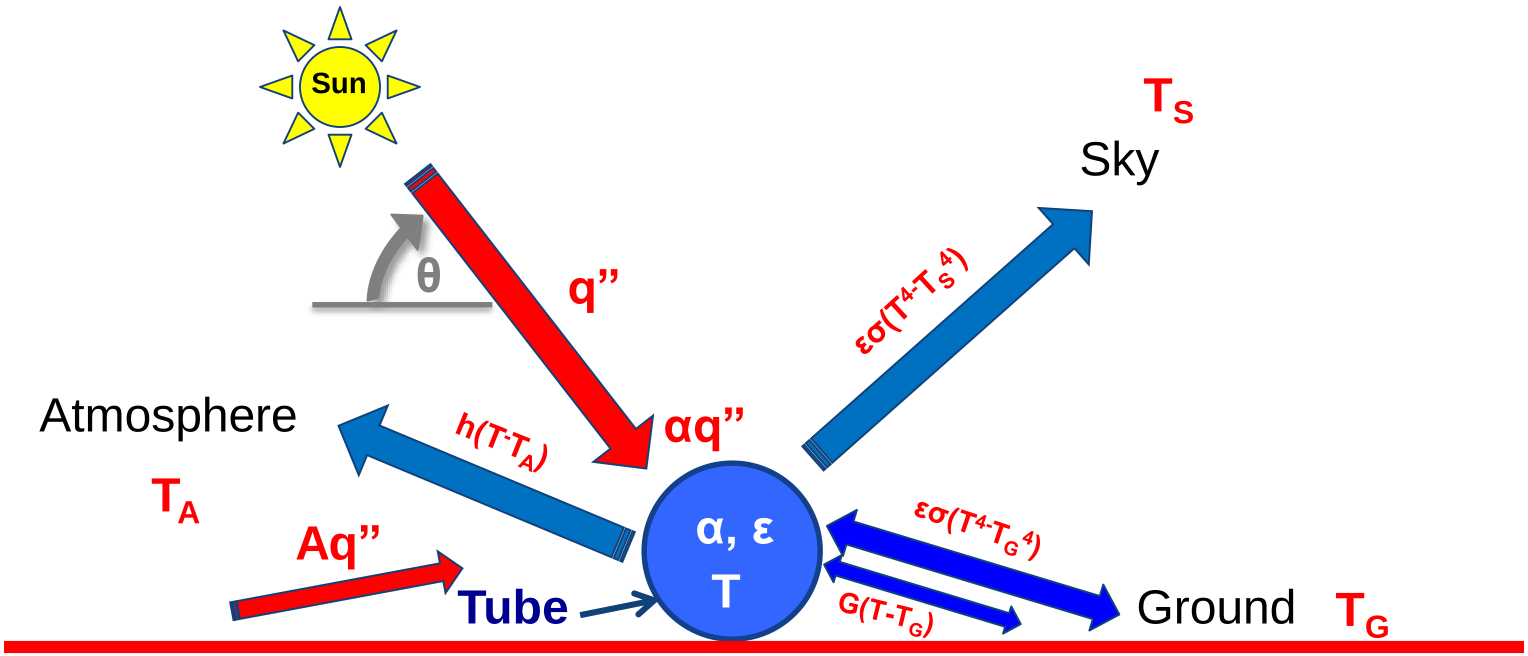
1. No Dust (BOL Properties):
   - Al_2O_3: **α = 0.45, ε = 0.83**
   - TiN: **α = 0.37, ε = 0.07**

2. Thin Layer of Dust (changes solar absorptivity, but not thermal emissivity):
   - Al_2O_3: **α = 0.7, ε = 0.83**
   - TiN: **α = 0.7, ε = 0.07**

Worst Case Used for Analysis

3. Totally Covered in Dust (Dust Properties):
   - Al_2O_3: **α = 0.7, ε = 0.9**
   - TiN: **α = 0.7, ε = 0.9**

Closed Form Model



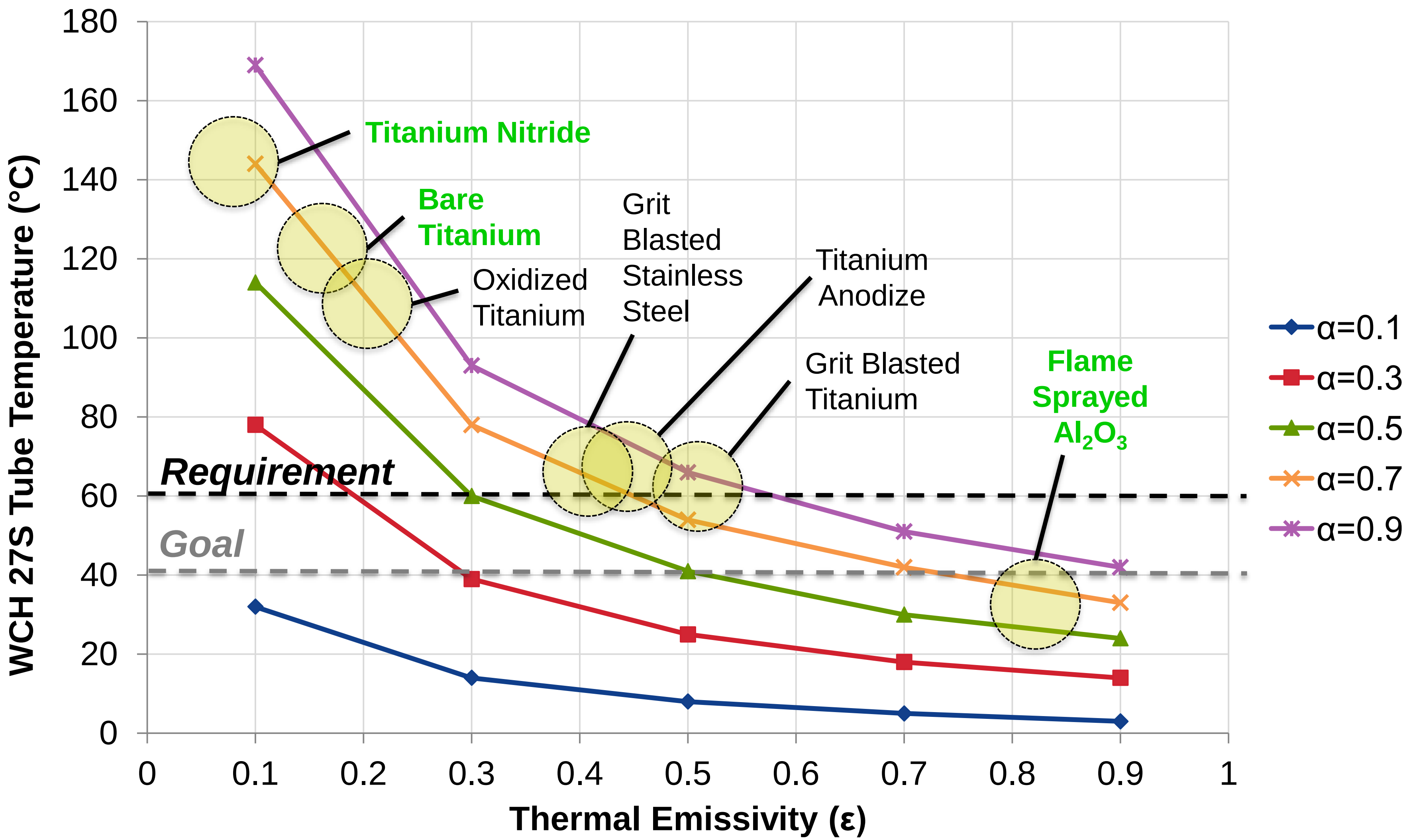
$$Q_{in} = Q_{out} \tag{1}$$

$$Q_{DirectSolar} + Q_{DirectReflectedSolar} + Q_{DiffuseSolar} + Q_{DiffuseReflectedSolar} + Q_{GroundIR} + Q_{SkyIR} + Q_{Convection,In} = Q_{Convection,Out} + Q_{Emitted} \tag{2}$$

$$q''_{direct}\alpha DL + q''_{direct}\sin(\theta)\, A\alpha\frac{\pi DL}{2} + q''_{diffuse}\alpha\frac{\pi DL}{2} + q''_{diffuse}A\alpha\frac{\pi DL}{2} + \frac{\pi DL}{2}\sigma\epsilon T_G^4 + \frac{\pi DL}{2}\sigma\epsilon T_S^4 + h(\pi DL)T_A = h(\pi DL)T + (\pi DL)\,\sigma\epsilon T^4 \tag{3}$$

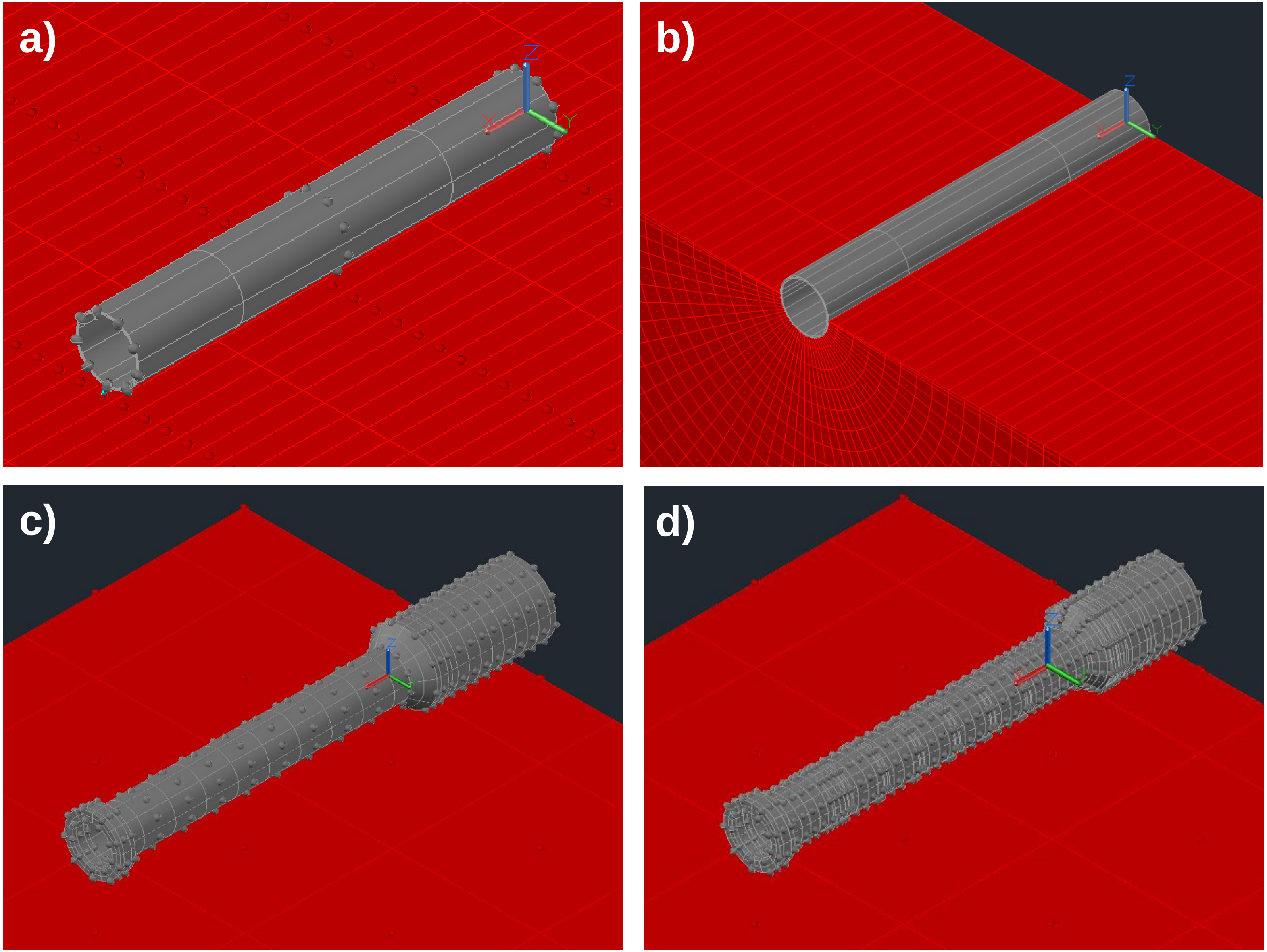
$$q''_{direct}\alpha + q''_{direct}\sin(\theta)\, A\alpha\frac{\pi}{2} + q''_{diffuse}\alpha\frac{\pi}{2} + q''_{diffuse}A\alpha\frac{\pi}{2} + \frac{\pi}{2}\sigma\epsilon T_G^4 + \frac{\pi}{2}\sigma\epsilon T_S^4 + h\pi T_A = h\pi T + \pi\sigma\epsilon T^4 \tag{4}$$

WCH 27 S Tube Temperatures



Green = Surface Treatments and Coatings selected for use on the Mars 2020 Sample Tube

Detailed Tube on Ground Models



Effect of Ground Slope

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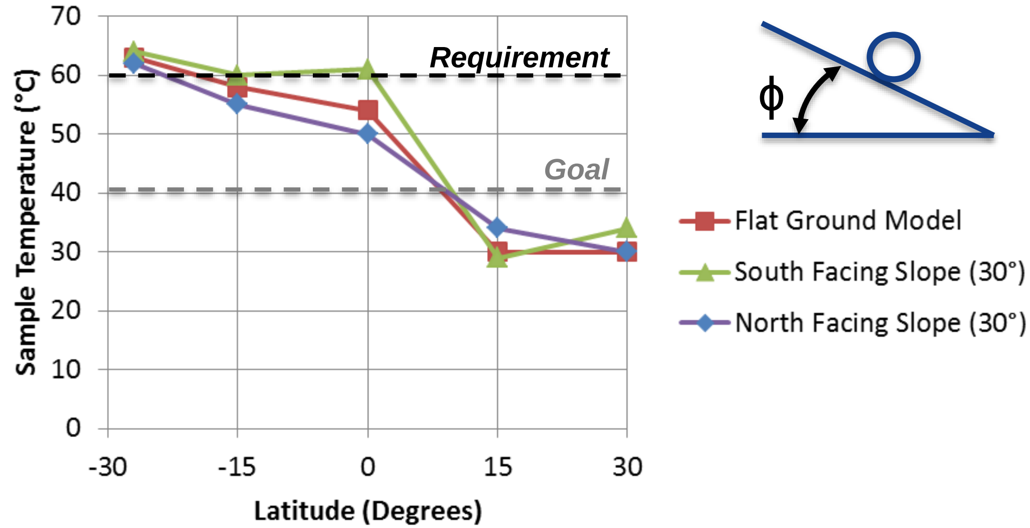
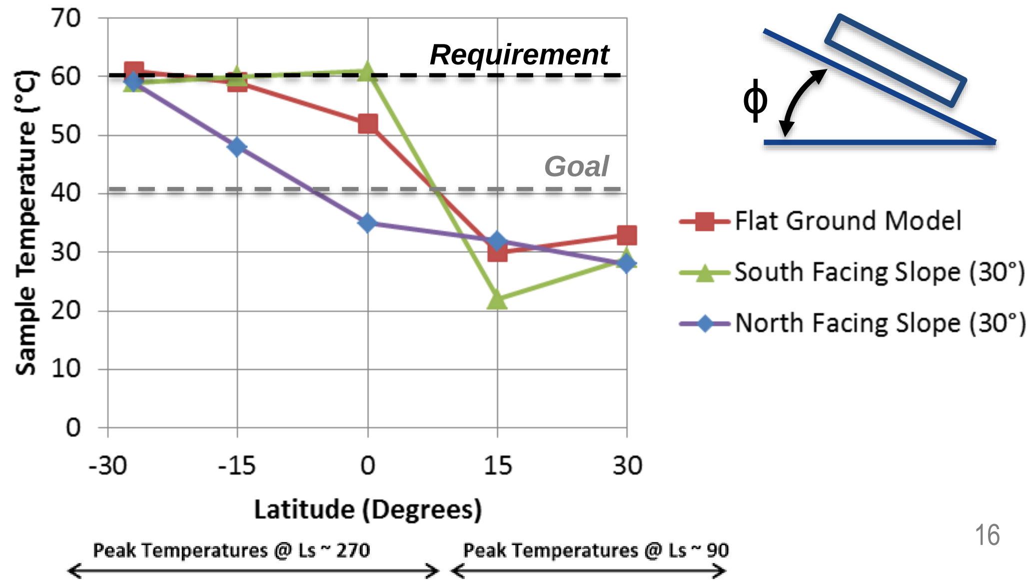
- Assume dust covered grit blasted stainless steel tube (ε = 0.38, α = 0.7)
- No contact with ground
- TI = 220 $Jm^{-2}K^{-1}s^{-1/2}$

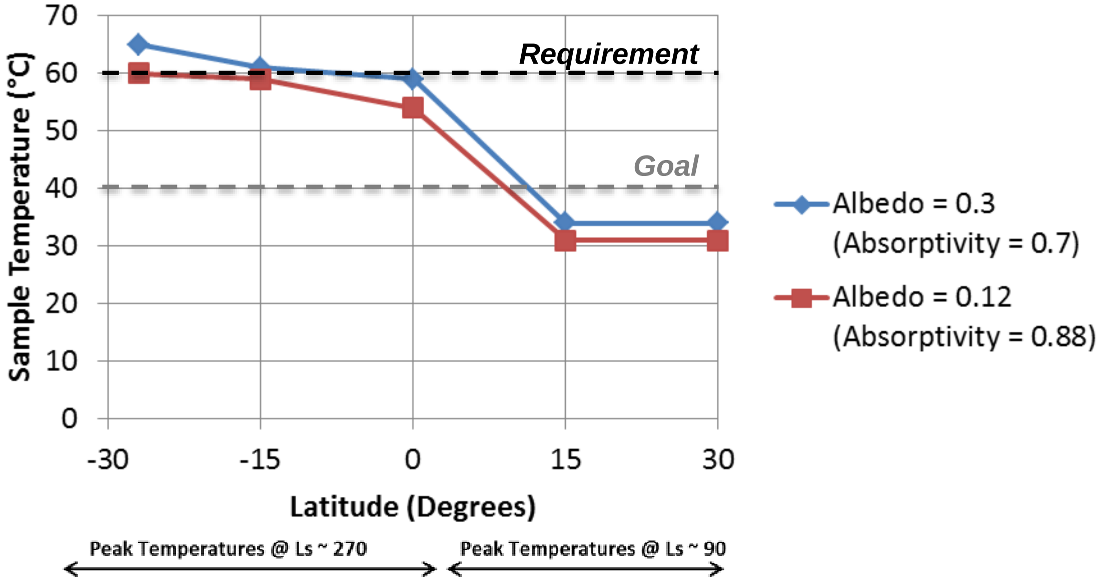


- **5 – 25 C Sensitivity Max**
  - Landing site dependent
  - Orientation dependent
  - Slope dependent



Effect of Ground Albedo

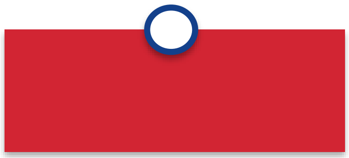
- Assume dust covered grit blasted stainless steel tube (ε = 0.38, α = 0.7)
- No contact with ground
- TI = 220 $Jm^{-2}K^{-1}s^{-1/2}$



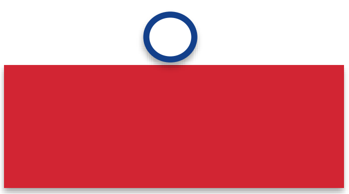
- Higher ground albedo results in
  - Cooler ground temperatures
  - Increased reflected solar flux on tube
  - **Increased tube temperatures by ~ 5 C**

Tube Contact with Ground

- Sandier Location
  - Good Thermal Contact (+)
  - Easier to “bury” Tube (+)
  - Lower Thermal Inertia
    - Higher Peak Ground Temperature (-)
    - Poor Heat Sink (-)



- Rockier Location
  - Poor Thermal Contact (-)
  - Harder to “bury” Tube (-)
  - Higher Thermal Inertia
    - Lower Peak Ground Temperature (+)
    - Better Heat Sink (+)



- Tube-Ground Thermal Contact:
  - Tube eccentric break off features could create 2 mm gas gap
  - Pebbles, rocks, or uneven soil could create <u>additional</u> gas gaps

Effect of Tube-Ground Contact

(Ground TI = 220 J m^{-2} K^{-1} $s^{-1/2}$)

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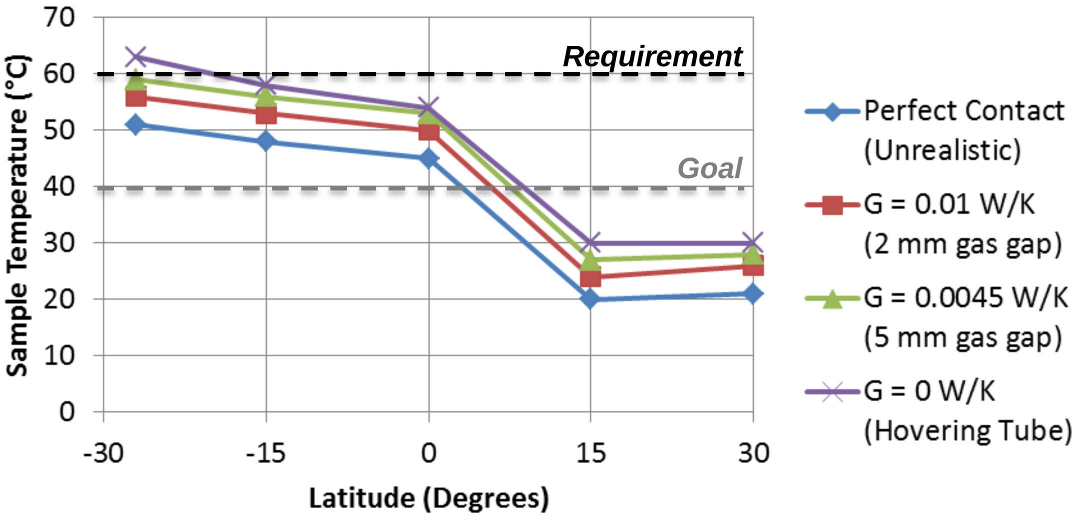
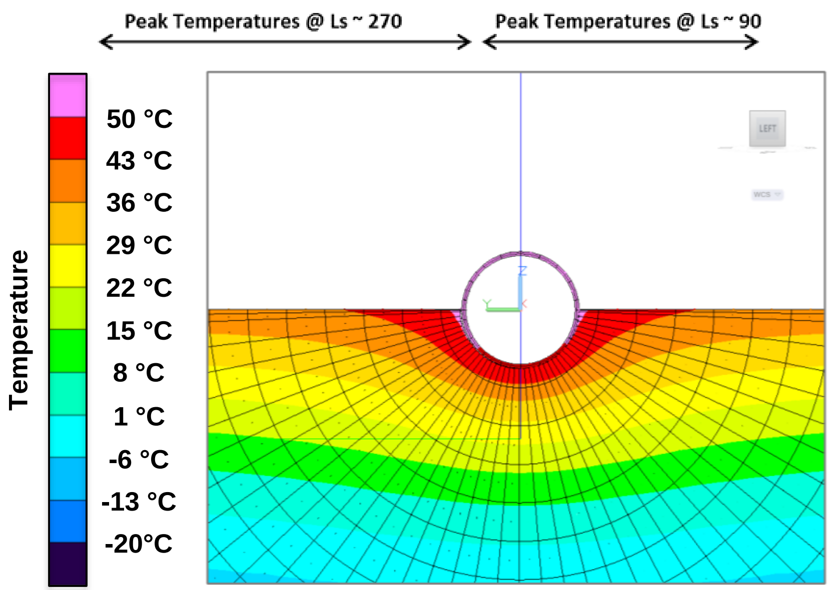


- Assume dust covered grit blasted stainless steel tube ($\varepsilon = 0.38$, $\alpha = 0.7$)



- Effect of Tube-Ground contact is relatively small
  - Only the CO2 gas conduction can be relied upon.
  - Even with (unrealistic) perfect contact the ground is not a good heat sink.
  - **Expected effect of < 5 C for low TI**

Effect of Tube-Ground Contact

(Ground TI = 350 J m^{-2} K^{-1} $s^{-1/2}$)

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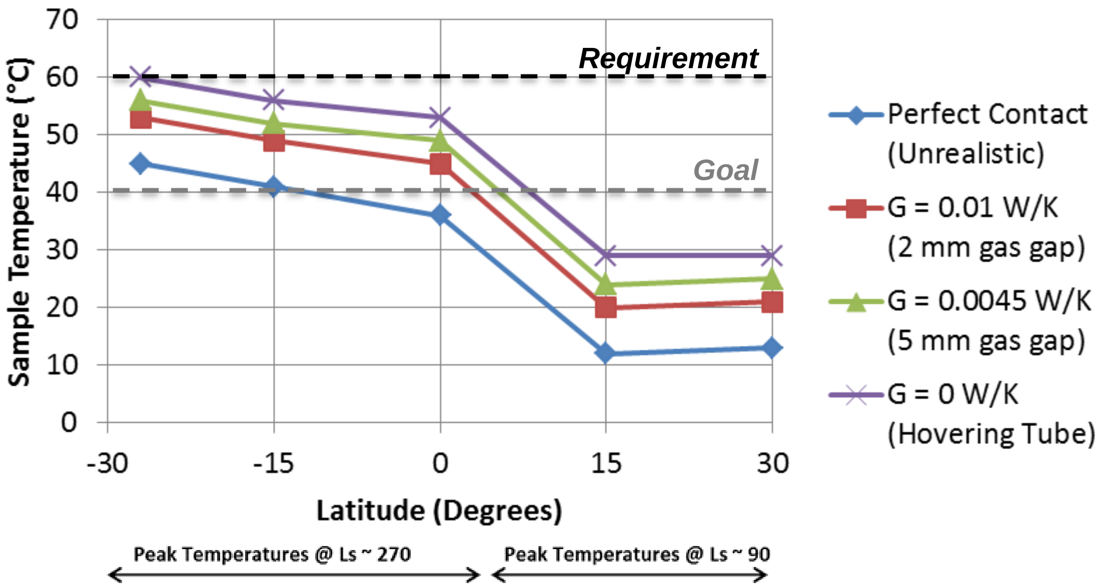
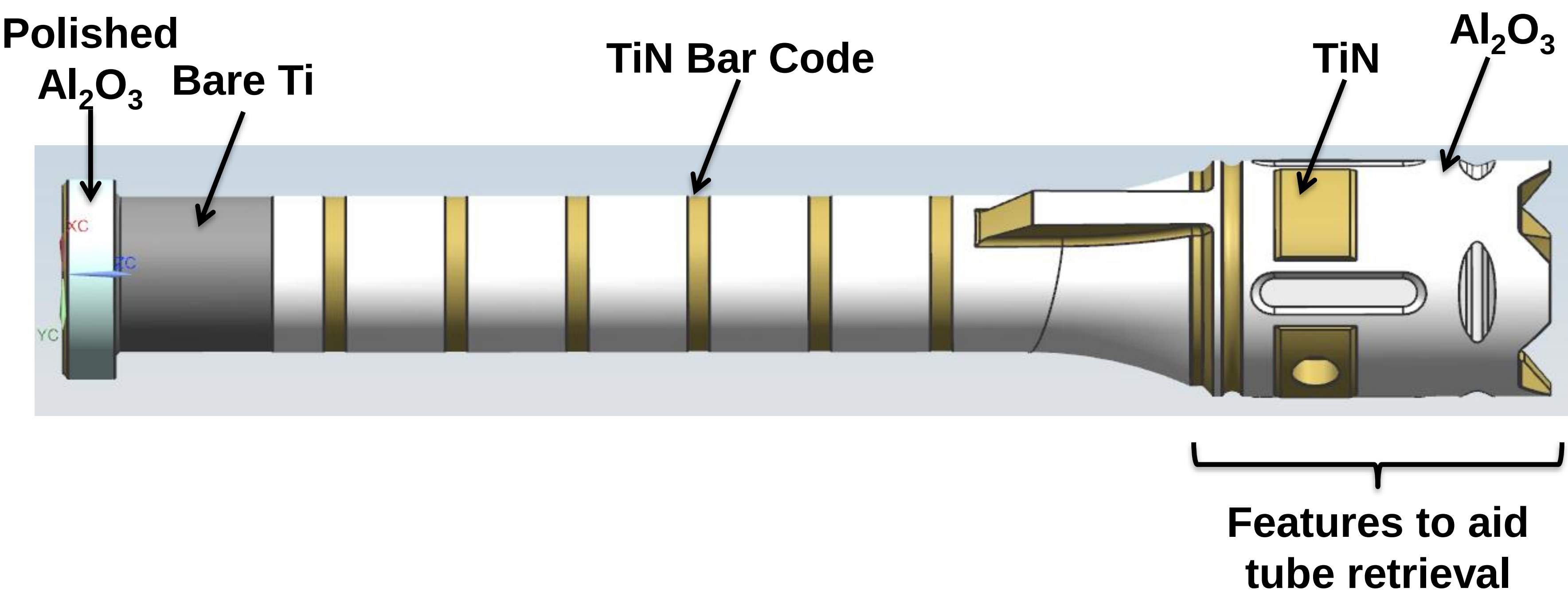


- Assume dust covered grit blasted stainless steel tube (ε = 0.38, α = 0.7)

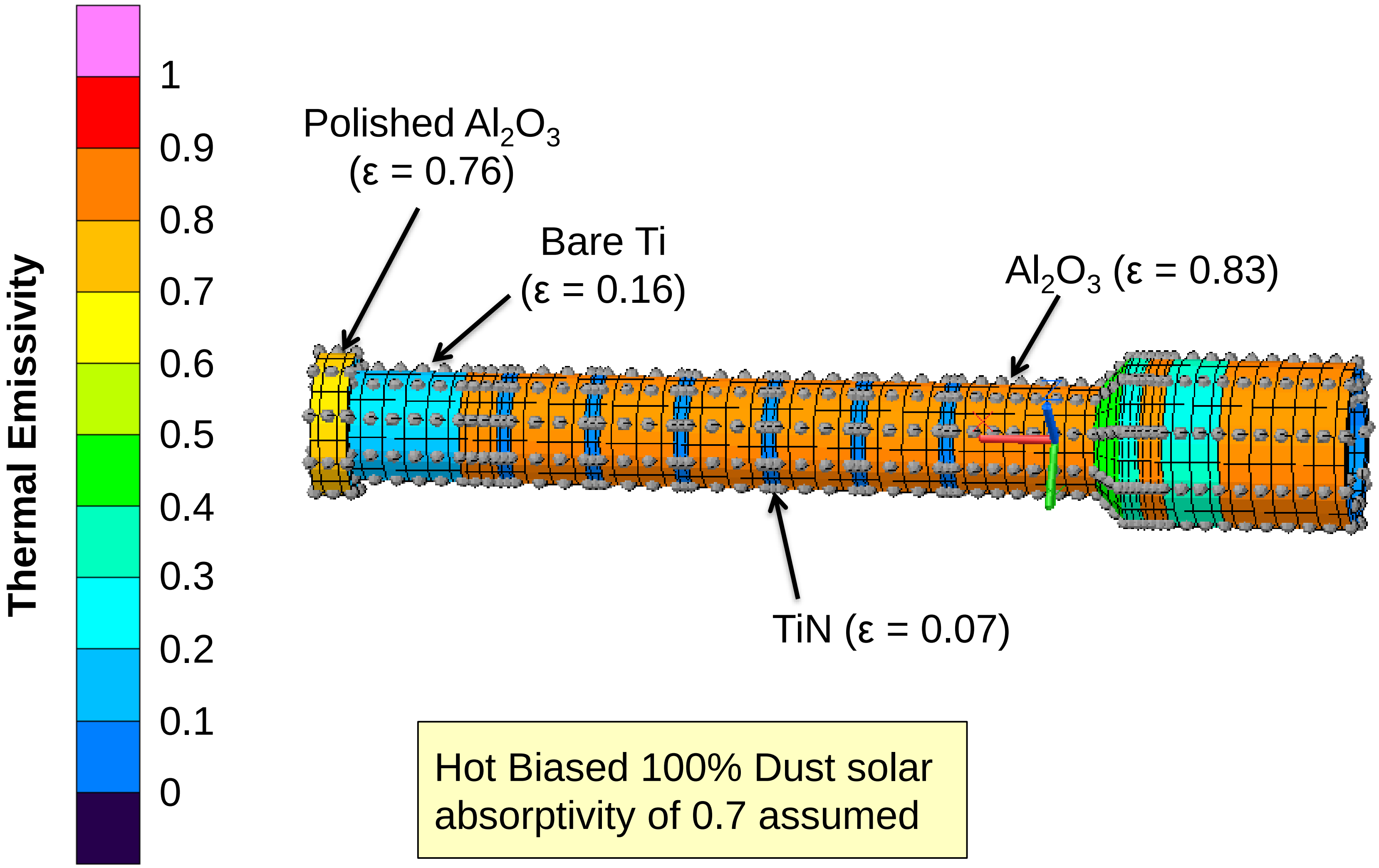
- Effect of Tube-Ground contact is relatively small
  - Only the CO2 gas conduction can be relied upon.
  - **Expected effect of < 10 C for low TI**

Flight Tube Design

- Tube has completed Detailed Design Review (DDR).
- Design Features
  - Al_2O_3 coating for thermal control
  - Features to aid in potential tube retrieval by a future mission
  - TiN “Bar Code” to allow for visual identification on Mars
  - Bare Ti region enables sealing at sealing station
  - Polished Al_2O_3 on bearing race to aid in the drilling operation



Tube Thermal Emissivity



Hot Biased 100% Dust solar absorptivity of 0.7 assumed

WCH Tube Temperature Contours

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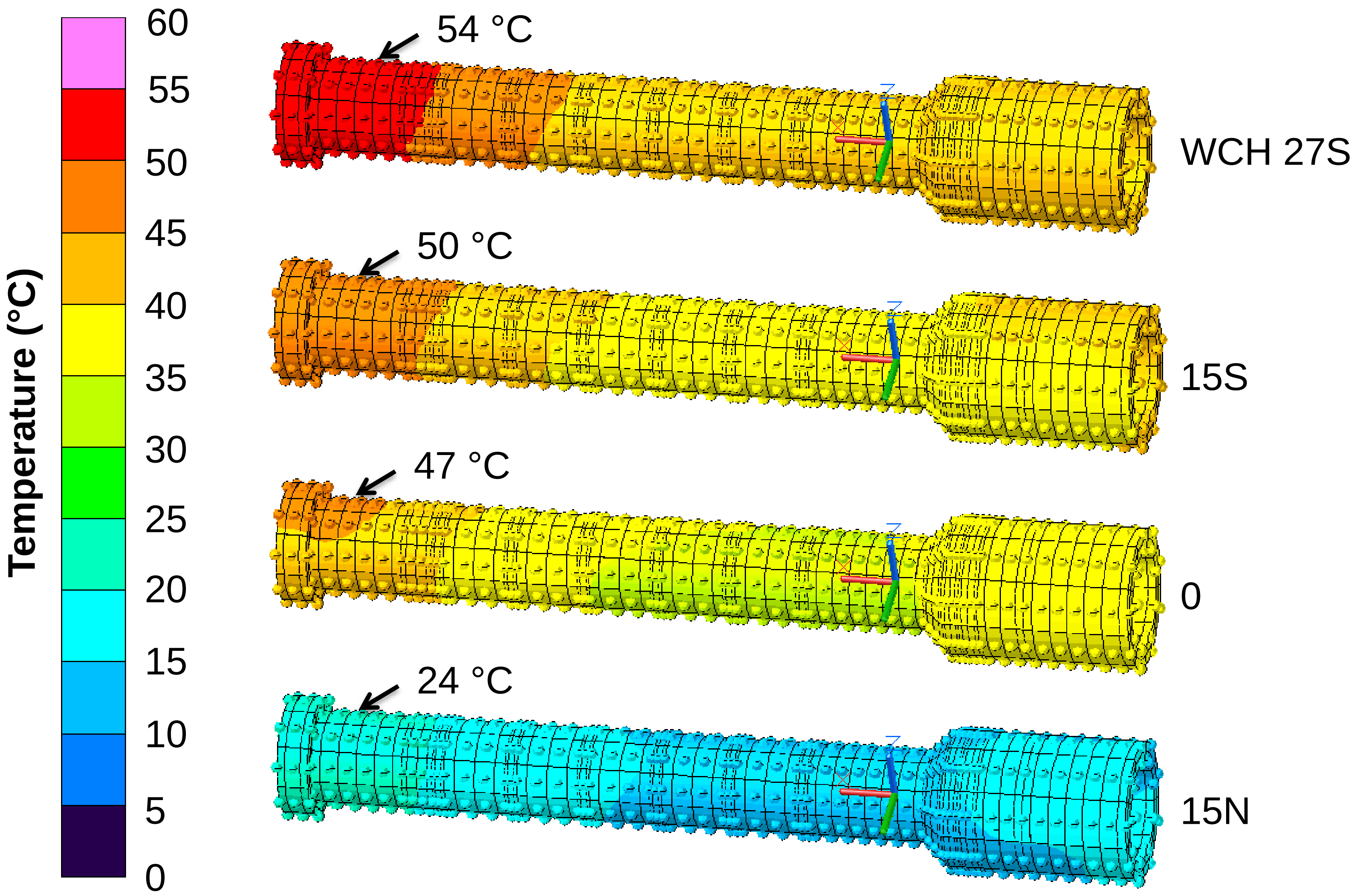
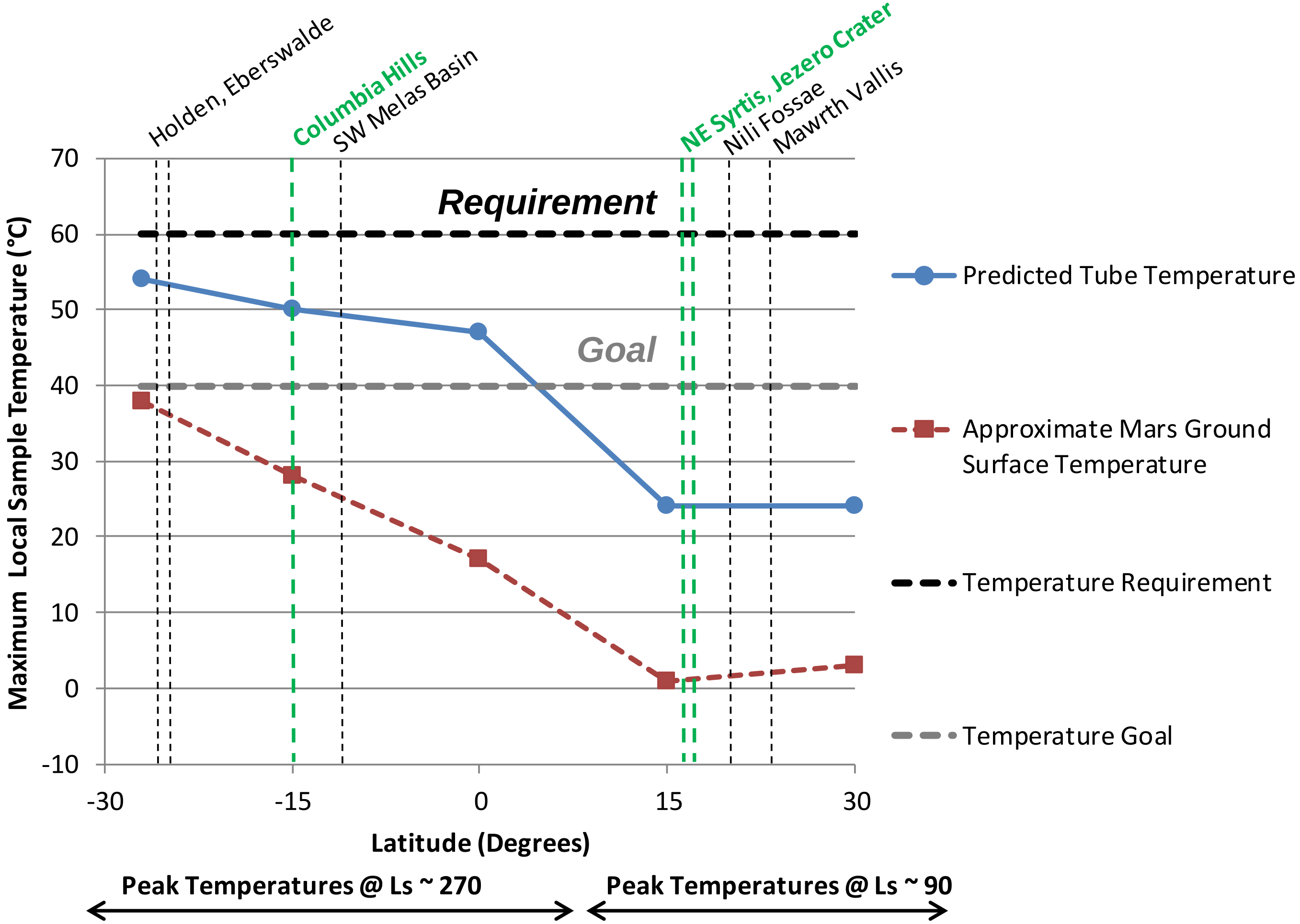


Sample Temperature vs. Latitude

- Sample Predicts for the Current Baseline Design:
  - Sample < 60 °C requirement across the entire latitude range.
  - Sample < 40 °C goal across many latitudes and 2 of top 3 landing sites.



- Results are for stacked worst case scenario:
  - 100% Dust (α only)
    - > 10 °C effect
  - TI = 220 $Jm^{-2}K^{-1}s^{-1/2}$
    - ~ 4 °C effect
  - Albedo of 0.3
    - ~ 5 °C effect
  - No tube-ground contact
    - ~ 5 °C effect
  - Free convection only

Note: Temperatures are for flat ground locations, roughly corresponding to the hottest part of the year at each latitude

Operational Considerations

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- Mission operations strategy already being planned.
  - Future rovers should be able to identify caching location:
    - ~ 1 m accuracy using orbital imagery
    - ~ 1 cm accuracy using rover cameras
  - Likely do not want to cache tubes:
    - By sand dunes which can migrate over time
    - On the side of a hill where tubes can roll

- Rover should not drive over tubes to avoid heating the tubes by the RTG.

- Some strategies might be used to reduce tube temperature:
  - Deposit tubes in a high thermal inertia region where peak local ground and atmospheric temperatures are reduced.
  - Samples would be exposed to room temperatures (~ 25 °C) upon return to Earth, so there is no reason to do this at the northern landing sites.

Conclusion

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- Sample tube design recently completed Detailed Design Review (DDR)
  - Design is mature and not expected to change
- Tube thermal design meets requirements
  - Sample < 60 °C requirement across the entire latitude range.
  - Sample < 40 °C goal across many latitudes and 2 of top 3 landing sites.
- Additional tube temperature predictions may be useful once we get closer to launch
  - Use selected landing site environment to inform temperature predictions.
  - Inform mission operations team on the best place to cache samples.