# The Design and Testing of Large Cryogenic Space Radiators for the James Webb Space Telescope


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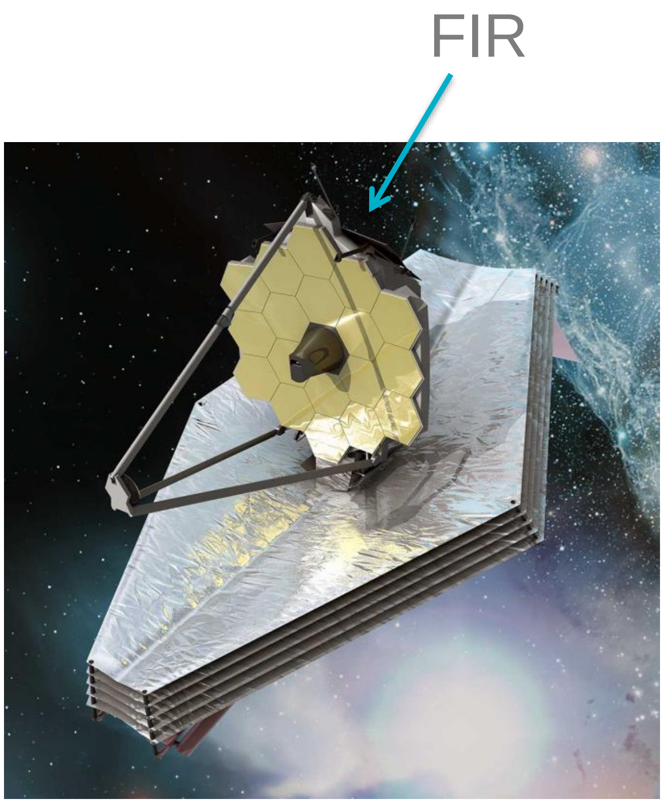
# Overview

- Fixed ISIM Radiator (FIR) Design
- FIR Thermal Vacuum Testing
- Conclusion

# James Webb Space Telescope (JWST)

- JWST has four cryogenic science instruments:
  - MIRI
    - Detector cooled to 4K via cryocooler
  - FGS/NIRISS
    - Radiatively cooled to ~40K via Aft Deployable Radiators
  - NIRCam
    - Radiatively cooled to ~40K via one Fixed ISIM Radiator
  - NIRSpec
    - Radiatively cooled to ~40K via two Fixed ISIM Radiators
- The FIR sit behind the primary mirrors with a constant view to deep space

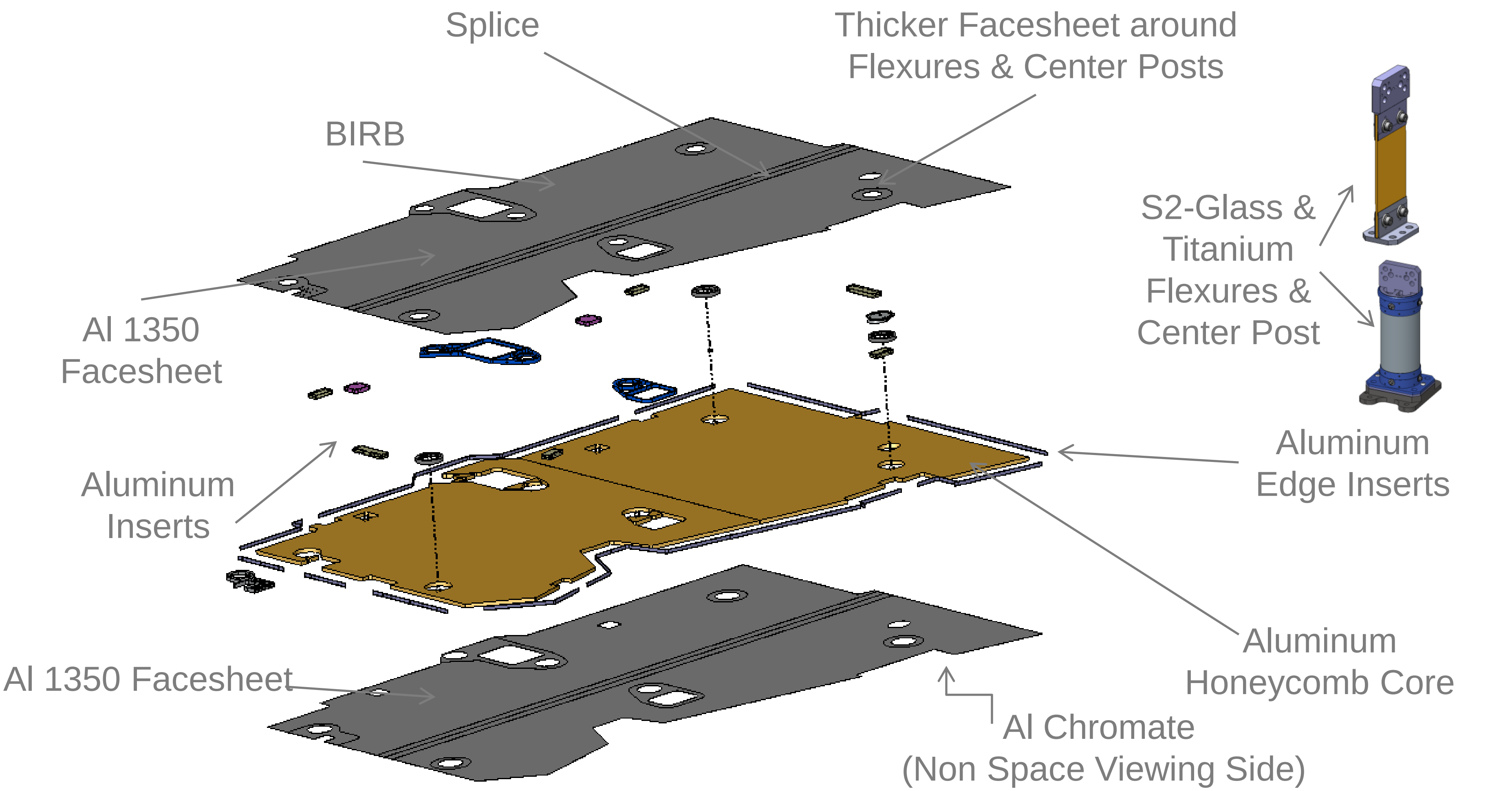


# Fixed ISIM Radiator (FIR) Design

- The FIR consist of three separate radiators:
  - NIRCam Radiator
    - Capacity: 453 mw at 39.6K
  - NIRSpec OA Radiator
    - Capacity: 223 mW at 39.2K
  - NIRSpec FPA Radiator
    - Capacity: 180 mW at 37.5K

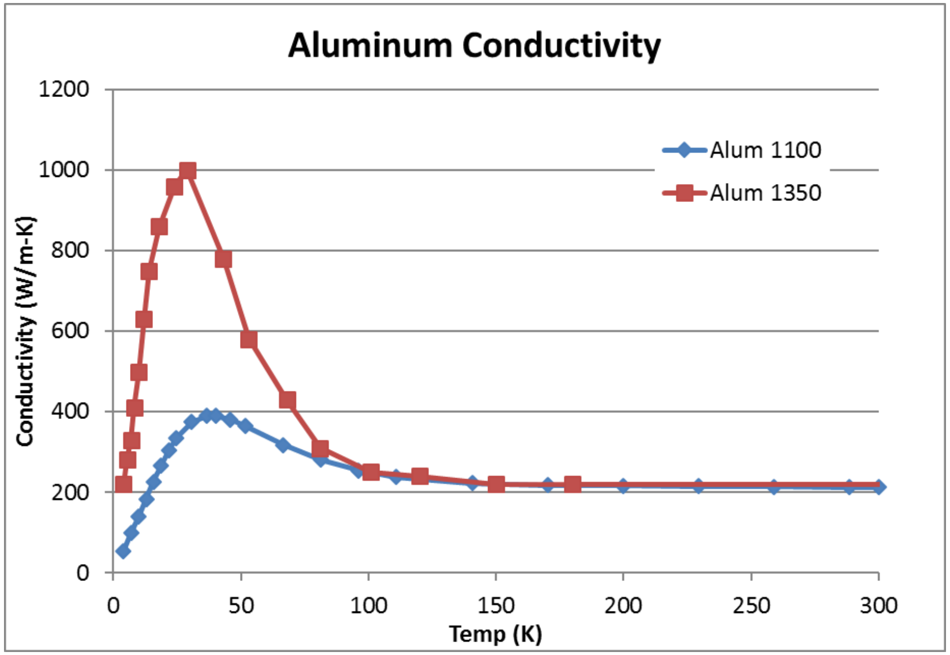
FIR Integrated on JWST

# FIR Panel Construction



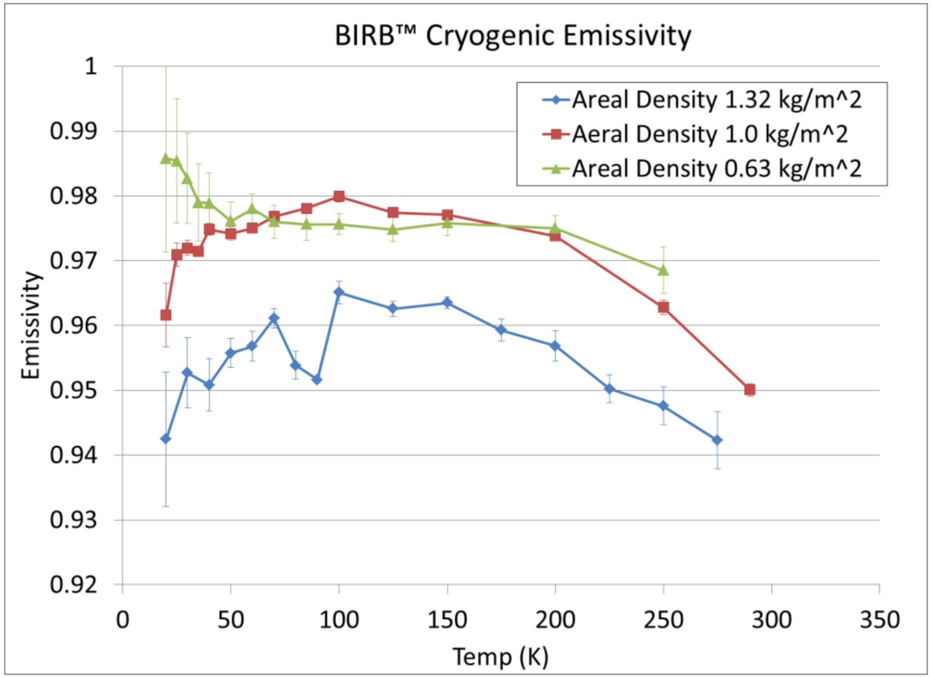
# FIR Aluminum 1350 Overview

- Aluminum 1350 selected for FIR facesheets
  - Aluminum 1350 is at least 99.5% pure
    - Flight material was 99.6% pure
  - Improved cryogenic thermal conductivity compared to aluminum 1100
  - Available in large sheets
- Thermal conductivity testing at cryogenic temperatures performed at GSFC
  - Approx. 905 W/m-K at 38K
- Radiator capacity increased 4 to 6% by using aluminum 1350



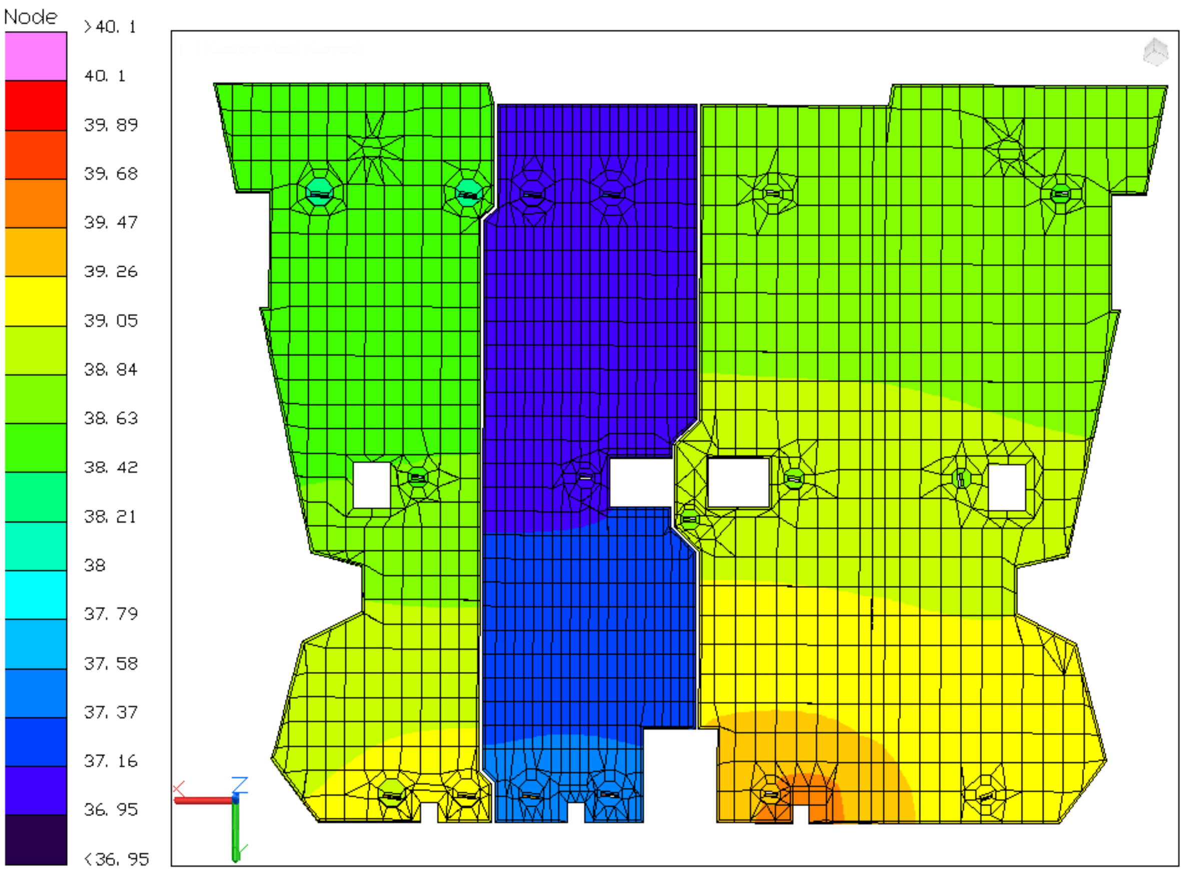
# FIR Ball Infrared Black (BIRB) Overview

- BIRB is a black surface coating with high emissivity at cryogenic temperatures
- BIRB can be damaged by direct contact, yet is clean enough for use around sensitive optics
- Heritage flight programs include the Spitzer Space Telescope
- Nominal value of 0.96 with 0.02 uncertainty used for analysis at 40K
- Samples of the flight application were tested as GSFC for cryogenic emissivity at 40K:
  – NIRCam: 0.97
  – NIRSpec OA: 0.98
  – NIRSpec FPA: 0.96



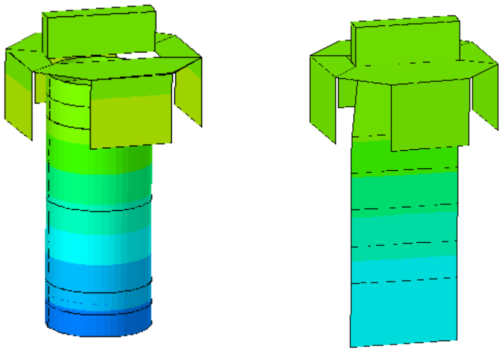
# FIR Final Performance

| NIRSpec OA Fin Efficiency: | NIRSpec FPA Fin Efficiency: | NIRCam Fin Efficiency: |
|---|---|---|
| 96.3% | 97.5% | 94.9% |




All fin efficiencies are greater than 94%

Largest panel gradient is 0.8K in NIRCam



Center Post

Flexure

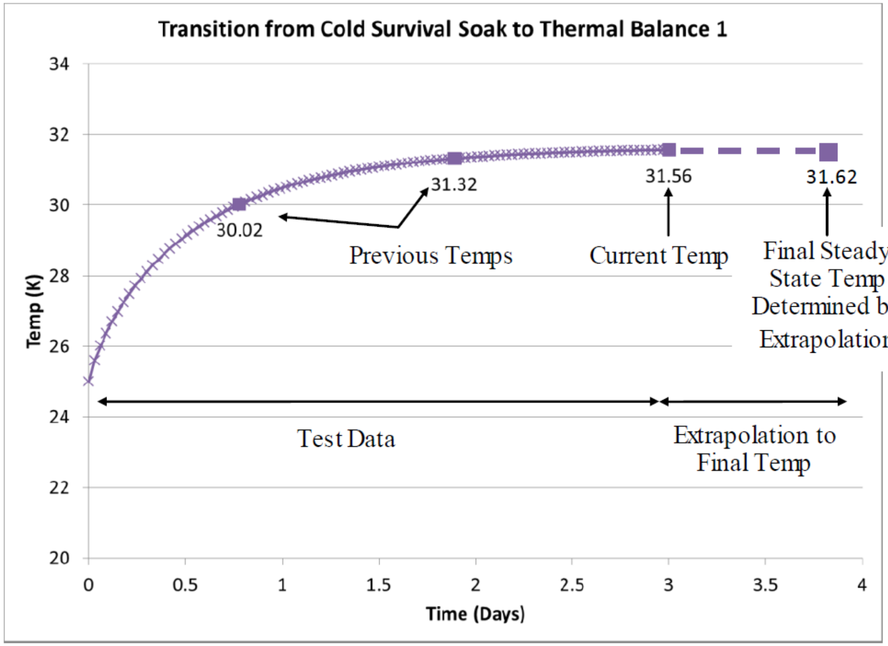
# FIR Thermal Vacuum Testing

- The FIR were subjected to a thermal balance test to verify performance
- The Ground Support Equipment (GSE) is designed to safely take the FIR to an environment which closely mimics deep space
- Once the hardware reaches the desired temperature, no environmental changes are made to allow it to reach steady state conditions

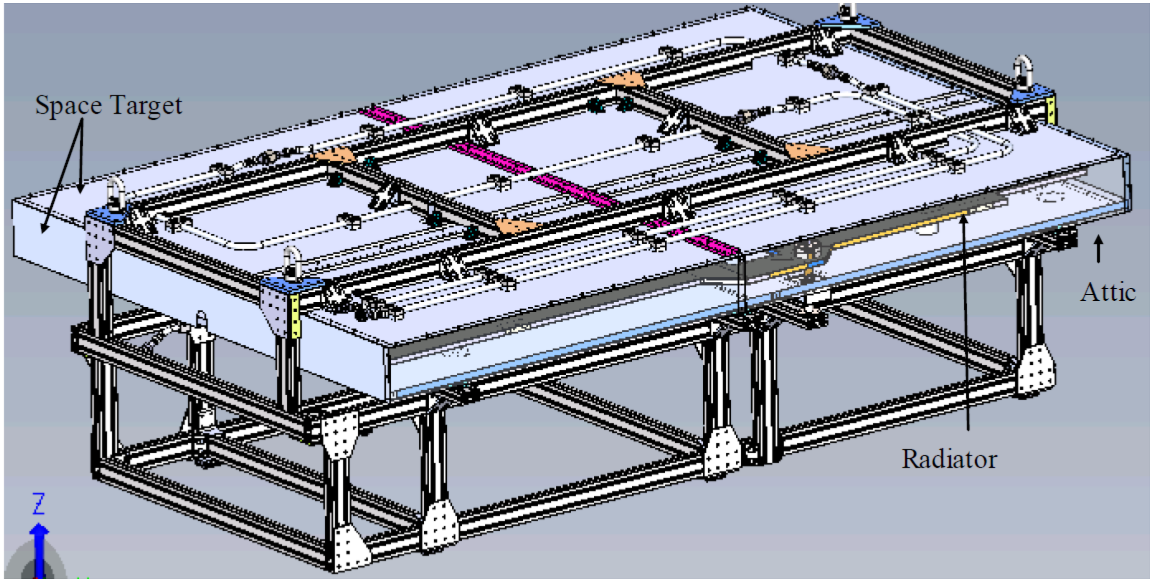
**Thermal Vacuum Chamber**

# FIR Thermal Vacuum Testing

- For the FIR, the declaration of steady state conditions occurred once the radiators had less than 1.5% of their remaining radiating capacity remaining
  - Determined by extrapolating the current temperatures, and comparing the current radiator capacity to the extrapolated radiator capacity
- Two thermal balance points were tested:
  - “Cold” with lowest possible heat load applied to radiators
  - “Hot” with radiators at hottest operational temperature
- Test GSE was designed to minimize uncertainty for accurate correlation
  - Thermal model is correlated to test predicts, then used to verify final flight performance

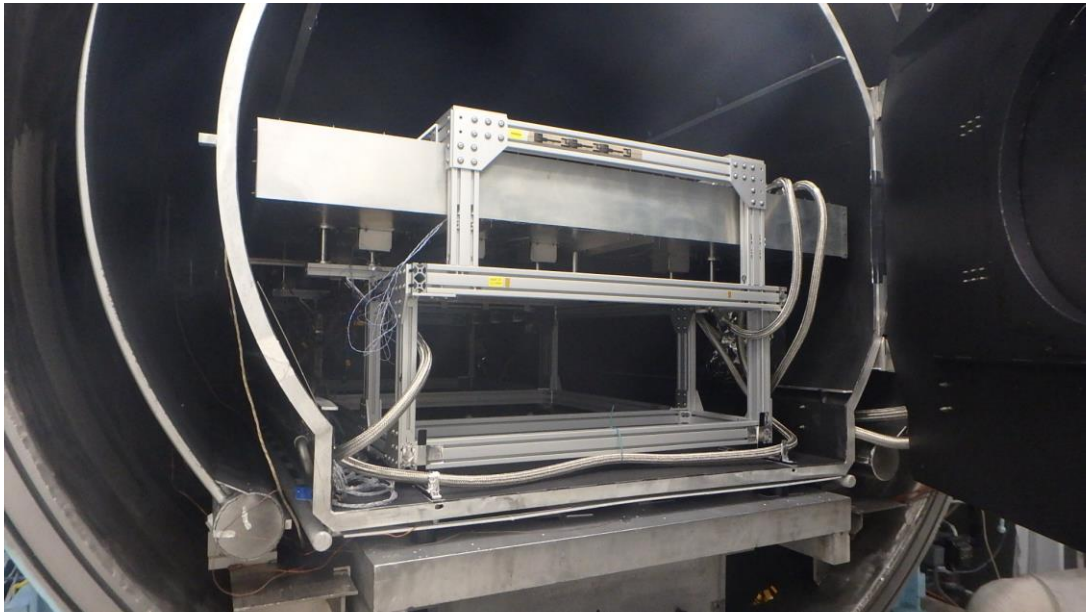


# Thermal Vacuum Testing Ground Support Equipment (GSE) Design



# Thermal Vacuum Testing Ground Support Equipment (GSE) Design

- Ball Rambo chamber previously fitted with a helium shroud
  - For previous JWST testing
- Helium shroud includes an auxiliary plumbing loop
  - Used to plumb the space target to ensure space target was extremely cold



# Space Background Simulator (SBS)

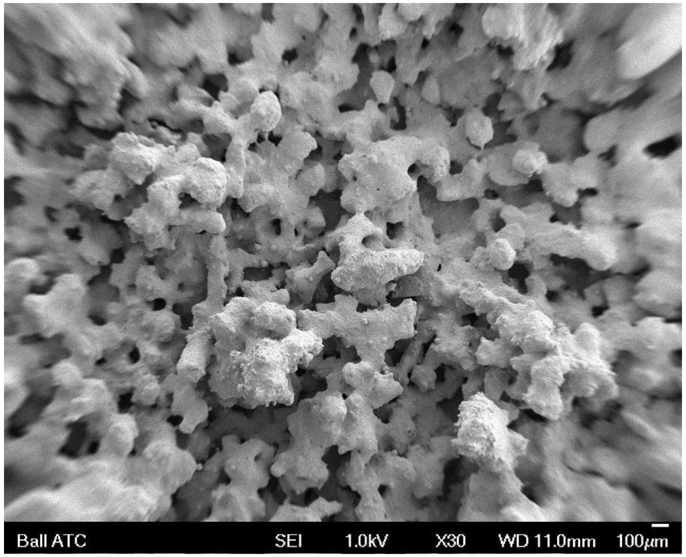
- Space Background Simulator (SBS) is designed to mimic deep space as closely as possible
  - The same emissivity uncertainty on a surface finish with a lower emissivity produces a higher test uncertainty than that same uncertainty on a surface finish with a higher emissivity
- Candidate surface finishes:

| Surface Finish | Emissivity at 40K | Reference |
|---|---|---|
| Z307 | 0.80 | 3 |
| Ball InfraRed Black (BIRB™) | 0.98 | 1 |
| Black Open Cell Honeycomb | 0.98 | 2 |

- While there are other black surface finishes available, these are the only ones considered

# Space Background Simulator (SBS)

- Z307 doesn't maintain a very high emissivity at 40K
- Open Cell Honeycomb carried some manufacturing difficulties
  - The use of open cell honeycomb upside-down in a gravity environment is not very common
  - Because of chamber restrictions and the need for the SBS and the attic to both have a high emissivity surface finish
  - There was no possible orientation that would eliminate open cell honeycomb from being directly above the radiators
- BIRB was selected for a variety of reasons:
  - Maintained high emissivity at 40K
    - Reduces test uncertainty
  - Large scale applications process already developed for the radiators




BIRB under a microscope at 30X

# Space Background Simulator (SBS)

- With the plumbing, the SBS will run around 13K, while the radiators will operate between 30 and 40K
  - Substantial difference in emitting energy:

$$Q_{SpaceTarget} = \sigma \cdot A_{SpaceTarget} \cdot \varepsilon_{SpaceTarget} \cdot T_{SpaceTarget}^4 = 5.67e^{-8} \frac{W}{m^2 K^4} \cdot 6m^2 \cdot 0.98 \cdot (13K)^4 = 0.0095W$$

$$Q_{Radiator} = \sigma \cdot A_{Radiator} \cdot \varepsilon_{Radiator} \cdot T_{Radiator}^4 = 5.67e^{-8} \frac{W}{m^2 K^4} \cdot 4.61m^2 \cdot 0.98 \cdot (40K)^4 = 0.6557W$$

- Therefore, the SBS will act as more of an absorber of the radiators 40K energy than an emitter of it's own 13K energy.
  - The emissivity of the SBS at 40K is more important than the emissivity at 13K

# Space Background Simulator (SBS)

- BIRB has a known batch-to-batch variation due to it's inherent morphology and the extremely high surface area being coated
- The SBS emissivity uncertainty was the single greatest source of uncertainty in the thermal balance test
- Using the radiative heat transfer equation and assuming parallel flat plates for simplicity:

$$Q_{1-2} = \sigma \cdot A_1 \cdot \Im_{1-2} \cdot (T_1^{\,4} - T_2^{\,4})$$

$$\Im_{1-2} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

- A BIRB emissivity of 0.98 on both surfaces with a uncertainty on the space target of 0.01 produces a 6mW heat load uncertainty
  - Around 1.3% of the radiating capacity of the NIRCam radiator!
- Targeted test uncertainty was 5% of radiating heat load

# Space Background Simulator (SBS)

- The SBS applications of BIRB were tested for cryogenic emissivity at GSFC
- The test determined the emissivity of the SBS at 40K to be 0.99 +/- 0.007
- The total test uncertainty due to the SBS emissivity for the NIRCam radiator test was 4 mW, which is less than 0.8% of it's radiating capacity
- The cryogenic emissivity testing resulted in a significant test uncertainty savings
- Final total test uncertainty for the NIRCam radiator test was 12 mW, or 3% of radiating capacity

# Conclusions

- The JWST FIR radiators use a high purity aluminum and BIRB surface coating to produce highly efficient cryogenic radiators
- Thermal balance besting of the JWST FIR radiators reduced uncertainty in testing by selecting and testing BIRB for the targets

# References


1. Tuttle, J. et al, “A High Resolution Measurement of the Low-Temperature Emissivity of Ball Infrared Black,” *AIP Conf*. 2012.
2. Yan, Lu, et al, “Theory Analysis and Test Study of Cold Black Target for Space Radiative Cooling Environmental Simulator”. *Advances in Cryogenic Engineering*. pp 1181-1188. 1996.
3. Tuttle, J et al, “Recent NASA/GSFC cryogenic measurements of the total hemispheric emissivity of black surface preparations”, *IOP Conference Series: Materials Science and Engineering 102.* 2015.