Jet Propulsion Laboratory
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2016 Spacecraft Thermal Control Workshop

Review and Comparison of Thermal Insulation for Mars Surface Missions

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Outline

- A look at previous Mars Surface Missions
- Review of Insulation for Mars Surface Missions
- Mars 2020 Rover: A Case Study

Motivation

There is significant interest in future Mars missions:

Previous JPL Mars Surface Missions

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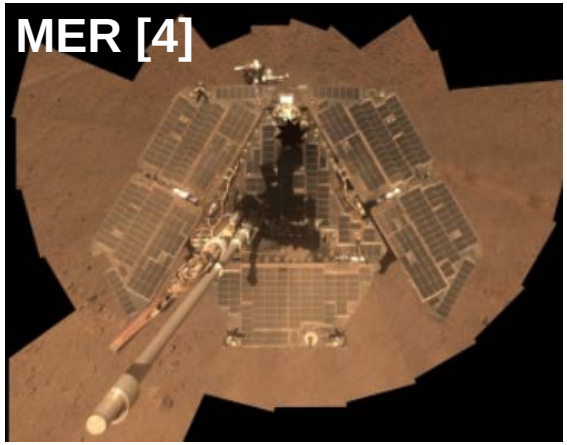
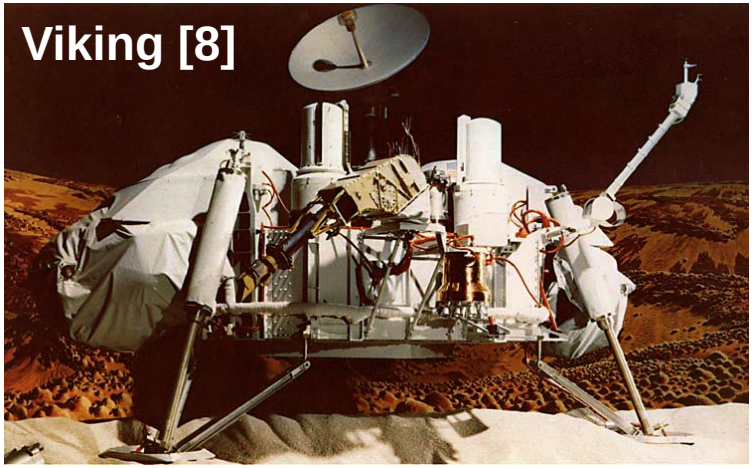




Mars Thermal Architecture

- Regardless of the power system, energy is always at a premium for Mars missions.
  - RTGs provide consistent, moderate levels of power regardless of weather, time of day, and season.
  - Solar arrays are often more cost effective, but available power and energy varies greatly depending on solar flux (time of day, season, orientation, tilt) and dust.
- Electrical heaters are used to keep components within their allowable temperature range as a last resort.
- RHUs and RTG waste heat can be used to reduce electrical heater needs in the cold case, but often are accompanied by a thermal switch, LHP, or fluid loop to protect from overheating.
- Exterior surface coatings prevent excessive temperatures in the hot case.
- Insulation is an essential component of any thermal architecture for any Mars Mission.
  - It is always cold at night, even in summer
- Minimize heat leaks through insulation due to structural and electrical feed throughs.

Summary of Mars Surface Missions

Mission	Launch Date	Operator	Spacecraft Type	Mission Outcome	Electric Power	Thermal Power	Thermal Insulation	Ref.
Viking 1 lander	1975	NASA	Lander	Operated 2245 Sols	RTG	Up to 120 W from RTG via thermal switches	Fibrous Insulation	[9]
Viking 2 lander	1975	NASA	Lander	Operated 1281 Sols	RTG	Up to 120 W from RTG via thermal switches	Fibrous Insulation	[9]
Mars Pathfinder	1996	NASA	Lander	Operated 83 Sols	Solar	None	Eccofoam	[10, 11]
Sojourner Rover	1996	NASA	Rover	Operated 83 Sols	Solar	3 x ~ 1W RHUs	Silica Aerogel and Eccofoam	[10, 11]
Mars Polar Lander	1999	NASA	Lander	Unsuccessful	Solar	None	Fibrous Insulation	[12]
Beagle 2	2003	ESA	Lander	Unsuccessful	Solar	None	Rohacell and Basotect Foam	[13]
Phoenix	2007	NASA	Lander	Operated 157 Sols	Solar	None	Fibrous Insulation	[14]
Spirit (MER-A)	2003	NASA	Rover	Operated 2208 Sols	Solar	8 x ~ 1W RHUs paired with thermal switches	Carbon Opacified Silica Aerogel	[15]
Opportunity (MER-B)	2003	NASA	Rover	Operational	Solar	8 x ~ 1W RHUs paired with thermal switches	Carbon Opacified Silica Aerogel	[15]
Curiosity (MSL)	2011	NASA	Rover	Operational	RTG	~ 350 W RTG Waste Heat via HRS	CO2 Gas Gap	[16]
InSight	2018 ?	NASA	Lander	N/A	Solar	None	Fibrous Insulation	
ExoMars	2018	ESA	Rover	N/A	Solar	2 x ~ 8.5 W RHUs paired with LHP	CO2 Gas Gap	[17]
M2020	2020	NASA	Rover	N/A	RTG	~ 350 W RTG Waste Heat via HRS	CO2 Gas Gap	[18]

Note: Numerous attempts were made to land on Mars by Russia. One of these (Mars 3) was successful in 1971, but stopped returning data soon after landing. These missions are omitted from the table due to a lack of available information.

Foam Insulation

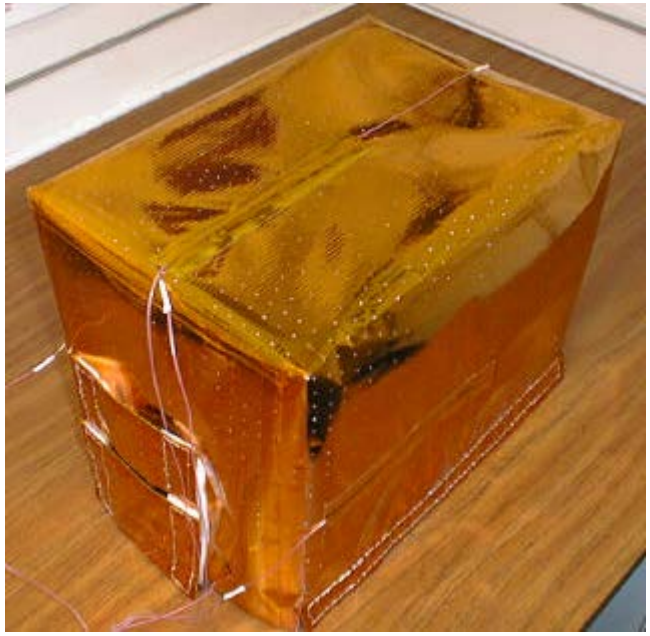
- **Flight Heritage:** Pathfinder, Sojourner Rover, Beagle 2, MER Cable Tunnels
  - Basotect, Rohacall, and Eccofoam
    - Eccofoam and Basotect are open cell foams
    - Rohacell is closed cell structural foam
- **Density:** Moderate (10 to 50 Kg/m^3)
- **Thermal Performance:** Moderate (As low as ~ 0.02 W/m-K @ -80 C)
  - Convection and radiation are included in conductivity measurements
- **Cost/Ease of Installation**: Good
  - Easy to handle and machine
  - Can be used in structures
  - Foams are able to withstand depressurization
  - Loses structural integrity at very low densities

Eccofoam [12]

Rohacell [19]

Fibrous Insulation

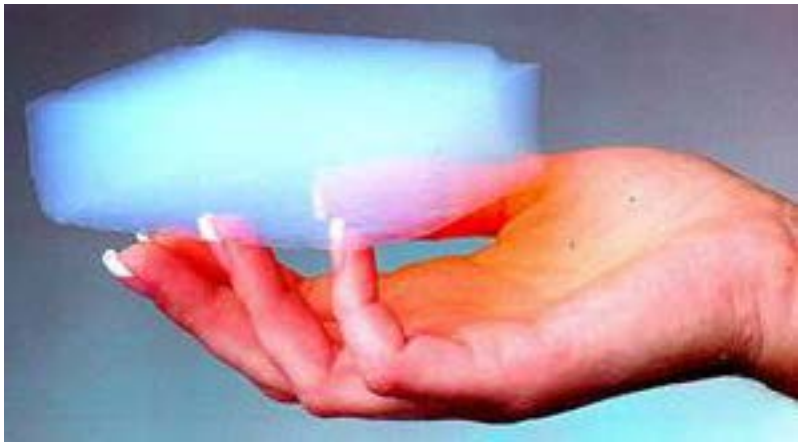
- **Flight Heritage**: Viking, MPL, Phoenix, Insight
- **Density:** Good (7 kg/m^3 to 30 kg/m^3)
- **Thermal Performance**: Very Good (As low as ~ 0.012 @ -80 C)
  - Convection and radiation are included in conductivity measurements
- **Cost/Ease of Installation:** Moderate
  - Can Shed Fibers
    - Must be wrapped in MLI and HEPA filters



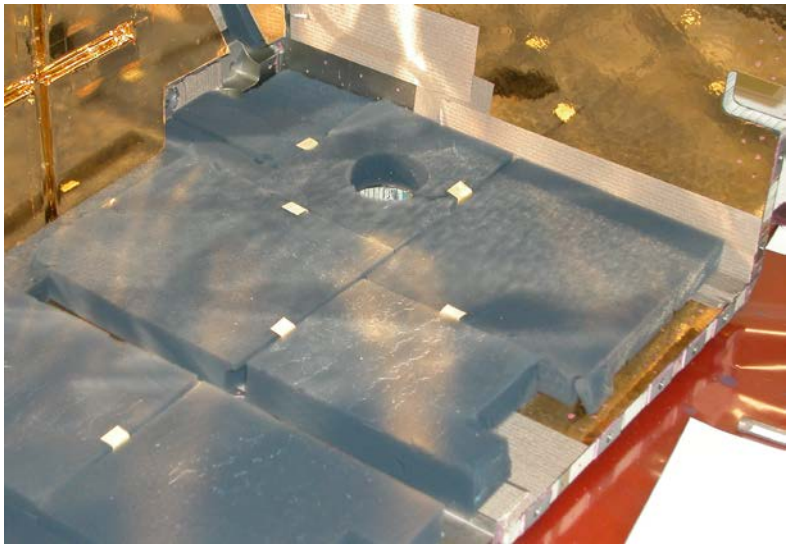
Mars 2001 Electronic Box Batt Enclosure [12]

Aerogel Insulation

- **Flight Heritage**: Pathfinder, MER
- **Density:** Very Low (15 Kg/m^3)
  - Structure can add significant mass
- **Thermal Performance**: Excellent (As low as ~ 0.006 @ -80 C)
  - Radiation is included in conductivity measurements for opacified aerogel
  - Non-opacified aerogel is transparent to radiation
  - Performance depends significantly on structural supports
- **Cost/Ease of Installation:** Poor
  - Expensive to fabricate
  - Difficult to install
  - Very Fragile
    - Hard to machine
    - Needs good structural support
  - Can Shed Particles
    - Needs to be contained and incorporate HEPA filters



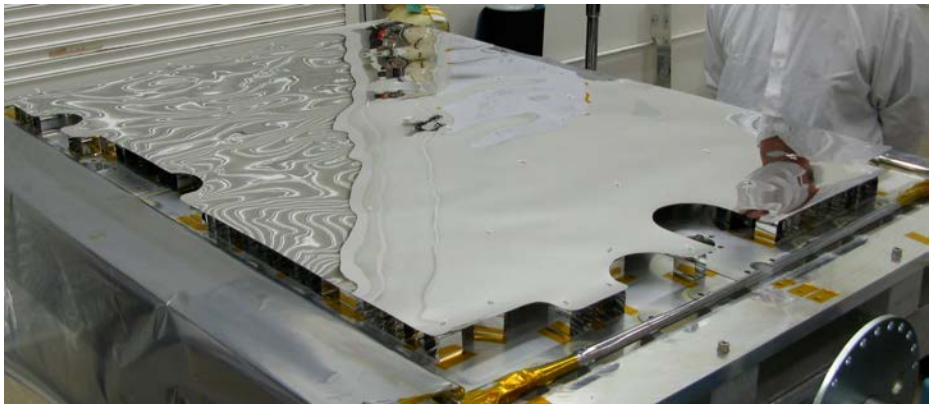
Stardust/Pathfinder Aerogel [20]



MER Opacified Aerogel

CO_2 Gas Gap

- **Flight Heritage**: MSL, ExoMars, M2020
- **Density:** Excellent (0 Kg/m^3 launch mass)
- **Thermal Performance**: Very Good (~ 0.009 @ -80 C)
  - Convection and radiation not included in conductivity measurements
    - Convection is negligible for gaps < 2” – 2.5” (0.05 m – 0.06 m) [12, 17, 21, 22]
  - Additional Performance can be gained using Radiative Shields
    - Aluminized Mylar Bumpers and Aluminized Kapton can be used to suppress convection, and reduce radiative heat losses [12]
- **Cost/Ease of Installation:** Excellent
  - Easy to allocate empty volume for gas to fill on Mars



MSL Belly Pan Aluminized Mylar Bumpers and Aluminized Kapton

Insulation Comparison Summary

- CO_2 gas gap insulation seems to be the best choice in most circumstances
- Aerogel can offer improved performance when volume is constrained, but should be used only where absolutely necessary.

	Foam Insulation	Fibrous Insulation	Aerogel	CO_2 Gas Gap
Heritage	Good	Good	Good	Good
Launched Density	10 to 50 Kg/m^3	7 to 30 Kg/m^3	15 Kg/m^3	0 Kg/m^3
Thermal Conductivity*	0.02 W/m-K	0.012 W/m-K	0.006 W/m-K	0.009 W/mK
Cost/Ease of Installation	Good	Moderate	Poor	Excellent

* Approximate Thermal Conductivity at -80 C, 8 torr CO_2

Other Insulators Considered for Mars

- Powders
  - Collodial Powder removed from consideration for Viking Lander due to weight, fabrication cost, and performance uncertainty [23]
  - Concern that opacified powders could reduce the effectiveness of structural epoxy [10]
  - Wacker WDS SiC-NT Fused Silica Powder Compound showed very low values of thermal conductivity [24]
  - Crushed Opacified Aerogel Powders were used in the MSL nomex honeycomb heat exchangers, but had thermal conductivity ranging form 0.4 to 1.5 W/m^2-K [25]

- Porous Spheres [26,27]
  - Flexible
  - Potential for Breakage and clumping could occur

- Micro Fibers [26,27]
  - Degradation will occur when fibers are broken down
  - Medical hazards due to fibrous contamination

- Vacuum Insulated Panels
  - Edge effects significant – so size scaling is important [11]
  - Reliability concerns – puncture and maintenance of vacuum over time. [11]
  - Too stiff for space suits [27]
  - Heavy, does not tolerate sterilization process [28]

- Solimide Foam (50 Kg/m^3) [24]

Aspen (Commercial) Aerogel

- Product Data Sheet gives data for 1 Earth Atmosphere [29, 30]:
  - Cryogel® : 0.014 W/m-K @ -80 C (200 Kg/m^3)
  - Pyrogel® : 0.020 W/m-K @ 0 C (180 Kg/m^3)

- Based on published data for other Aerogels [31], the thermal conductivity should decrease by ~ 50% from 1 Earth Atmosphere (760 torr) to 1 Mars Atmosphere (10 torr)
  - The approximate thermal conductivity is guessed to be 0.09 W/m-K at -80 C and 10 torr.

- Pyrogel® measured thermal conductivity is approximately 0.01 W/m-K [32].

Pyrogel® [29]

Cryogel® [30]

Thermal Conductivity of Insulation

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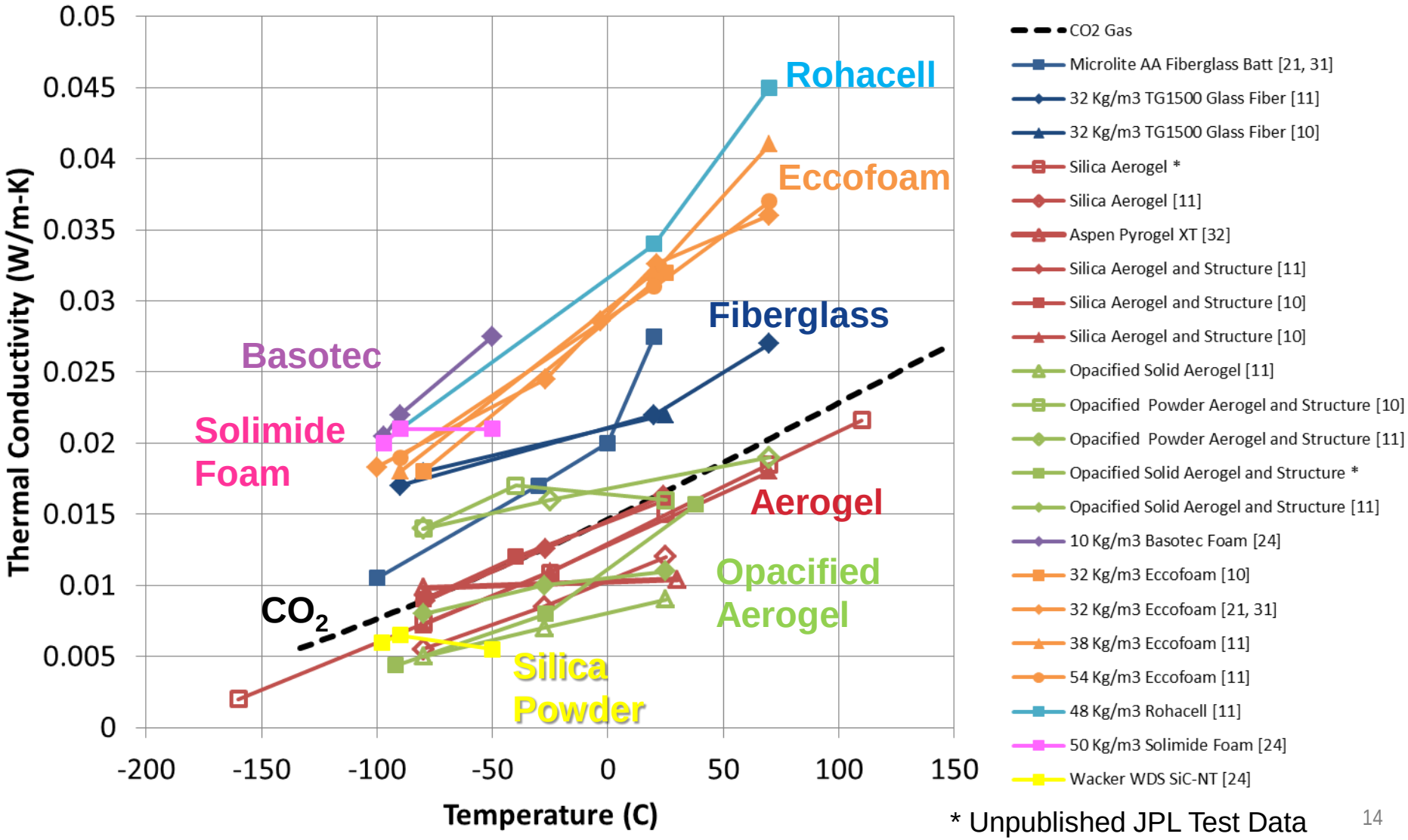
- All properties measured in 7.5 to 10 torr CO_2



* Unpublished JPL Test Data

M2020 Insulation Case Study

- MSL Thermal Performance has been very good [33]
  - Rover Avionics Mounting Panel (RAMP) temperatures have remained between 5 and 40 C for the duration of the mission
  - RAMP AFT range is -40 C to + 50 C
  - Gale Crater is a relatively low wind landing site

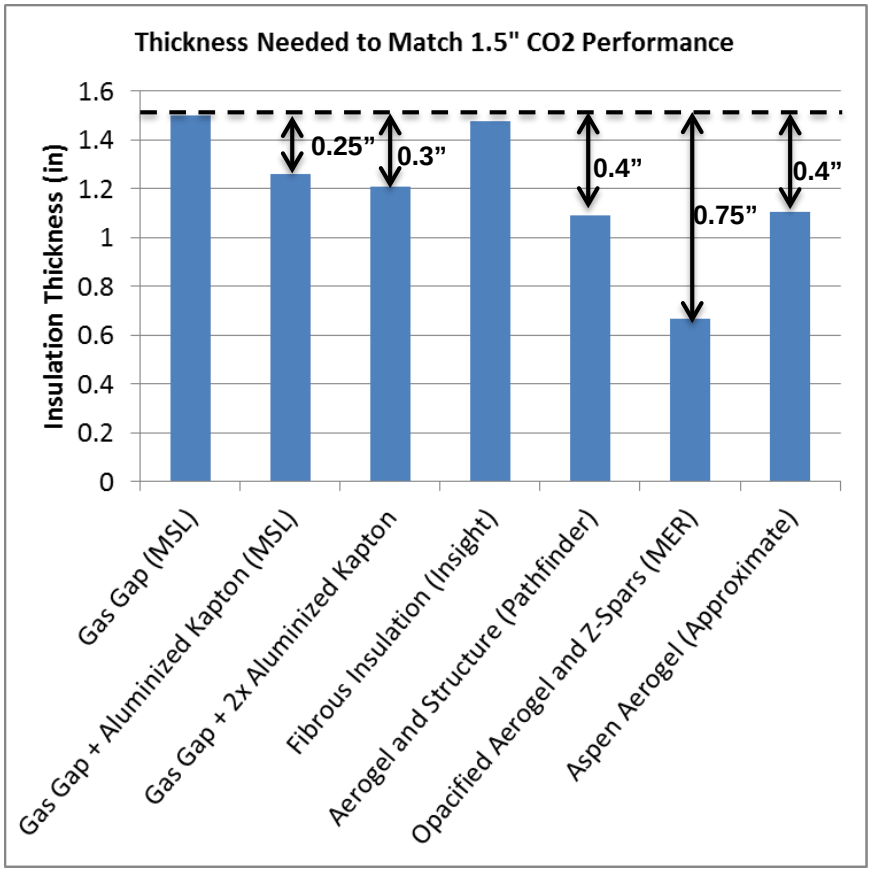
- MSL used CO_2 Gas Gap insulation, with an aluminized mylar layer on the belly pan to enhance performance.

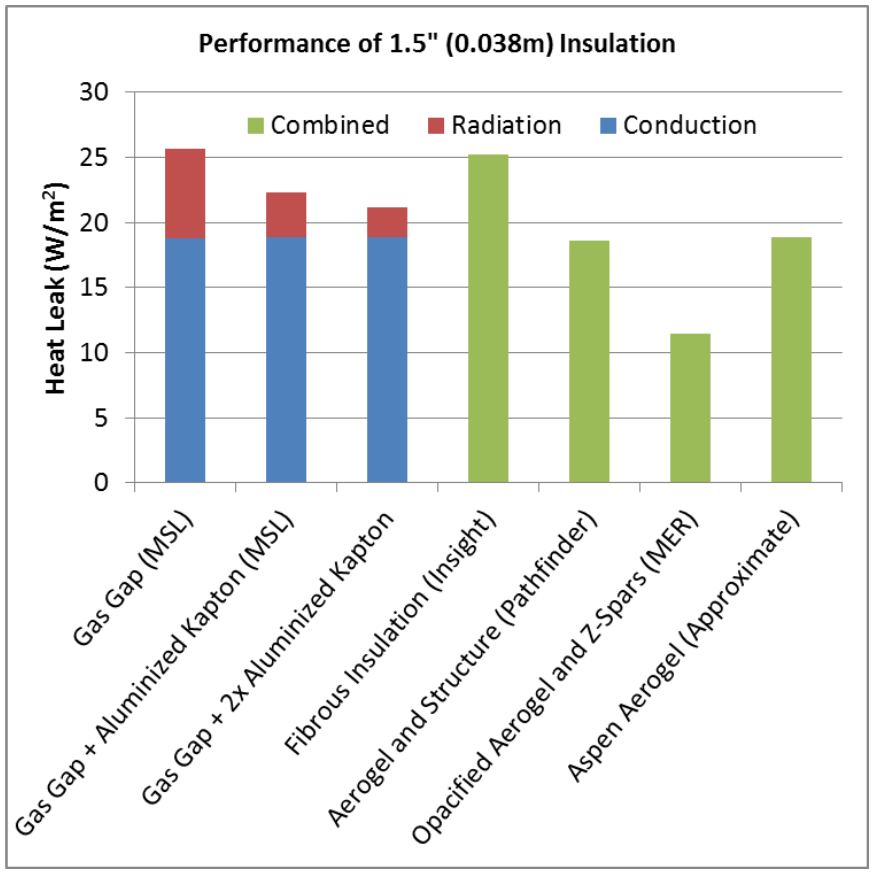
- An insulation sensitivity study was undertaken in March 2015 for M2020 to see if insulation thickness could be reduced.

M2020 Insulation Comparison

- Assumptions
  - T_{hot} = -40 C
  - T_{cold} = -120 C
  - Thermal Conductivity Evaluated at T_{avg} = -80 C

Can Automatically Rule Out:
- **Fibrous Insulation (No Benefit vs. CO2)**
- **Pathfinder Aerogel (MER Aerogel Better)**
- **2x Aluminized Kapton (Marginally better than 1x)**





Insulation Mass – Rover Side Walls

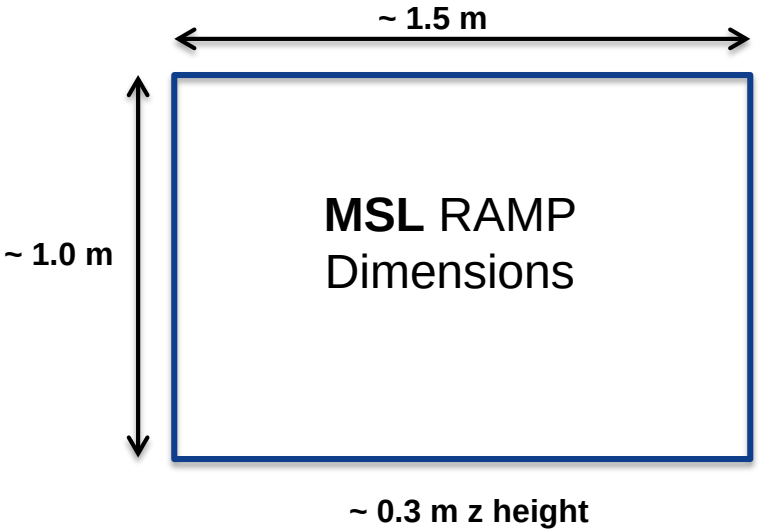
- Aspen Aerogel may be easier to work with than MER or Pathfinder aerogel, but it is also the most dense.

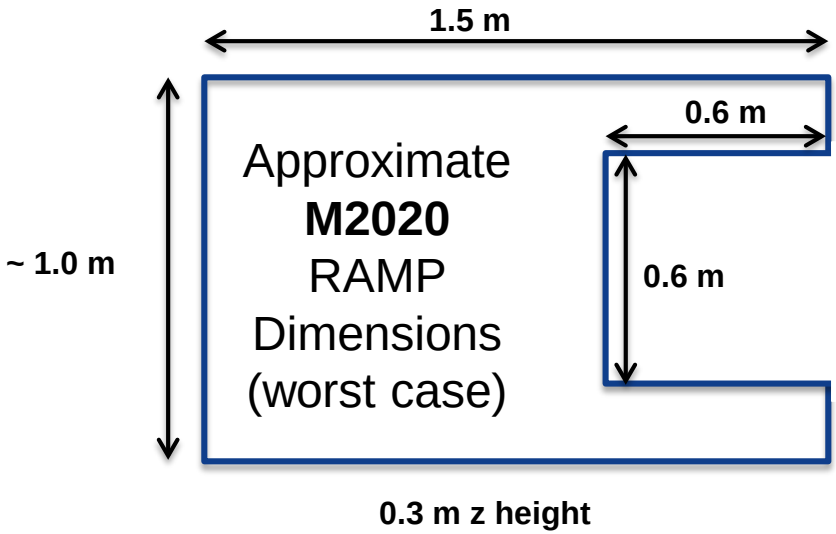
- MER Opacified Aerogel has the best performance, but requires an entirely new design to contain it.
  - MSL chassis ribs can't be used to contain aerogel since they are aluminum
  - Additional structural support would result in additional mass and implementation risk.

- **Best Option to improve existing design is to use Aluminized Kapton on Side Walls**

	Density (Kg/m^3)	Mass (Kg)	Total Mass (Kg)
Gas Gap (MSL)	0	0	0
Gas Gap + 5 mil Double Aluminized Kapton	**0 ~1400**	**0 ~0.4**	**~ 0.4**
Opacified Aerogel + Structure and Z-Spars (MER)	15 ~1800	0.5 ~3.6	~ 4
Aspen Aerogel	50 - 200	2 - 8	2 - 8

Rover Heat Leak Areas





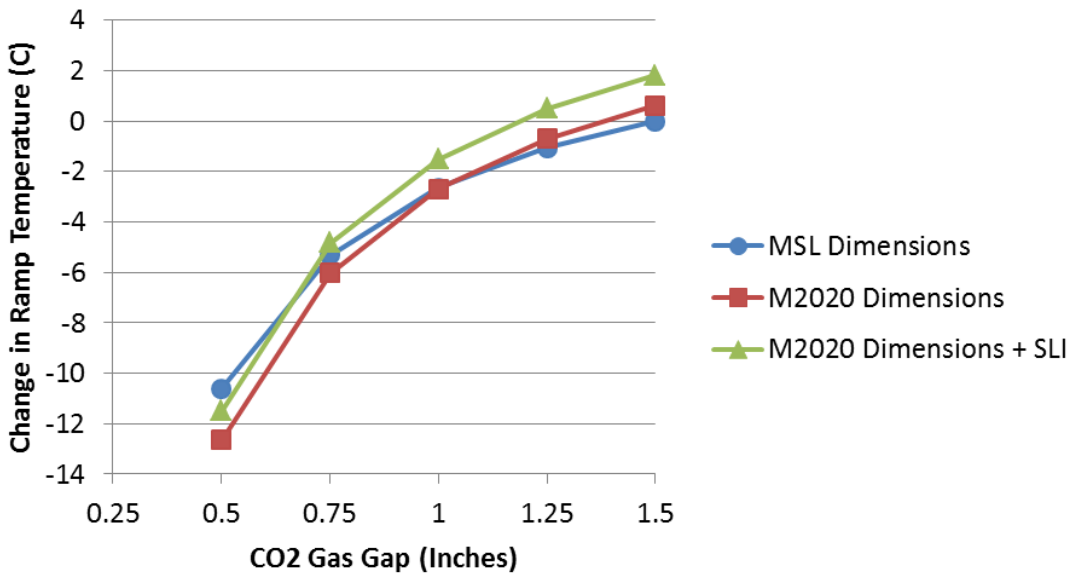
- Top Deck Area= 1.5 m^2
- Belly Pan Area = 1.5 m^2
- Side Wall Area = 1.6 m^2

- Top Deck Area= 1.2 m^2
- Belly Pan Area = 1.2 m^2
- Side Wall Area = 2.0 m^2

Note: Final design of the M2020 RAMP is roughly a square 1 m x 1 m area.

Ramp Temperature vs. Side Wall Gap

- Results are based off estimates for heat loss and a sensitivity study using the MSL Rover Thermal Model:

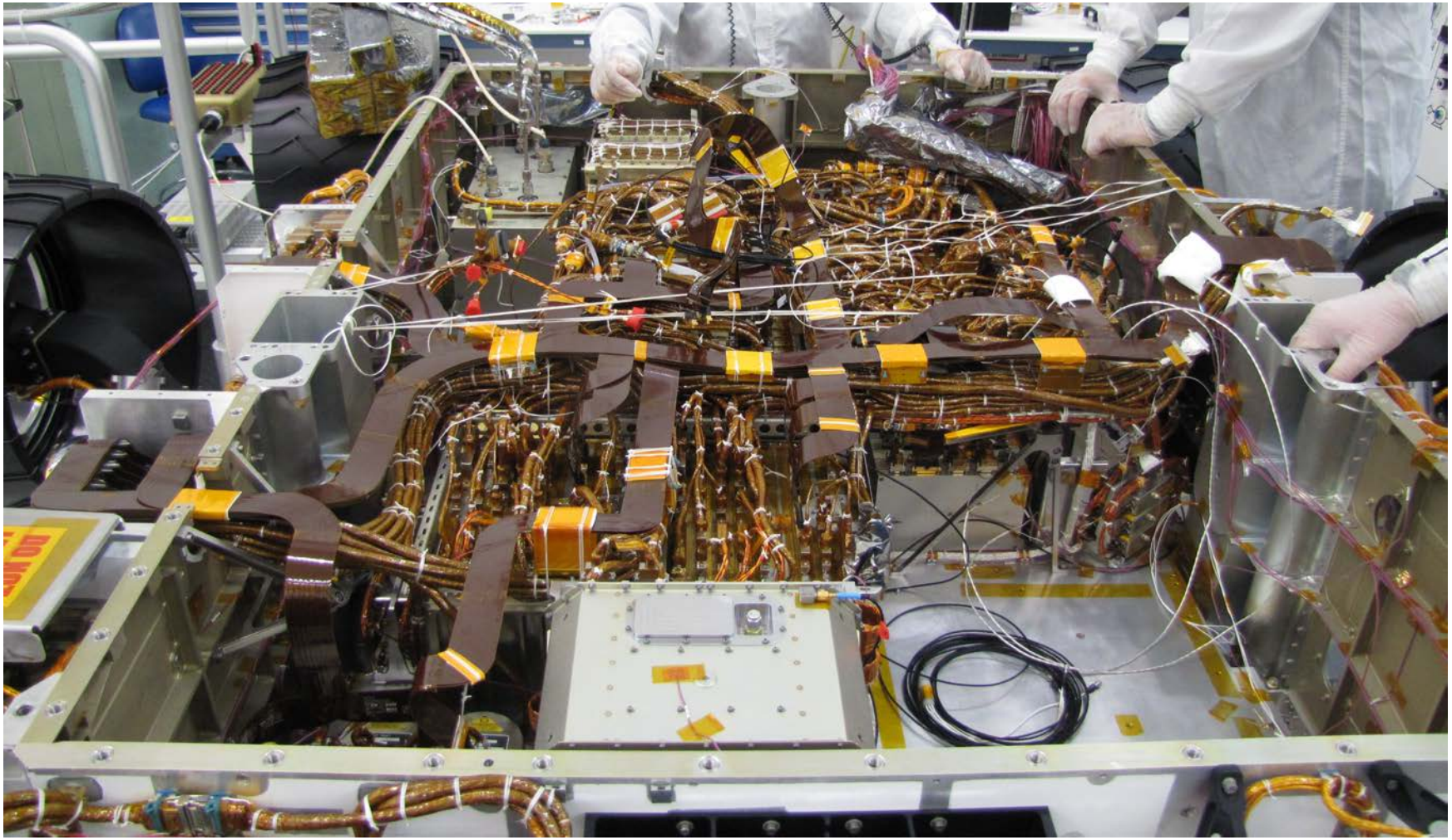


- With addition of Double Aluminized Kapton SLI with aluminized mylar stand offs:
  - Can reduce Gas Gap to 1.25 inches with no performance loss

- 1.0 inch Gas Gap is pretty much the edge of the cliff (absolute limit – can't get smaller)
  - Smaller gas gaps drastically increase heat loss and decrease Ramp Temp.

The Challenges of Adding SLI

- Limited Space, lots of interaction with Rover Side Walls:



Conclusion

- CO_2 gas gap insulation seems to be the best choice in most circumstances.
  - Can be augmented using aluminized mylar
- Aerogel can offer improved performance when volume is constrained, but should be used only where absolutely necessary.
- M2020 will be using the MSL heritage CO_2 Gas Gaps on the side walls and top deck, with an aluminized mylar layer added to the belly pan.
  - The insulation thickness is not reduced relative to MSL
  - CO_2 is mass, cost, schedule, and complexity optimal

Acknowledgements

- This presentation draws on the previous contributions of many JPL Engineers, including but not limited to: Gaj Birur, Gregory Hickey, Jim Stultz, and Glenn Tsuyuki.

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References (1 of 2)

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