NASA

Thermal Design of the Landing Gear and its Actuator on the Mars Sample Retrieval Lander

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Presented By
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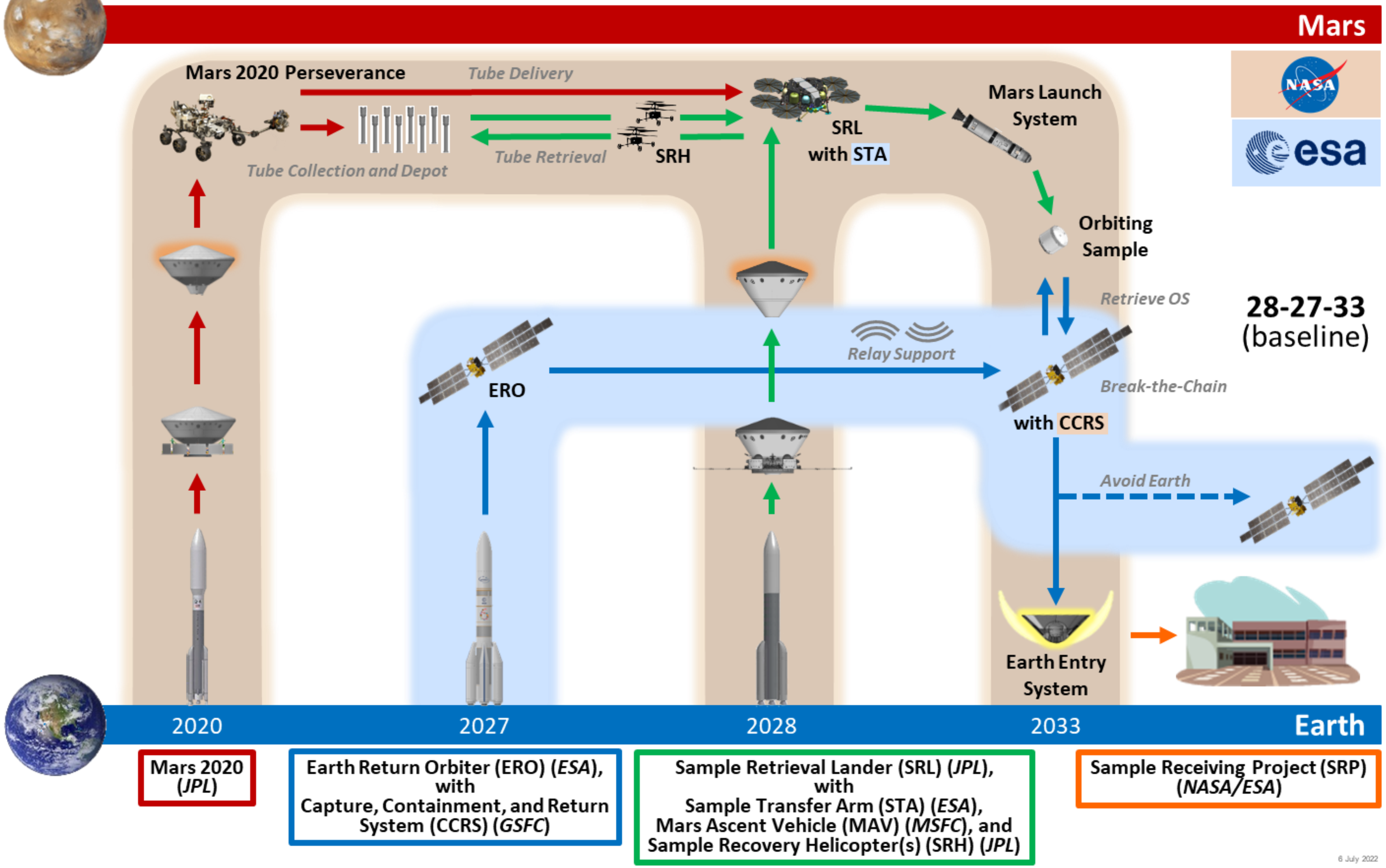
NASA Goddard Space Flight Center
Greenbelt, MD

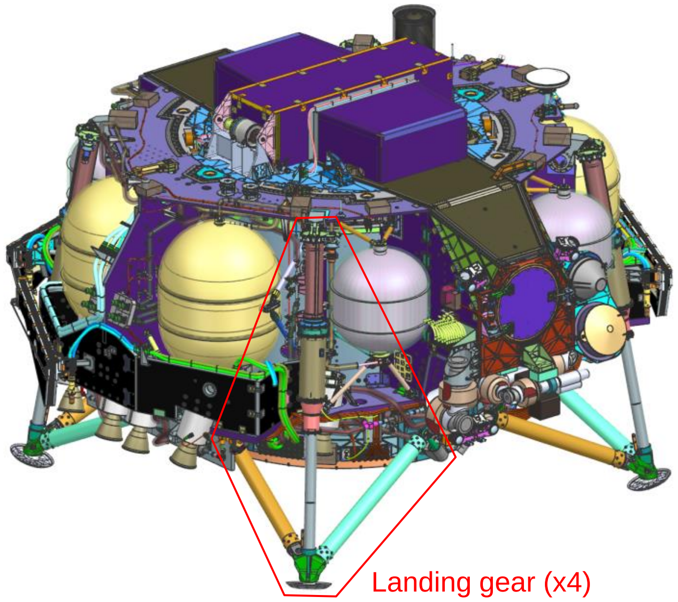
Mars Sample Return (MSR) Campaign Planning Overview

Goal: First sample return from another planet



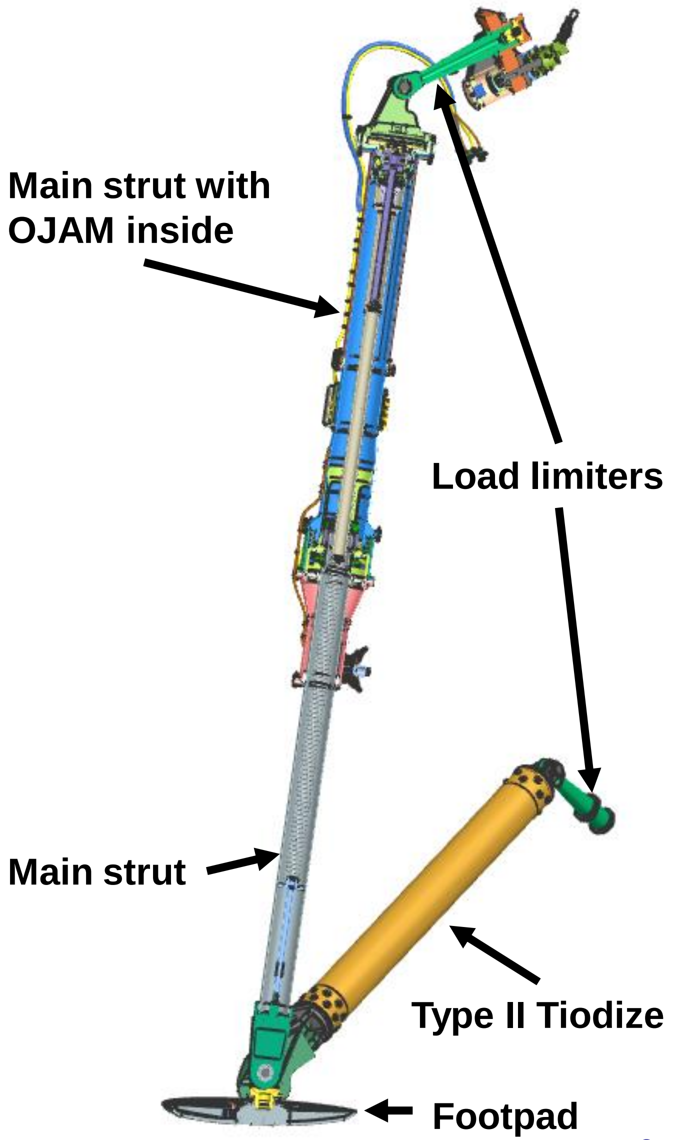
Sample Retrieval Lander

Artist's Concept

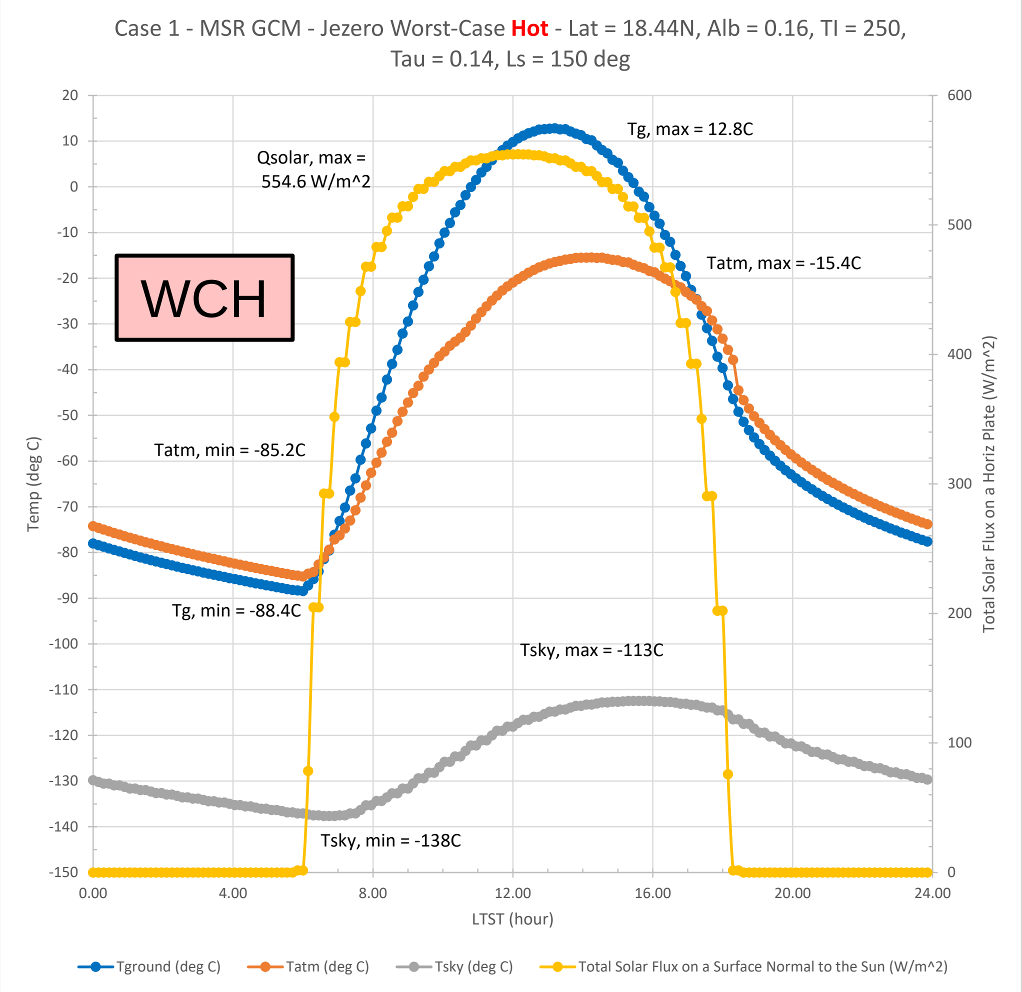


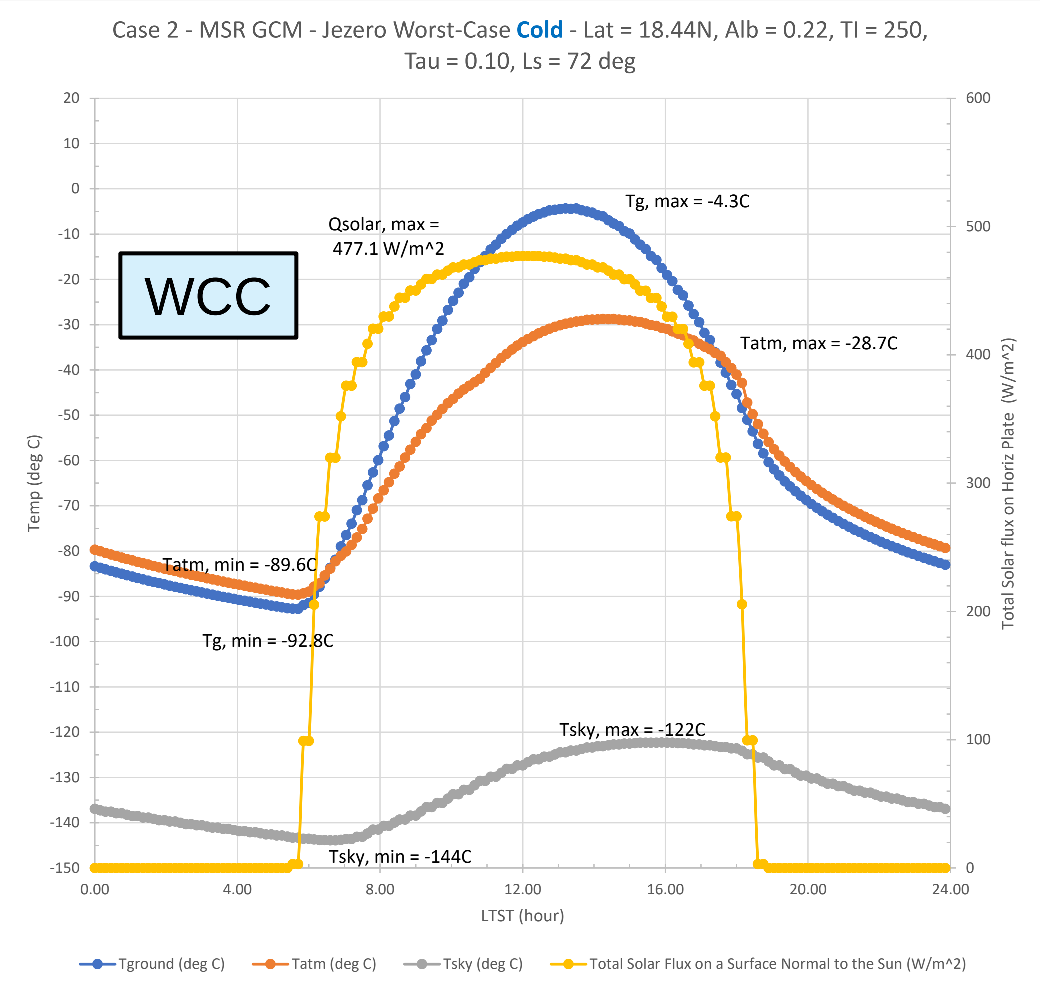
Sample Retrieval Lander (SRL) Landing Gear Overview

- Legs absorb landing energy and provide launch isolation when launching the samples from Mars
- Lubricated offset jackscrew adjustment mechanism (OJAM) in the main strut is used to ensure all four legs are in contact with the ground and the lander is stable
  - **Actuator requires warmup heaters**
  - **Lubricated OJAM needs to be at least -55C** before beginning adjustment – warmup energy far too large and so will require time of day restrictions on leg adjustment
- Optical properties
  - All aluminum parts are black anodized (a/e=0.88/0.88) and Ti parts Type II Tiodized (a/e=0.5/0.8)
  - The main strut is bare titanium as requested per Lander Mech
  - The footpad is bare aluminum since it will most likely be covered in Mars dirt or dust regardless
- Thermal coupling
  - The leg is thermally decoupled from the structure through the steel load limiters



Predicted Mars Environments for SRL





Albedo: ground reflectivity

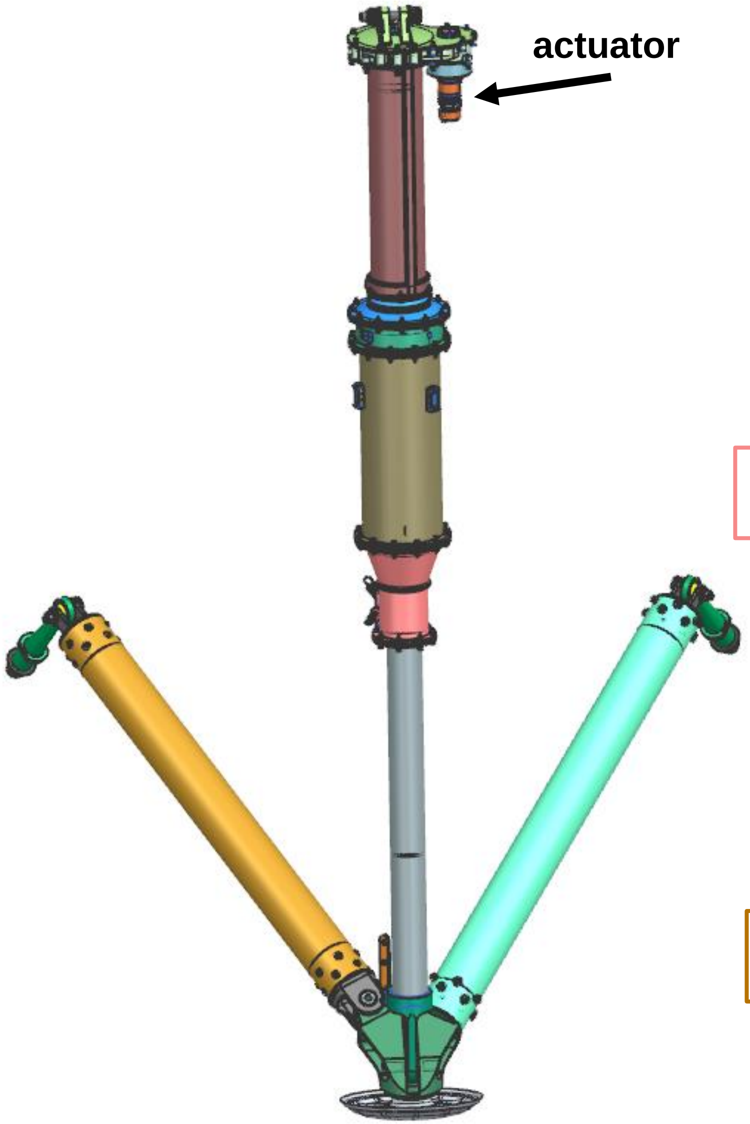
TI: thermal inertia of ground, $\mathrm{TI} = \sqrt{k\rho c_p}$

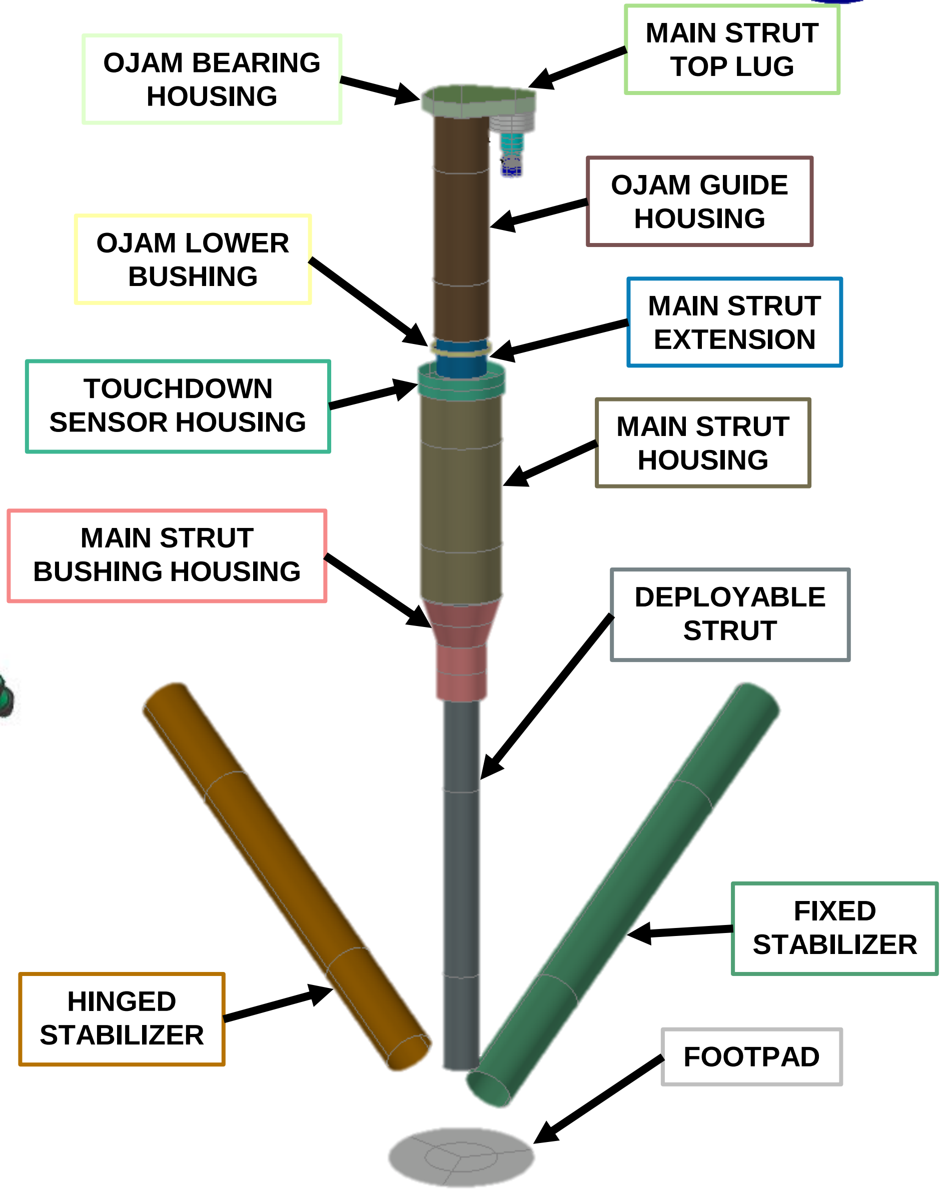
Tau: atmospheric optical depth

Ls: solar longitude

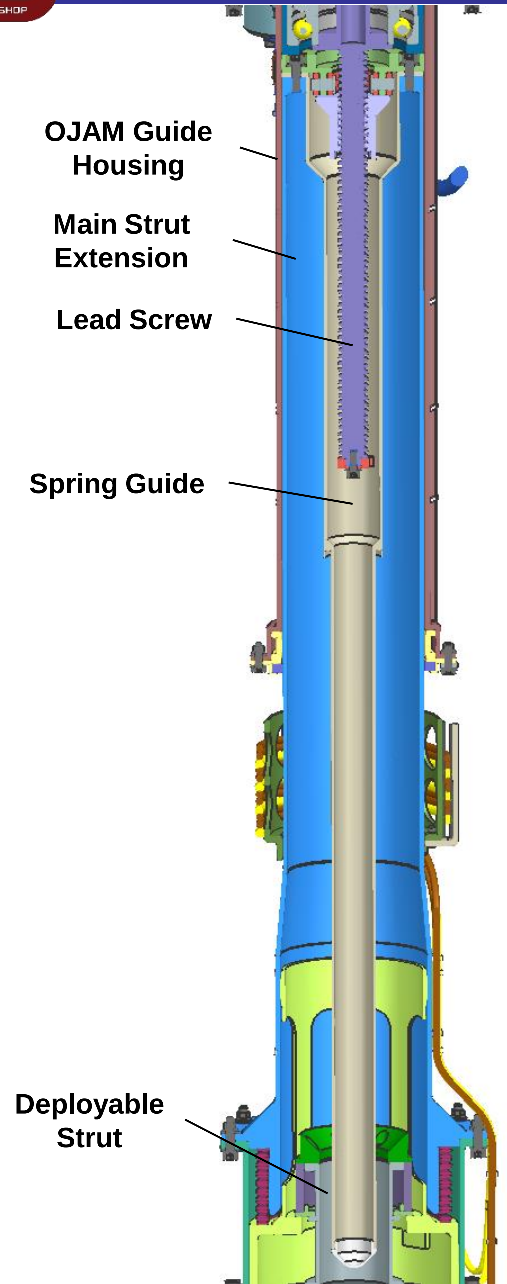
Landing Gear Modeling Assumptions

- Model only includes the external structure of the landing gear, no internal parts like bearings
- Assumes a dust factor of 0.65, excluding the footpad which is assumed to be fully covered in dust
  - Requirement is 10%, landing could kick up even more dust
- Heat transfer coefficients calculated using Nu correlation for flow across a cylinder
  - $0.3 < h_{free} < 0.5 \frac{W}{m^2K}$
  - $2.9 < h_{forced} < 3.5 \frac{W}{m^2K}$
  - Range is obtained using possible leg and atmosphere temperatures



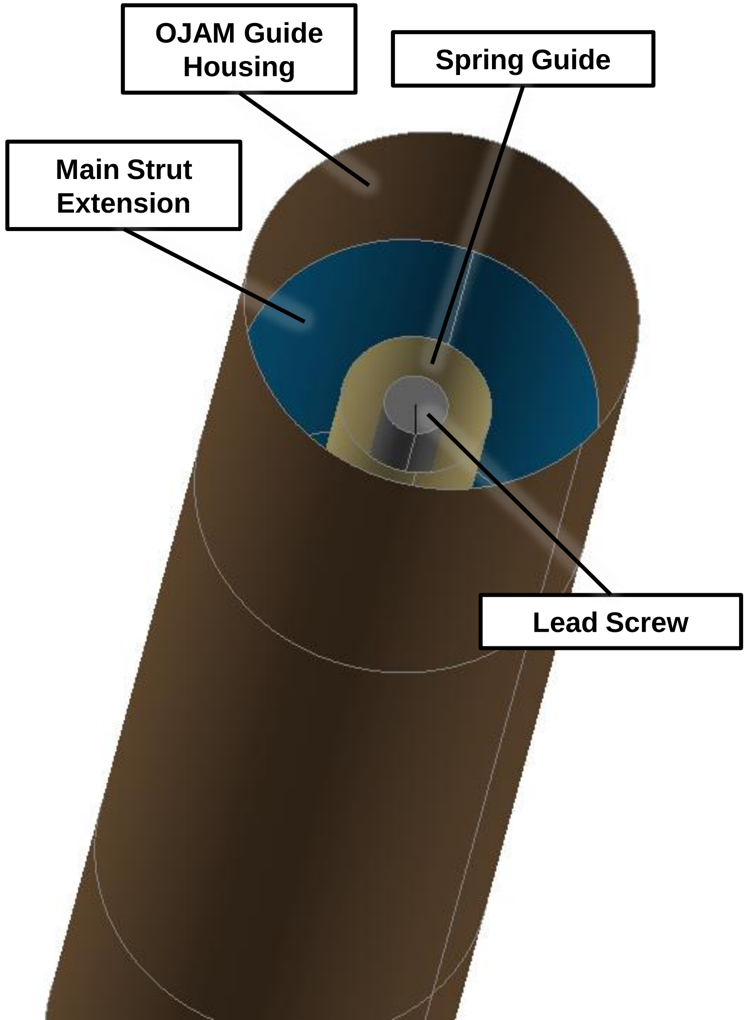


Adjustment Mechanism Detail



- Assumes lube is used in ball bearing and along the lead screw, so will need to warm up entire lead screw before use
- Added density factor to OJAM surfaces/solids to account for missing parts
- Lead screw and spring guide are coupled to OJAM housing
  - Estimated bearing conductance, gas gaps, etc

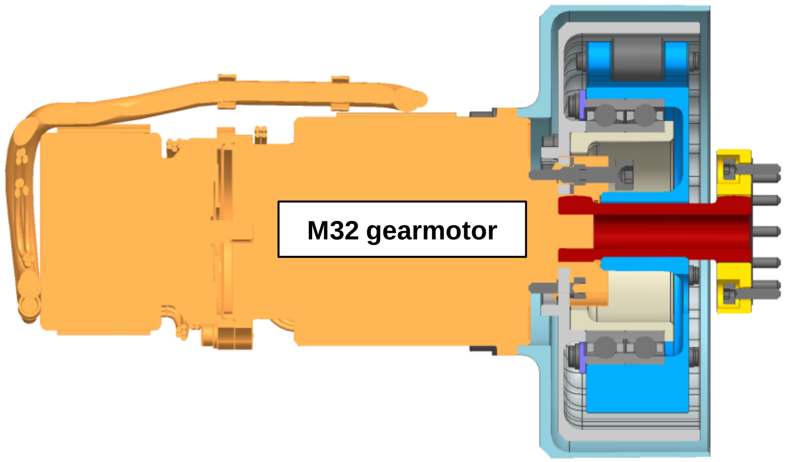
OJAM Thermal Desktop Model



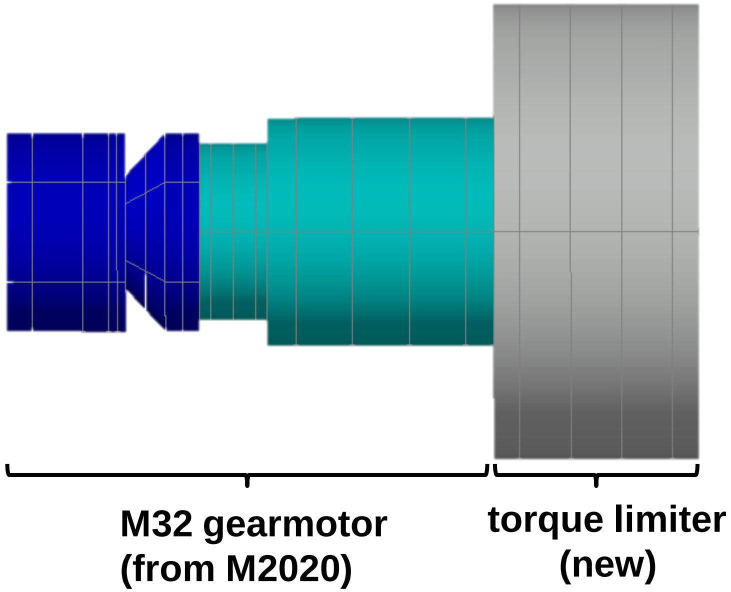
Actuator Overview

- Test correlated Mars2020 thermal models used for the motors and gearboxes
  - Torque limiter on M32 gearbox output is a new addition to the thermal model
- Warm-up time was calculated based on how long it took the torque limiter rotor (final output node) to reach the lube min operating temp

Actuator Solid Model

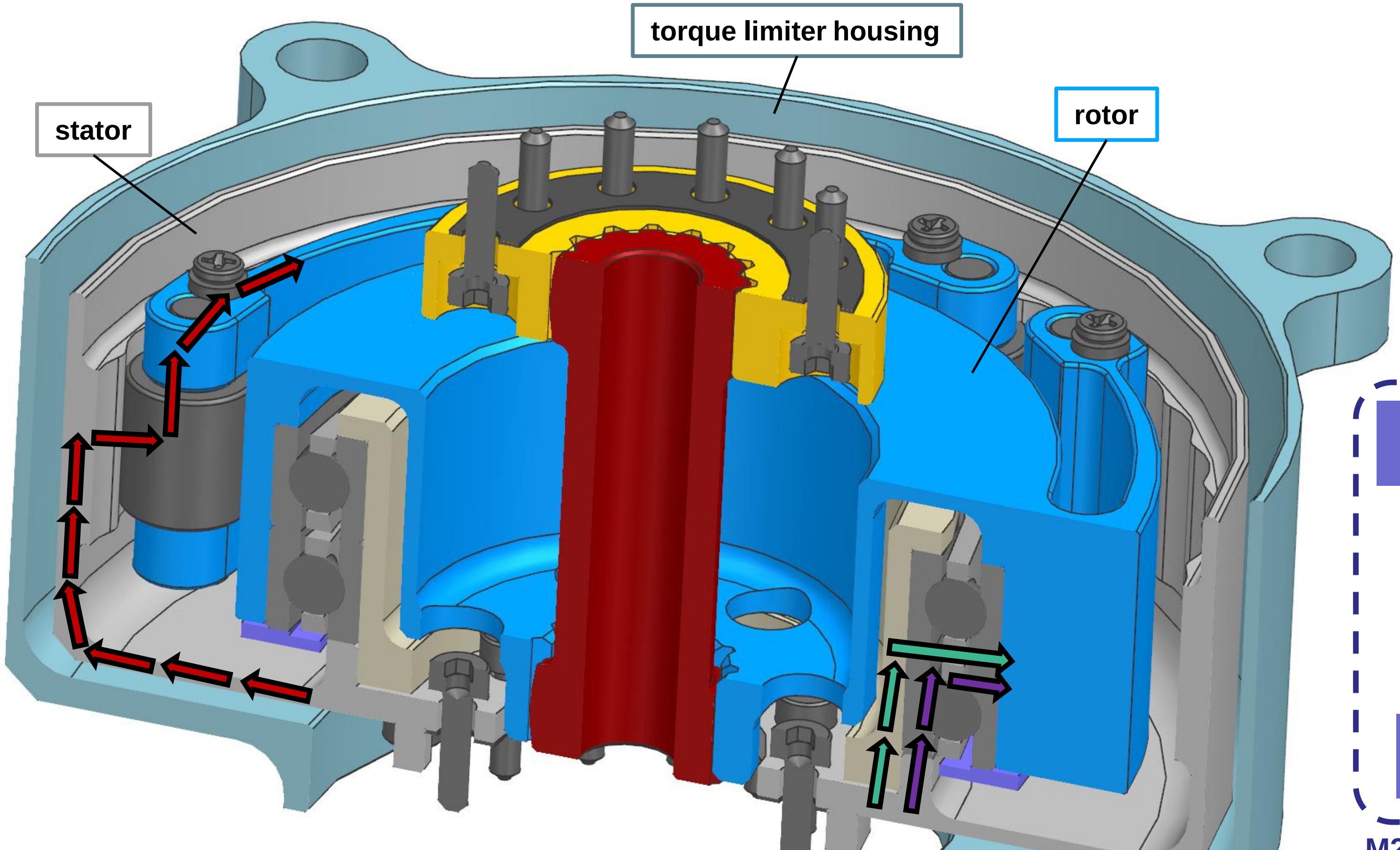


Actuator Thermal Desktop Model

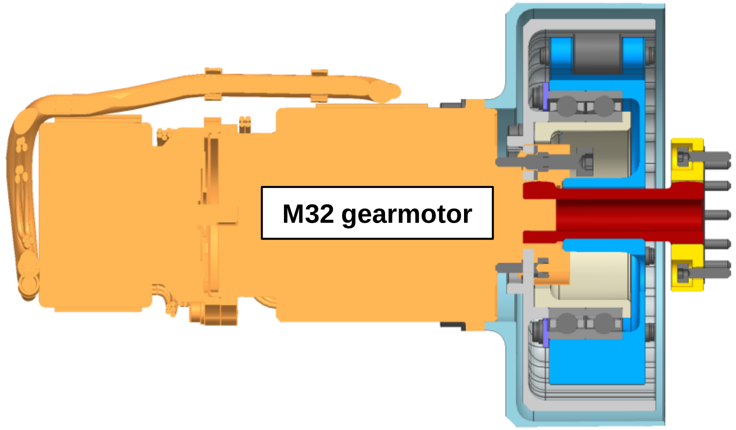


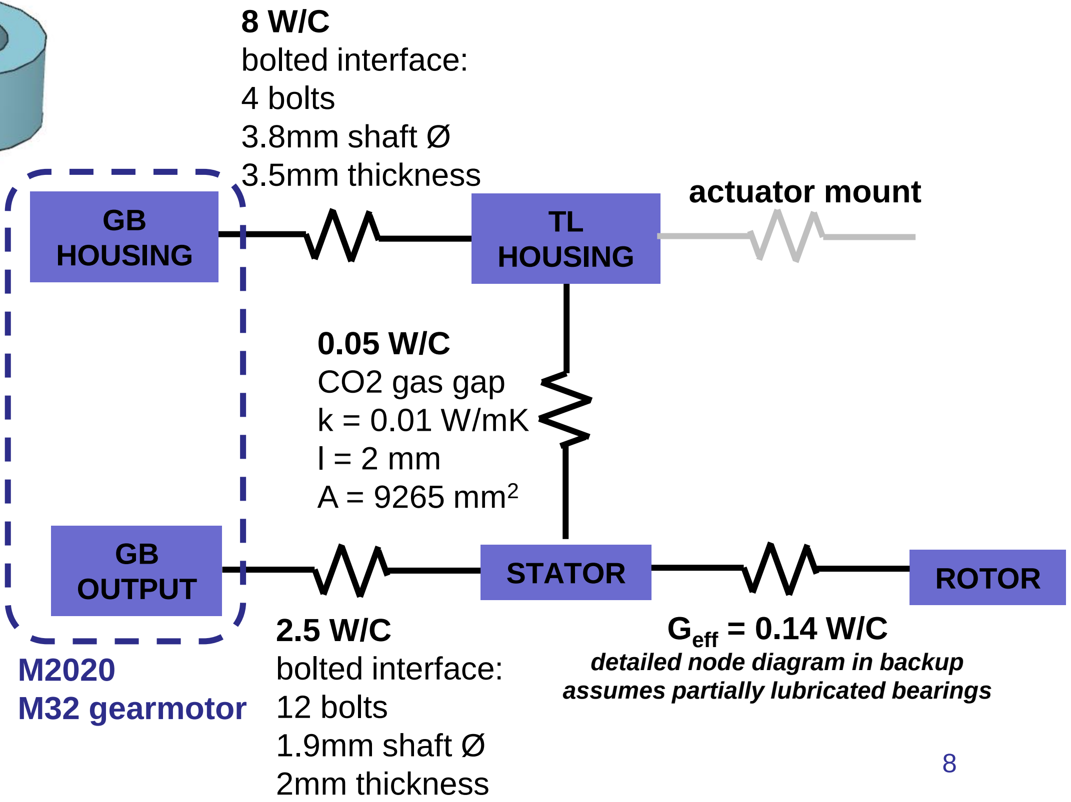
Torque Limiter Detail

- Stator and rotor modeled as diffusion nodes, torque limiter housing modeled as cylindrical surface
- Bolted interface conductances approximated based on size and number of bolts
- Used marginal lubrication bearing correlation to estimate ball bearing conductance



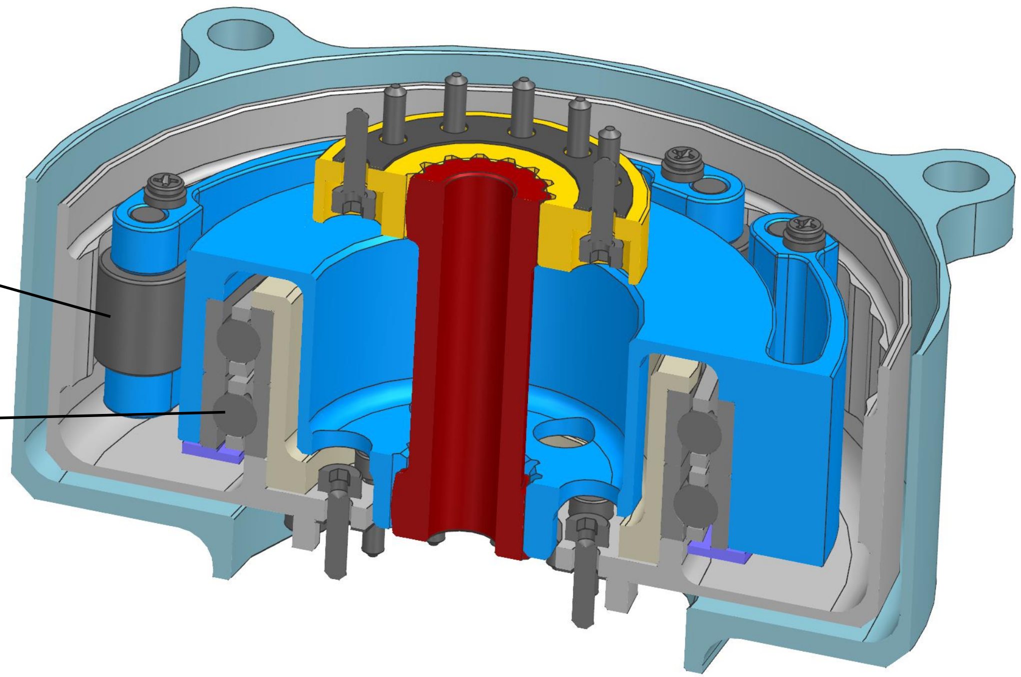
Heat flow paths from stator to rotor shown using arrows





Bearing Conductance Correlation and Sensitivity

Source: Static Ball Bearing Thermal Conductance in Air and Vacuum: Review and Correlation (Matthew Redmond, Keith Novak, Virgil Mireles), Journal of Thermophysics and Heat Transfer Vol 31, No. 4, October-December 2017



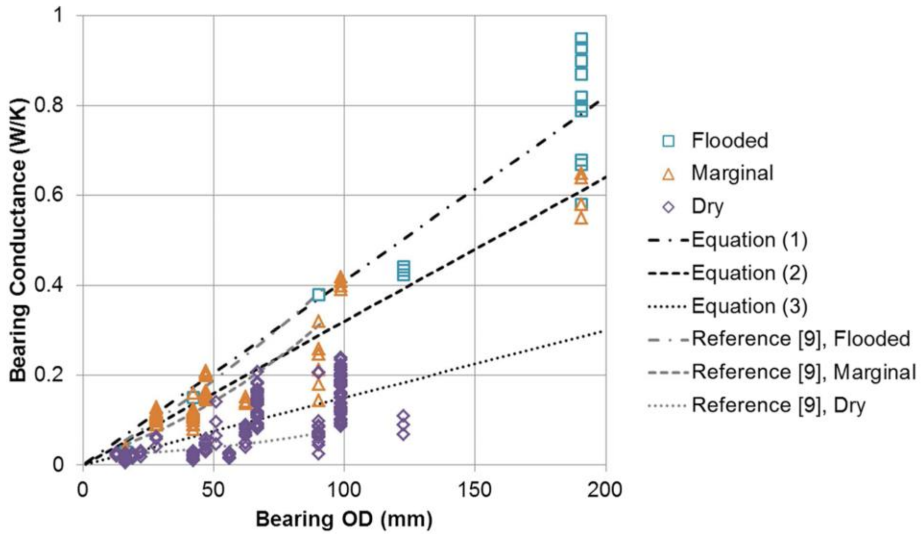


Fig. 3 Correlations of bearing conductance in vacuum as a function of bearing OD for dry, marginal, and flooded lubrication states.

Lubrication	Stator to Rotor Conductance (W/C)	Warmup Time (hours) Actuator @ 28V
Flooded	0.20	0.8
Marginal	0.16	0.8
Dry	0.09	0.9

$$G_{flooded} = 0.0041 * Do \quad R^2 = 0.87 \quad (1)$$

$$G_{marginal} = 0.0032 * Do \quad R^2 = 0.89 \quad (2)$$

$$G_{dry} = 0.0015 * Do \quad R^2 = 0.53 \quad (3)$$

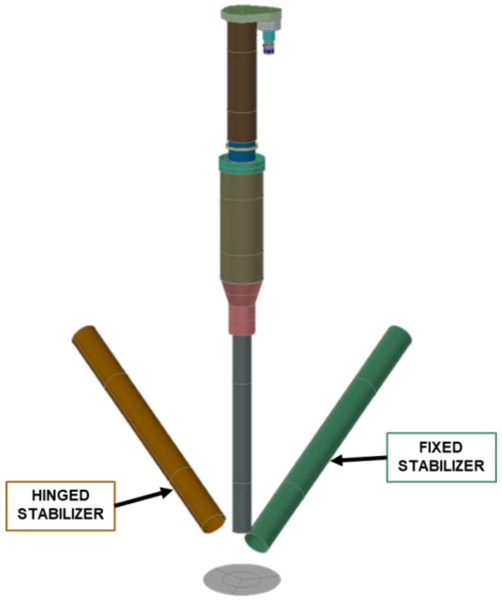
Landing Gear Sensitivities

Case	WCC Min		WCC Max		WCH Min		WCH Max		Comments
	T (C)	ΔT (C)	T (C)	ΔT (C)	T (C)	ΔT (C)	T (C)	ΔT (C)	
Baseline	-92.4	-	-6.2	-	-94.5	-	36.5	-	WCC h = 3.5 W/m^{2}K WCH h = 0.5 W/m^{2}K
WCC h = 0.5 W/m^{2}K	-99.1	**-6.6**	21.3	**27.5**	-	-	-	-	Free convection, WCC
WCC h = 0.3 W/m^{2}K	-100.7	**-8.3**	25.0	**31.2**	-	-	-	-	Even smaller h, WCC
Fully covered in dust	-92.7	**-0.3**	-7.1	**-0.9**	-95.2	**-0.8**	24.8	**-11.7**	Assumes $\varepsilon = 0.95, \alpha = 0.7$ for all
With ground effects	-86.6	**5.8**	-0.5	**5.7**	-92.2	**2.3**	43.3	**6.9**	Current ground model is coarse, more detailed modeling will occur later

- From these we can pull out WCC and WCH assumptions to use as our most conservative cases:
  - **WCC:** free convection, fully covered in dust
  - **WCH:** free convection, with ground effects

Overall Temperatures

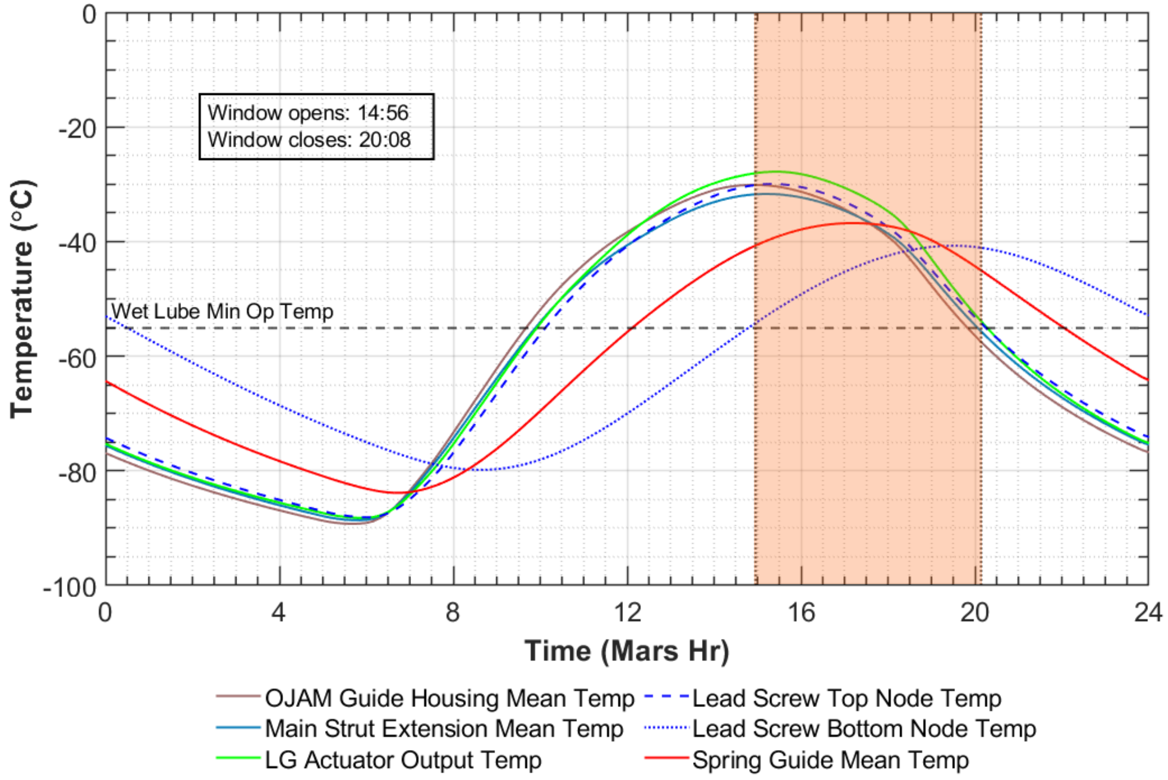
- Landing gear stabilizers get slightly too hot – can be resolved by increasing maximum allowable flight temperature (max AFT) or adjusting Tiodize α/ε
- Landing gear sensitivities:
  - Less wind: min ↓, max ↑
  - Fully covered in dust: ↓ temps
  - With ground effects: ↑ temps
  - Warmup time is not sensitive to torque limiter bearing conductance



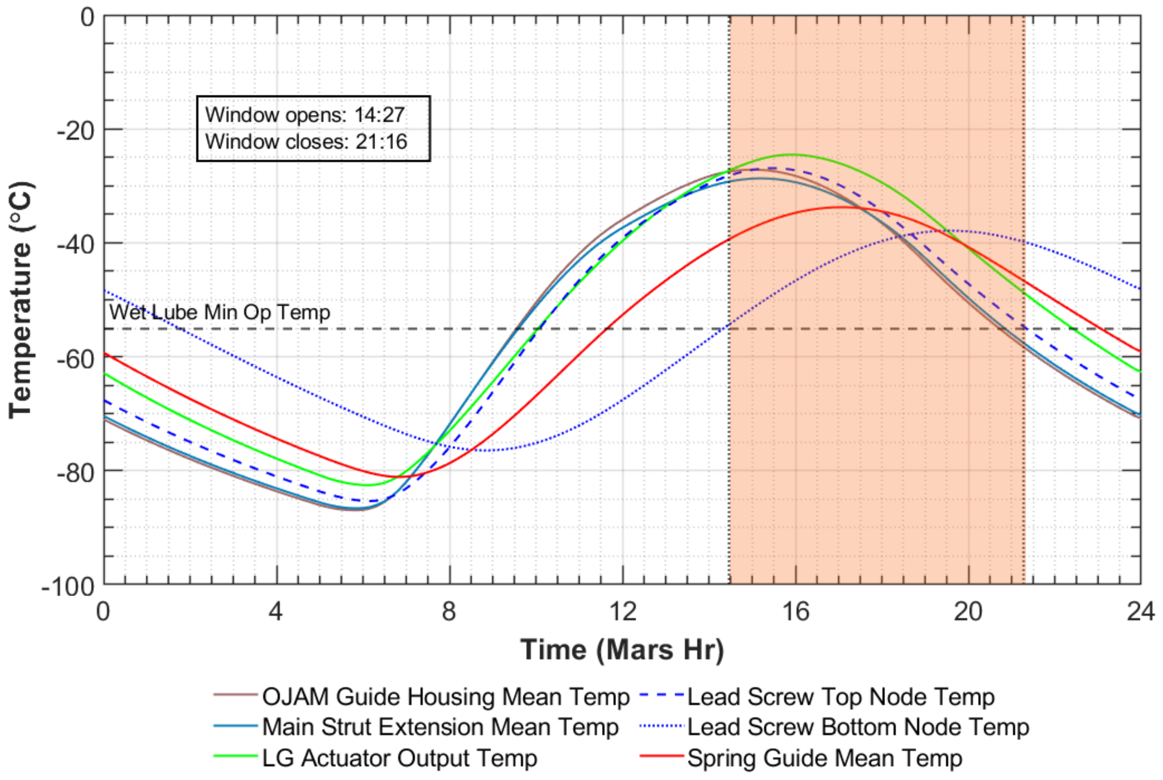
SRL FS Hardware	Temperature, °C Allowable Flight Operational Min	Operational Max	Non-Operational Min	Non-Operational Max	WCC Ls72 Tau 0.1 Min Predict	WCC Ls72 Tau 0.1 Max Predict	Margin OP/NonOP	Margin Min Margin	Margin Max Margin	WCH Ls150 Tau 0.12 Min Predict	WCH Ls150 Tau 0.12 Max Predict	Margin OP/NonOP	Margin Min Margin	Margin Max Margin
Acadia Actuator	-55	50	-105	50	-90.9	-25.7	NONOP	14.1	75.7	-87.2	32.5	NONOP	17.8	17.5
Landing Gear Main Strut Assembly (including Pivots)	-105	50	-105	50	-91.4	-14.6	NONOP	13.6	64.6	-93.5	49.7	NONOP	11.5	0.3
Landing Gear Restraint Pin Puller (3/8")	-70	65	-105	91	-90.8	-25.9	NONOP	14.2	116.9	-91.2	18.8	NONOP	13.8	72.2
Landing Gear Deployment Latch (internal to Main Strut Assembly)	-55	50	-105	50	-91.2	-27.4	NONOP	13.8	77.4	-91.8	17.0	NONOP	13.2	33.0
Landing Gear Footpad	-105	50	-105	50	-92.6	-7.1	NONOP	12.4	57.1	-84.3	18.2	NONOP	20.7	31.8
Landing Gear Touchdown Sensor	-105	50	-105	50	-91.2	-27.3	NONOP	13.8	77.3	-91.8	17.4	NONOP	13.2	32.6
Landing Gear Stabilizer Assembly (including Pivots and Hinge)	-105	50	-105	50	-90.9	-12.7	NONOP	14.1	62.7	-88.8	51.9	NONOP	16.2	-1.9
Landing Gear Post-Landing Adjustment Mechanism	-105	50	-105	50	-91.4	-26.2	NONOP	13.6	76.2	-93.5	18.3	NONOP	11.5	31.7
Landing Gear Adjustment Mechanism Actuator	-55	50	-105	50	-90.9	-25.7	NONOP	14.1	75.7	-87.2	32.5	NONOP	17.8	17.5

Adjustment Mechanism No Heat Operating Window

WCC Ls 72 Tau 0.1
Forced Convection



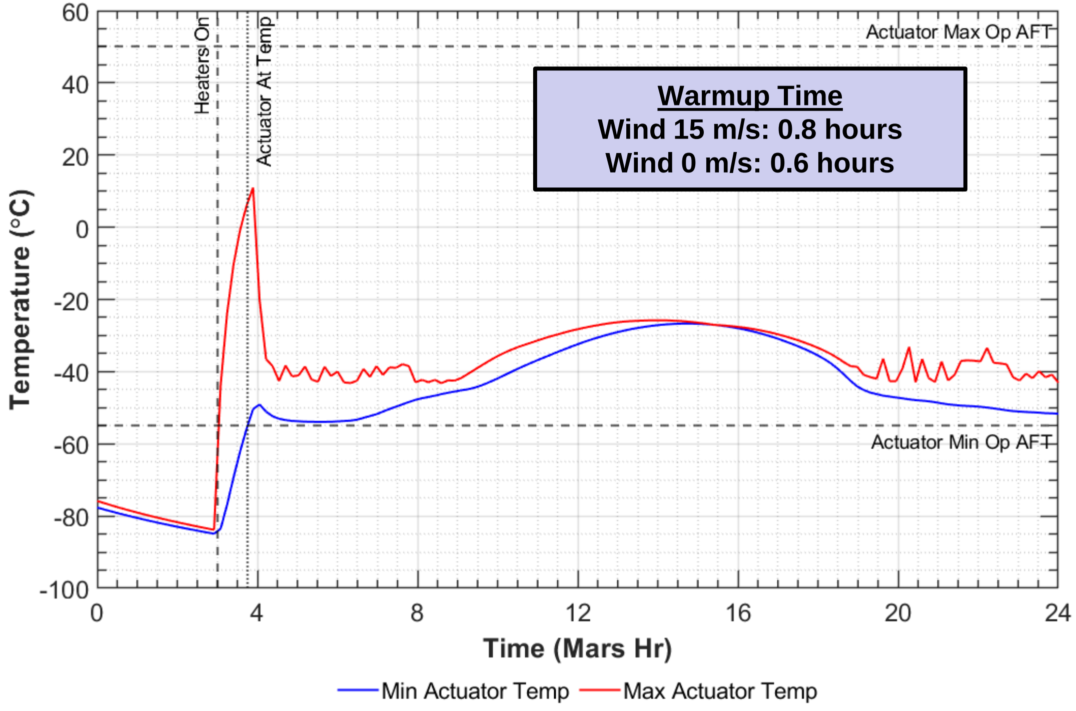
WCC Ls 72 Tau 0.1
Free Convection

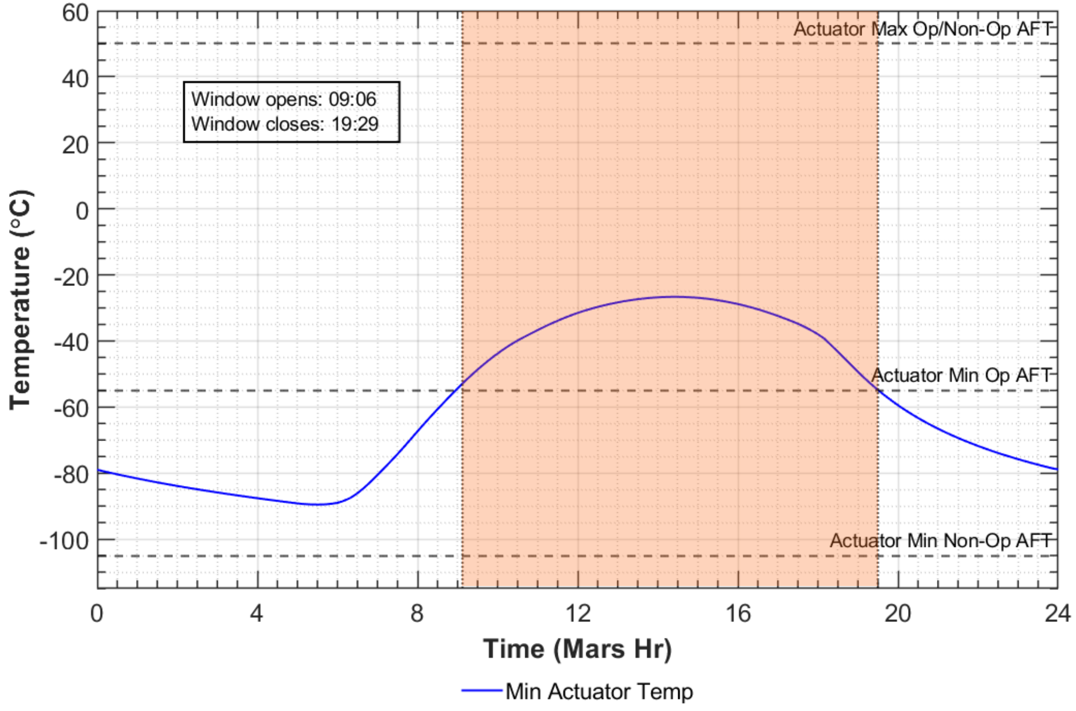


No heat is required to operate between:
Wind 15 m/s: 15:00-20:10 LTST
Wind 0 m/s: 14:30-21:20 LTST

Actuator Warmup Time and No Heat Operating Window

Jezero Ls 72 Tau 0.1 Forced/Free Convection





Parameter	Value	Parameter	Value
On Temp (Warmup)	20 C	Chuck Gearbox Heater Max Power	6.2 W
Off Temp (Warmup)	25 C	Chuck Motor Heater Max Power	4.5 W
On Temp (Maintenance)	-45 C	Warmup Time	0.8 hours
Off Temp (Maintenance)	-40 C	Warmup Energy	8.4 Whr
		Daily Average Maintenance Power	1.6 W

No heat is required to operate between:
Wind 15 m/s: 09:00-19:30 LTST
Wind 0 m/s: 08:40-20:10 LTST

Warmup Time: time from when the heaters turn on to when the rotor reaches the min op AFT
Warmup Energy: integral of max heater power over the warmup time
Maintenance Power: daily average heater power after actuator reaches min op AFT

Conclusions and Future Work

- Conclusions
  - Sensitivities highlight parameters important to the landing gear model
  - Model provides windows during the day when the leg adjustment can be done without warmup heaters
  - Also estimates how much energy the actuator warmup heaters would use if we operate outside of that window
- Future Work
  - JPL will deliver our current thermal model to Lockheed Martin and will receive an updated thermal model for our critical design review
  - Tilt analysis: how does the lander orientation affect the leg temperatures?
  - Lubrication trade: wet vs. dry lube?

Acknowledgements

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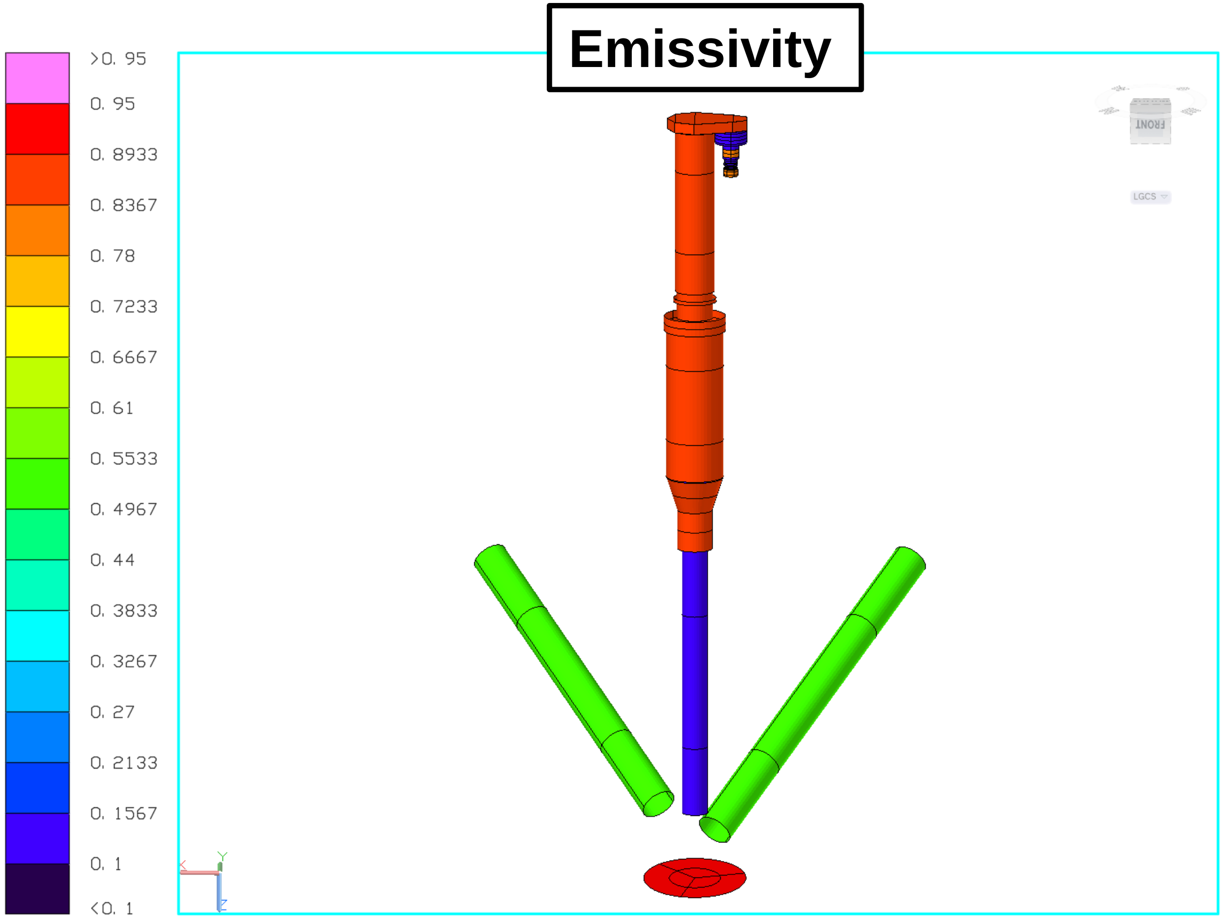
- The authors would like to thank **Nikhil Damle, Chris Kartawira, Kaustabh Singh, and Aziz Wong** for their contribution and support to the Sample Return Lander.

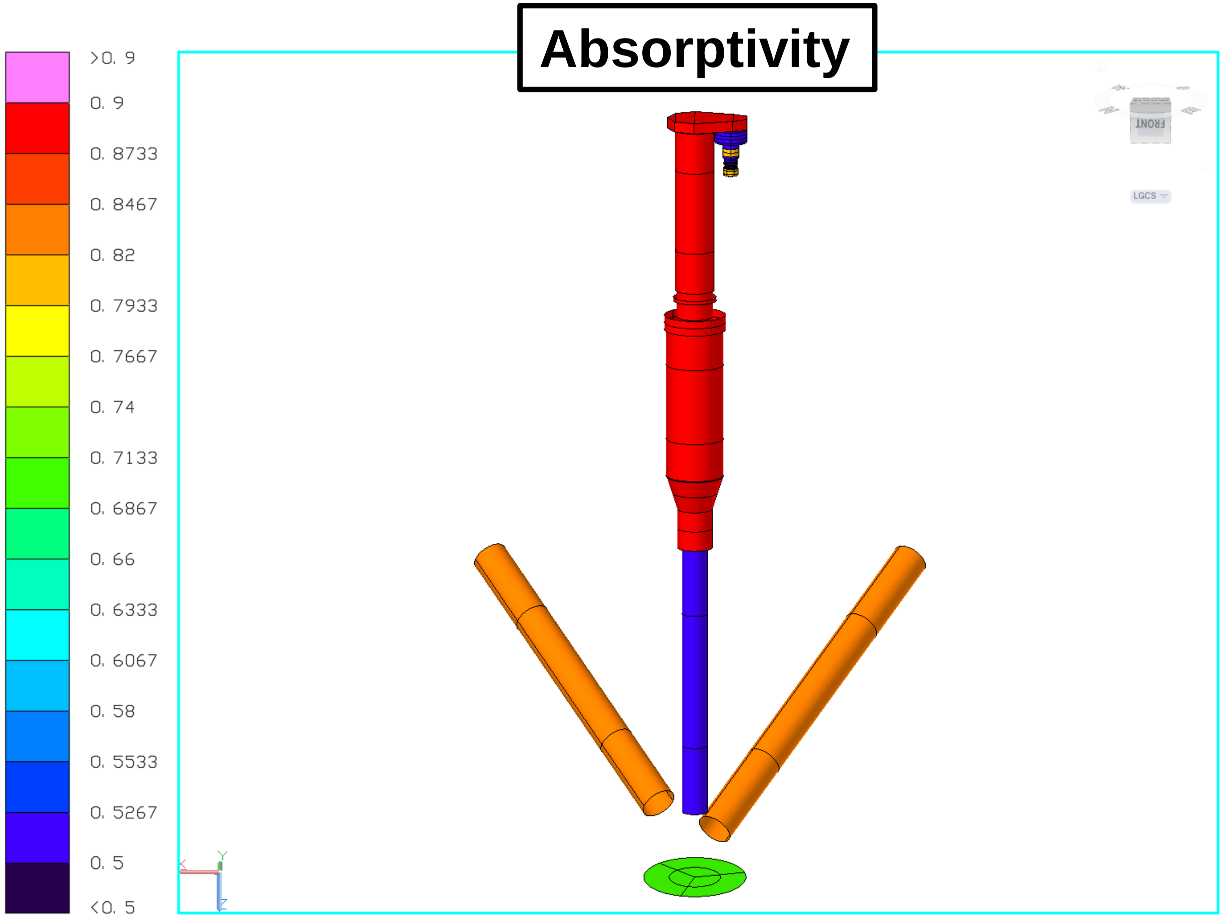
QUESTIONS?

BACKUP

Landing Gear Optical Properties

- Black anodized aluminum: $\varepsilon = 0.88, \alpha = 0.88$
- Bare Ti w/ dust: $\varepsilon = 0.1, \alpha = 0.51$
- Tiodize Type II: $\varepsilon = 0.51, \alpha = 0.82$
- Footpad w/ dust: $\varepsilon = 0.95, \alpha = 0.7$
- Bare SS w/ dust: $\varepsilon = 0.1, \alpha = 0.57$
- Kapton: $\varepsilon = 0.8, \alpha = 0.8$

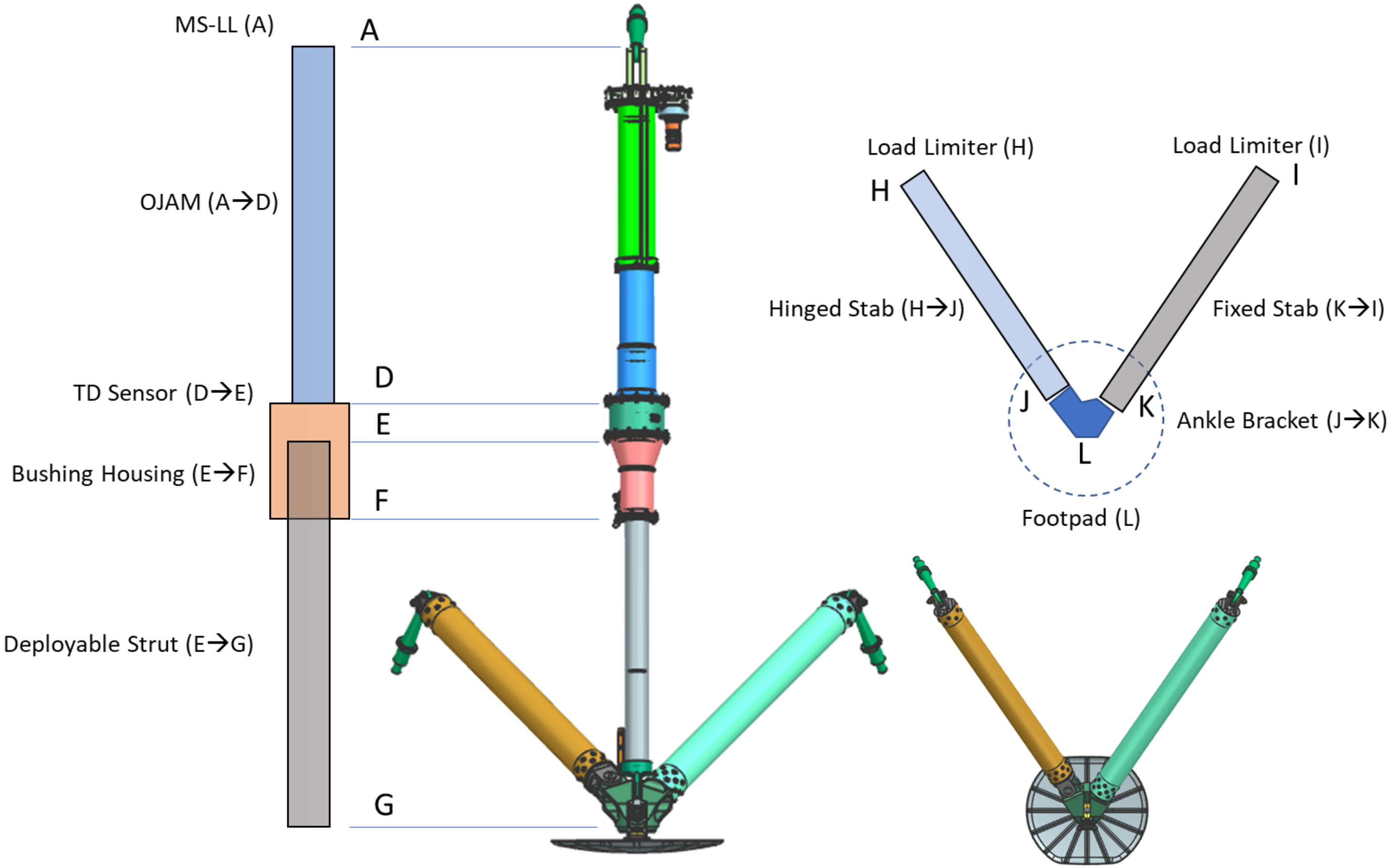




Landing Gear Mass Distribution

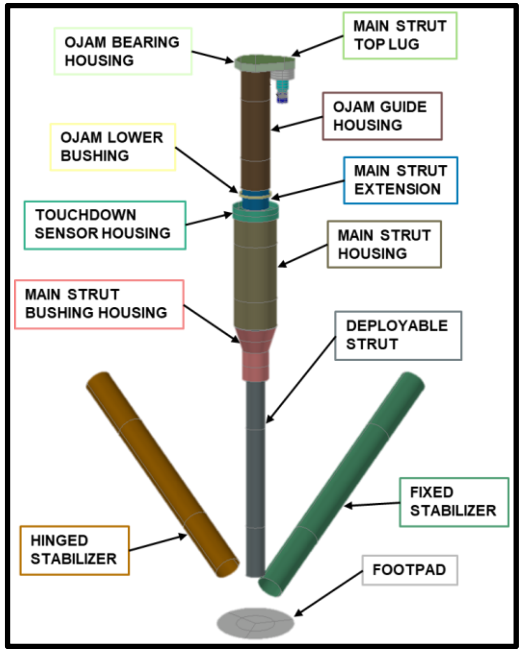
Assembly	CBE Mass (kg) *as of 12-21-2022*	TD Mass (kg)	TD/CBE (%)
MS-LL (A)	2.6	0.0	0%
OJAM (A→D)	11.9	3.9	32%
TD Sensor (D→E)	1.5	0.2	11%
Bushing Housing (E→F)	1.7	2.0	115%
Deployable Strut (E→G)	3.9	2.8	71%
Load Limiter (H)	1.4	0.0	0%
Hinged Stab (H→J)	3.4	2.3	66%
Load Limiter (I)	1.4	0.0	0%
Fixed Stab (K→I)	3.2	2.5	80%
Ankle Bracket (J→K)	4.4	0.0	0%
Footpad (L)	1.8	0.8	46%
Total:	**37.2**	**14.5**	**39%***

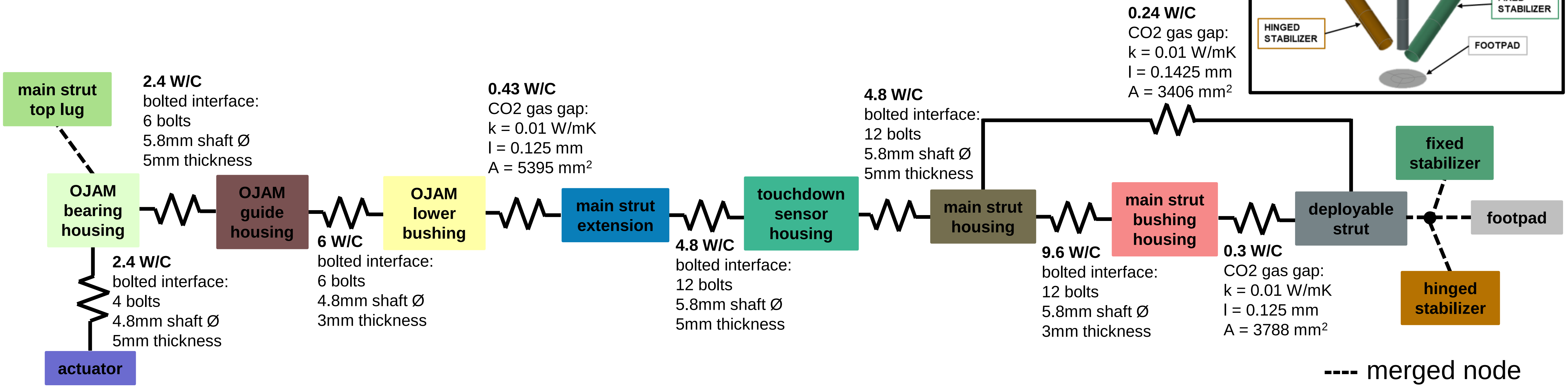
*Large mass margin is an artifact of modeling only the external landing gear components



Landing Gear Complete Node Diagram

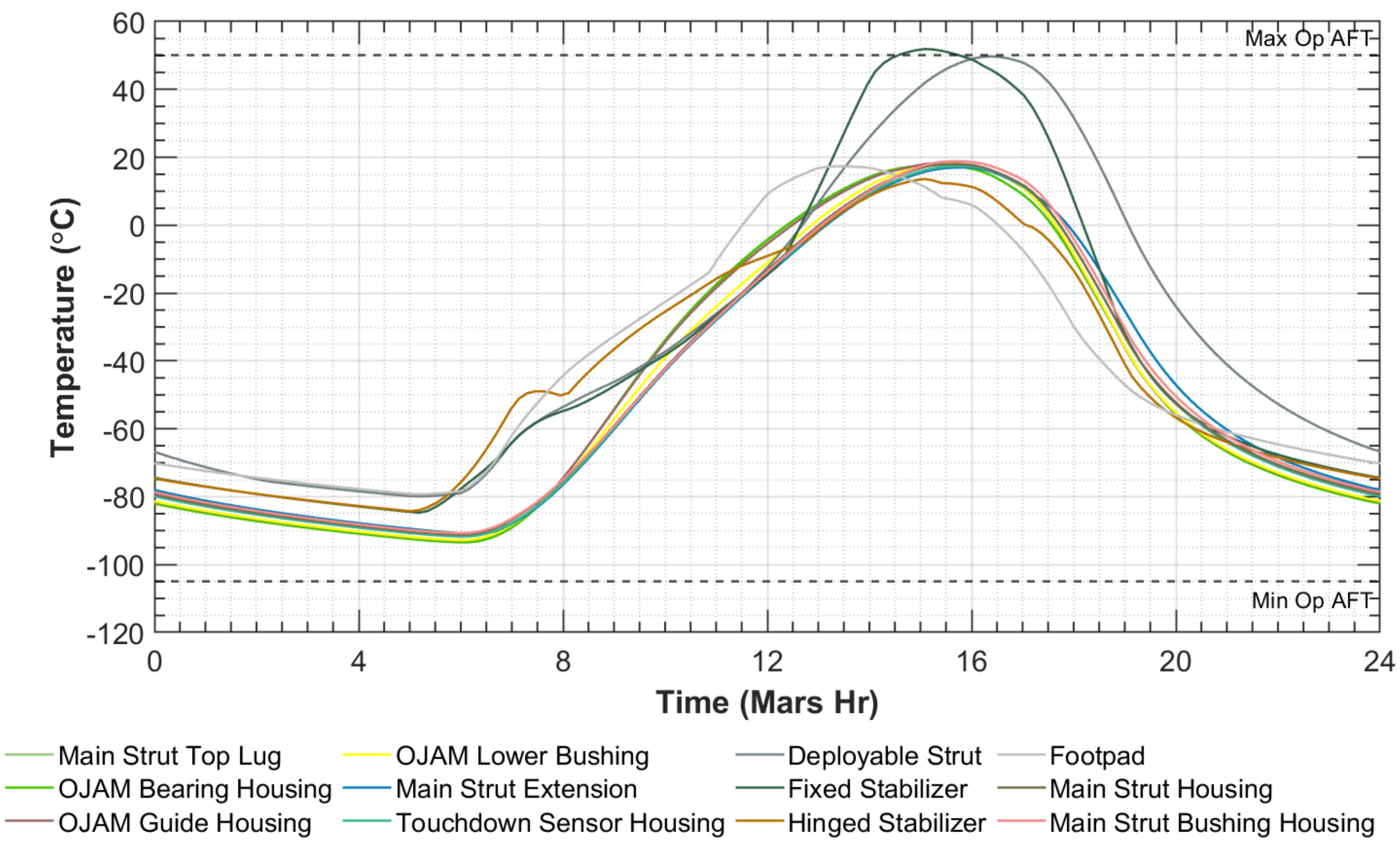
- Bolted interface conductances approximated based on size and number of bolts
- Gas gaps couple deployable strut to main strut housings

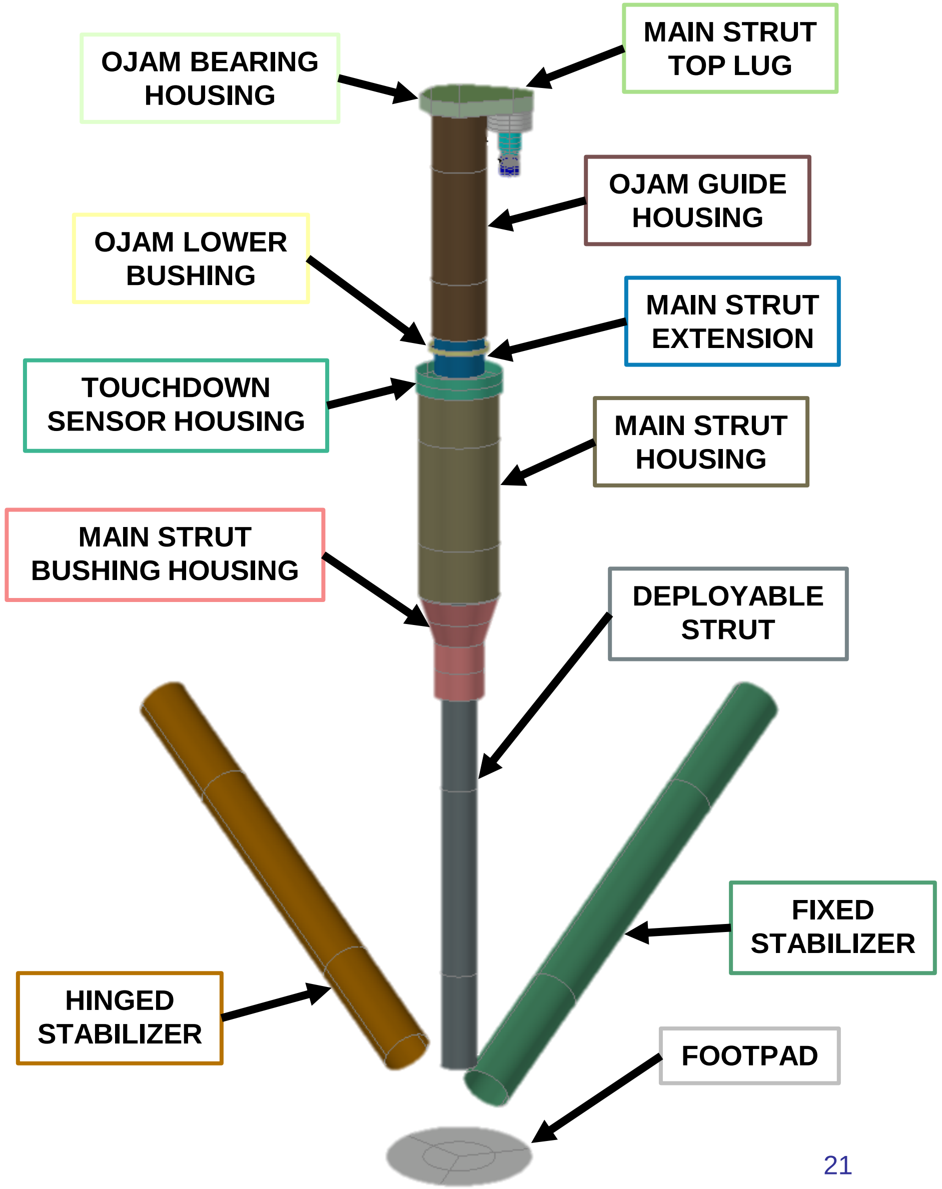




Landing Gear Worst-Case Hot Diurnal

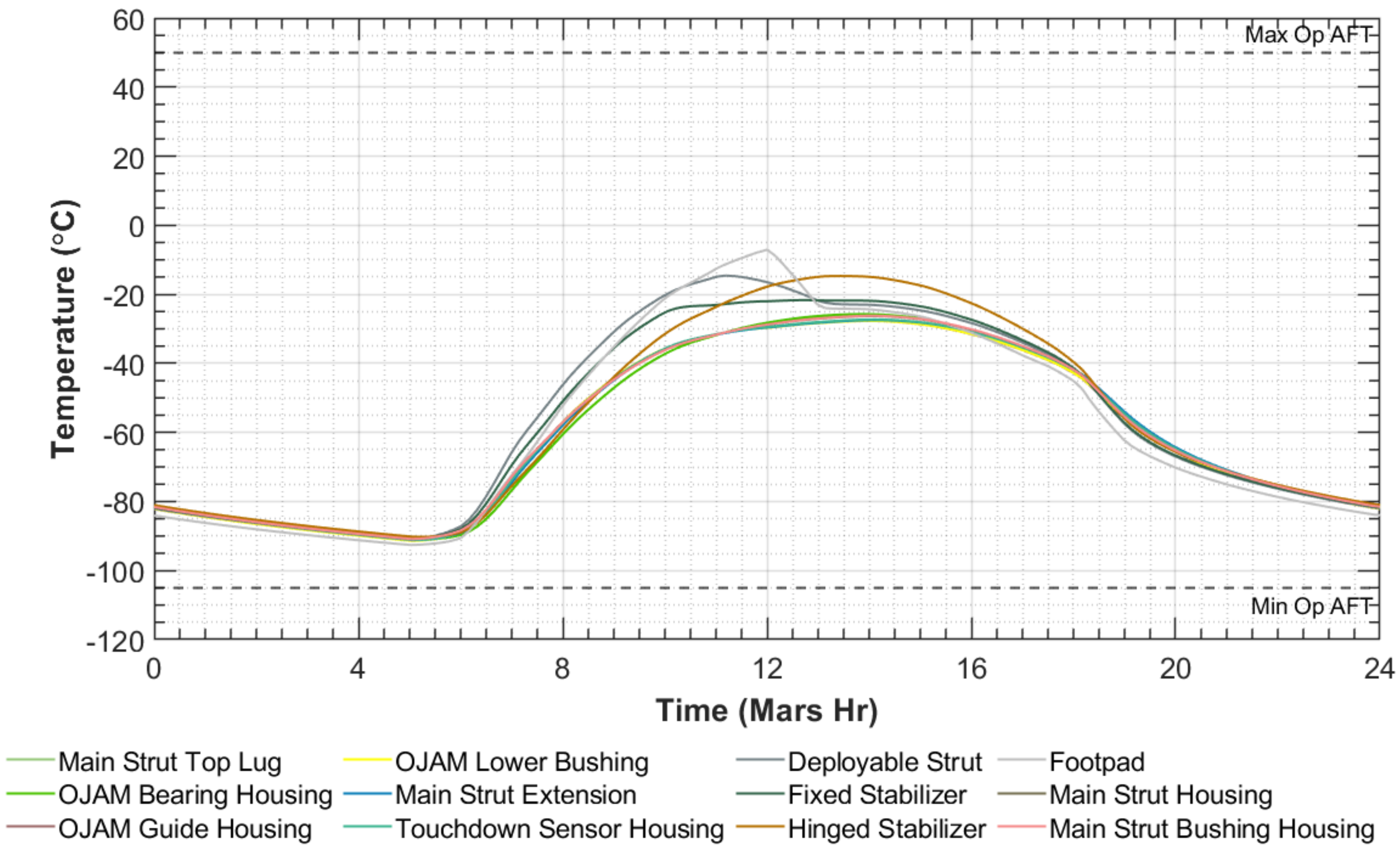
Jezero Ls 150 Tau 0.14 Free Convection

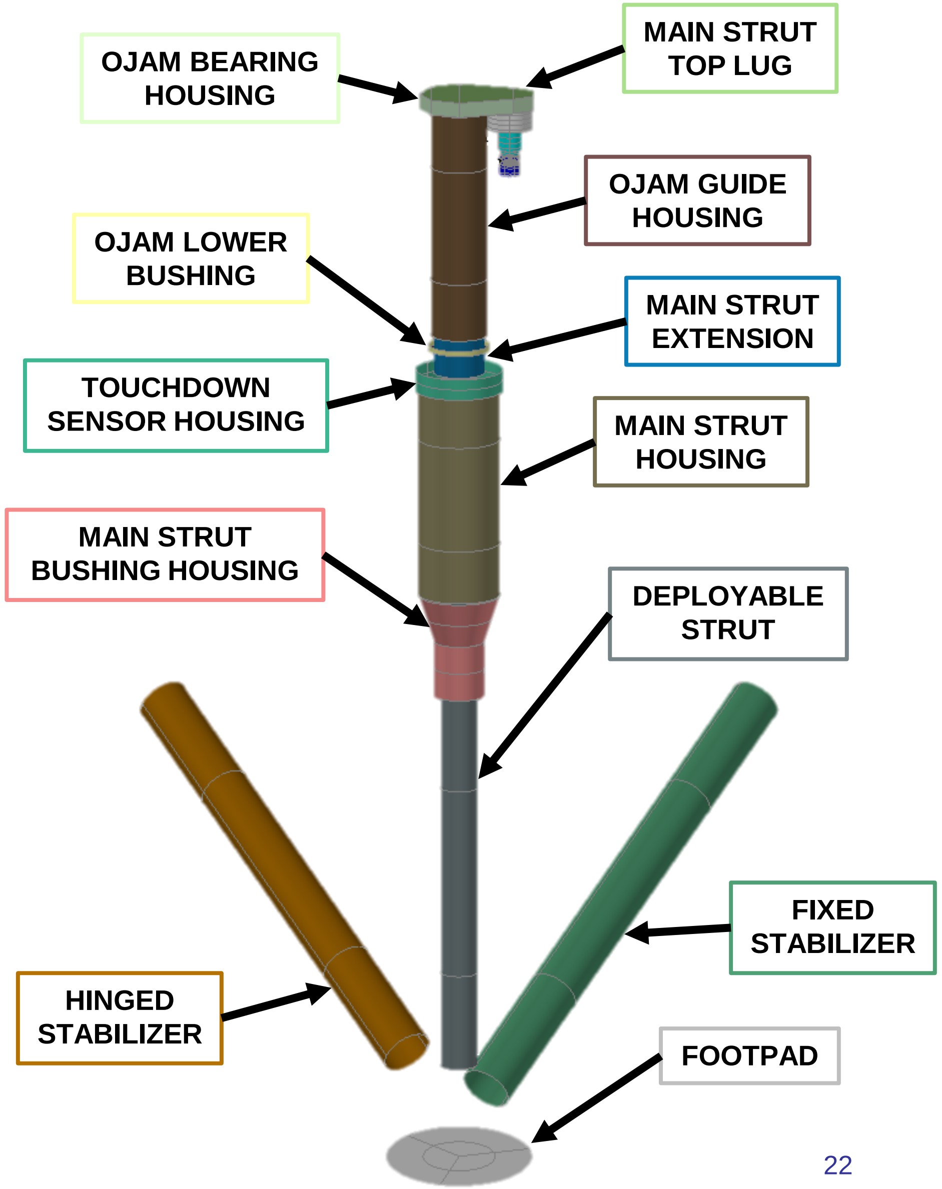




Landing Gear Worst-Case Cold Diurnal

Jezero Ls 72 Tau 0.1 Forced Convection

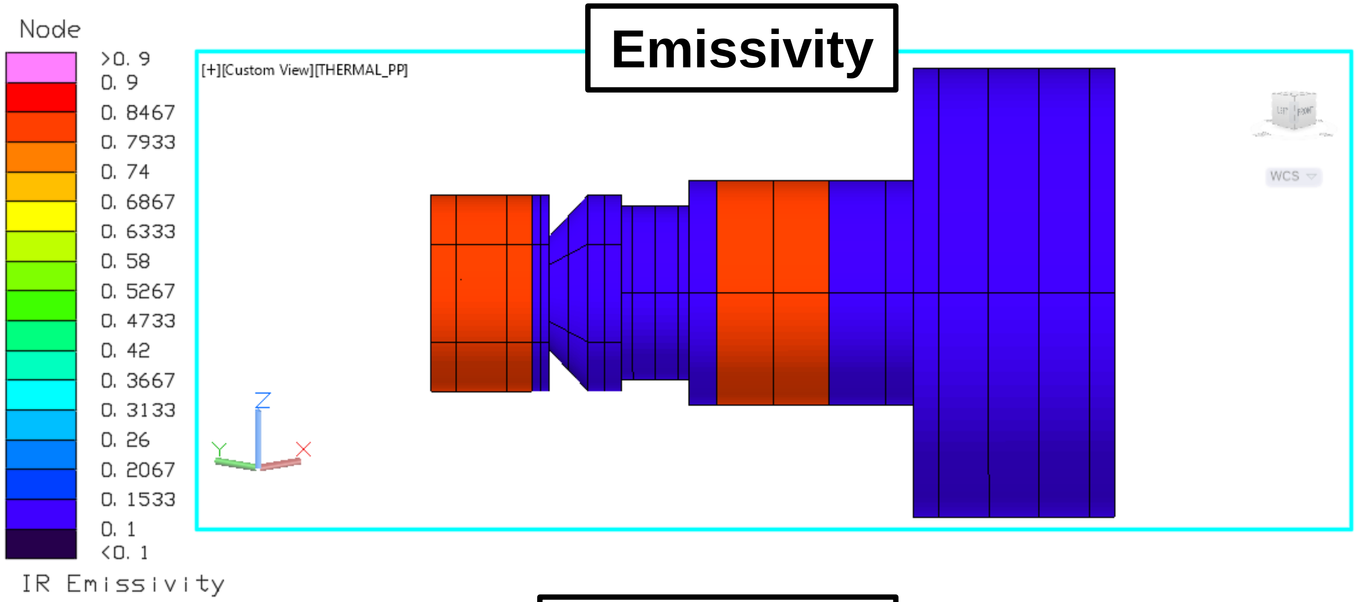


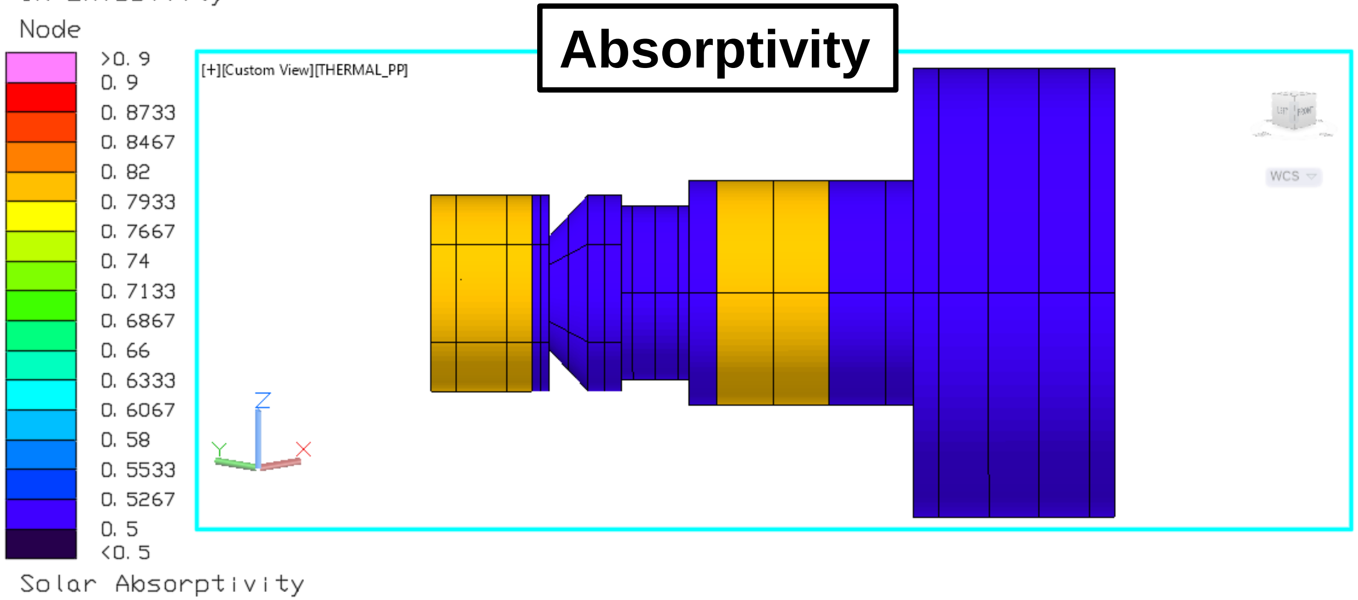


Actuator Mass, Material, and Optical Properties

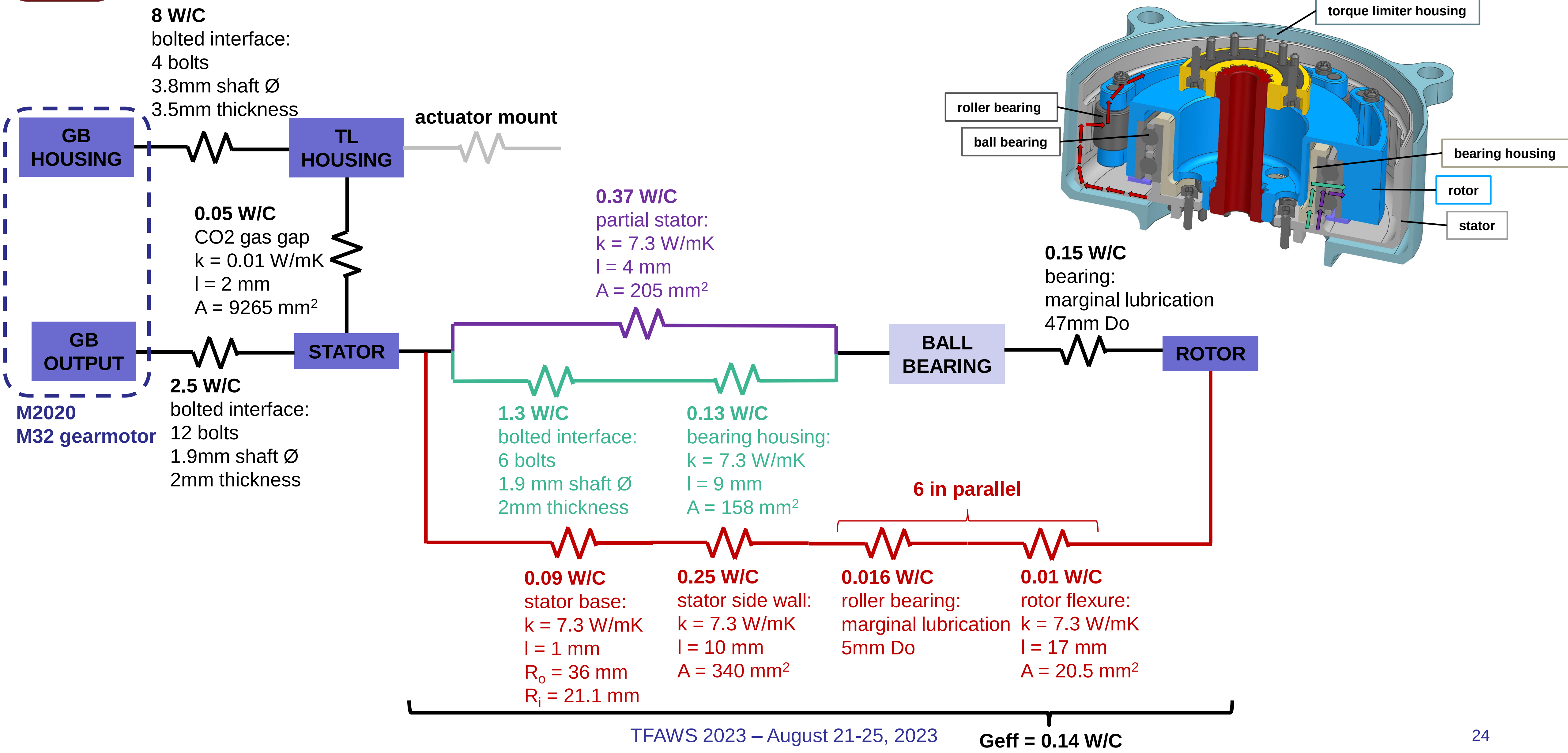
Part	Material	TD Mass (kg)
TL Housing	Titanium	0.08
TL Stator	Titanium	0.08
TL Rotor	Titanium	0.07
Gearbox + Motor	Mixed	0.65
	Total:	0.87

- CBE mass: 0.99kg
  - TD model mass is ~88% CBE mass
- Optical properties:
  - Bare SS: $\varepsilon = 0.1, \alpha = 0.5$
  - Bare Ti: $\varepsilon = 0.1, \alpha = 0.5$
  - Kapton: $\varepsilon = 0.8, \alpha = 0.8$





Torque Limiter Complete Node Diagram



Landing Gear Heat Transfer Coefficient – Forced

Nu Correlation for Flow Across a Cylinder

$$h = Nu * \frac{k}{L}, \qquad Nu = 0.3 + \frac{0.62 Re^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{2}}}{\left(1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right)^{\frac{1}{4}}}$$

Assumptions:

- Velocity = 15 m/s
- Fluid properties evaluated at $T_{fluid} = \frac{T_s + T_{amb}}{2}$, 8 torr CO2 on Mars
- L = 0.1 m (approximate average diameter of landing gear)

Temperature Ranges:

- $-105 < T_s < 50\ C$ (taken from min/max operating AFT limits)
- $-89.443 < T_{amb} < -27.528\ C$ (WCC_Jezero_Ls74_Low_Tau)

HTC Range: $\mathbf{2.9 < h_{forced} < 3.5 \frac{W}{m^2 K}}$

Landing Gear Heat Transfer Coefficient – Free

Nu Correlation for Flow Across a Cylinder

$$h = Nu * \frac{k}{L}, \qquad Nu = 0.36 + \frac{0.518 Ra^{\frac{1}{4}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}}$$

Assumptions:

- Fluid properties evaluated at $T_{fluid} = \frac{T_s + T_{amb}}{2}$, 8 torr CO2 on Mars
- L = 0.1 m (approximate average diameter of landing gear)

Temperature Ranges:

- $-105 < T_s < 50\ C$ (taken from min/max operating AFT limits)
- $-89.443 < T_{amb} < -27.528\ C$ (WCC_Jezero_Ls74_Low_Tau)
- $-84.757 < T_{amb} < -13.49\ C$ (WCH_Jezero_Ls150_LowTau)

HTC Range: $\mathbf{0.3 < h_{free} < 0.5 \frac{W}{m^2 K}}$

Landing Gear Actuator Heat Transfer Coefficient – Forced

Nu Correlation for Flow Across a Cylinder

$$h = Nu * \frac{k}{L}, \qquad Nu = 0.3 + \frac{0.62Re^{\frac{1}{2}}\mathrm{Pr}^{\frac{1}{2}}}{(1+\left(\frac{0.4}{Pr}\right)^{\frac{2}{3}})^{\frac{1}{4}}}$$

Assumptions:

- Velocity = 15 m/s
- Fluid properties evaluated at $T_{fluid} = \frac{T_s+T_{amb}}{2}$, 8 torr CO2 on Mars
- L = 0.06 m (approximate average diameter of actuator shell)

Temperature Ranges:

- $-105 < T_s < 50\ C$ (taken from min/max non-operating AFT limits)
- $-89.634 < T_{amb} < -28.703\ C$ (WCC_Jezero_Ls72_Tau_0.1_v12)

HTC Range: $\mathbf{3.8 < h_{forced} < 4.7\,\frac{W}{m^2K}}$

Landing Gear Actuator Heat Transfer Coefficient – Free

Nu Correlation for Flow Across a Cylinder

$$h = Nu * \frac{k}{L}, \qquad Nu = 0.36 + \frac{0.518 Ra^{\frac{1}{4}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}}$$

Assumptions:

- Fluid properties evaluated at $T_{fluid} = \frac{T_s + T_{amb}}{2}$, 8 torr CO2 on Mars
- L = 0.06 m (approximate average diameter of actuator shell)

Temperature Ranges:

- $-105 < T_s < 50\ C$ (taken from min/max non-operating AFT limits)
- $-89.634 < T_{amb} < -28.703\ C$ (WCC_Jezero_Ls72_Tau_0.1_v12)

HTC Range: $\mathbf{0.1 < h_{free} < 0.6 \frac{W}{m^2 K}}$