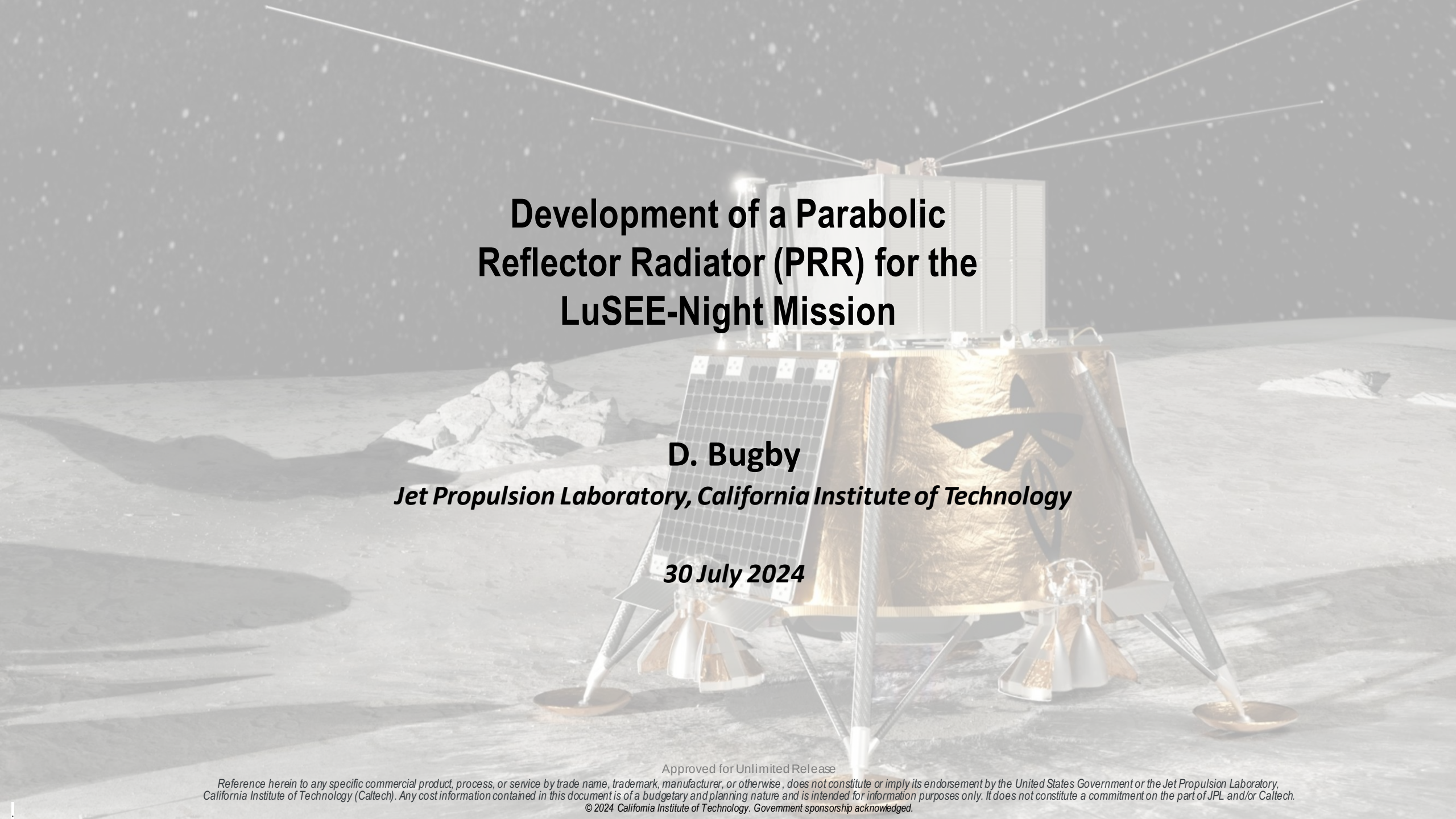

Development of a Parabolic Reflector Radiator (PRR) for the LuSEE-Night Mission

D. Bugby

Jet Propulsion Laboratory, California Institute of Technology

30 July 2024

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Outline

- **Overview** … *project, mission, teams, responsibilities*
- **Background** … *parabolic reflector radiator (PRR) details*
- **History** … *PRRs that have flown in the past*
- **Requirements** … *agreed to by JPL and LuSEE-Night*
- **Trades** … *in support of PRR design, build, and test*
- **Design** … *CAD models of flight and subscale PRRs*
- **Development** … *developmental activities prior to design/build/test*
- **Analysis** … *thermal/structural analyses of PRR in test/flight*
- **Fabrication** … *how full-size and subscale PRRs were made*
- **Testing** … *subscale PRR RV/TVAC, flight reflector acceptance*
- **Summary** … *overall results summary and mission impact*
- **Acknowledgments** … *project organization chart of key contributors*

Overview

Outline

Project Start to Flight Hardware Delivery in Just 10 Months (Aug 2023 → June 2024)

- ***PROJECT:*** PALETTE PRR for LuSEE-Night is a FY23-24 NASA GCD follow-on project to FY20-23 NASA GCD PALETTE project, which developed new thermal tools for extreme environments. One of those tools is an ***affordable, two-piece (radiator + reflector) parabolic reflector radiator (PRR).***

- ***MISSION:*** In 2026, a CLPS lander will carry ***LuSEE-Night*** to a 20° S lunar farside site. From that RF-quiet location, it will perform radio astronomy (21 cm cosmology) for 24 lunar day/night cycles (2 Earth years). ***A daytime surface temp of 385 K and a side-facing radiator view necessitate a PRR.***

- ***TEAMS:*** University of California, Berkeley Space Sciences Laboratory (SSL), Brookhaven National Laboratory (BNL), Jet Propulsion Laboratory (JPL). LuSEE-Night mission jointly funded by NASA SMD and DOE Office of Science. ***PALETTE PRR for LuSEE-Night project funded by NASA STMD/GCD.***

- ***ROLES:*** UCB/SSL and BNL to produce the LuSEE-Night instrument, which includes the flight PRR radiator plate. JPL to produce ***9 flight PRR reflectors*** that mate with PRR radiator plate to form the flight PRR. JPL also responsible for ***design/build/test of a (1/9th full-size) subscale PRR.***

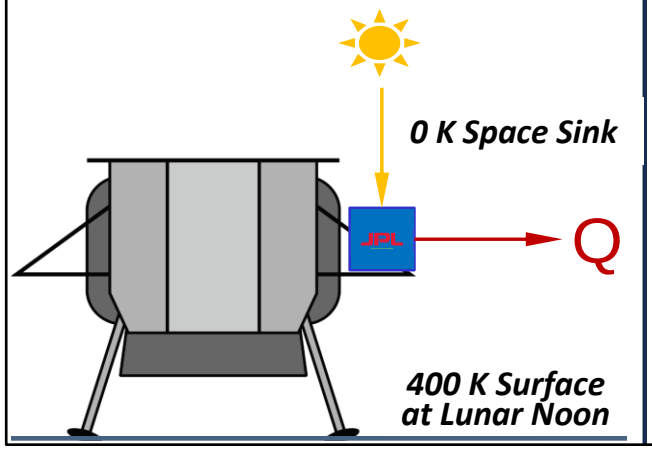
Background

Outline

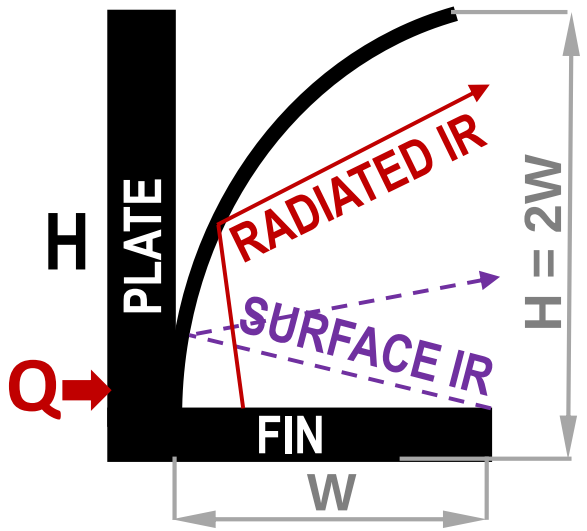
For a side-facing radiator on a hot lunar surface, the ***parabolic reflector radiator (PRR)*** provides a low sink temperature by reflecting away a large fraction of lunar surface IR. An affordable PRR design was developed on PALETTE that is being adapted for the PALETTE PRR for LuSEE-Night Project.

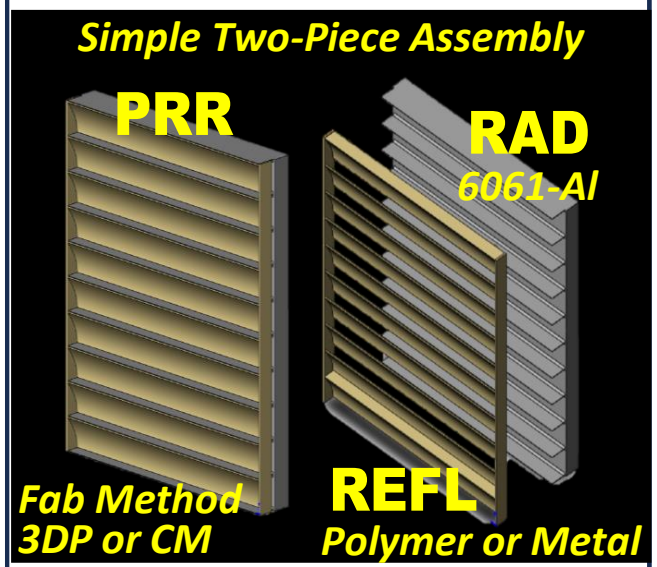
Radiative Sink Temp (TS) of Conventional Side-Facing Radiator Much Too High for a Typical Science Payload

$TS = (0^4/2 + 400^4/2)^{1/4}$
$= 336\ K = 63\ °C$



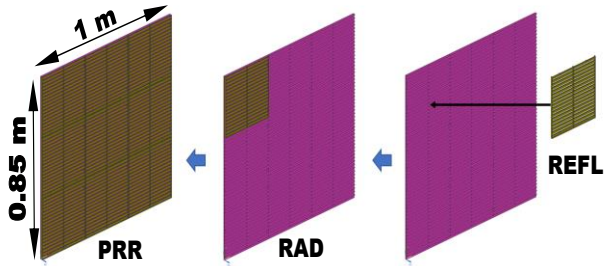
PRR Reflects Surface IR, Instrument Radiated IR



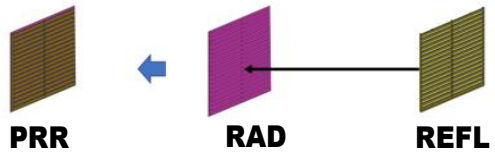


3DP = 3D Printing
CM = Conventional Machining

Full-Scale PRR (Flight Unit)
Large Rad Plate (LuSEE-Night)
9 Flight Reflectors (JPL)



Subscale PRR (Test Unit)
1/9th Scale Rad Plate (JPL)
Single Flight Reflector (JPL)



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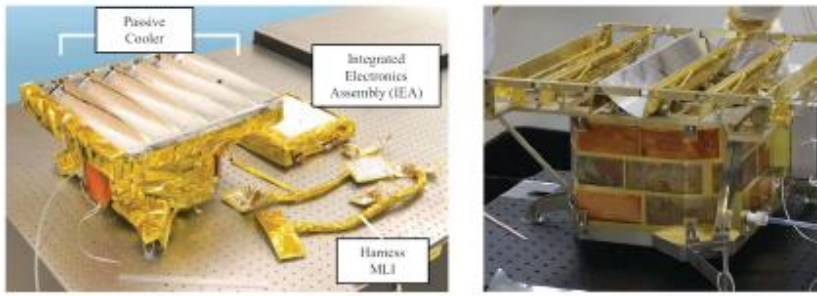
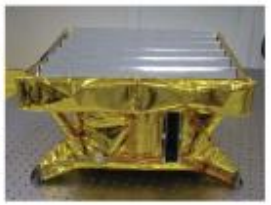
History

Outline

Chandrayan-1 M3 Instrument *(used parabolic reflector radiator or PRR)*





k-core composite Radiators

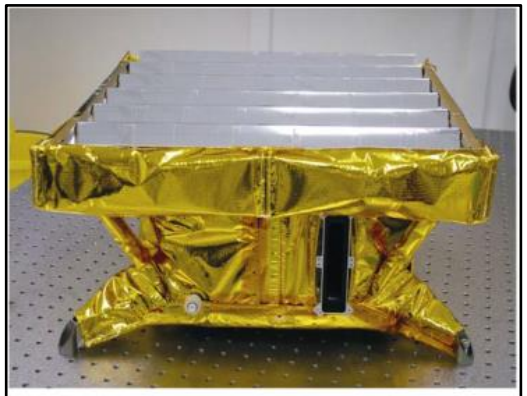
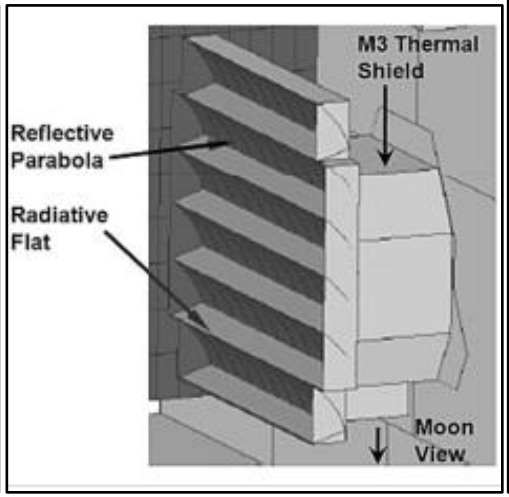
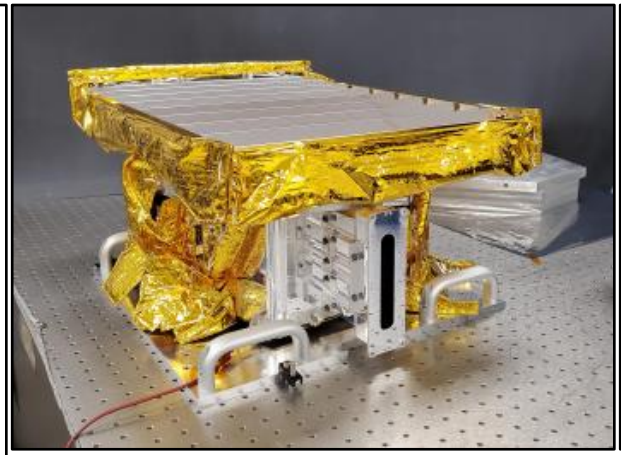
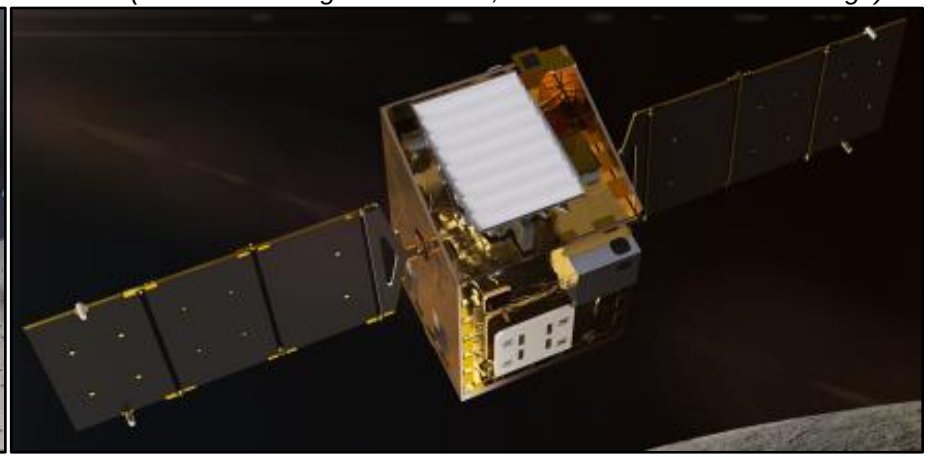


Figure 3. The M^3 Optical Bench Assembly (spectrometer). The radiator is on top with the entrance aperture in front. This side faces the Moon. Dimensions of the OBA are approximately 420 W × 350 D × 220 H (mm).

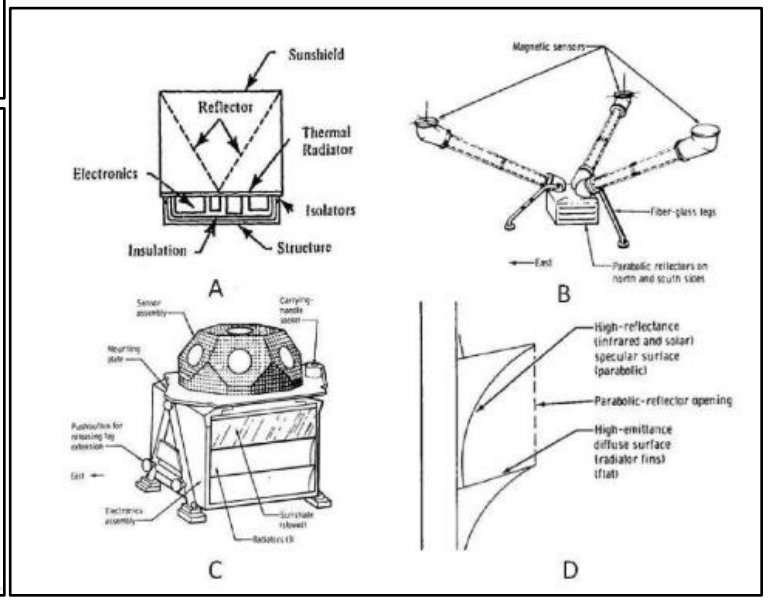


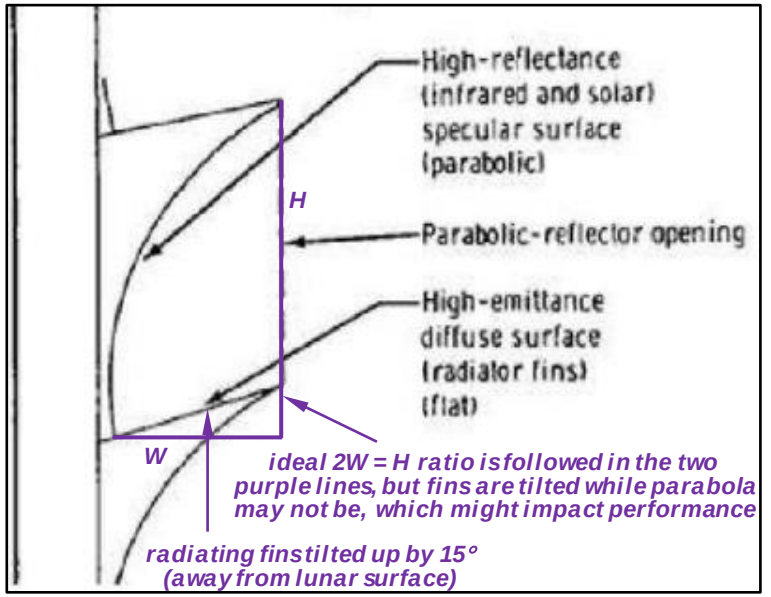
Lunar Trailblazer HVM3 Instrument to Launch in 2024 *(extends M3 range to 3600 nm; seems to be same PRR design)*





ALSEP Experiments on Apollo Used PRRs *(B-Lunar Surface Magnetometer and C-Solar Wind Spectrometer used D)*





Requirements

Outline

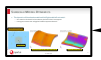
	REQUIREMENT	VERIFICATION
1.	***Lunar Latitude 20° S Farside*** *(PRR tilted back 12° to avoid IR from N-to-S 10° upslope)*	*A*
2.	***GEVS Protoflight*** *(14.1 grms, Subscale PRR vibe analytically-linked to Flight PRR)*	*A, T**
3.	***PRR Sink Temperature ≤ 231 K*** (main performance goal***, *with **these** heat leaks*)	*A, T**
4.	***Solar Flux 1400 W/m²*** *(12° below perpendicular, 1 rev/hour transit****)*	*A*
5.	***Lunar Surface Temperature 385 K*** *at Lunar Noon (90 K at night, regolith emissivity 0.95)*	*A, T**
6.	***Reflectors Electrically Grounded*** *to Al Radiator Plate (R ≤ 1 kΩ)*	*T*
7.	***Meet LuSEE-Night (LN) Mechanical ICD*** *(to be derived from jointly-developed drawings)*	*A, T***
8.	***Ensure that Aluminized Kapton Tape (AKT) Adheres*** *to Aluminum 6061 Reflectors*	*T******
9.	***Subscale PRR Vibe, TVAC Perf. Tests*** *(Subscale PRR vibe analytically-linked to Flight PRR)*	*T**
10.	***Flight Reflector Acceptance Tests*** *(simplified due to reflector polishing)*	*T*

* *subscale unit only*
** *flight reflectors only*
*** *target only, not requirement*
**** *full trajectory + lunar orbital analysis not in plan*
***** *requirement eliminated due to polishing success*

JPL Subscale PRR Vibe Test to Follow Variant of Quartus Proposal B

Clarification at MRR of "analytically-linked to Flight PRR" made by D. Goggin that Subscale PRR vibe level should be adjusted (most likely increased) from the GEVS 14.1 grms level so that the Subscale PRR Reflector vibe environment matches that of the Flight PRR Reflectors.

JPL Structural SME Evaluation: *above goal is **NOT ACHIEVABLE** by simply adjusting the GEVS 14.1 grms profile due to significant mounting constraint differences. For vibe test to have flight linkage, a larger radiator plate will need to be fabricated and tested. See **Proposal B**.*



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Trades

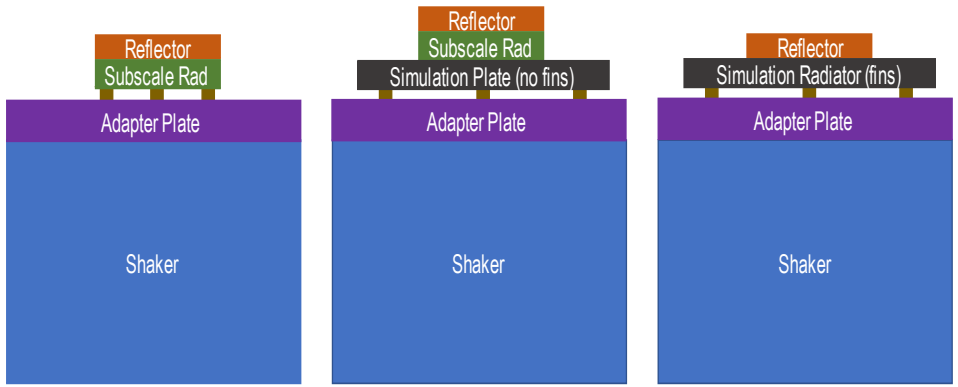
Outline

1. Applicability of the ***Subscale PRR RV test*** to the Flight PRR structural environment
2. Applicability of the ***Subscale PRR TVAC test*** to the Flight PRR thermal environment

Subscale PRR RV Test Trade Study

Key Question: *Given that Case 1 is not acceptable and the Quartus recommendation is Case 3 (see Proposal B in this slide package), is Case 2 an acceptable alternative to Case 3, which would then allow direct TVAC testing of the Subscale PRR?*

Case 1: PRR Reflector bolted to Subscale Radiator Plate bolted to Adapter Plate — ***not acceptable*** (see embedded object above)
Case 2: PRR Reflector bolted to Subscale Radiator bolted to Simulation Plate bolted to Adapter Plate — ***acceptable*** (see embedded object below)
Case 3: PRR Reflector bolted to Simulation Plate bolted to Adapter Plate — ***acceptable*** (see embedded object below)



= Force Limiting Washers

Quartus Modeling Results Indicate Case 2 is Acceptable

Subscale PRR TVAC Test Trade Study

Key Question: *What IR plate temperature should be utilized during TVAC testing to properly simulate the lunar environment?*

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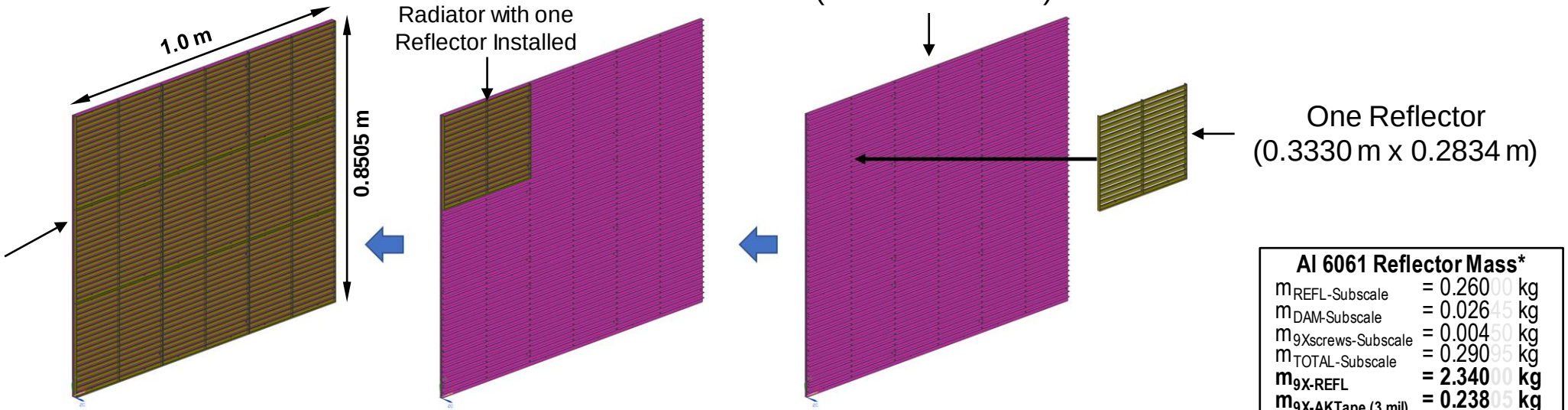
Design

Outline

Full-Scale PRR

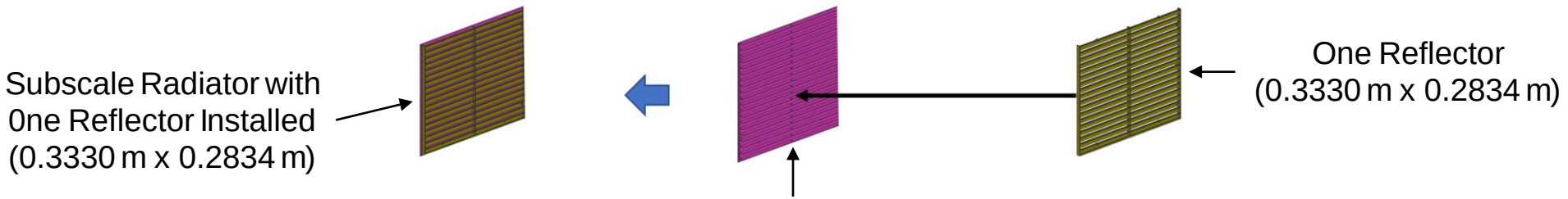


Al 6061 Reflector Mass*

$m_{REFL\text{-}Subscale}$	= 0.26000 kg
$m_{DAM\text{-}Subscale}$	= 0.02645 kg
$m_{9Xscrews\text{-}Subscale}$	= 0.00450 kg
$m_{TOTAL\text{-}Subscale}$	= 0.29095 kg
$m_{9X\text{-}REFL}$	**= 2.34000 kg**
$m_{9X\text{-}AKTape\ (3\ mil)}$	**= 0.23805 kg**
$m_{81X\text{-}screws}$	**= 0.04050 kg**
$m_{TOTAL\text{-}Flight}$	**= 2.61855 kg**

* ***0.8 mm blade thickness*** *(no deflection reducing enhancements to cross-section)*

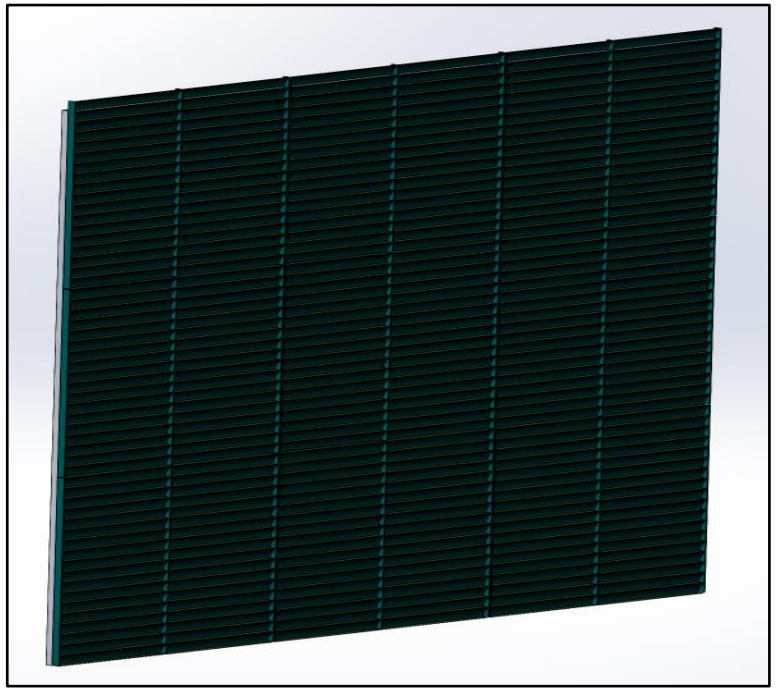
Subscale PRR



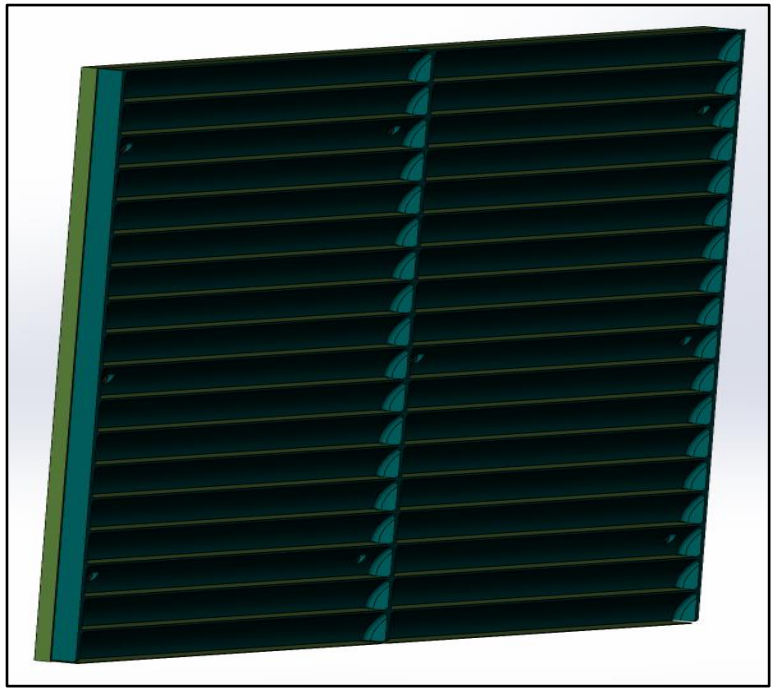
Design (cont'd)

Outline

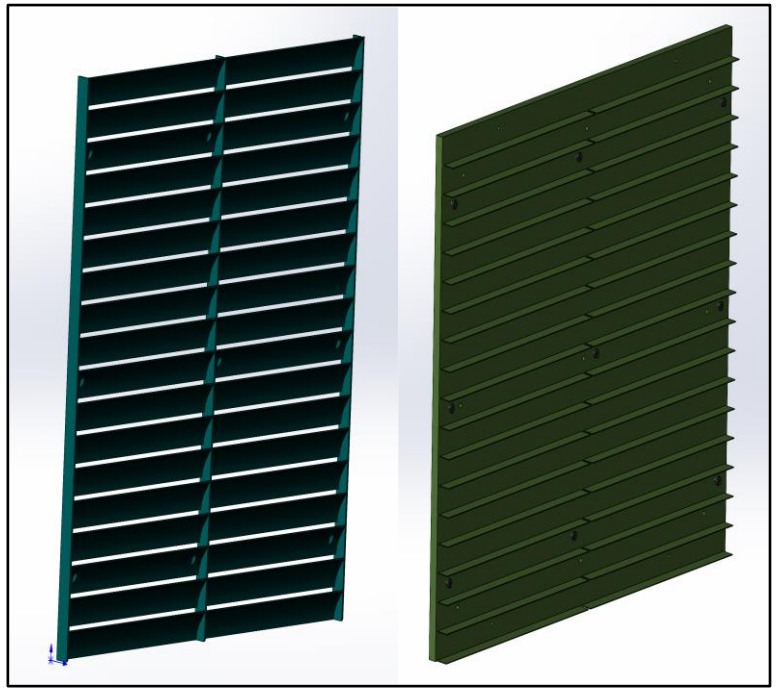
Full-Scale PRR



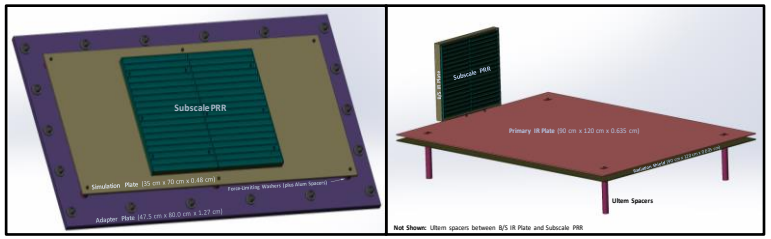
Subscale PRR



PRR Reflector, Subscale Radiator



Subscale PRR RV/TVAC Test Units



Development

Outline

Development activities during this evolving flight project included the following areas of investigation: **(1) Reflector Material**; **(2) Reflector Coating**; **(3) Manufacturing Method**; **(4) Electrical Grounding.** The results of those developmental activities (test and/or analysis) are summarized in the table below.

Reflector Material	Reflector Coating	Manufacturing Method	Electrical Grounding	Main Advantage(s)	Main Drawback(s)	Design Decision
Ultem 1010	AKT	3DP	Modified AKT	PALETTE Heritage	High 3DP FOS, High CTE	Not Selected
Ultem 9085	AKT	3DP	Modified AKT	PALETTE Heritage	High 3DP FOS, High CTE	Not Selected
Ultem 1000	AKT	CM	Modified AKT	No 3DP Safety Factor	High CTE	Not Selected
Ultem 2300	AKT	CM	Modified AKT	Al-6061 CTE Match	CM Cost/Schedule	Not Selected
Ti64	AKT, VDA/G, Polished	3DP	Coating Dependent	High Strength	High Mass	Not Selected
Al-6061	AKT, VDA/G, Polished	3DP	Coating Dependent	Intrinsically Conductive	3DP Complexity	Not Selected
Al-6061	AKT, VDA/G, Polished	CM	Intrinsically Conductive	Intrinsically Conductive	None	Selected

PRR Reflector Design Decision:

Conventionally machined Al-6061 with hand-polished 2 microinch finish as a fabrication target

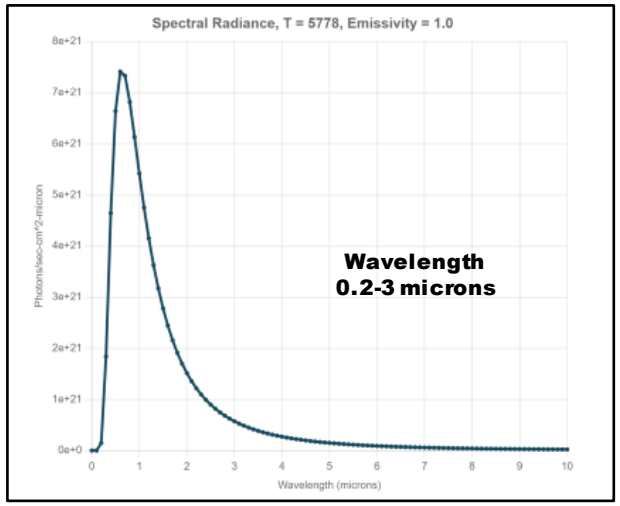
(see next 2 slides for more information on this target surface roughness and its efficacy)

Development (cont'd)

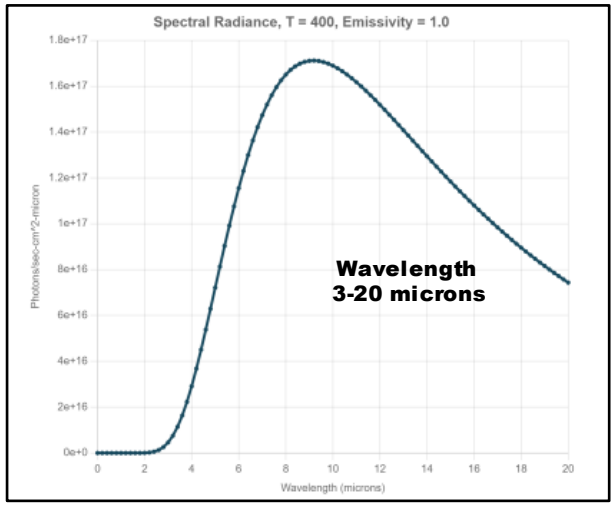
Outline

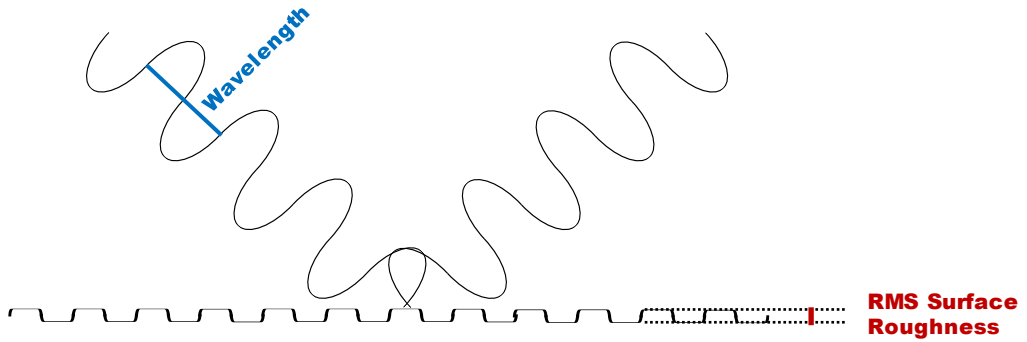
If the **wavelength** of incoming light is much larger than the **RMS surface roughness**, ***reflections will be primarily specular***

Solar UV: Effective Temp of 5778 K



Lunar IR: Surface Temp of 400 K

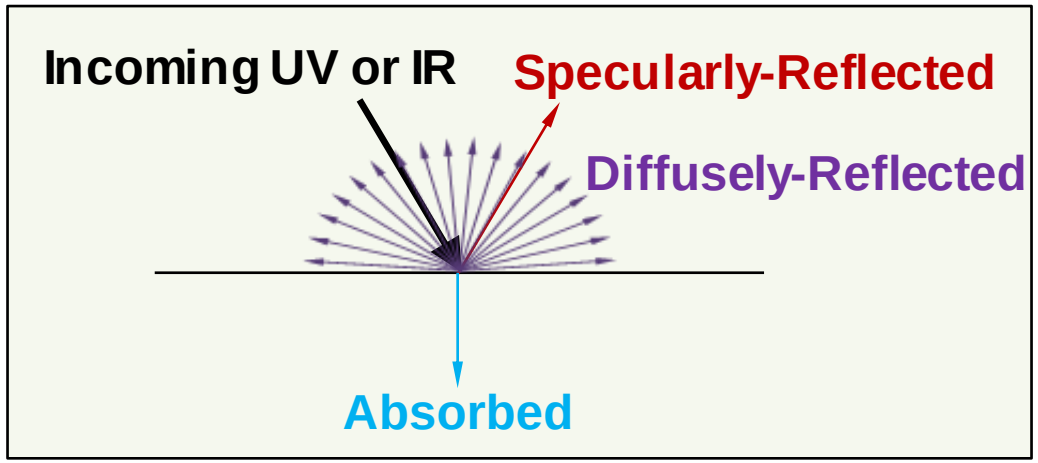




Target: 2 micro-inch surface finish = 0.05 micron

Fine enough to be good IR specular reflector

Not fine enough to be good UV specular reflector



The ideal PRR Reflector will have …

1.	low absorptivity to UV	low alpha
2.	low absorptivity to IR	low emissivity
3.	high specular reflectivity to IR	IR wavelength >> roughness
4.	low diffuse reflectivity to IR	IR wavelength >> roughness
5.	high diffuse reflectivity to UV	UV wavelength ~ roughness
6.	low specular reflectivity to UV	UV wavelength ~ roughness

Development (cont'd)

Impact of surface roughness on specularity for He-Ne laser (0.63 microns) linearly scaled to lunar surface IR wavelengths

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Study of engineering surfaces using laser-scattering techniques

C BABU RAO and BALDEV RAJ

Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India
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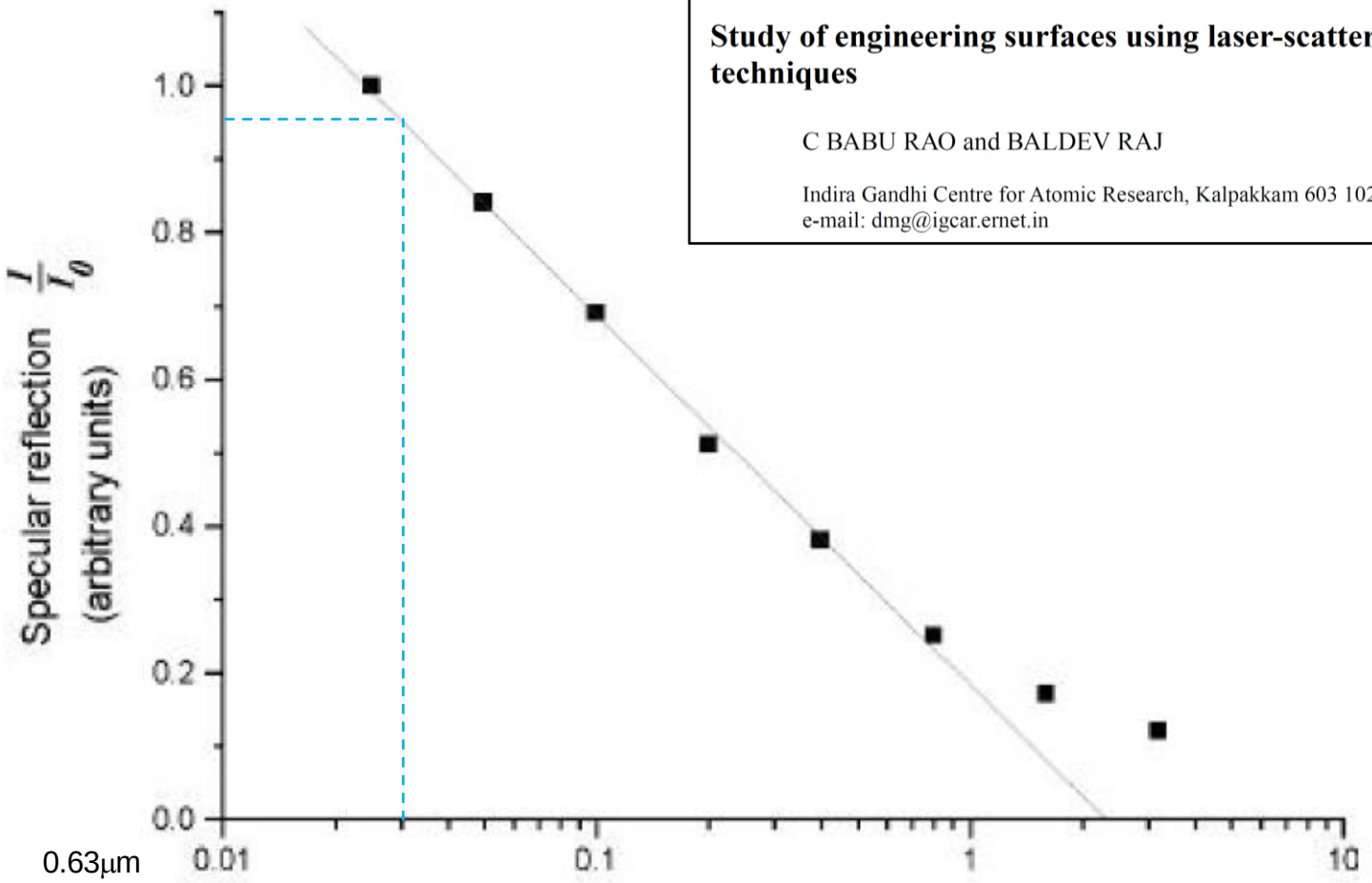
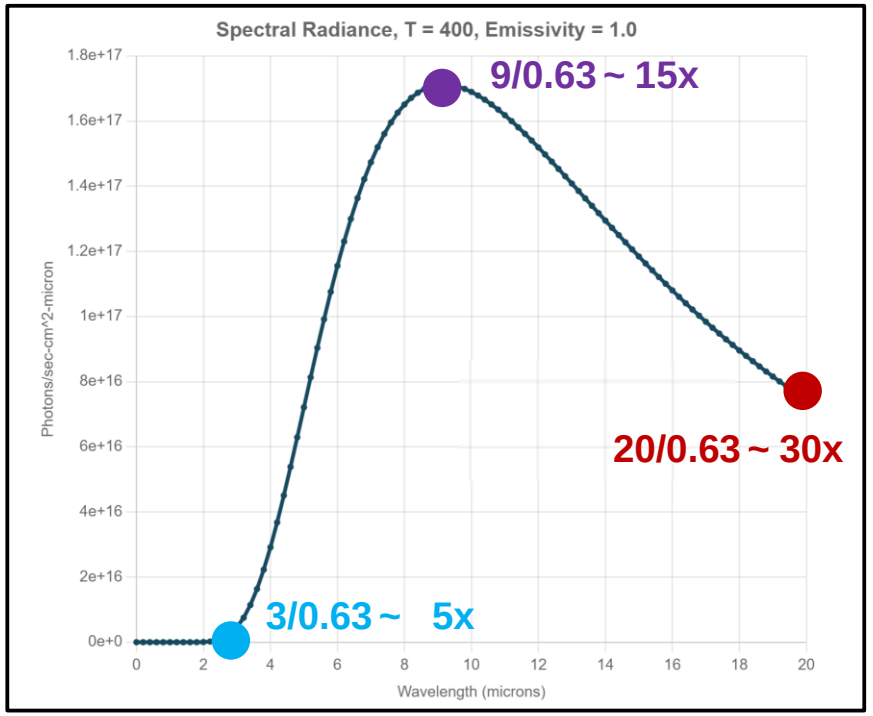


Lunar IR: Surface Temp of 400 K

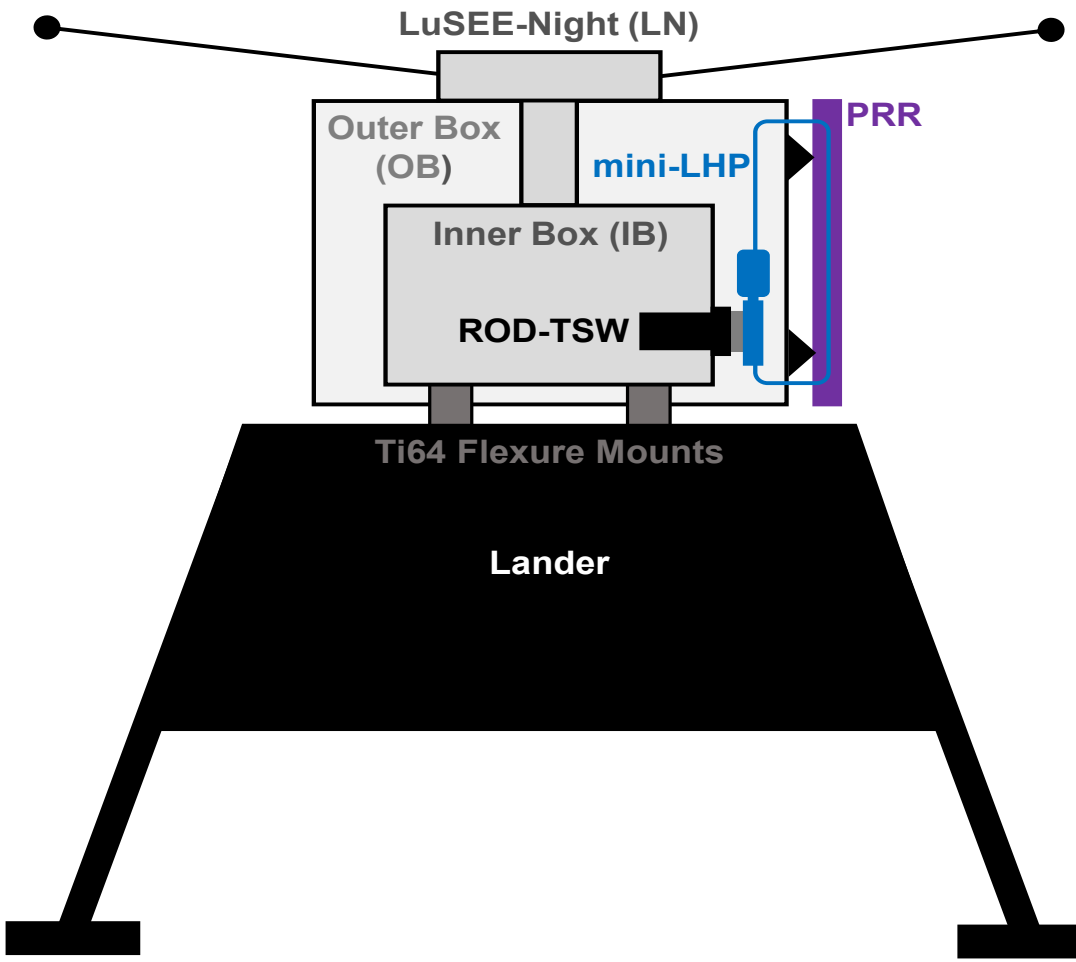


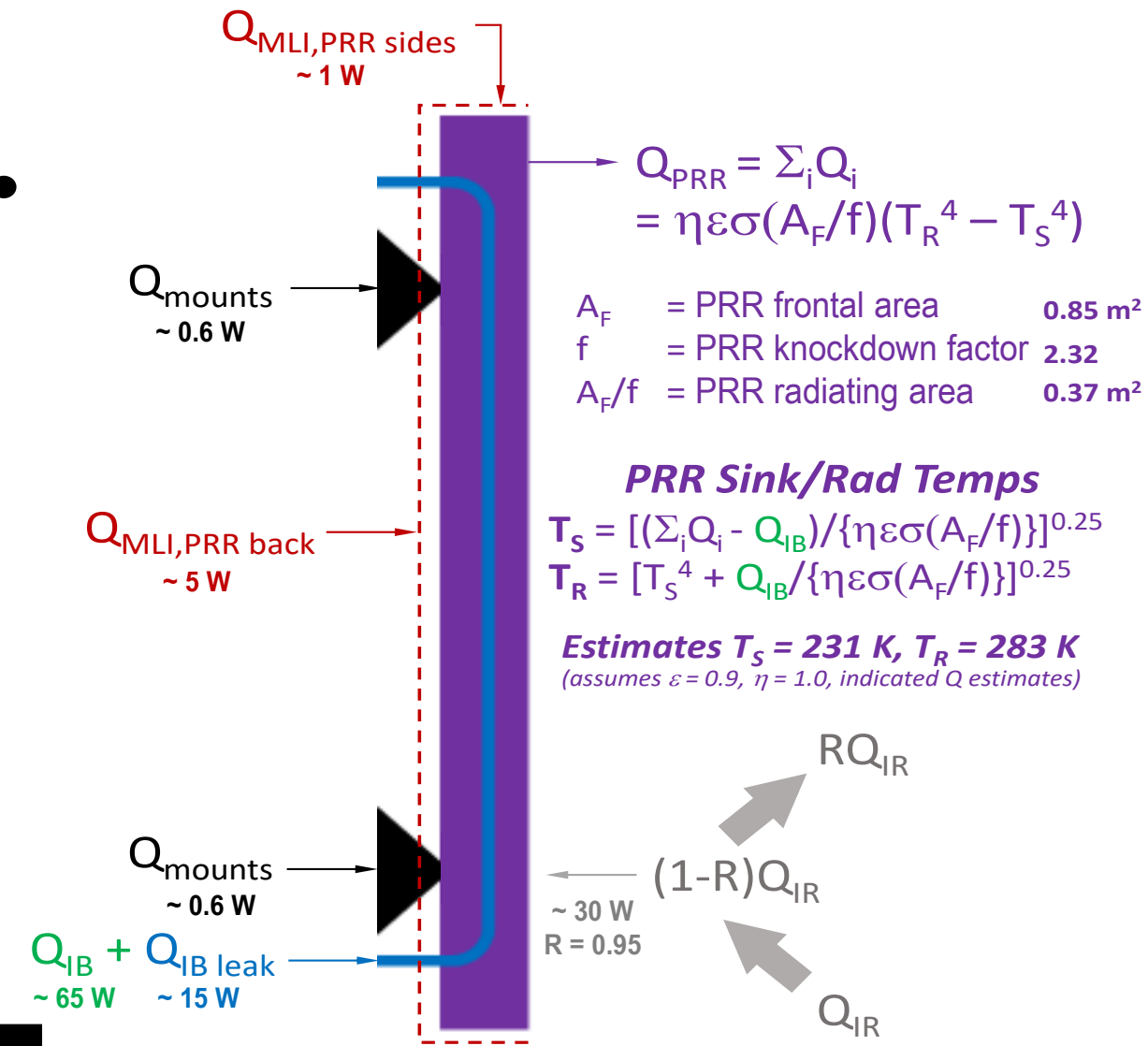
CONCLUSION: although target surface roughness for flight PRR reflectors is 0.05 μm (2 μ-in), this curve shows that ***PRR reflectors will likely have a specularity of ~ 1.0 if their surface roughness is 0.15 μm or less.*** As will be seen later, this fact will be important given the Acceptance Test results for the flight PRR reflectors.

Analysis

Outline

Controlled by JPL: R, f
Controlled by UCB: Everything except R, f





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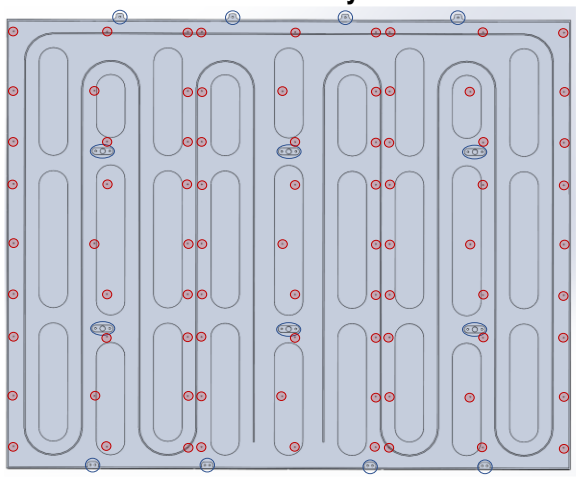
Analysis (cont'd)

Outline

Analysis Guidelines Provided to Quartus Engineering

Full-Scale PRR Structural Analysis Guidelines



Full-Scale PRR Radiator Plate (View of Back Surface)

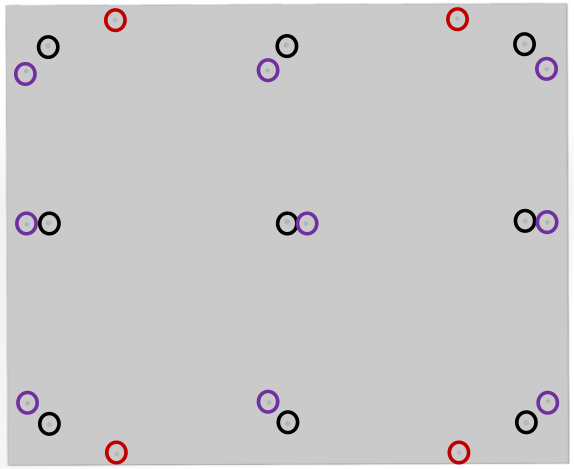
Assembly
- 24 rigid attach points to LuSEE-Night structure (see blue circles)
- 81 screw-on attach locations for 9 PRR reflectors (low-profile head M2.5 screws; see red circles)

Materials
- PRR radiator plate: 6061 Al
- PRR reflector: 6061 Al

Environment
- GEVS Proto-Qual 14.1 Grms

		Slope	Acceleration
FREQ(Hz)	ASD(G^2/Hz)	dB/OCT	Grms
20	0.026	*	*
50	0.160	5.97	1.58
800	0.160	0.00	11.07
2000	0.026	-5.97	**14.14**

Subscale PRR Structural Analysis Guidelines



Subscale PRR Radiator Plate (View of Back Surface)

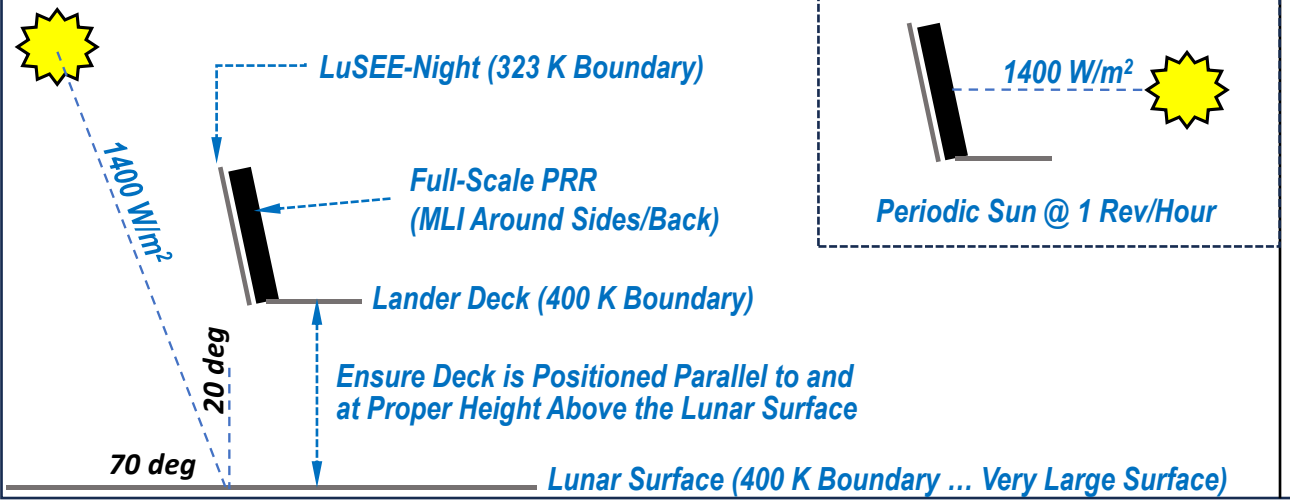
Assembly
- 9 screw-on attach locations to support structure (see black circles)
- 9 screw-on attach locations for each PRR reflector (low-profile head M2.5 screws; see purple circles)
- 4 old/unused PRR reflector to radiator attach points (see red circles)

Materials
- PRR radiator plate: 6061 Al
- PRR reflector: 6061 Al

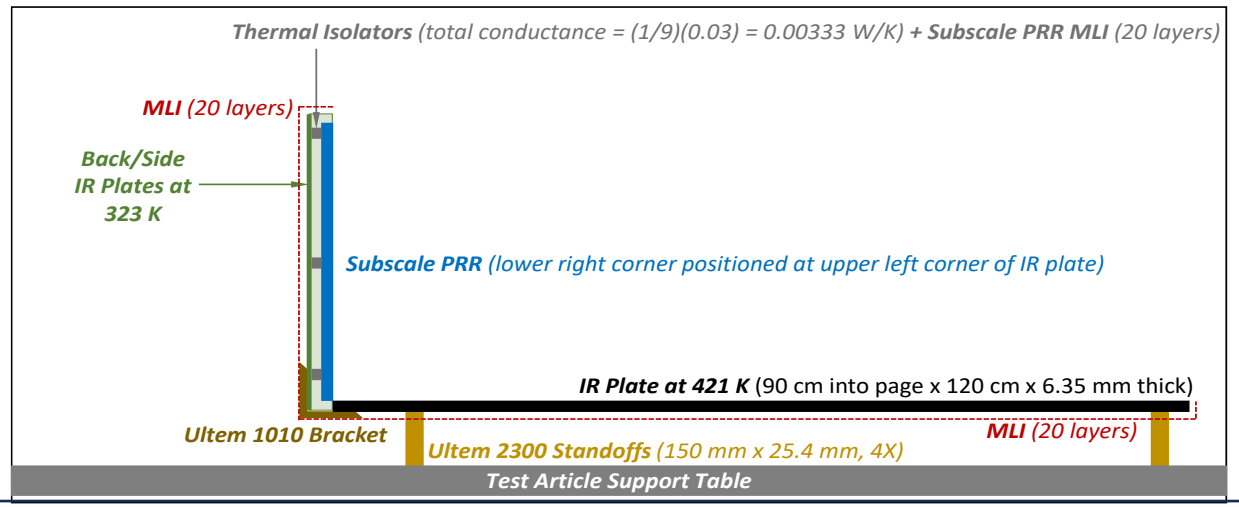
Environment
- GEVS Proto-Qual 14.1 Grms

Analytical Linkage to Full-Scale PRR
- See ***Testing*** section later in paper

Full-Scale PRR Thermal Analysis Guidelines



Subscale PRR Thermal Analysis Guidelines



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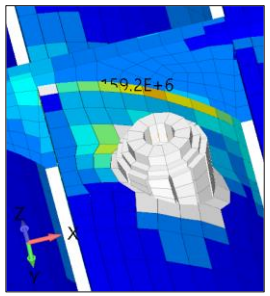
Analysis (cont'd)

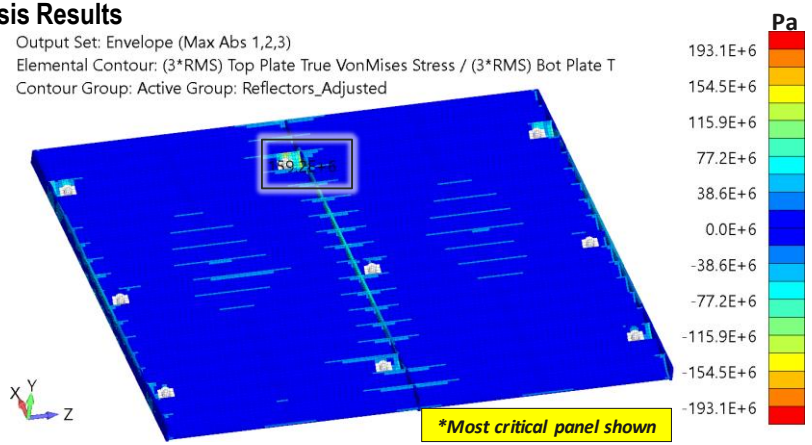
Outline

Analysis Results Provided by Quartus Engineering

Full-Scale PRR Structural Analysis Results



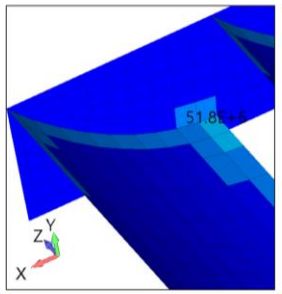
Critical region is the edge of the reflector near the constraint



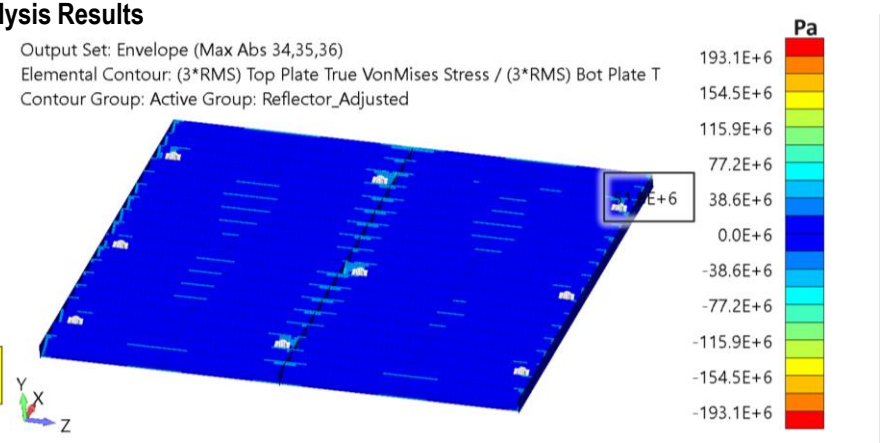
Center PRR Reflector Peak Stress in Y-Direction 159E6 Pa vs 241E6 Pa Allowable (FTY): Margin 0.21 (All Other Margins >> 1)

Group ID	Component	Material	Fty	Ftu	FS_y	FS_u	RV X - Max Stress	RV Y - Max Stress	RV Z - Max Stress	Random X MS_y	Random Y MS_y	Random Z MS_y	Random X MS_u	Random Y MS_u	Random Z MS_u
1	Reflectors	AL6061-T6	241E+6	290E+6	1.25	1.40	45.8E+6	159.2E+6	34.2E+6	3.21	0.21	4.65	3.51	0.30	5.05

Subscale PRR Structural Analysis Results



Critical region is the bottom edge of the reflector blade near the rib



PRR Reflector Peak Stress in Y-Direction 52E6 Pa vs 241E6 Pa Allowable: All Margins >> 1

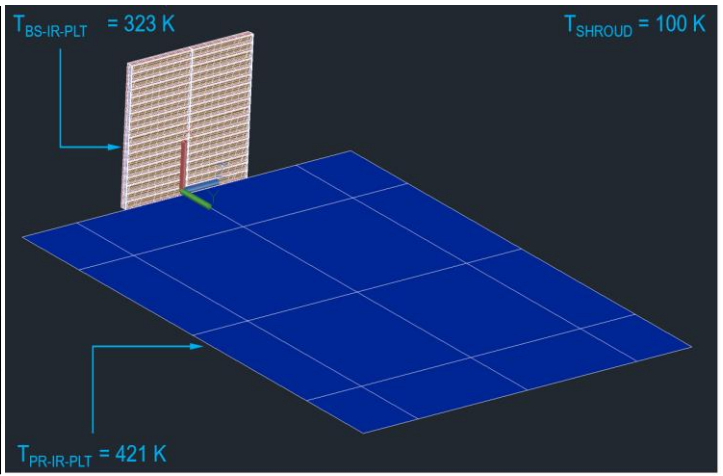
Group ID	Component	Material	Fty	Ftu	FS_y	FS_u	RV X - Max Stress	RV Y - Max Stress	RV Z - Max Stress	Random X MS_y	Random Y MS_y	Random Z MS_y	Random X MS_u	Random Y MS_u	Random Z MS_u
1	Reflectors	AL6061-T6	241E+6	290E+6	1.25	1.40	31.3E+6	51.8E+6	32.6E+6	5.17	2.73	4.93	5.61	2.99	5.35

Full-Scale PRR Thermal Analysis Results

Analysis Results	Hot Op	Sink Temp	Cold Op	Transit 1 Rev/Hr
Radiator Min (K)	268	223	172	194
Radiator Max (K)	269	224	172	197
Reflector Min (K)	268	223	171	195
Reflector Max (K)	272	229	172	209
Model Inputs				
Lunar Surface (K)	400	400	100	n/a
Lander Deck (K)	323	323	100	273
Instr. Structure (K)	323	323	253	273
Heat Load (W)	80	15.8	12	0
Radiator Tilt	0	0	0	12
PRR Refl. Emissivity	0.05	0.05	0.05	0.05

Subscale PRR Thermal Analysis Results

Analysis Results	Hot Op	Sink Temp
Radiator Avg (K)	285	226
Model Inputs		
Primary IR Plate (K)	421	421
TVAC Shroud (K)	100	100
B/S IR Plate (K)	323	323
Heat Load (W)	10.2	1.7
Radiator Tilt	0	0
PRR Refl. Emissivity	0.05	0.05



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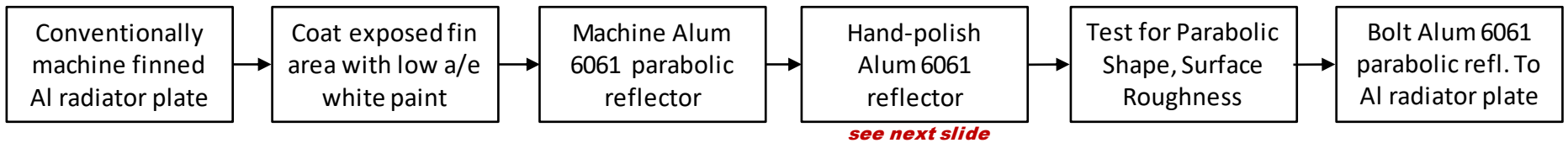
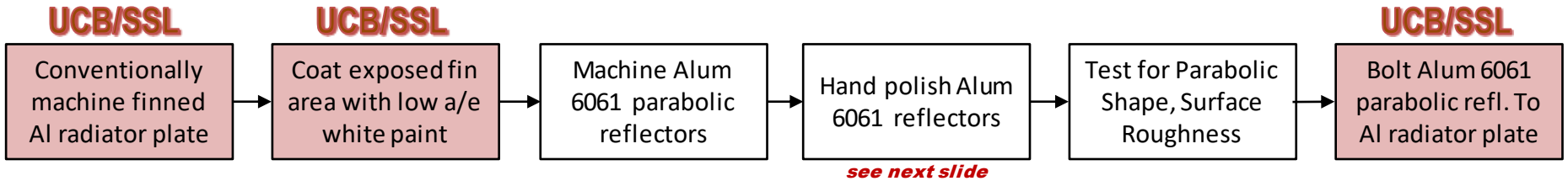
Fabrication

Outline

Subscale PRR Fabrication (JPL Fully Responsible for Subscale PRR Fabrication)



Flight PRR Fabrication (JPL Responsible for Flight PRR Reflector Fabrication Only)



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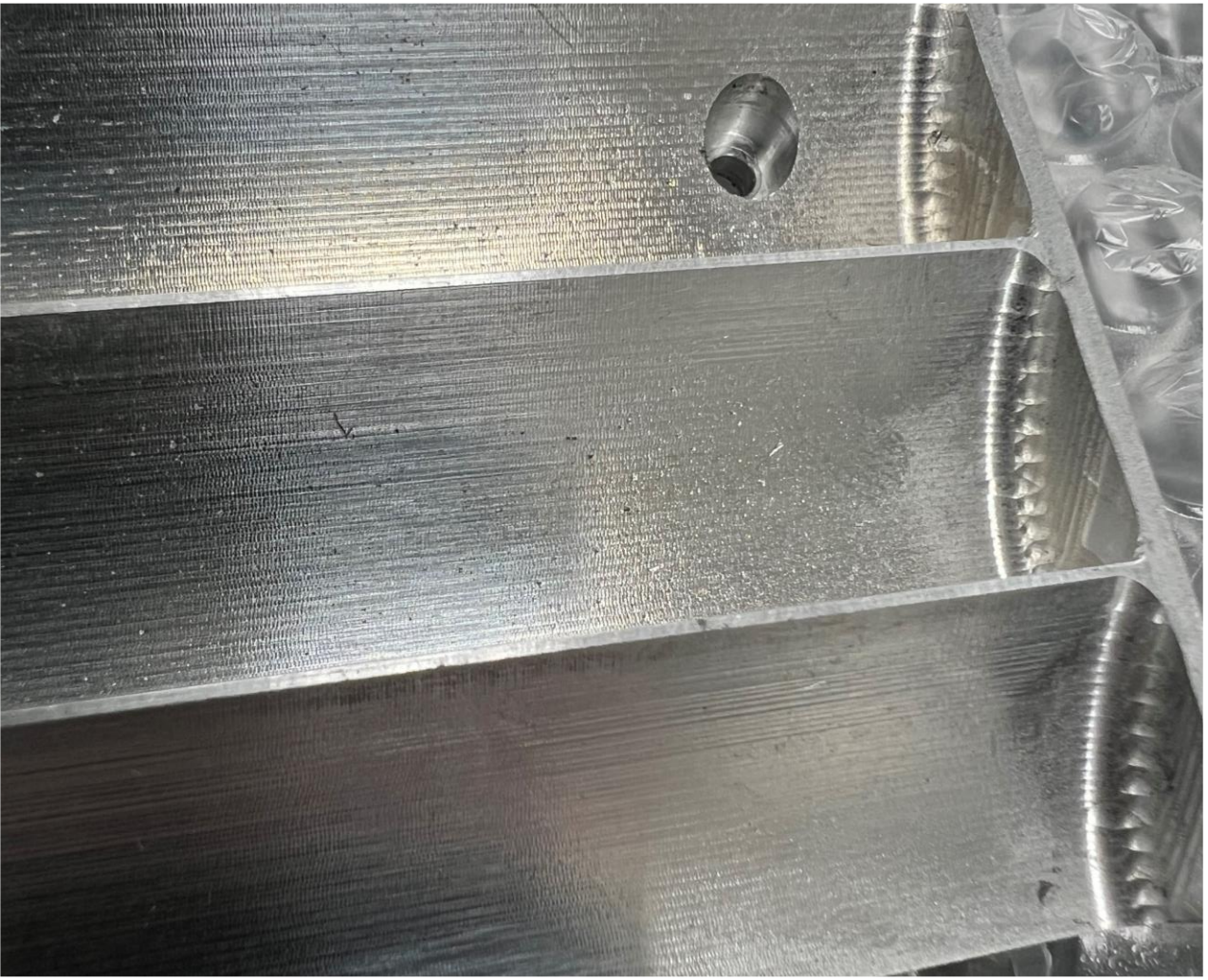
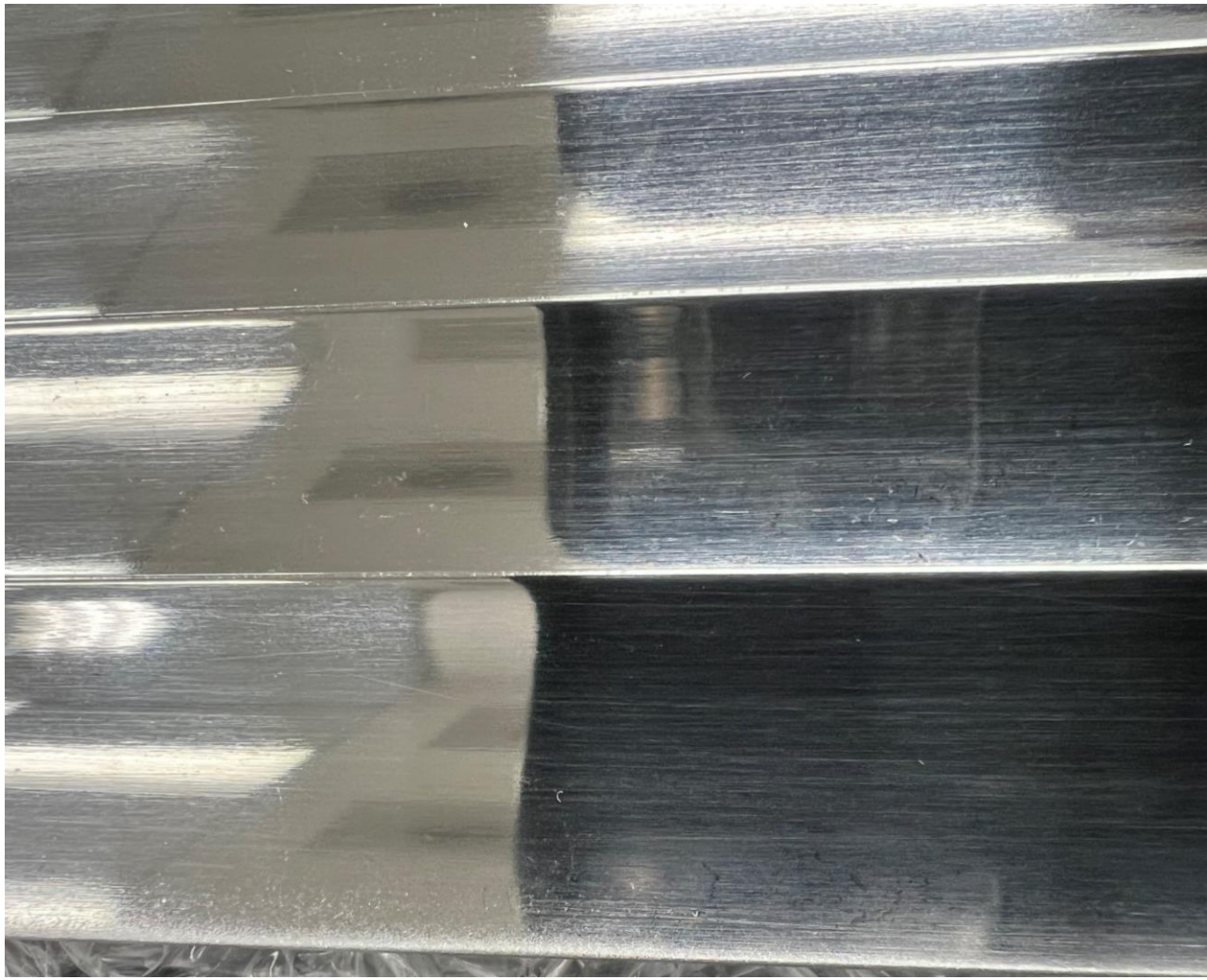
Fabrication

Outline

Completed PRR Reflector: *Unpolished Surfaces*



Completed PRR Reflector: *Polished Surfaces*



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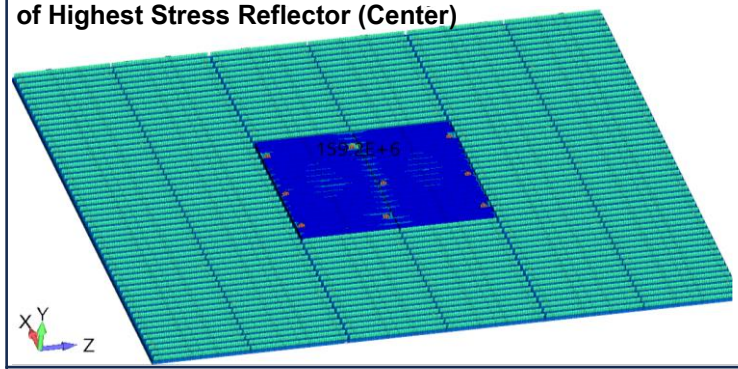
Testing

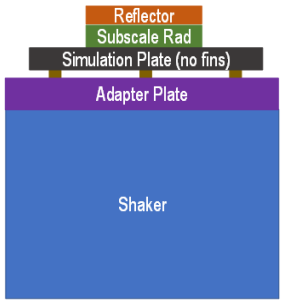
Outline

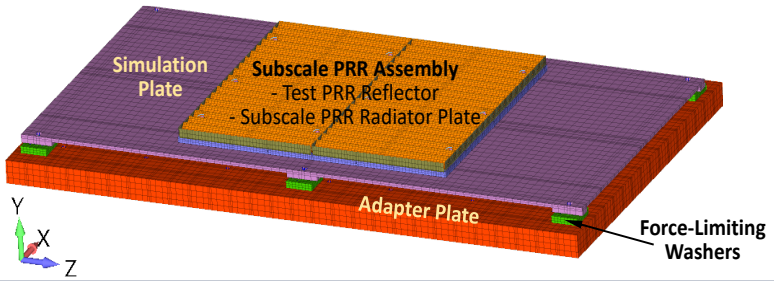
Subscale PRR Random Vibe (RV) Test Plan

Goal → Match Vibe Environment of Highest Stress Reflector (Center)



Approach → Mount Subscale PRR on Simulation Plate, RV Test in Y-Direction Only





Details → Test Sequence, Low Level Survey, GEVS Protoflight Definition

Test Sequence

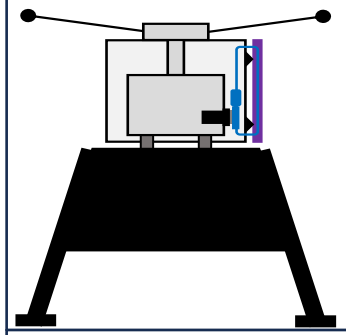
1. Force Sensor Cal. Run #1
2. Force Sensor Cal. Run #2
3. Pre-RV Sig. Survey (60 sec)
4. -12 dB RV (30 sec)
5. -6 dB RV (30 sec)
6. -3 dB RV (30 sec)
7. Pre-0 dB RV Sig. Survey (60 sec)
8. Full Level 0 dB RV (**120 sec***)
9. Post-RV Sig. Survey

***exceeded GEVS Protoflight duration**

Frequency, Hz	Survey Level
20 – 2000	0.0001 g^2/Hz
Overall grms	0.445 grms
Duration:	1 minutes per survey
Frequency	**GEVS Protoflight**
20 Hz	0.026 g^2/Hz
50 Hz	0.16 g^2/Hz
800 Hz	0.16 g^2/Hz
2000 Hz	0.026 g^2/Hz
Overall	14.1 grms
Duration	60 sec

Subscale PRR Thermal Vacuum (TVAC) Test Plan

Goal → Measure PRR Sink Temp (TS) at Zero Load, PRR Rad Temp (TR) at Flight-Like Load



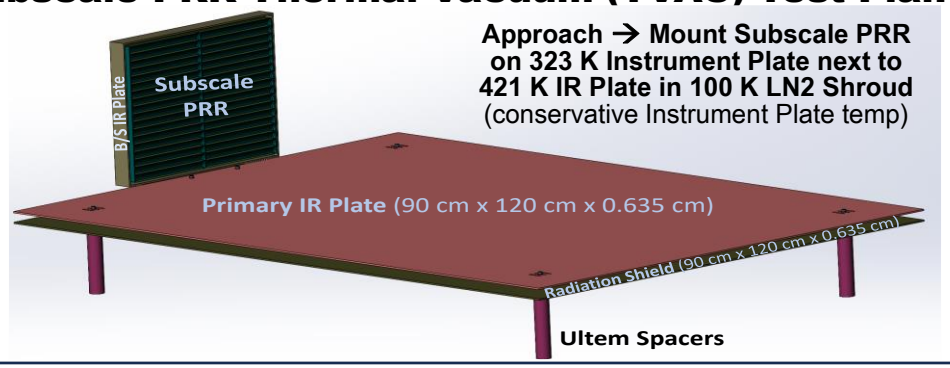
Heat Load	Flight PRR	Subscale PRR
Instrument	65 W	65/9 = 7.2 W*
Parasitics 1	15 W	15/9 = 1.7 W*
Parasitics 2	8 W	8/9 = 0.9 W**
Environment	30 W	30/9 = 3.3 W**
TOTAL	113 W	113/9 = 12.6 W

* *Q from test heaters*
** *Q from test plates*

Flight/Subscale PRR Excel Model

T_S = 231 K (-42 °C)
T_R = 283 K (+10 °C)

Approach → Mount Subscale PRR on 323 K Instrument Plate next to 421 K IR Plate in 100 K LN2 Shroud (conservative Instrument Plate temp)



Details → Original 3-6 Cycle Test Abbreviated to 1 Cycle Due to Project Cost Constraints (Per/Cycle Values Below)

$T_{IR\ Plate}$ = 421 K
$T_{Instrument\ Plate}$ = 323 K
$T_{LN2\ Shroud}$ = 100 K
$Q_{TS\ Measurement}$ = 1.7 W*
$Q_{TR\ Measurement}$ = 11.9 W**

* revised to 0.0 W during test
** revised to 8.1 W during test

Flight PRR Reflector Acceptance Test (AT) Plan

Original Plan

Temp. Extreme	***(TE)***	*TE testing → 3 cycles from 90 K to 330 K in Bemco (non-TVAC) test chamber*
Reflectance*	***(RF)***	*Before/after TE, RF measured on a flat side surface (RF ≥ 0.97, ε ≤ 0.03, +/- 0.02)*
Specularity*	***(SP)***	*After each RF, SP measured on a flat side surface (SP ≥ 0.96, +/- 0.03)*
Surface Shape*	***(SS)***	*After each SP, SS measured using TBD procedure (needed only if parts are 3DP)*
Elec. Resistance*	***(ER)***	*After each SS, ER measured from bottom right blade to top left mount (ER < 1 kΩ)*
Adherence*	***(AD)***	*AD assessed after TE-cycled AKT test coupons (must pass tape AD test)*

* *RF, SP tests not required if AKT used (AKT properties already measured by JPL)*
** *SS test not required as parts are conventionally machined (CM) not 3D-printed (3DP)*
*** *ER test significantly more time consuming/costly if AKT is used (more test points required)*
**** *AD test eliminated if reflector hand polishing successful and AKT use unnecessary*

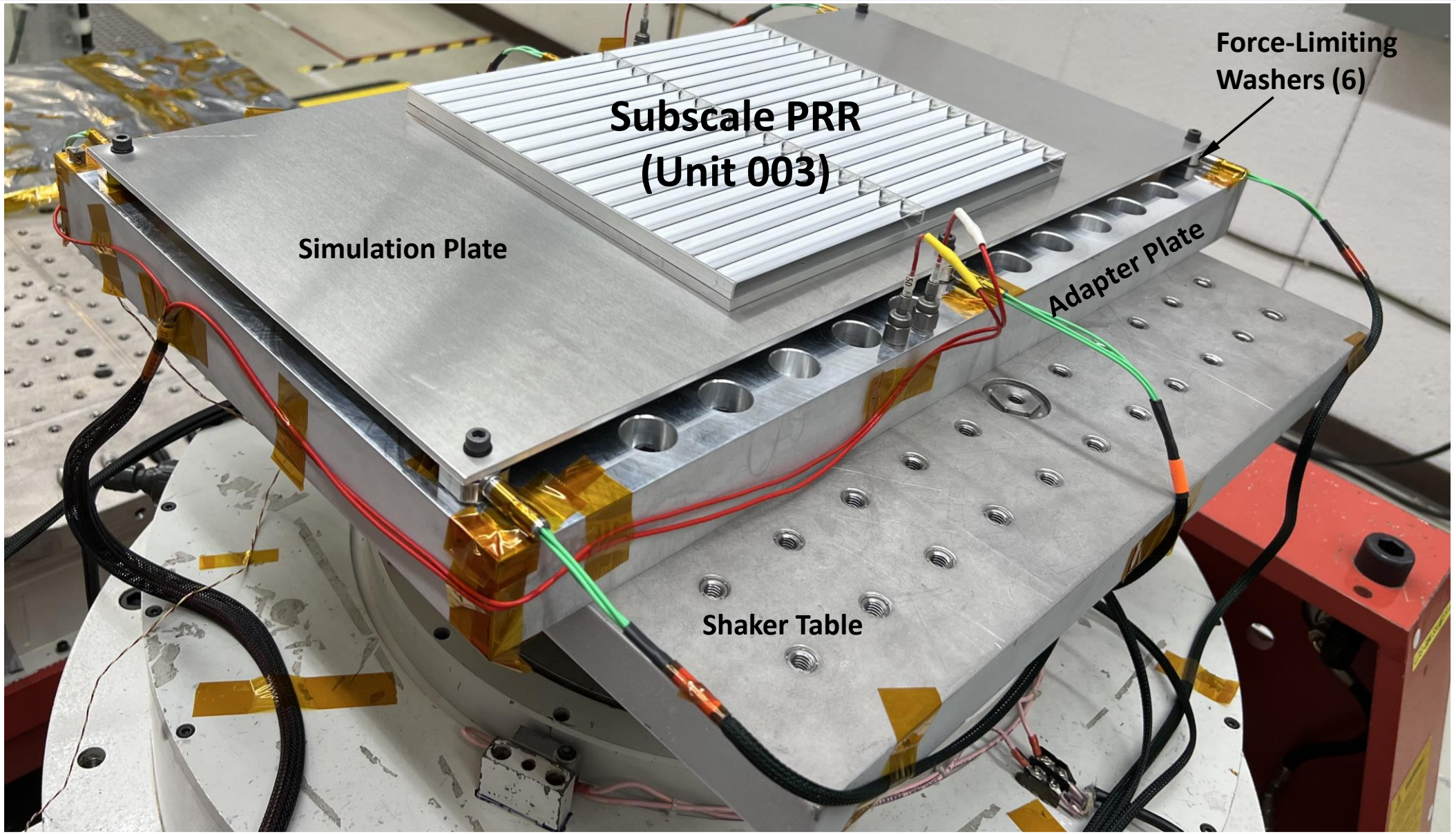
Revised Plan*

- **TE test eliminated** as 6061-Al unaffected by temperature cycling
- **RF, SP, SS tests modified** to inspection by JPL QA that will measure surface roughness and shape and compare to RV/TVAC test unit values
- **ER test eliminated** as 6061-Al is highly electrically conductive
- **AD test eliminated due** to 6061-Al polishing process (AKT unnecessary)

*project cost constraints were an additional issue in revising the scope of Acceptance Testing

Testing (cont'd)

Outline



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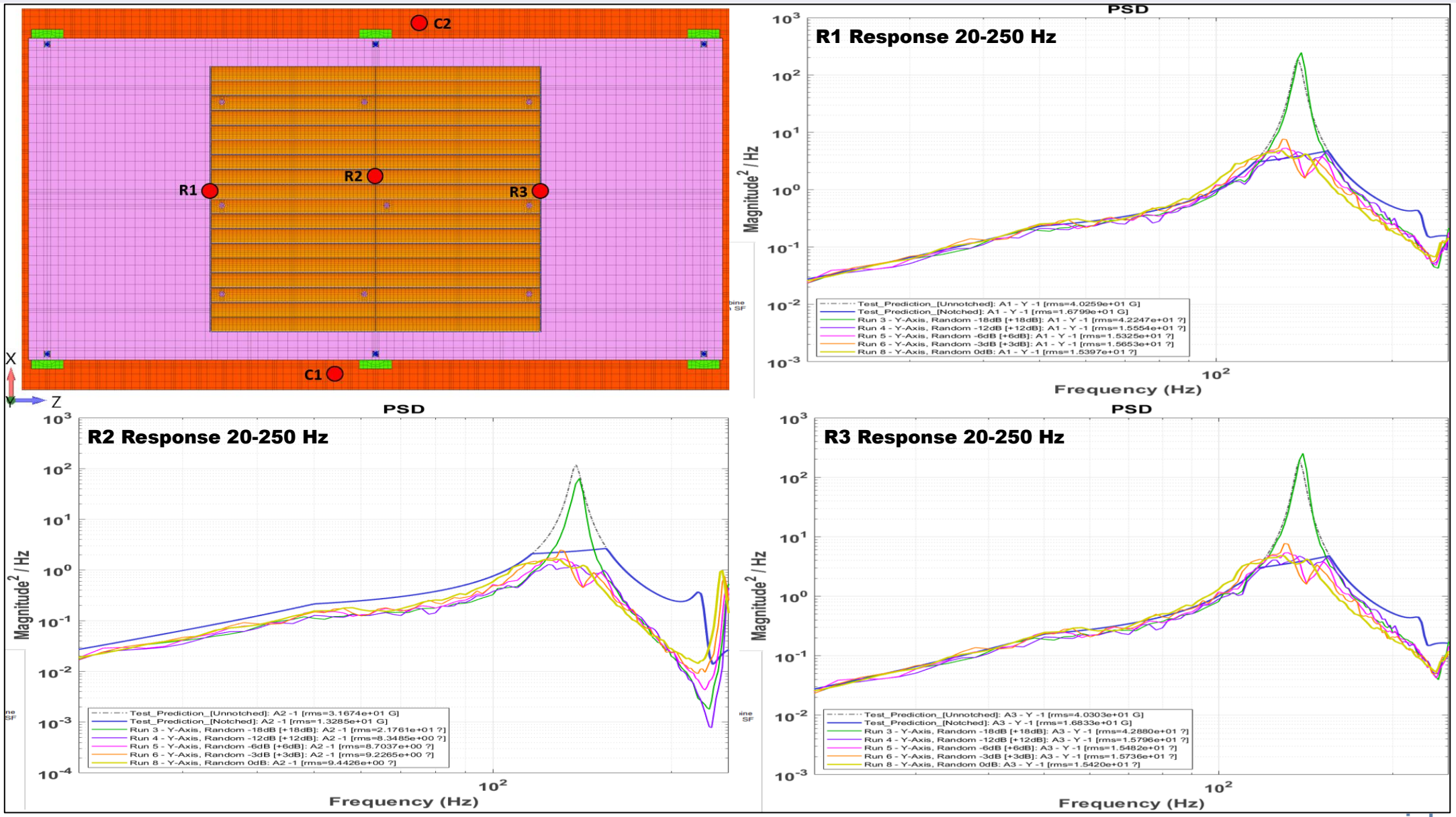
Testing (cont'd)

Outline



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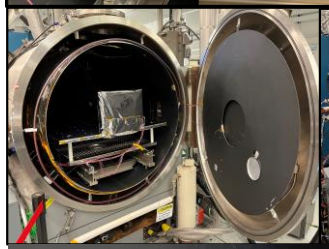
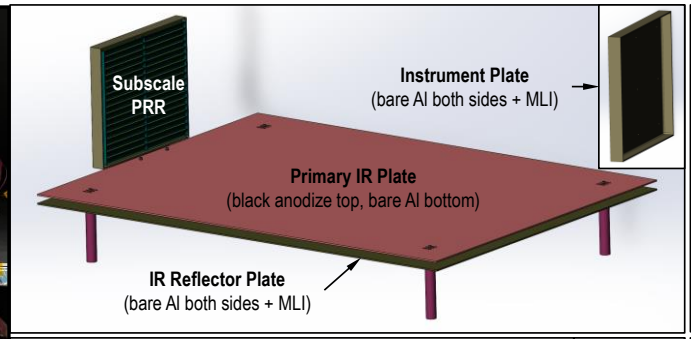
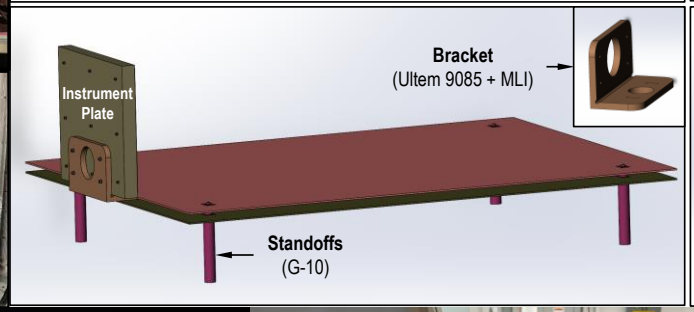
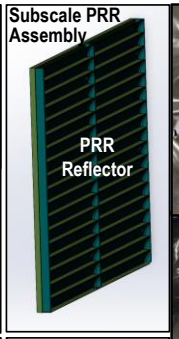
Testing (cont'd)

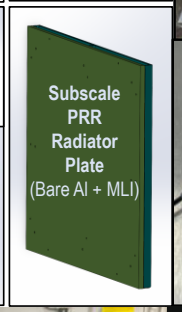
Outline

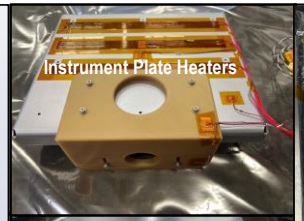


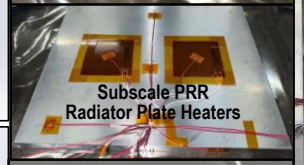


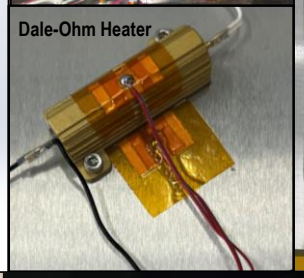


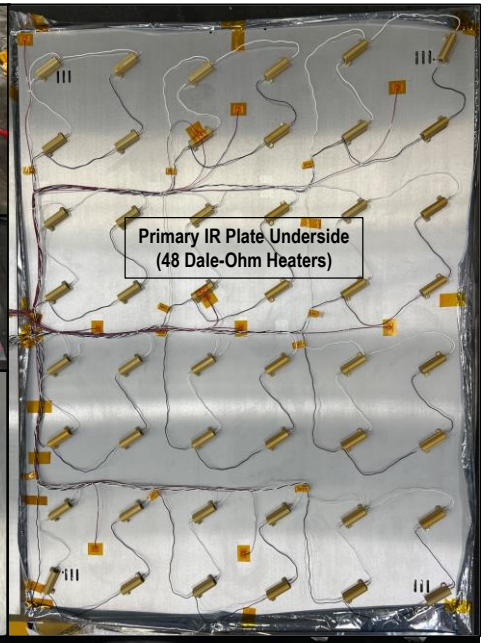


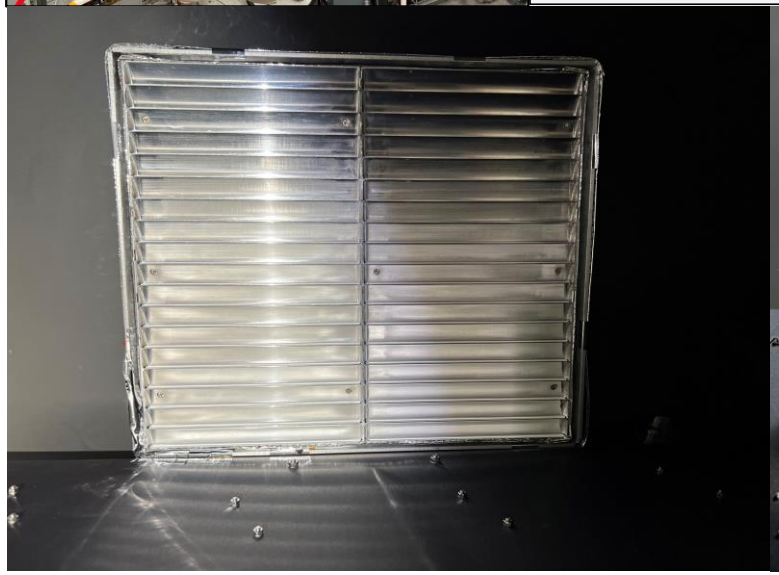


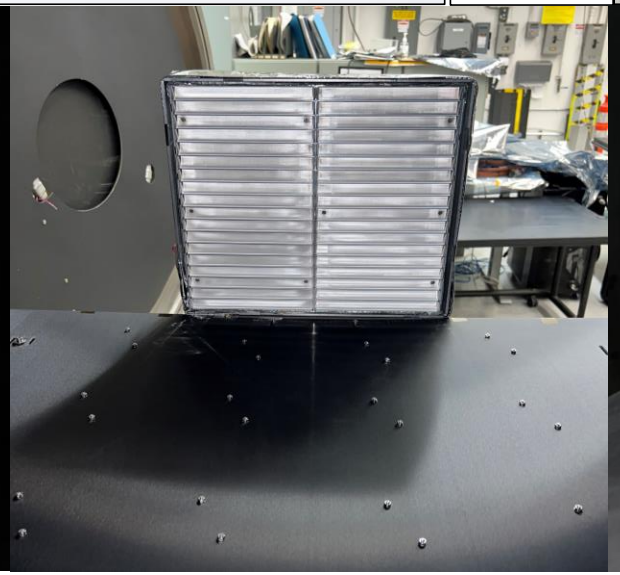












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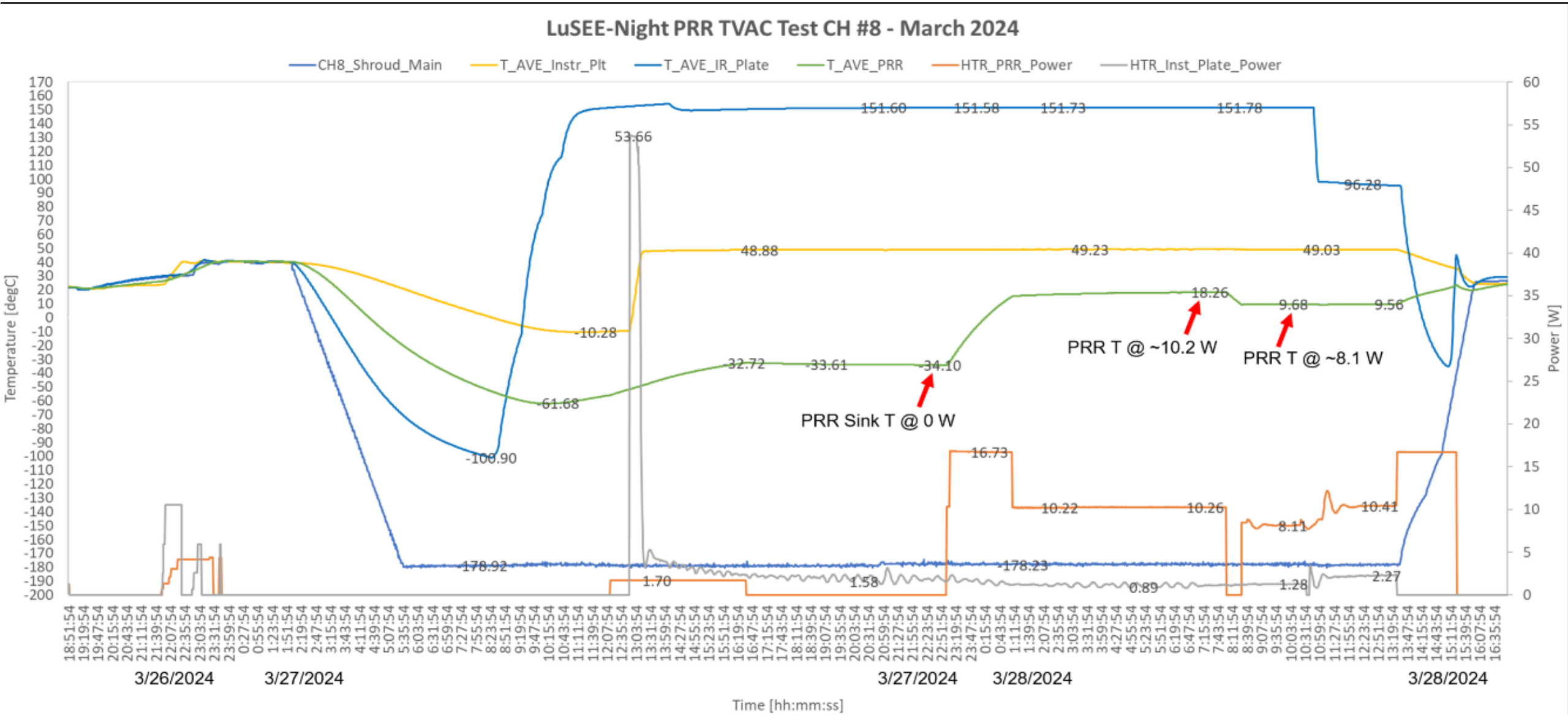
Testing (cont'd)

Outline



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Testing (cont'd)

Outline

Flight PRR Reflectors: *Acceptance Test Results*

- **Surface Roughness (SR)** *… surface roughness of reflecting side to be less than 0.05 μm Ra*
- **Surface Shape (SS)** *… deviation from perfect half-parabola to be less than +/- 0.125 mm*
- **Hole Assessment (HA)** *… location, size of nine through holes matches LuSEE-Night MICD*
- **Unit Dimensions (UD)** *… reflector width, height, thickness matches LuSEE-Night MICD*

Unit	Status	Manufacturer	SR (μm)	SS (uncompliant/total)	HA	UD
SN001	non-flight, no polish	JPL	0.148**	241/1190	matches LN MICD	matches LN MICD
SN003*	non-flight, polished	George Spencer	0.064**	004/1190	matches LN MICD	matches LN MICD
SN004	Flight, polished	George Spencer	0.073**	000/1190	matches LN MICD	matches LN MICD
SN005	Flight, polished	George Spencer	0.106**	006/1190	matches LN MICD	matches LN MICD
SN006	Flight, polished	George Spencer	0.071**	000/1190	matches LN MICD	matches LN MICD
SN007	Flight, polished	George Spencer	0.095**	000/1190	matches LN MICD	matches LN MICD
SN008	Flight, polished	George Spencer	0.093**	003/1190	matches LN MICD	matches LN MICD
SN009	Flight, polished	George Spencer	0.080**	000/1190	matches LN MICD	matches LN MICD
SN010	Flight, polished	George Spencer	0.153**	000/1190	matches LN MICD	matches LN MICD
SN011	Flight, polished	George Spencer	0.081**	004/1190	matches LN MICD	matches LN MICD
SN012	Flight, polished	George Spencer	0.140**	000/1190	matches LN MICD	matches LN MICD
SN013	Flight, polished	George Spencer	0.126**	000/1190	matches LN MICD	matches LN MICD

* RV/TVAC Test Unit

** greater than 0.05 μm Ra but will still perform as required based on ***Slide 12***

Summary

Outline

- Flight PRR for LuSEE-Night conceptualized/designed/analyzed
- Analysis indicated that < 231 K sink temperature goal achievable
- Subscale PRR (subscale radiator plate + PRR reflector) designed/built
- Subscale PRR RV test assembly designed/built
- Subscale PRR TVAC test assembly design/built
- Subscale PRR RV test completed successfully
  - ***notching at 1st mode frequency of 140 Hz***
  - ***notching should be implemented in flight system RV test***
- Subscale PRR TVAC test completed successfully
  - ***measured sink temperature of 239 K fell just short of 231 K goal***
  - ***impact to LuSEE-Night expected to be easily tolerable (click here)***
- Flight PRR reflectors were shipped to JPL by GSC in late May 2024
- Acceptance tests completed in one week followed by precision cleaning
- ***PRR Reflectors*** arrived at UCB/SSL (LuSEE-Night) on 7 June 2024
- Consulting support for LuSEE-Night integration to end of FY24
  - ***depends on availability of funding***
- Project to conclude at the end of FY24

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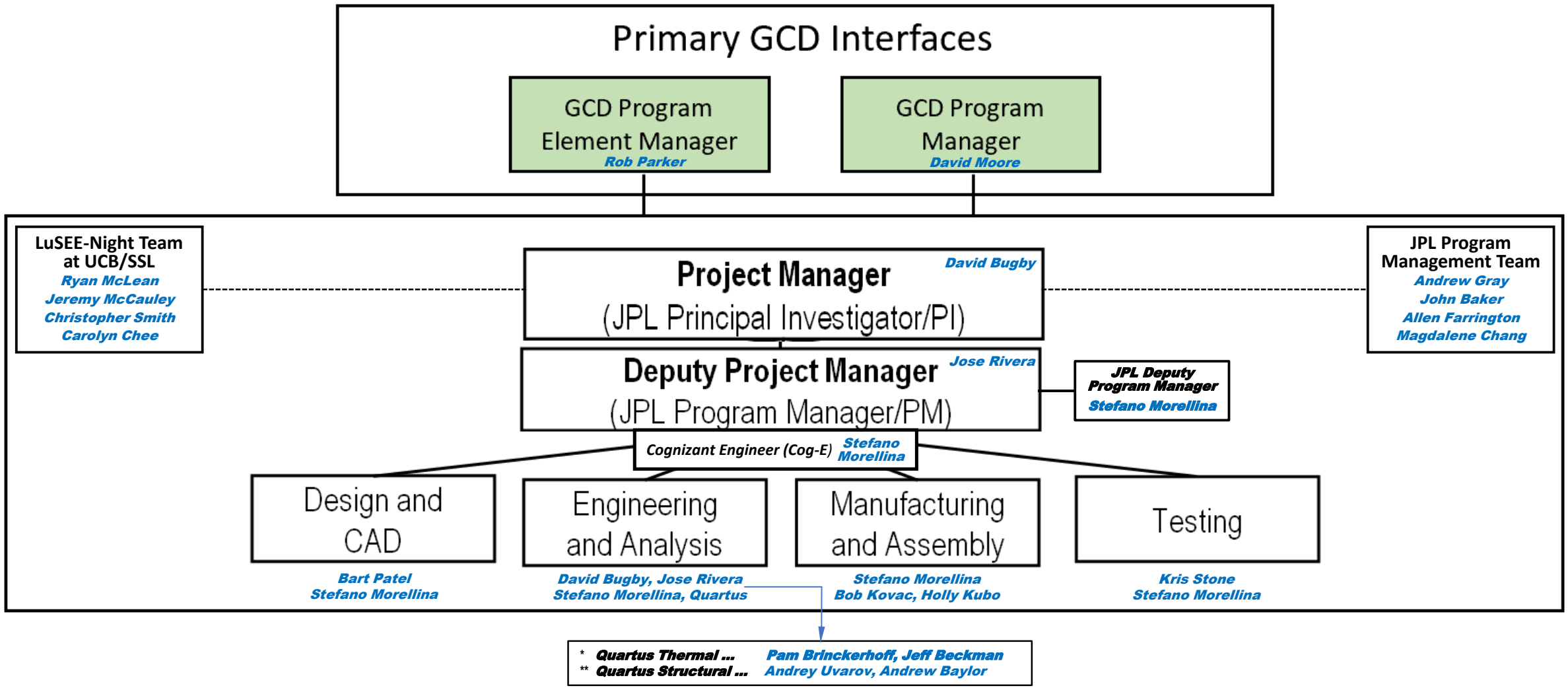
Acknowledgments

Outline

The authors would like to acknowledge the significant contributions of those listed below. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).



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