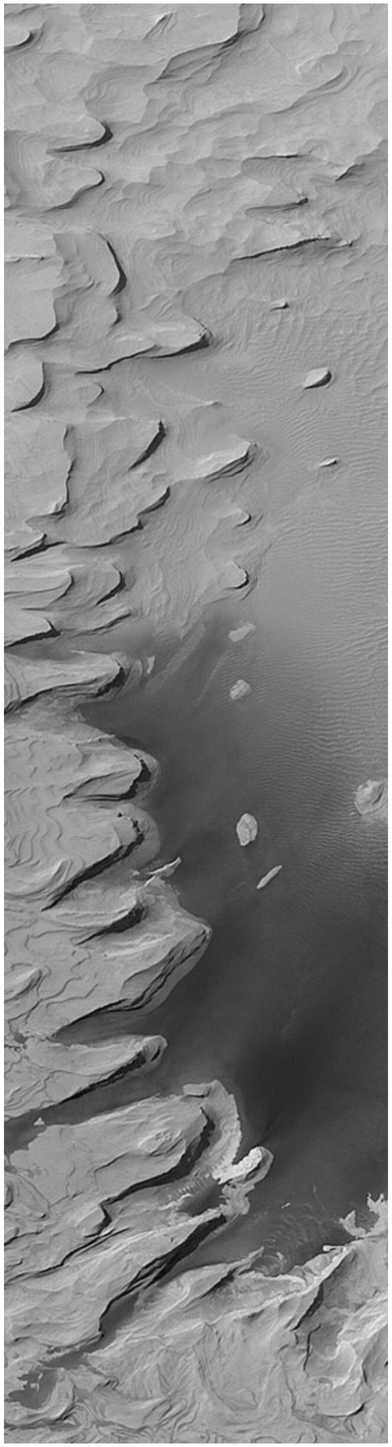

Mars Science Laboratory

Rover Actuator Thermal Design

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Spacecraft Thermal Control Workshop, Aerospace Corp.
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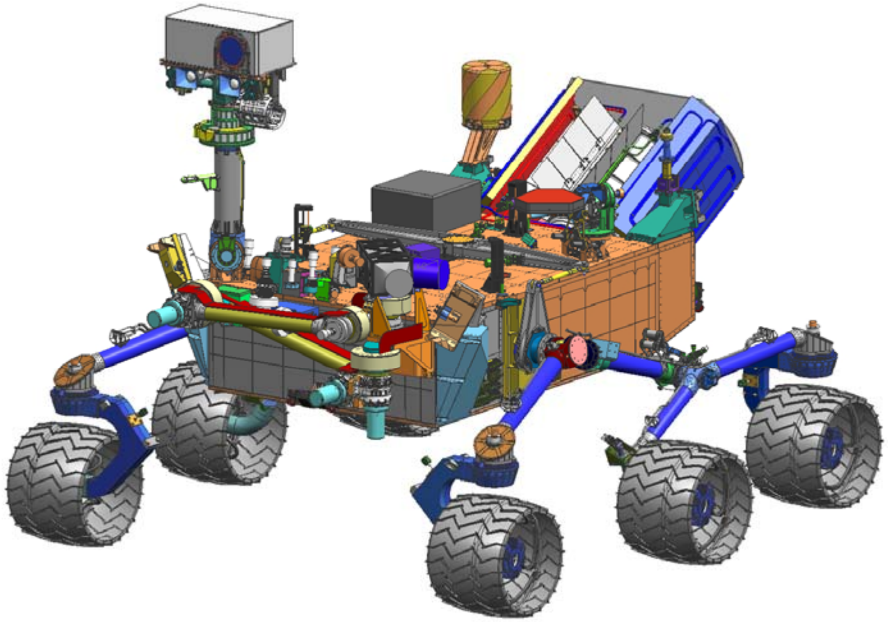
Agenda

- Project Overview
  - Spacecraft & Rover Configuration
  - Locations of Rover Actuators
- History of Actuator Thermal Design Work on MSL
  - “Wait-to-Use” Implementation & Operations Capability
  - “Heat-to-Use” for Performance Enhancement
  - “Input-Only” Heating
- Actuator Thermal Design Inputs
  - Requirements & Constraints
  - Design Environment
  - Model Building Procedure & Assumptions
- General Process for Sizing Heaters
- An Example – Remote Sensing Mast Elevation Actuator Heaters
  - Resources
  - Heater Design & Performance
- Major Conclusions

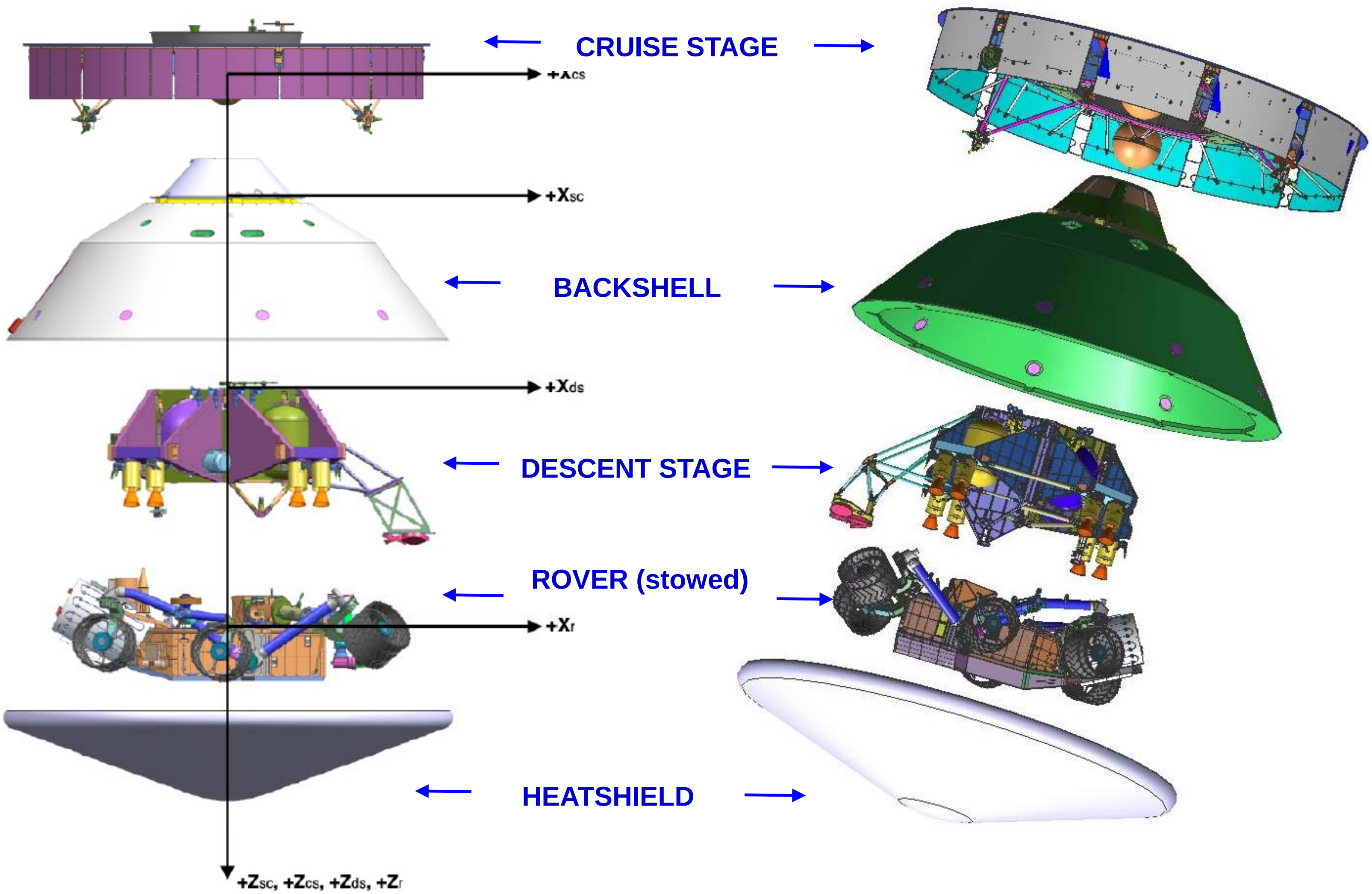
Project Overview

Salient Features
Mobile Science Laboratory
One Mars Year surface operational lifetime (669 sols/687 days)
Landing Capability over wide range of latitudes (± 30 deg) and altitudes (0 to +1 km)
Controlled Propulsive Landing
Precision Landing via Guided Entry

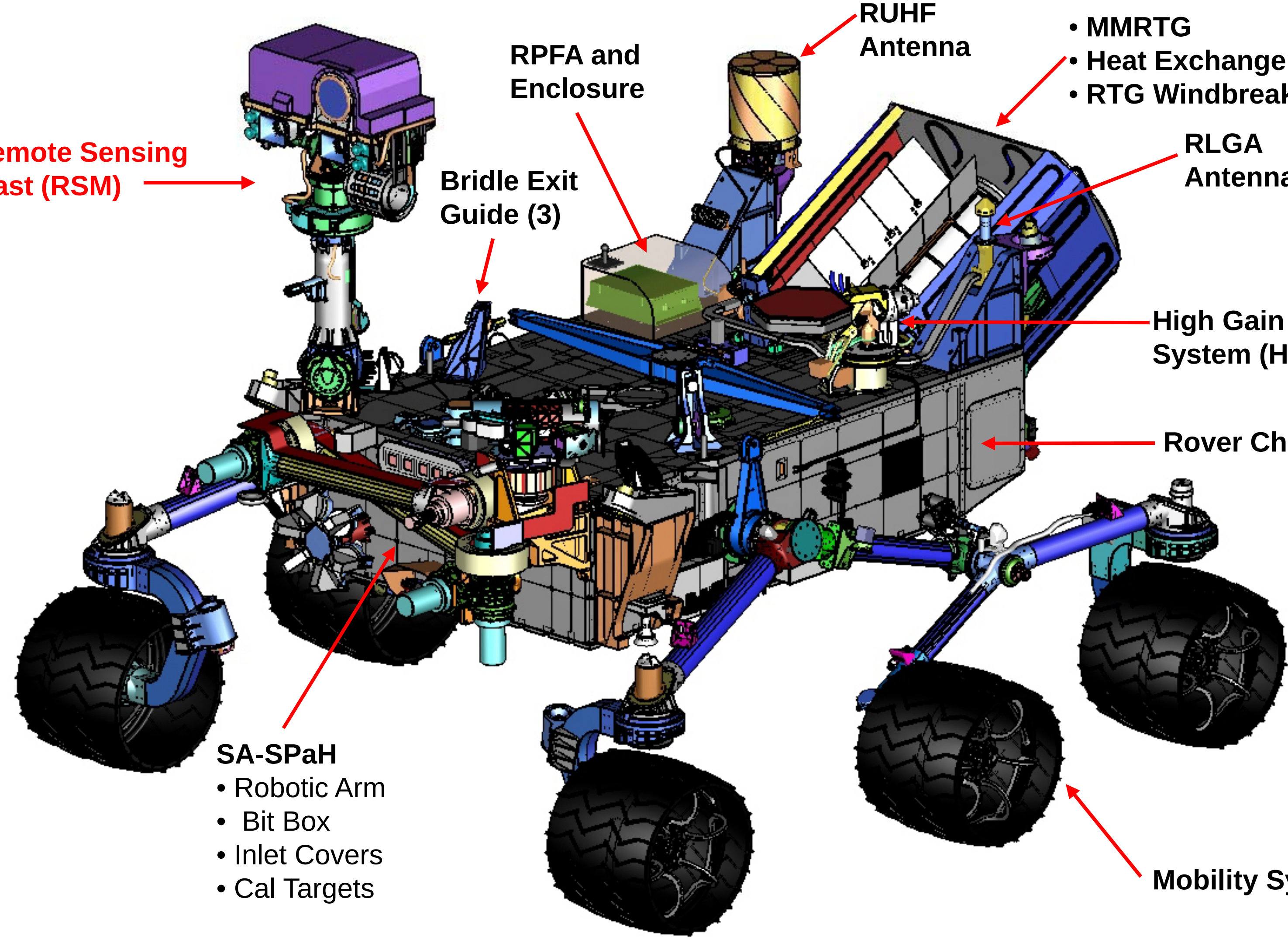


Science
Mission science will focus on Mars habitability
Next generation analytical laboratory science investigations (SAM & Chemin)
Remote sensing/contact investigations (cameras, APXS)
Suite of Environmental Monitoring Instruments (REMS, RAD)

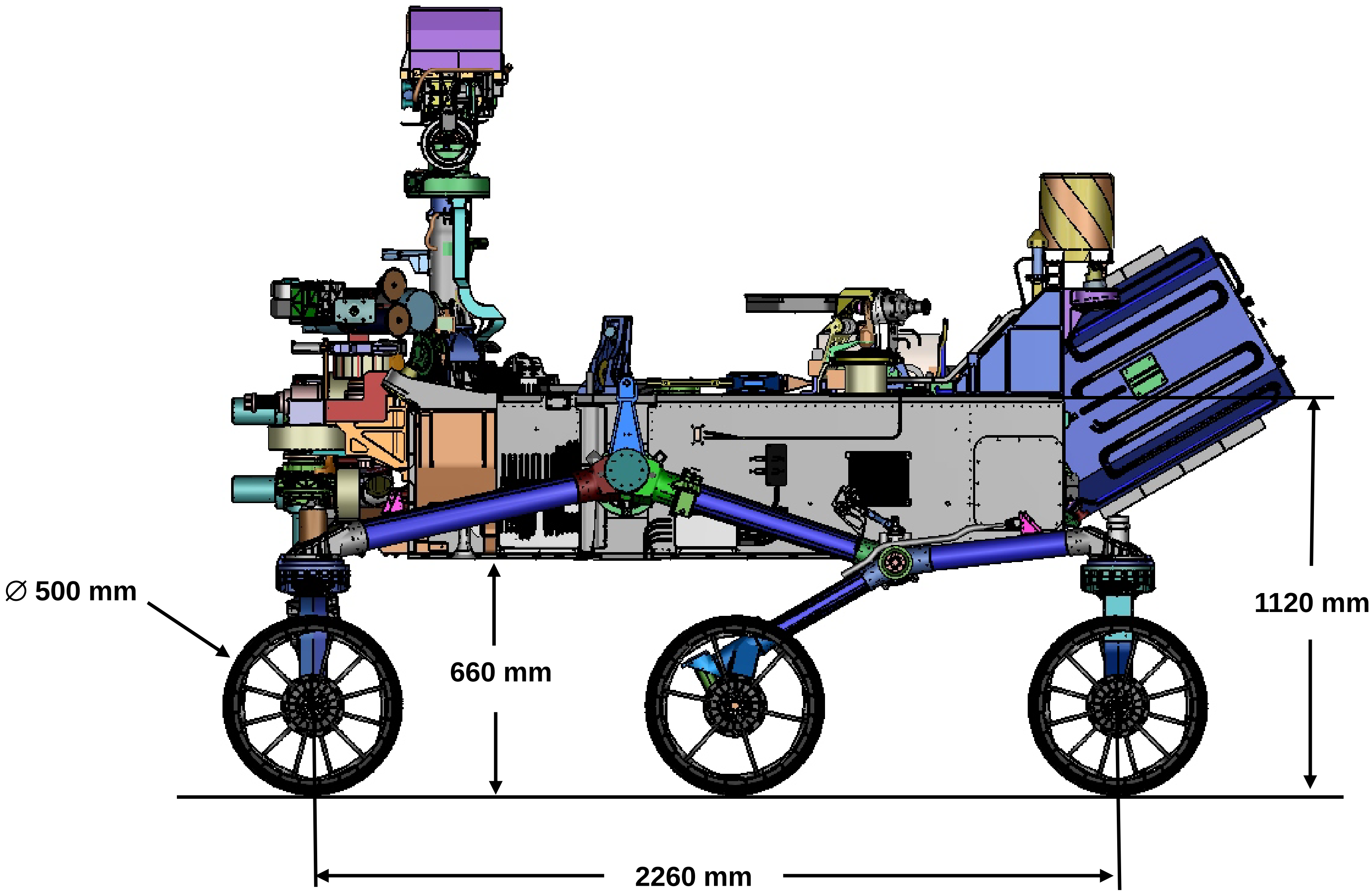
MSL Spacecraft



Rover Traverse Configuration



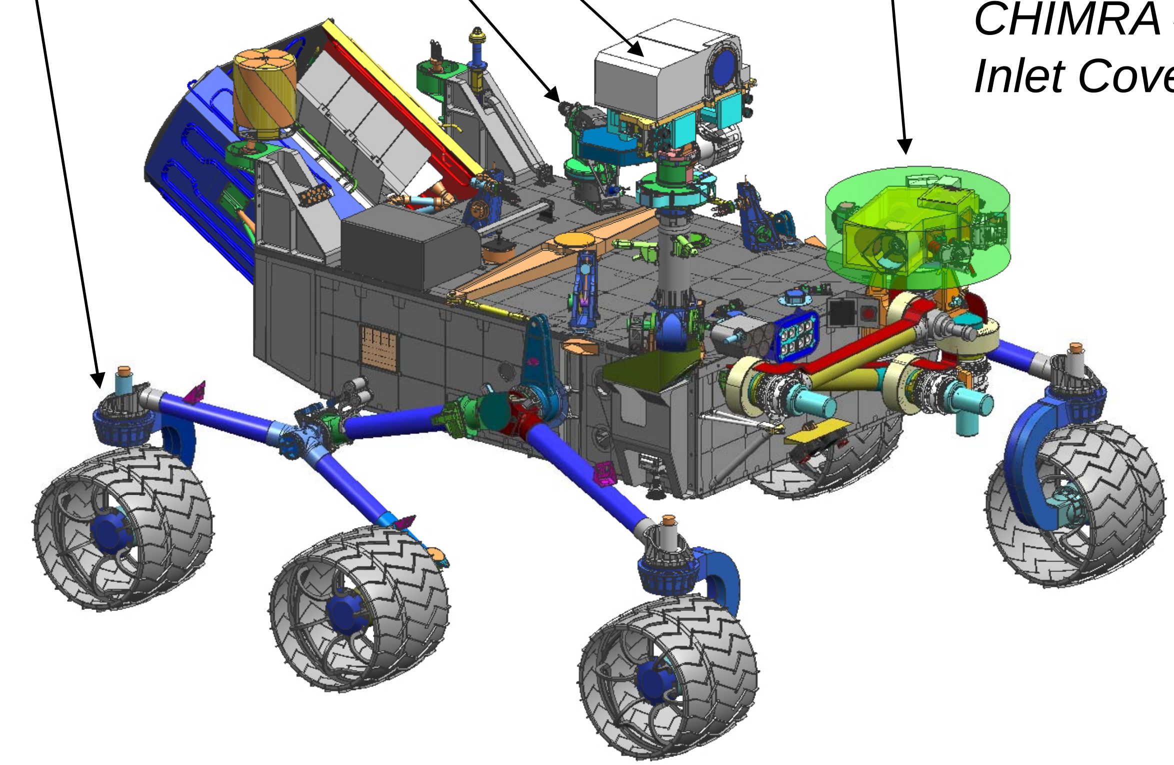
Rover Side View



Actuator Locations

Rover Motor Count: (15)
Mobility – 10
RSM - 3
HGA – 2

SA-SPaH Motor Count: (16)
RA – robotic arm – 5
PADS – percussive drill - 3
DRT – dust removal tool – 1
CHIMRA – scoop & sample handling – 4
Inlet Covers – SAM & CheMin - 3



Total Motor Count = 31

History of MSL Actuator Thermal Design Work

- Baseline design from start of project until Thermal CDR (May 1, 2007)
  - Cold temp actuators for majority of applications
    - Capable of operating at -135C; no heaters needed
    - Ti gearbox with dry lube
  - Only 4 of 35 applications were wet lube & “heat-to-use”
    - Concern that high number of revs would wear out dry lube in some SA-SPaH applications
- Concerns about cold actuator testing discussed at Mech CDR (May 15, 2007)
  - Life testing of representative gearbox failed 3 times
- Actuator Tiger Team recommends Stainless Steel (Vascomax) Gearboxes and wet lube (Braycote) as new baseline
  - Thermal design effort for “heat-to-use” across all actuators begins in June 2007

History of MSL Actuator Thermal Design Work

- November 2007
  - Actuator thermal team directed by Flight System to size actuator heaters for “input-stage-only” heating
    - Heat only the motor, first and second stage gearboxes to -55C
    - Leave rest of actuator cold (-75C)
  - Major reductions in required energy make this heating strategy feasible from a system level viewpoint
    - Actuator mech performance and lifetime is still uncertain
      - Risk to be retired through mechanical testing of actuators

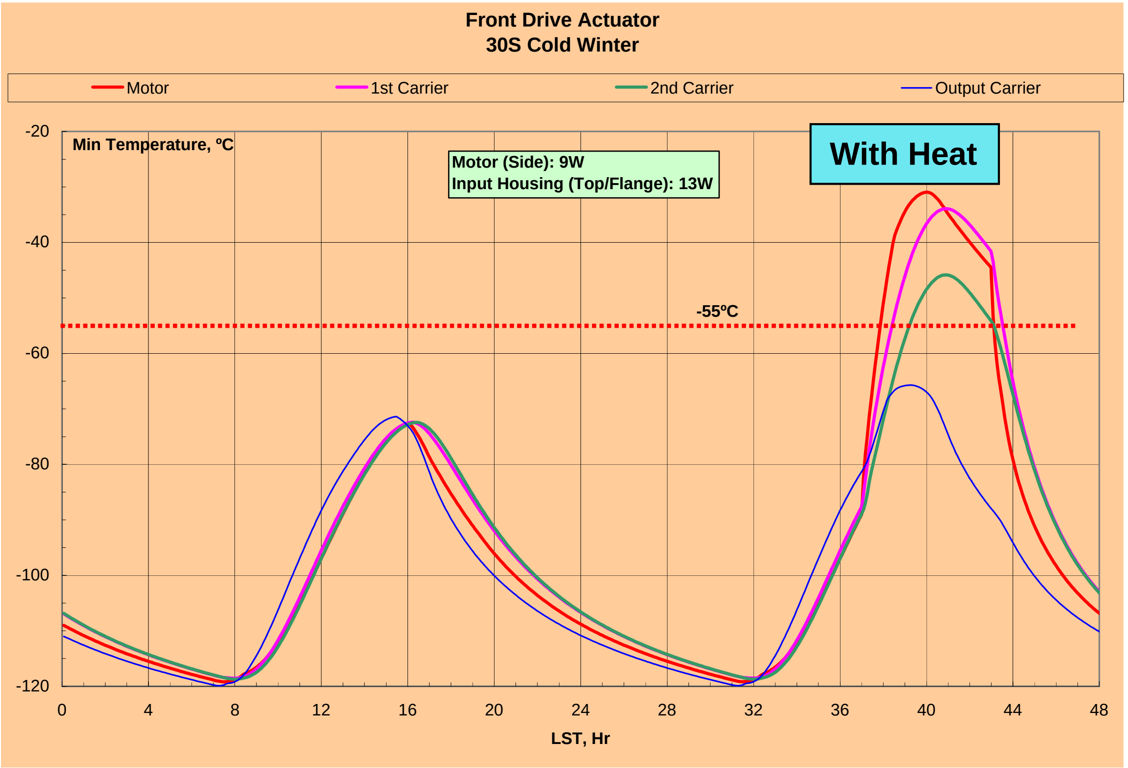
“Wait-to-Use” Implementation

Actuator: Ops Impact Summary

- Under these conservative analyses:
  - Rover can operate between 5S-15N over entire Mars year with virtually no loss of performance
  - Rover can operate between 5S-10S, or 15N-25N with only minor degradation in performance (90% of avg return), degradation becoming significant from 15S on
  - 28 sample rqmt still met to 45S (42% of avg science return) but significant winter stand-down and poor arrival conditions at 25-45S
- Current list of high priority landing sites
  - 2 sites at 22 deg N
  - 2 sites at equator
  - 2 sites at 25 deg S

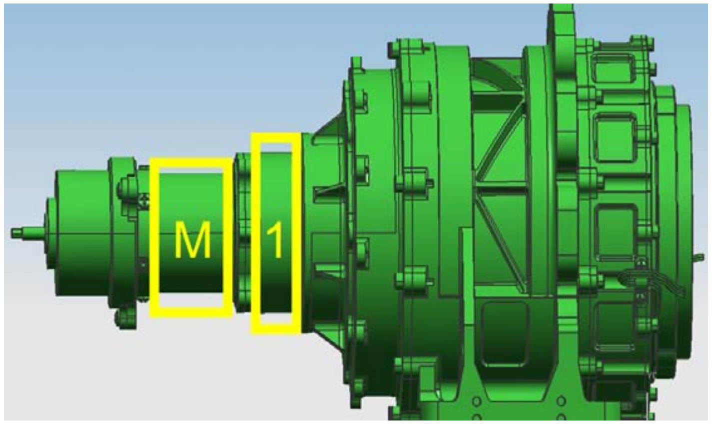
"Heat-to-Use" for Performance Enhancement

- "Heat-to-Use" Strategy
  - Heaters used for increased performance only, not for survival
    - Allows extension of daily ops window beyond the "wait-to-use" window
    - Allows flexibility in operations for moving activities prior to afternoon downlink sessions
    - Heaters can be used for anomaly resolution
      - For example – stuck mechanism due to jamming



"Input-Only" Actuator Heating

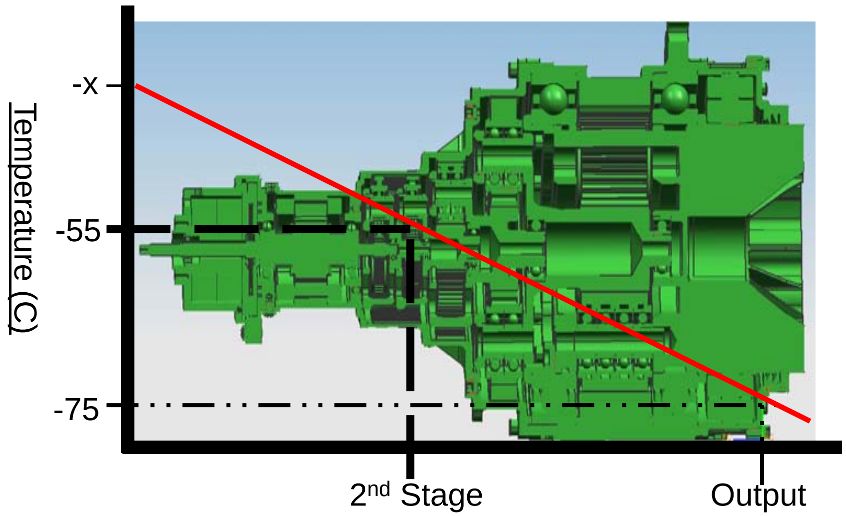
- Input Only Heating –
  - Baseline design for all high and medium torque actuators
  - Warm up motor encoder, brake, 1st and 2nd stage gearboxes to -55C
  - Reduce viscosity of wet-lube at high-speed, low-torque end of actuator
  - Leave high torque output gearboxes to power through -75C lube
  - Saves significant energy
  - Risks associated with mech performance and actuator life



LPHTA Input Heaters

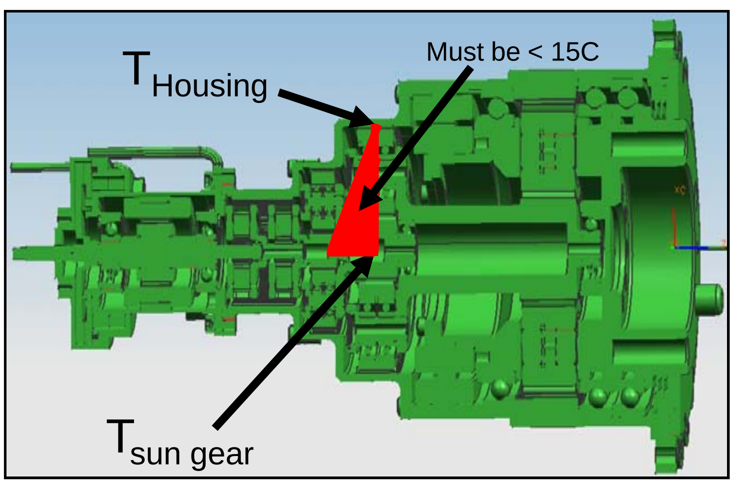
Thermal Design Inputs -Temp Requirements

- Operational Temperature Requirements:



1. Coldest Temperature of 2nd Stage must be > - 55C.

2. Coldest Temperature of Output must be > - 75C.



3. Radial temp gradient:

   $T_{sun\ gear} - T_{Housing} < 15C$ within a given stage.

   <u>No</u> axial gradient requirement

Thermal Design Inputs - Usage Requirements

Capability Driven: heaters should expand the operational capability of MSL to the greatest extent possible.

- This translates into a multitude of derived requirements such as...
  1. Reasonable warm-up time, 1-2hrs
  2. Balance actuator warm-up times for a given appendage.
  3. Redundancy
     - full functional redundancy everywhere
  4. Heater Sequencing & Duty cycling

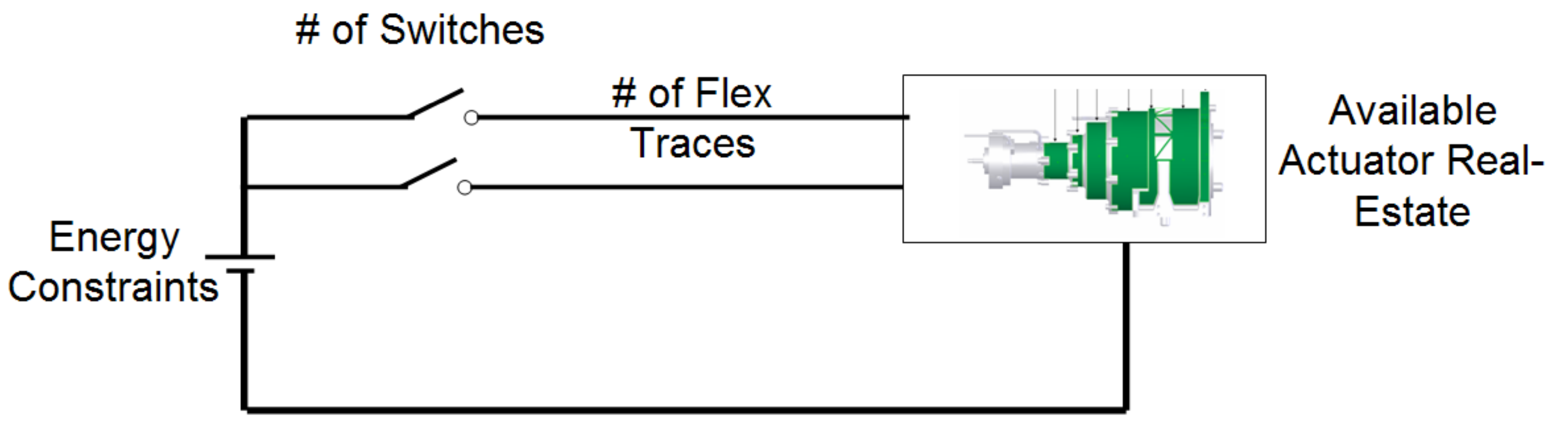
Thermal Design Inputs - Guidelines/Constraints

- Heater design should
  - observe 5W/in^2 power density guideline.
  - accommodate +/- 5% manufacturing tolerance on resistance.
  - utilize smooth areas on actuators to avoid peeling, denting, etc.
  - avoid usage of actuator heater areas less than 0.5” wide.
  - lead orientation should facilitate bundling of wires and provide sufficient clearance from adjacent hardware items.
  - enable a standardized set of heaters for each actuator type whenever possible.
  - Take into account bus voltage variations
    - Heater design voltage (28V)
    - Max bus voltage (32.8V)

Thermal Design Inputs - Resource Constraints

Constraints fell into the following general categories and will be elaborated on for specific devices later in the review.

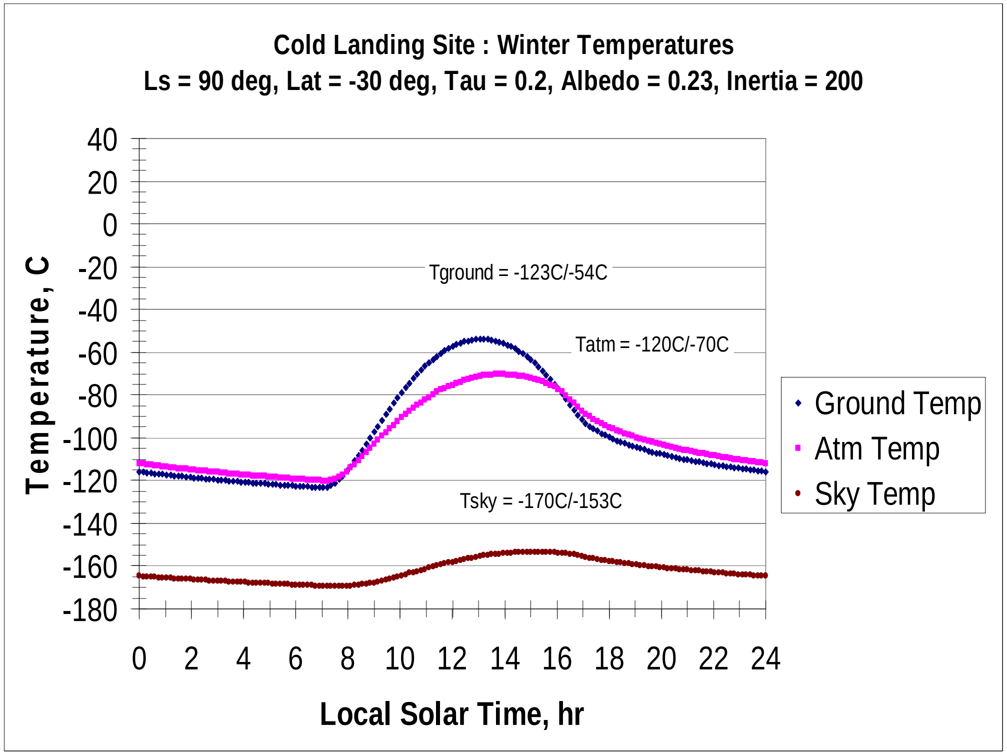
- Max energy available for heating during a given sol.
- Available Switches.
- Flex Traces & pinouts on connectors.



System Design Constraints

Model Building Procedure – Conservatism

- Worst Case Cold Environment
  - Convection coefficients from cross-flow at 15 m/s
- Worst Case Landing Site
  - -30S in winter
- Rover orientation selected to minimize solar heating.
- Restricted heat transfer through actuator internals
  - Neglect gear to gear heat transfer
  - Neglect CO2 conduction
- Heater power calculated at 28V; expect some additional power during a nominal operation due to higher bus voltage.

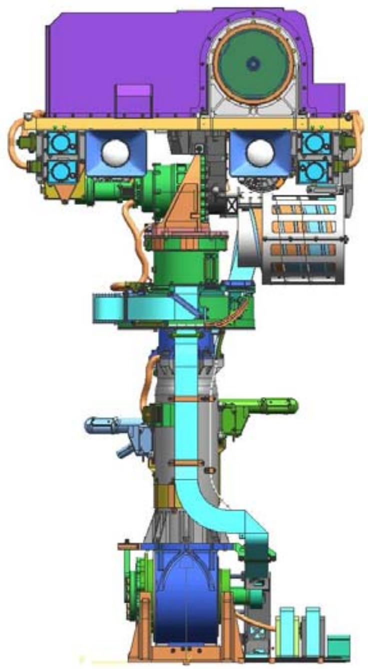


Warm-Up Heater Sizing Procedure

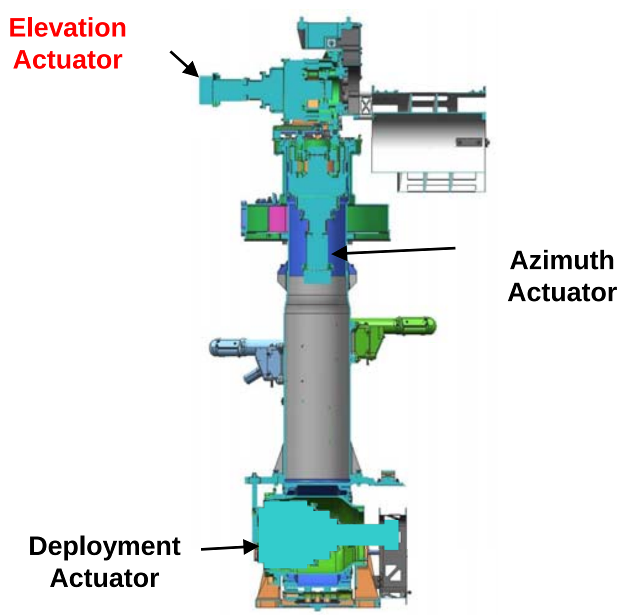
- For Mobility, Remote Sensing Mast & HGA
- Warm-Up heater sizing procedure: Input stage only
  - (1) ~10W (or ~ 5W/in^2 @32.8V) on the motor housing
  - (2) Iterate on input-gearbox housing power to achieve positive input-stage ΔT without exceeding 5W/in^2 goal
    - (2a) If not possible, add heater on mid gearbox housing
  - (3) Iterate on heater powers to arrive at:
    - Maximum warm-up capability: ~ -45ºC (10ºC above min OP AFT limit)
    - Reasonable OP window
    - Similar warm-up capability
      - Mobility: Among front drive & steer and mid drive
      - RSM: Between Azimuth & Elevation
      - HGA: Between Azimuth & Elevation

Remote Sensing Mast (RSM)

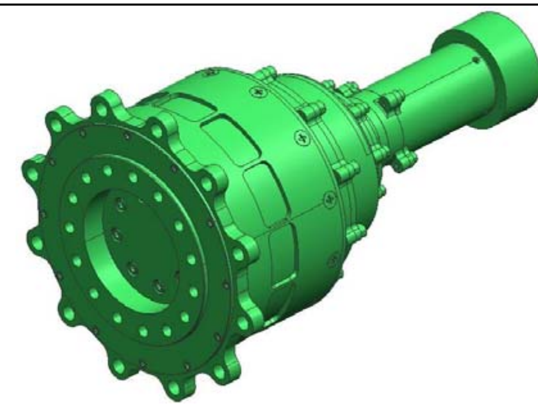
- The Remote Sensing Mast uses 3 actuators
  - Deploy, Azimuth and Elevation



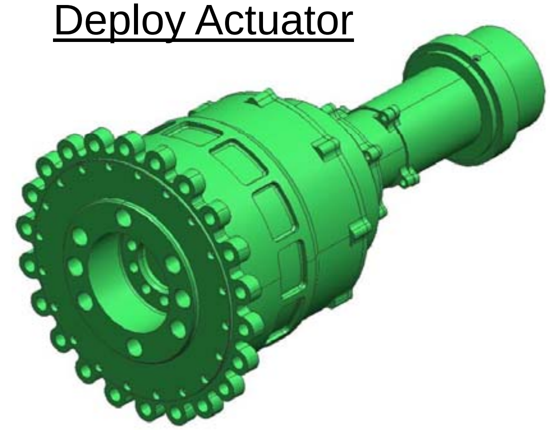
RSM Assembly



Cut-away Showing Actuators



Deploy Actuator

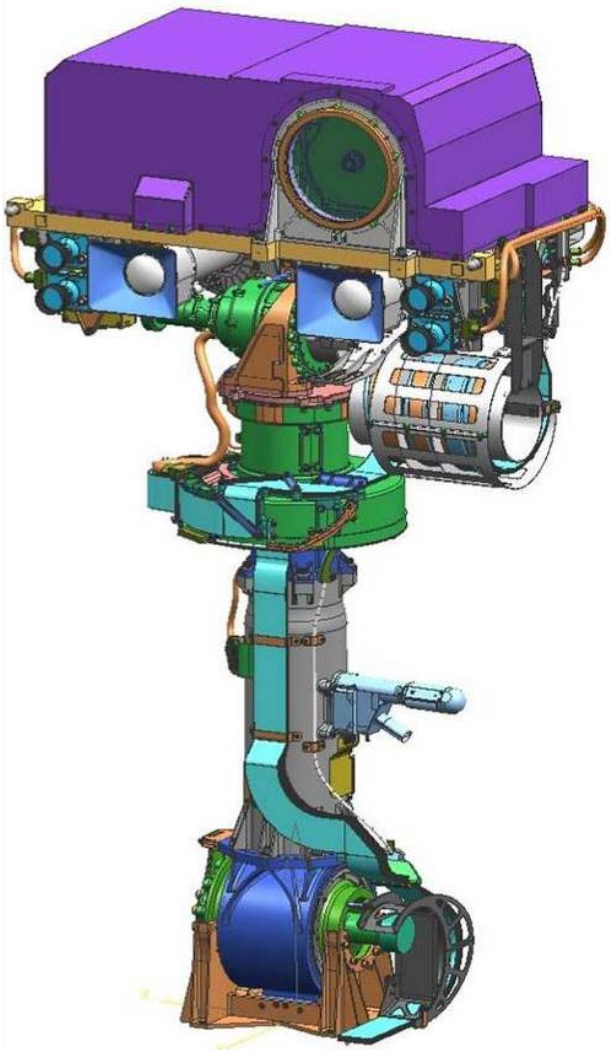


Az and El Actuator (WATER)

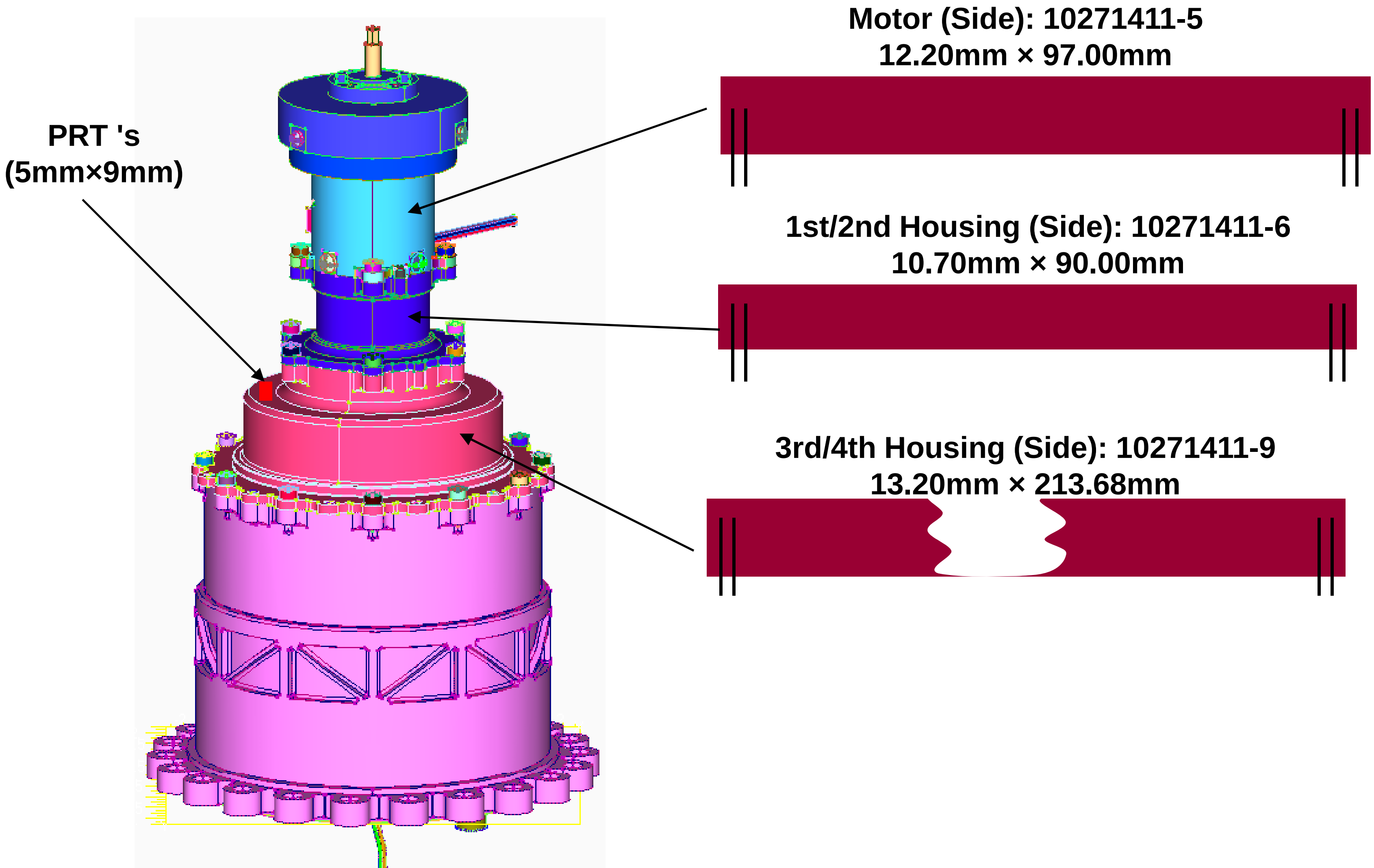
- The Azimuth and Elevation actuators are identical
- RSM Deploy actuator is unique.

RSM: Power Resources

- Power Resources
  - Azimuth and Elevation
    - Two 20W switches to be used for redundant input heaters
    - One switch for output (augmentation) heater
  - Deploy has 2 switches
    - Two 40W switches to provide full redundancy
    - Heater is single string

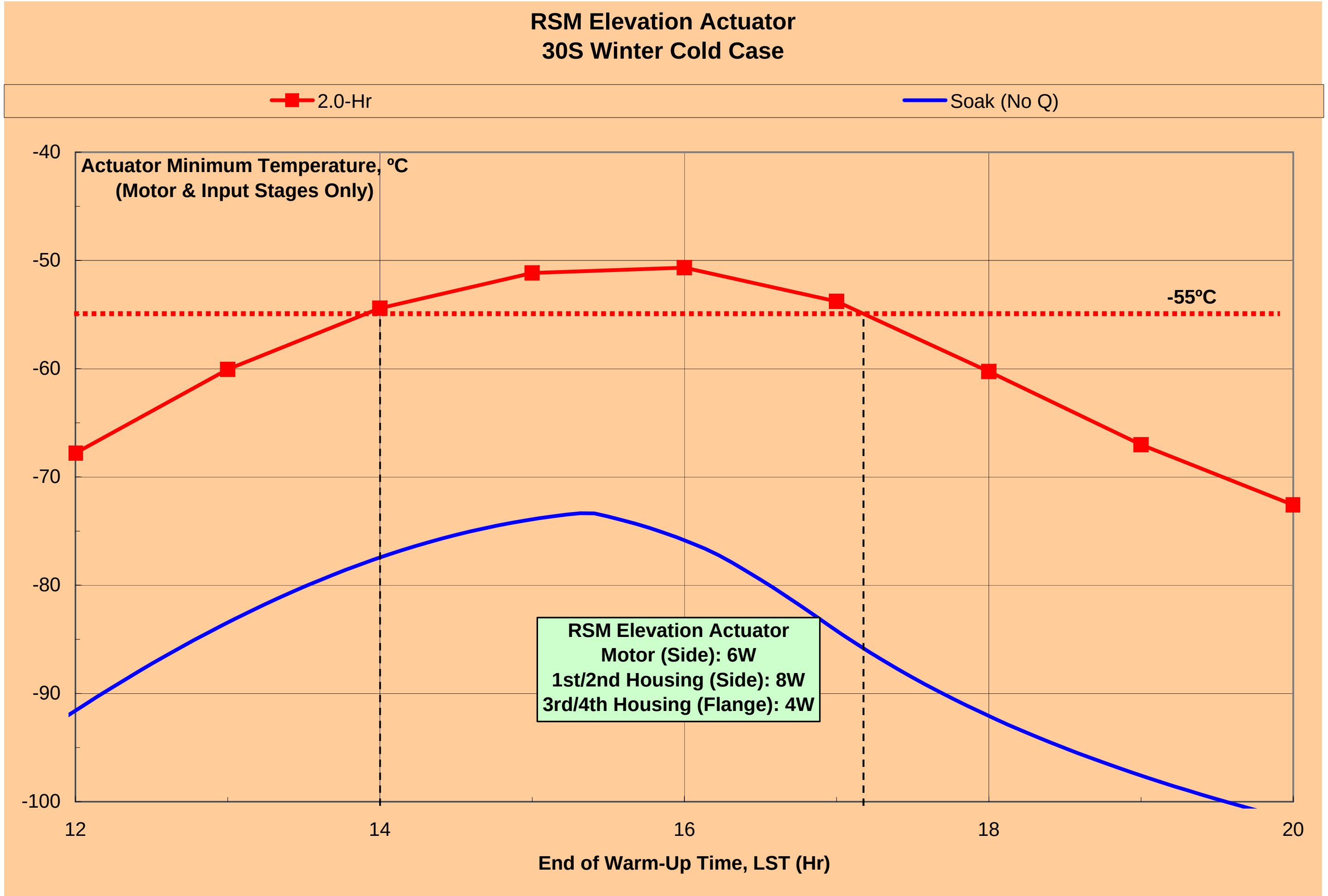


RSM Elevation Actuator: WATER (Flange) Warm-Up Heater & PRT Locations



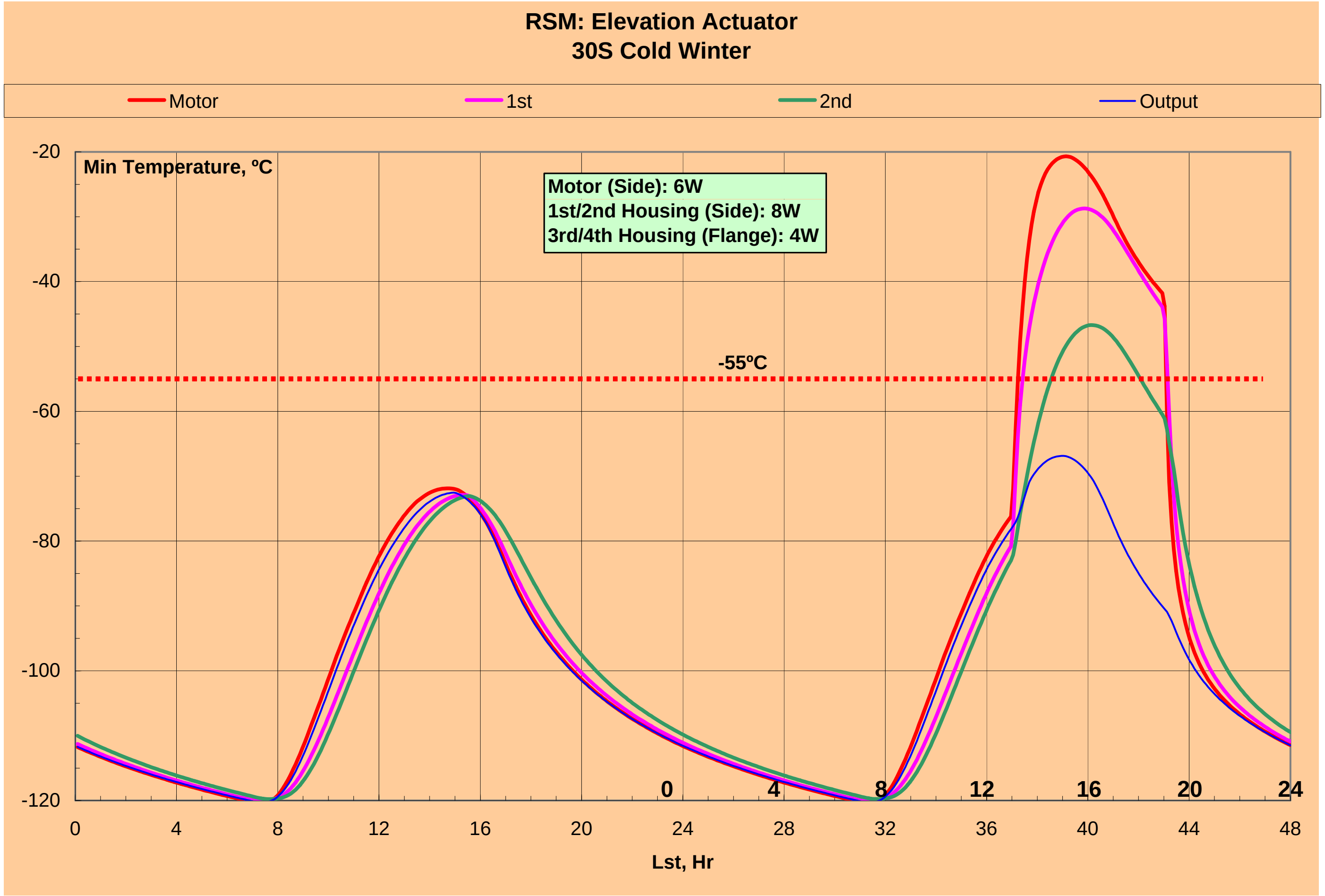
RSM Elevation Result Summary: 30ºS Winter Warm-Up Capability Window

RSM Elevation Actuator Operation Window
Worst Cold Case: 30ºS & Ls=90º
Q(Motor Housing)=6W; Q(1st/2nd Housing Side)=8W; Q(3rd/4th Housing Flange)=4W
Input Stage Only (Old Baseline)



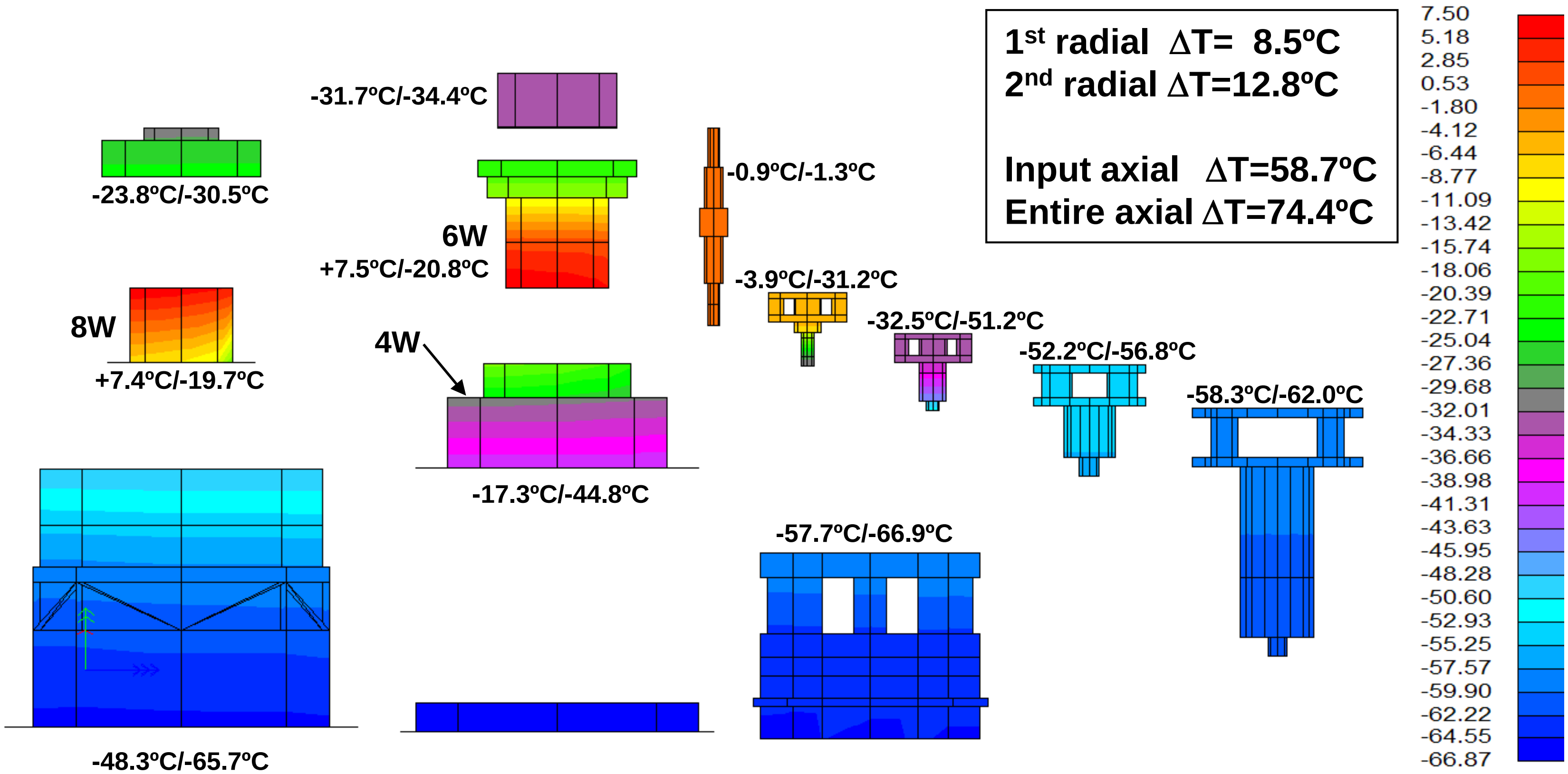
RSM Elevation Result Summary: 30ºS Winter Transient Plot

RSM Elevation Actuator: Transient Warm-Up Plots
Worst Cold Case: 30ºS & Ls=90º
Q(Motor Housing)=6W; Q(1st/2nd Housing Side)=8W; Q(3rd/4th Housing Flange)=4W
Turn on Time: 13:00 to 19:00 LST
Input Stage Only (Old Baseline)



RSM Elevation Result Summary: 30ºS Winter Contour Plot

RSM Elevation Actuator: Temperature Contour Plot
Worst Cold Case: 30ºS & Ls=90º
Q(Motor Housing)=6W; Q(1st/2nd Housing Side)=8W; Q(3rd/4th Housing Flange)=4W
2.0-Hr Warm Up: From 13:00 to 15:00 LST
Time=15:00 LST



Result Summary & Conclusions: RSM AZ & EL

- Under worst cold conditions: Cold Winter Solstice at 30º S
  - 12W/18W of warm-up heater power is sufficient to bring RSM AZ/EL actuator (motor/input stage) from soak condition to -55ºC

Location	Motor Housing (Side), W	1st/2nd Housing (Side), W	3rd/4th Housing (Flange), W	Total, W (@28V)	-55C		
					Warm-Up Time, Hr	Energy, W-Hr	OP Window, LST
Azimuth	6.0	6.0	0.0	12.0	2.0	24.0	14:50 - 18:00
Elevation	6.0	8.0	4.0	18.0	2.0	36.0	13:55 - 17:10
				Both OP	2.0	60.0	14:50 - 17:10

  - Cold Winter operation is feasible: Moderate warm-up energy
  - Extend AM/PM operational time in Spring/Fall
    - After initial warm up, cycle heater to maintain temperature
    - Actual operational time dependent on available energy
      - Function of planned Sol activities & timing

Actuator Heaters - Major Conclusions

- At many latitudes and seasons, “wait-to-use” strategy results in acceptable science return
- “Heat-to-Use” strategy offers enhanced operations capability
- Completed heater designs for all high & medium torque actuators
  - Conservative design assumptions ensure sufficient design margin.
  - Input-only heating strategy results in acceptable energy consumption for RSM, HGA & Robotic Arm
  - Mobility energy consumption in winter is excessive
    - Heaters will be useful in spring and fall to extend op window
- Low-Torque Actuator Design Cycle is underway
  - Significant progress on Drill & CHIMRA
  - Brush & inlet covers design not yet begun
- Testing Recommendations have been made to Flight System