

CONVERSION COATINGS IN EXTREME ENVIRONMENTS - ANALYSIS OF CHEMICAL AND MORPHOLOGICAL CHANGES

AUTOMOTIVE CORROSION SYMPOSIUM 2026

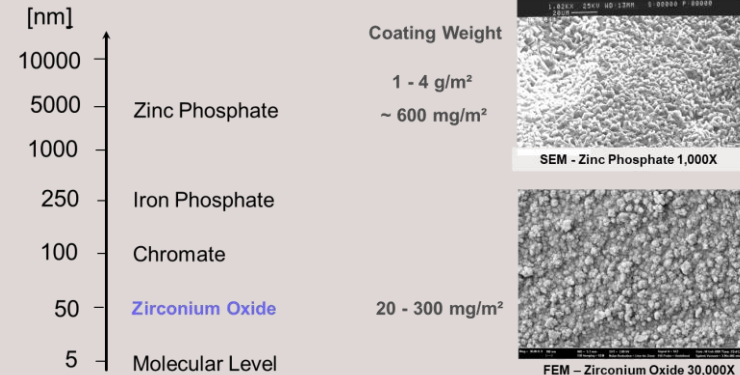
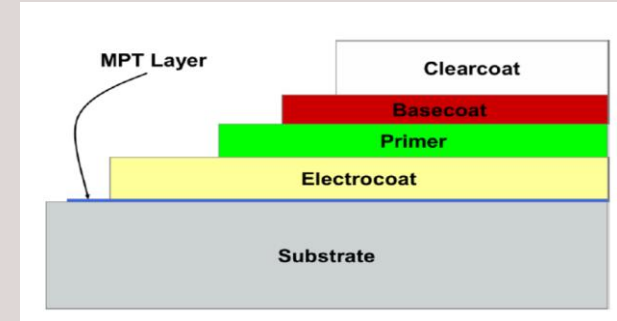
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150
YEARS

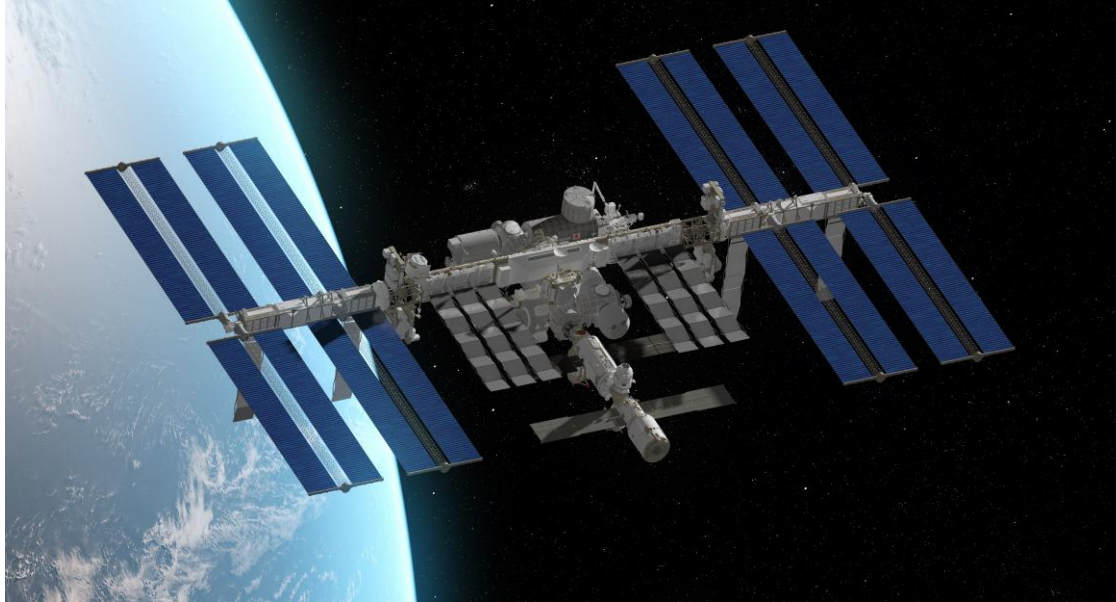
Henkel

WHAT IS A CONVERSION COATING?

- Coating formed on the metal substrate that improves adhesion to both substrate and subsequent paint layers and improves corrosion resistance.
- Known as conversion coatings, as the substrate surface is reacted, and forms part of the final coating
- Zirconium-based conversion coatings form an amorphous zirconium oxide layer over the substrate surface. Whereas zinc phosphate coatings are crystalline.
- The zirconium oxide conversion coatings are more sustainable than previous coating types. Eliminating toxic heavy metals, reducing waste, reducing water usage and energy usage.



EXTREME ENVIRONMENT – LOW EARTH ORBIT



Low Earth Orbit – LEO

Aggressive environment: -

- Extreme temperature changes
- Space debris
- UV radiation
- Atomic oxygen
- Solar wind / cosmic radiation

COATING SAMPLES

Samples: -

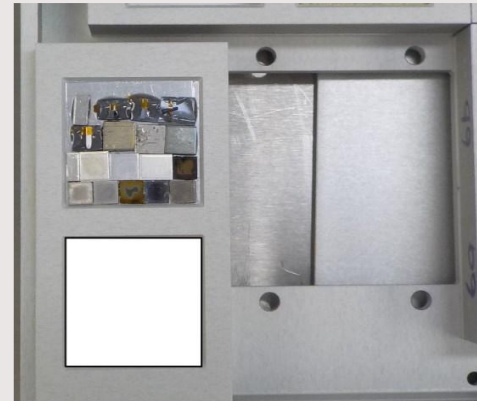
Bonderite® M-NT 1850 –

- Zirconium metal pretreatment
- Multi-metal substrates
- Steel test coupons

3 Variations of Bonderite® M-NT 1850 (CRS)

- 10 ppm Cu + 50 ppm PAA
- 10 ppm Cu + 200 ppm PAA
- 20 ppm Cu + 50 ppm PAA

Pristine, terrestrial, and LEO exposed samples sets



COATING PREPARATION AND SUBSEQUENT ANALYSIS

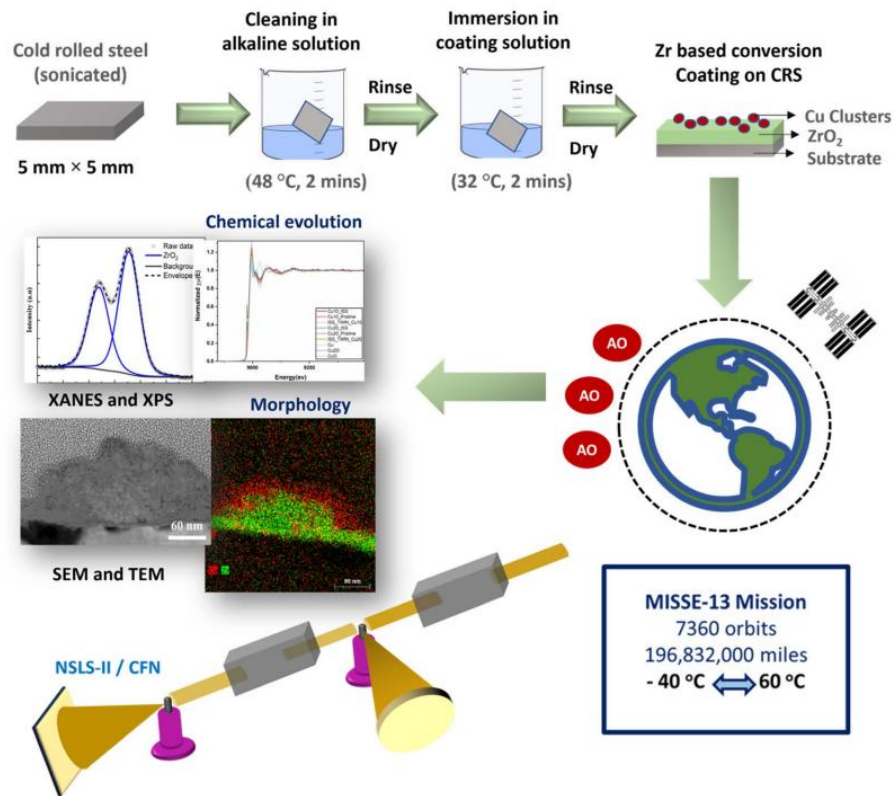


Fig. 1 Preparation of Zr-based conversion coating on CRS substrate, followed by exposure during the MISSE-13 mission outside the International Space Station. All schematic illustrations were created by the author. The samples returned to Earth were then subsequently analyzed using X-ray and electron-based characterization methods.

BROOKHAVEN NATIONAL LAB SYNCHROTRON LIGHT SOURCE II

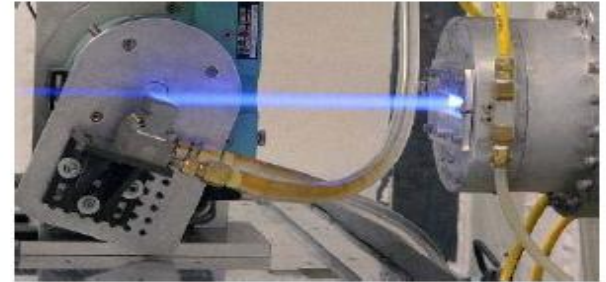
Synchrotron schematic



National Synchrotron Light Source II,
Brookhaven National Lab, NY, USA



X-ray beam at the beamline



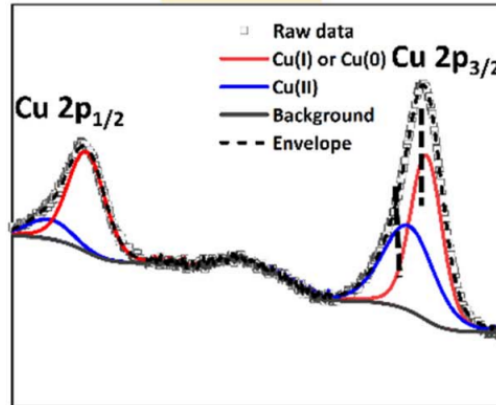
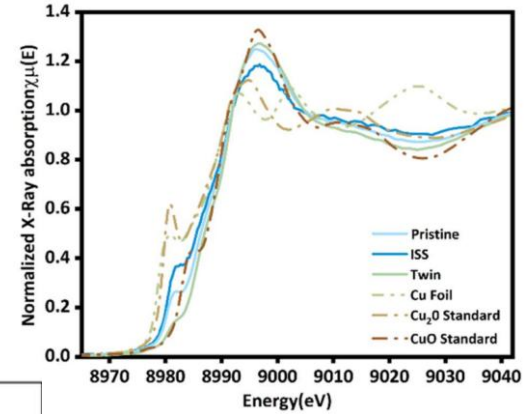
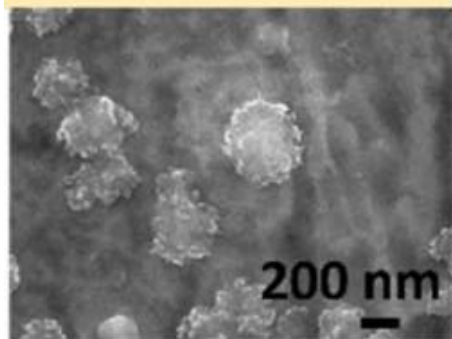
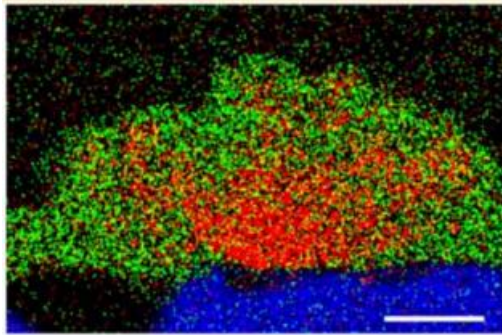
- High intensity X-rays = high speed, in situ, kinetics
- Variable energy = chemical sensitivity, in situ
- High beam collimation = high resolution



U.S. DEPARTMENT
of ENERGY

TECHNIQUES AND EQUIPMENT FOR ANALYSIS

- SEM, SEM-EDS, TEM, XPS, and XANES methods were used to analyze surface morphology, elemental distribution, and chemical states.



RESULTS – SURFACE MORPHOLOGY

- SEM images
- Comparison of 'pristine', terrestrial, and LEO exposed coatings at two concentrations of copper
- Pristine and terrestrial samples comparable
- LEO exposed samples, small amount of cracking and rougher surface – stress cracking from thermal cycling
- Cu10 – mostly physical, not chemical degradation, Cu20 – slight increase in oxidation of copper in the coating

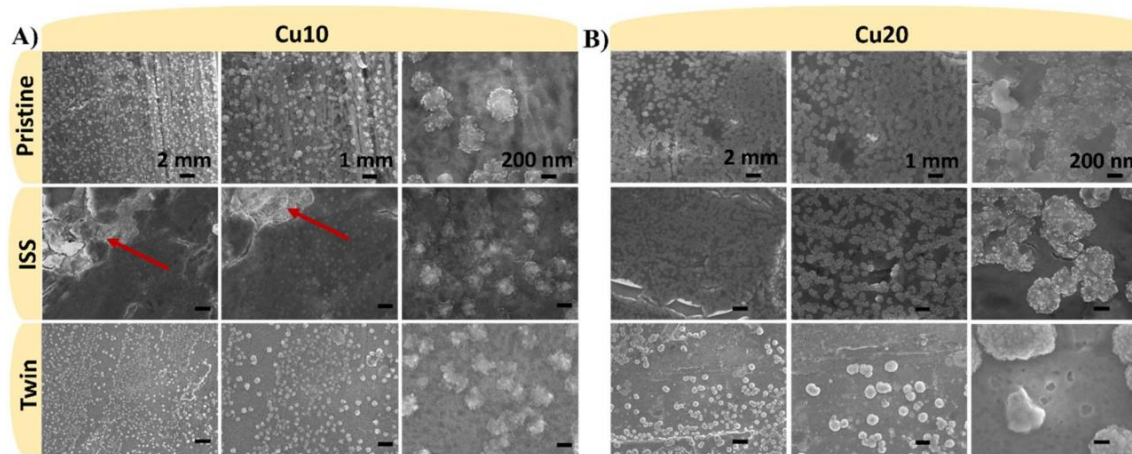
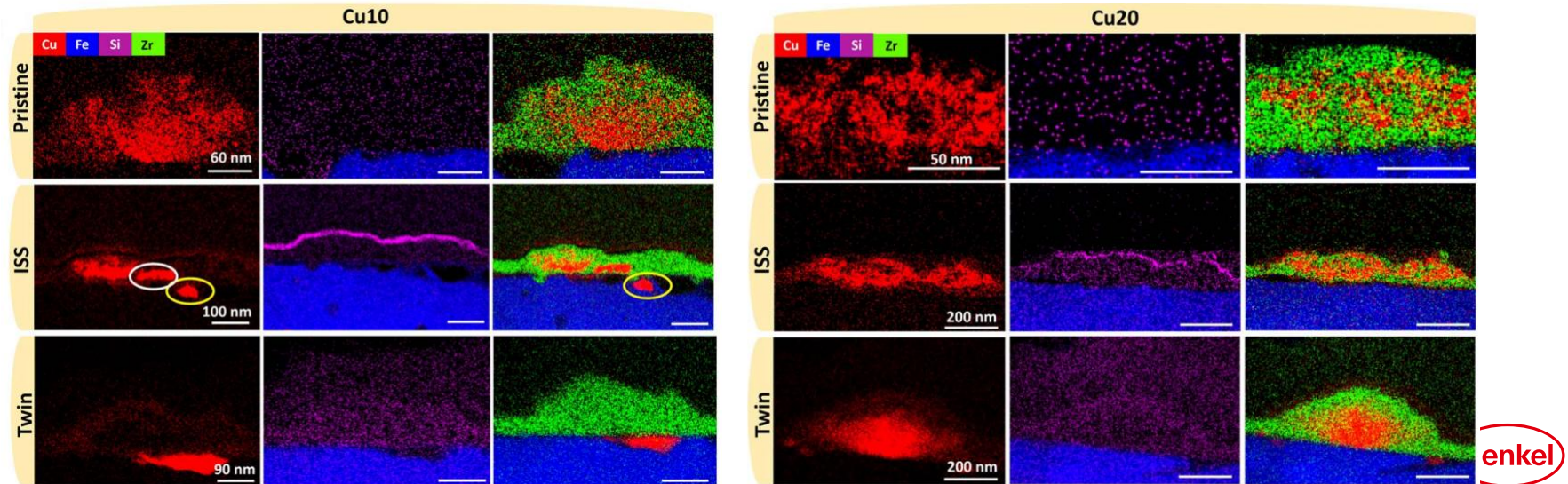


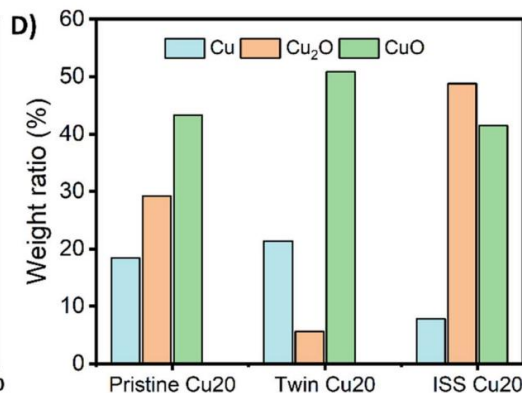
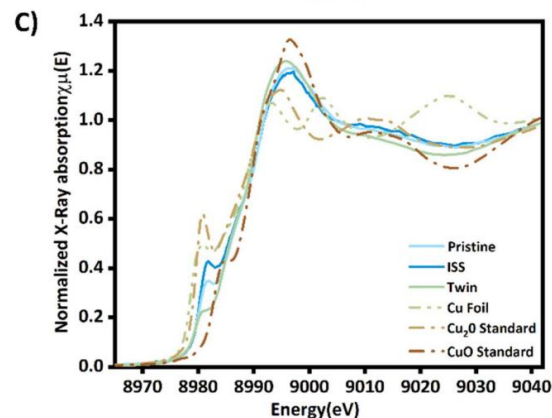
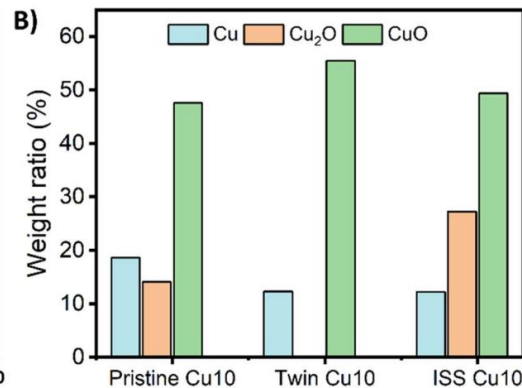
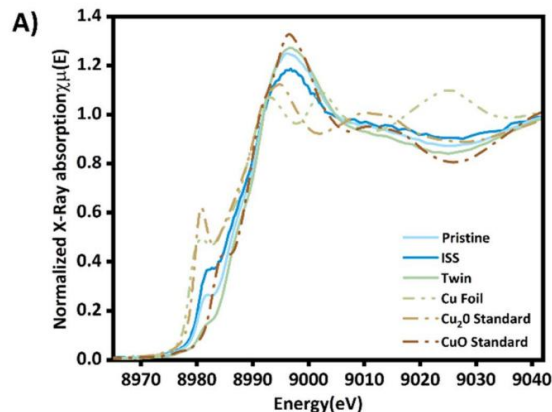
Fig. 2 Surface morphology of different coating samples on CRS in three different environmental conditions: as-coated, fresh samples (pristine), returned from the ISS after ~500 days exposure to the environment (ISS), and control twin. (A) Cu10, and (B) Cu20.

RESULTS – SEM EDS

- Core / shell type structure for pristine coating
- Si-rich layer formed on LEO exposed coatings – oxidation of volatile organosilicon species from outgassing of spacecraft
- Copper migration occurred over time to form larger agglomerates
- Less copper migration for Cu20 sample exposed to LEO – more oxidation of the copper in the coating



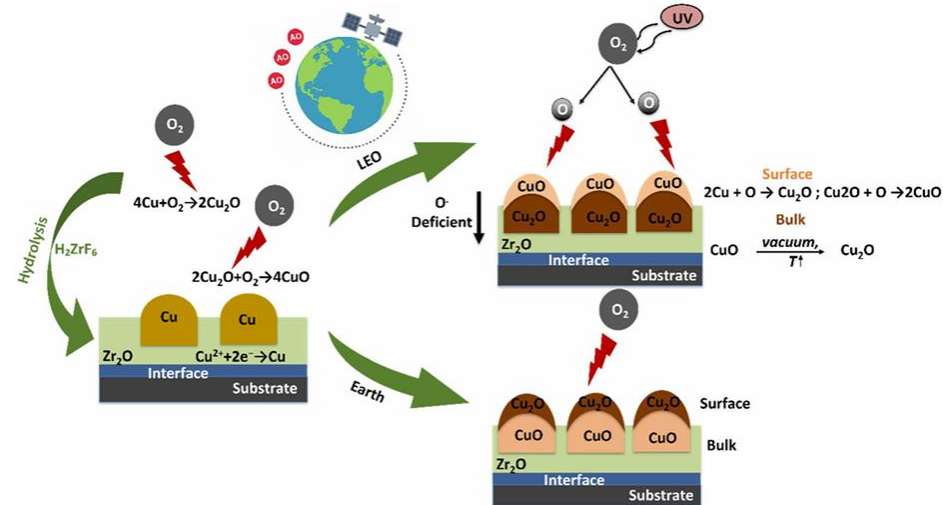
RESULTS – XANES – OXIDATION OF THE COATING



- Method to assess the oxidative states of the bulk (sub-surface)
- Oxidation of the copper occurs during deposition and exposure
- The terrestrial panels experienced a greater level of oxidation, with the bulk of the copper forming CuO
- Exposure to the LEO mostly led to oxidation of the copper to Cu_2O , without further conversion to CuO
- Cu10 and Cu20 samples followed similar trends
- Higher Cu_2O content in Cu20 samples due to higher level of copper available

SUMMARY

- All coatings exposed to the LEO environment remained intact, with a uniform covering of zirconium oxide with copper-rich clusters.
- A thin silicon-rich layer developed over the coatings from the outgassing of the space vehicle materials in the space environment.
- There was some evidence of atomic oxygen caused degradation of the copper in the coating.
- The coatings mostly maintained their chemical integrity and microstructure in the harsh LEO environment. The uniformity of the coatings after exposure indicate that they would continue to function as intended.



COLLABORATION PARTNERS



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The State University of New York



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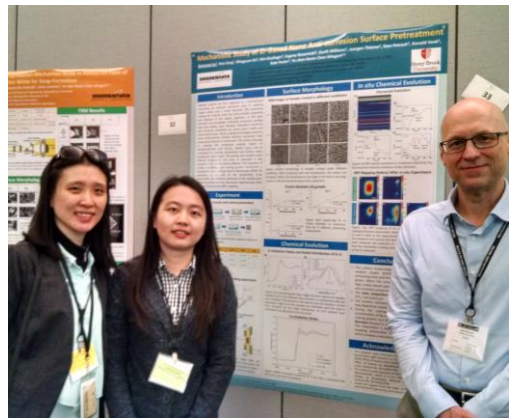
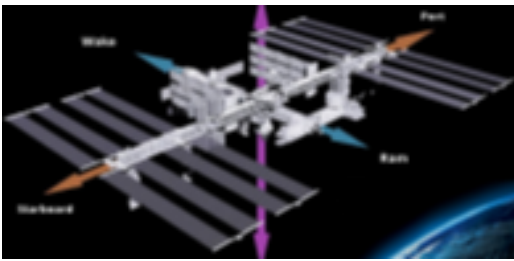
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Chemical and morphological evolution of hybrid conversion coatings in low-Earth orbit space environment

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THANK YOU

