UV Sterilization and Backward Planetary Protection for Mars Sample Return

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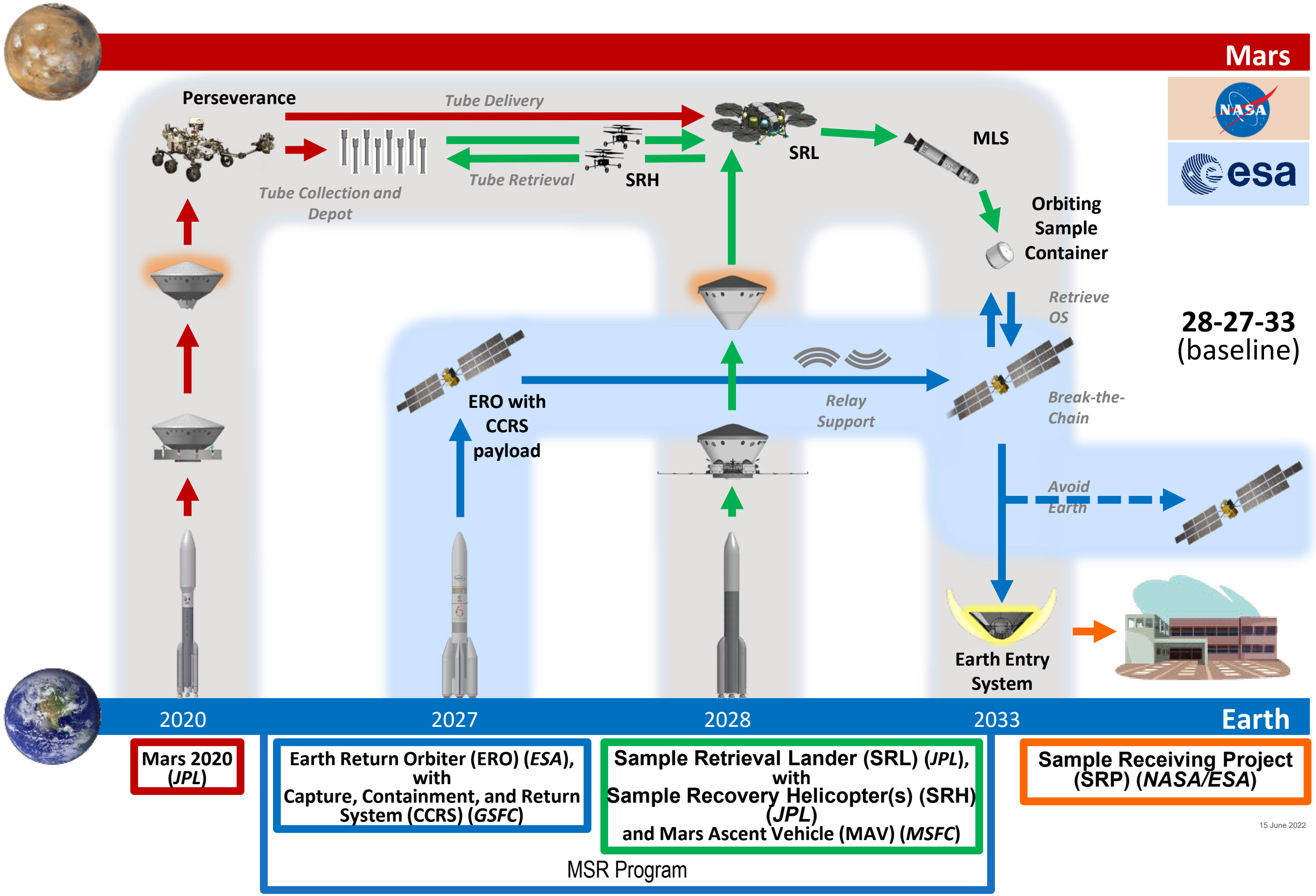
Talk Preview

- Brief overview of Mars Sample Return’s approach to backward planetary protection
- How MSR adopting passive and active ultraviolet light as a means for sterilization
  - Ongoing work to establish scientific consensus on the efficacy of in-flight UV sterilization
  - Developing a UV treatment concept, illumination system design and sterilization doses
- Progress and plans for developing passive and active sterilization process definitions in laboratory experiments

MSR Campaign Planning Architecture Overview



15 June 2022

Forward and Backward Planetary Protection

- Forward Planetary Protection (FPP) policies and measures address potential "contamination of other worlds by terrestrial organisms and organic materials carried by spacecraft in order to guarantee the integrity of the search and study of extraterrestrial life, if it exists."

- Backward Planetary Protection (BPP) policies and measures address potential "contamination of Earth by extraterrestrial life or bioactive molecules in returned samples from habitable worlds in order to prevent potentially harmful consequences for humans and the Earth's biosphere."

Quotes from NASA's OSMA Planetary Protection website, https://sma.nasa.gov/sma-disciplines/planetary-protection

Backward Planetary Protection and MSR

- Containment or sterilization measures are the default for extraterrestrial sample returns under current policies and standards
  - Containment measures are waived with a finding of “unrestricted Earth return” if the preponderance of scientific evidence indicates the target body is incompatible with life or if natural processes regularly deliver similar material to Earth
  - Unrestricted returns from targets, such as OSIRIS-REx, are not subject to planetary protection measures
- Mars Sample Return is classified by policy as a Restricted Earth Return
  - Natural transfer of material from Mars to Earth has been utilized in comparative risk assessments that yielded an unrestricted classification for JAXA’s proposed sample return from Mars moons (NASEM 2019)
  - However, our understanding of Mars is incomplete and both NASA (NPR 8715.24) and ESA directives call for implementing MSR as a Restricted Earth Return (Amann 2012, NRC 2009)
- MSR will use an assurance case to demonstrate compliance with NASA BPP policies
  - The assurance case will utilize quantitative and qualitative data to demonstrate an appropriate risk posture
  - Overall, MSR Program BPP approach will meet a standard of As Safe As Reasonably Practicable

The Mars Sample Return Program has developed stringent sterilization and containment requirements to meet the safety-first standards of a Restricted Earth Return

Backward Planetary Protection Strategy

Control

Limit Mars dust contamination of flight hardware to minimize potential downstream contamination

Sterilize

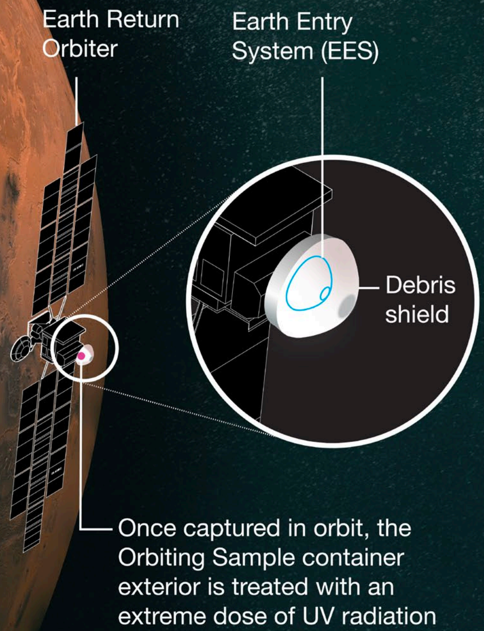
Inactivate potential Mars biology in uncontained dust

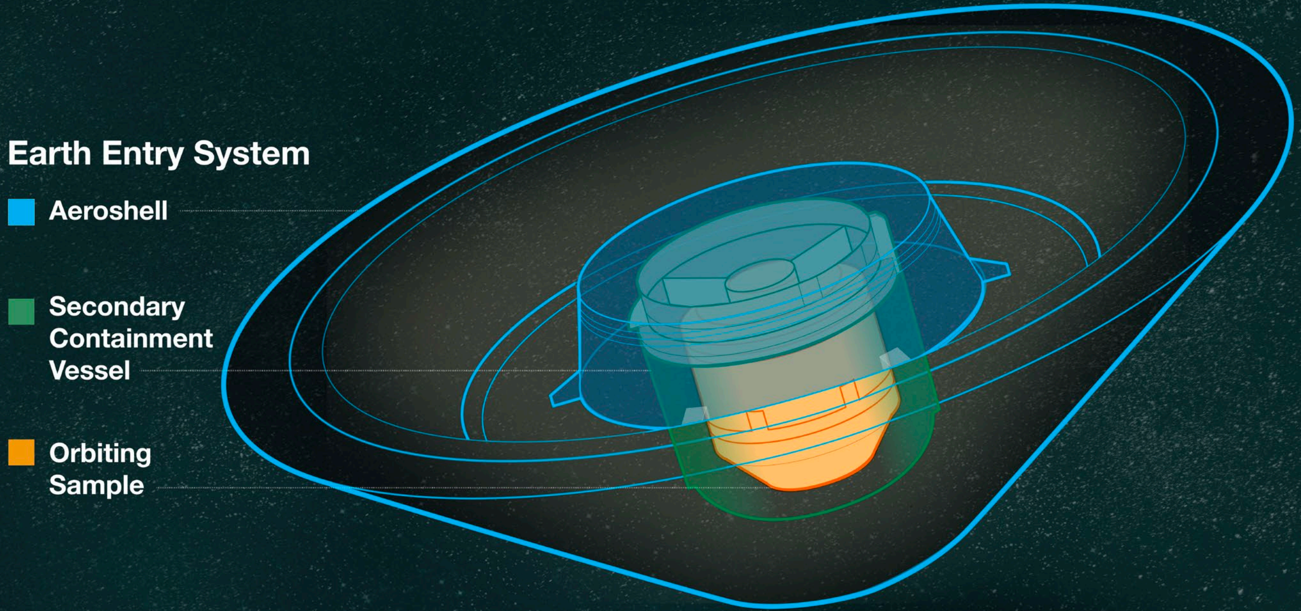
Contain

Redundantly contain all unsterilized Mars material *through* landing

Protecting the Mars Return Samples: In Space

- **Micrometeorite shield** protects Earth Entry System for years from Earth to Mars, and back
- **Orbiting Sample** is protected from dust on Mars, and launched into orbit with less than 0.001 ounces (40 mg) on its surface
- **Secondary Containment Vessel** provides container-within-a-container redundancy, meaning any one of the three elements (OS, SCV, sterilization) could be ineffective and MSR still safe
- **Aeroshell** protects the EES from the extreme forces and high heat of its entry into Earth's atmosphere





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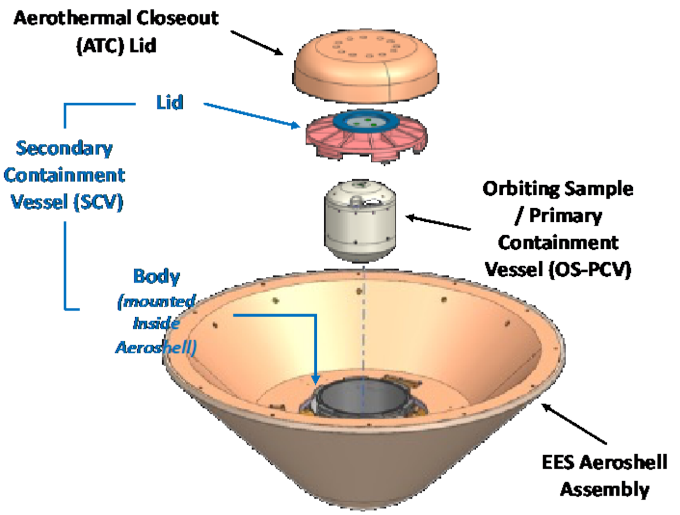
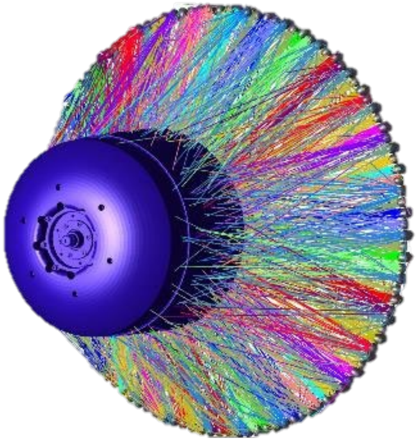
Sterilization in MSR

- Benefit: Sterilization enables true redundant containment
  - Redundancy ensures that containment efforts are not subject to isolated failures
  - Well-accepted practice for safely shipping potentially hazardous samples, such as medical specimens
  - MSR takes an additional step, sterilizing the external surface of the inner vessel to prevent cross contamination
- Challenge: In-flight sterilization is novel and has potential risks for the samples
  - The potential for sterilizing effects during space flight has previously been leveraged for planetary protection, but MSR would apply the first engineered process
  - Method selection is crucial to future science – MSR must limit sterilization impact to only external OS surfaces or risk sample degradation



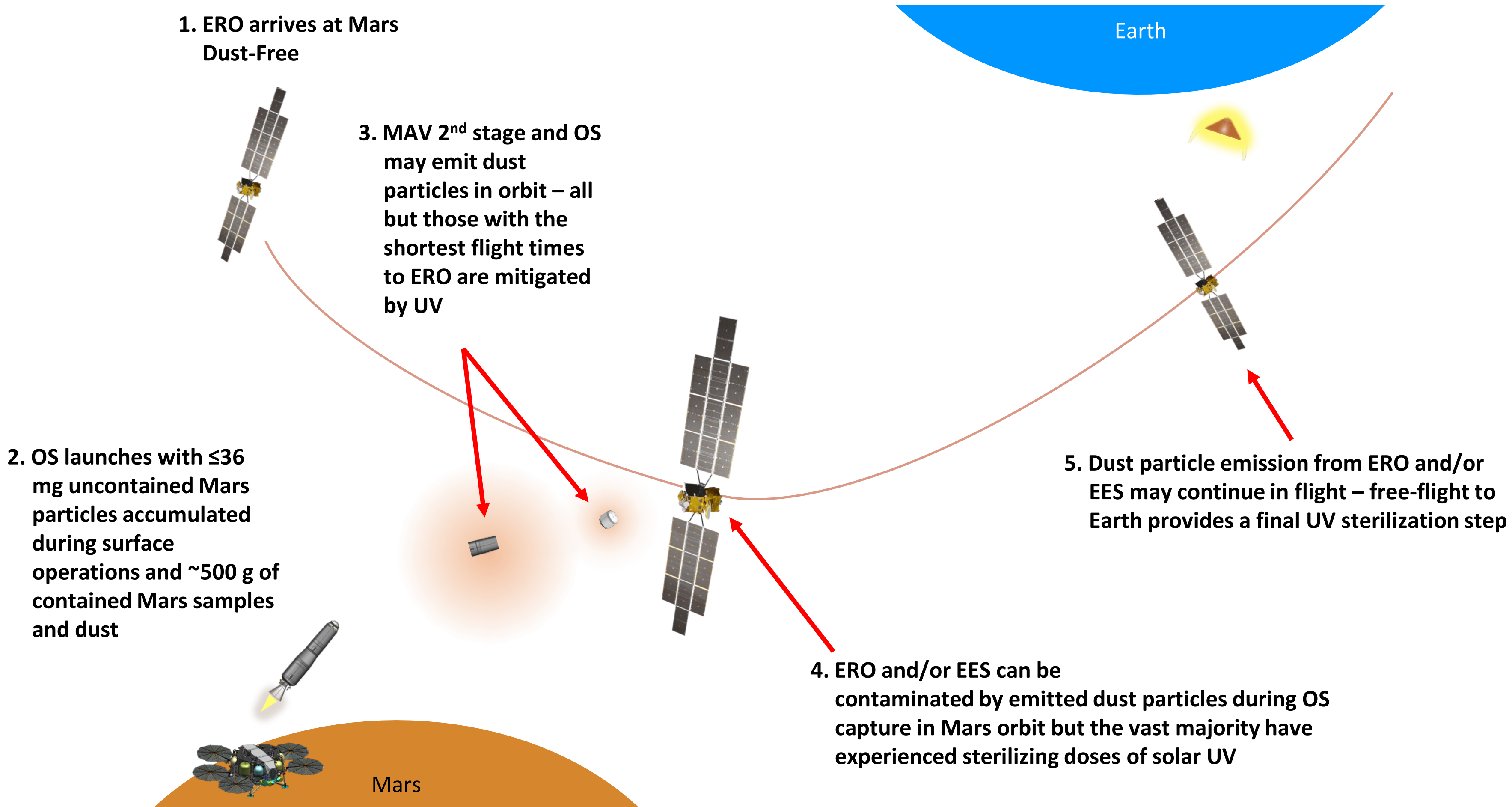
Ultraviolet (UV) Sterilization

- MSR has selected UV sterilization to mitigate any uncontained Mars material on the exterior of the Orbiting Sample container
  - The OS is expected to accumulate small amounts of Mars dust on its exterior during sample loading
  - Mars dust particles emitted from the OS in orbit may have a small chance of Earth by attaching to the Earth Return Orbiter
- UV sterilization reduces mechanical complexity and mass compared to other sterilization methods, while enhancing sample integrity relative to heat or gamma irradiation
- Active UV sterilization as applied by MSR would ensure the OS exterior is sterilized before being placed in the Secondary Containment Vessel (SCV)
- Establishing a passive, or Solar UV, sterilization process would confirm that free-flying particles are mitigated before reaching Earth's biosphere

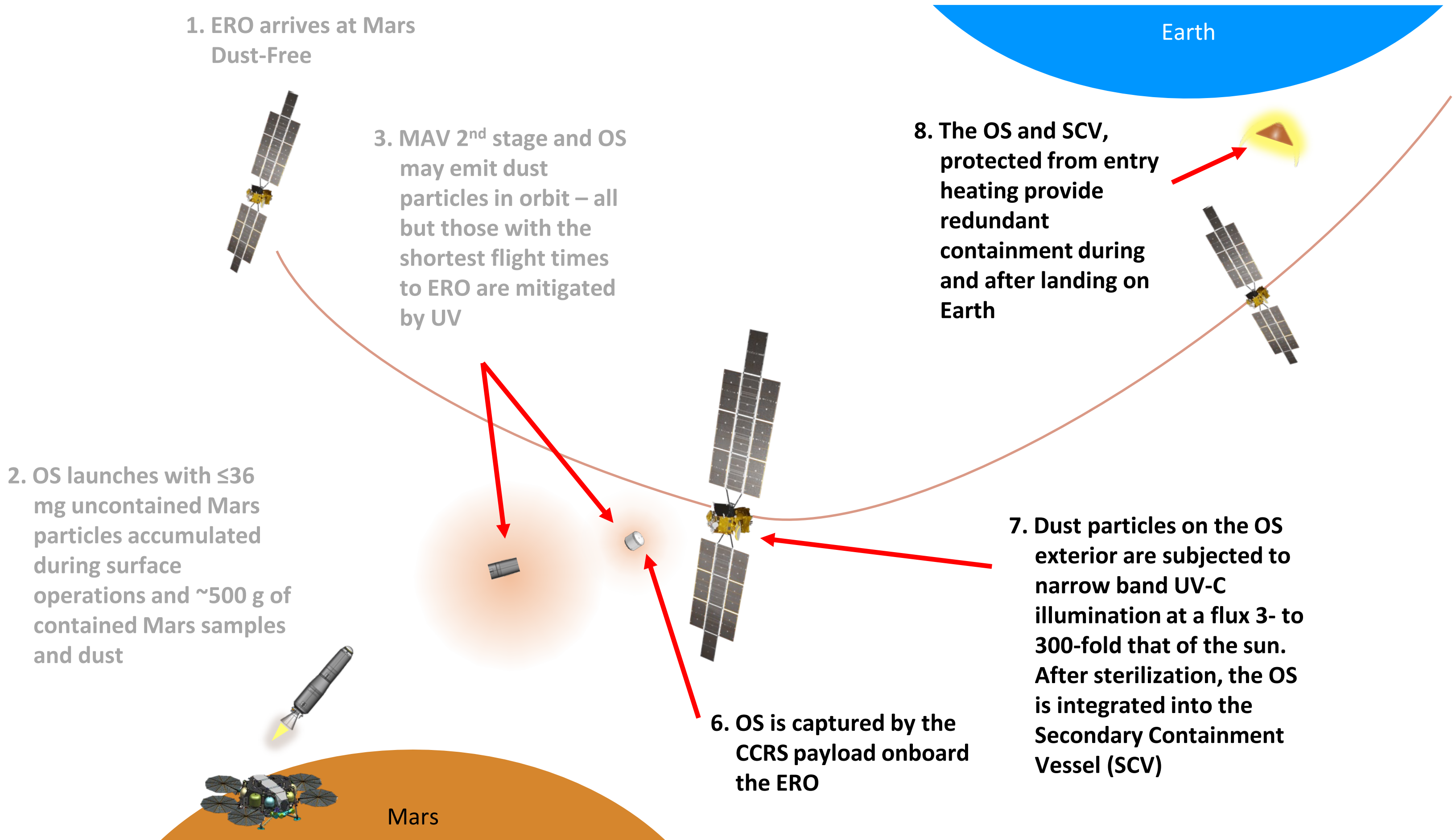


UV illumination modeling developed to guide preliminary system designs

Solar UV Sterilizes Free-Flying Particles

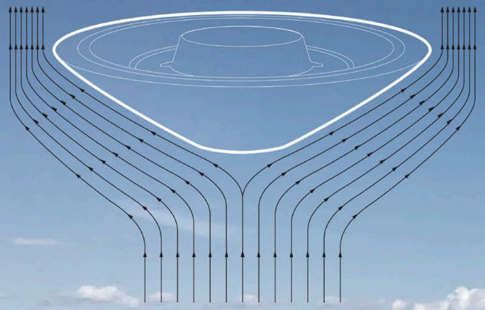


Active UV Sterilizes the Orbiting Sample Container Exterior



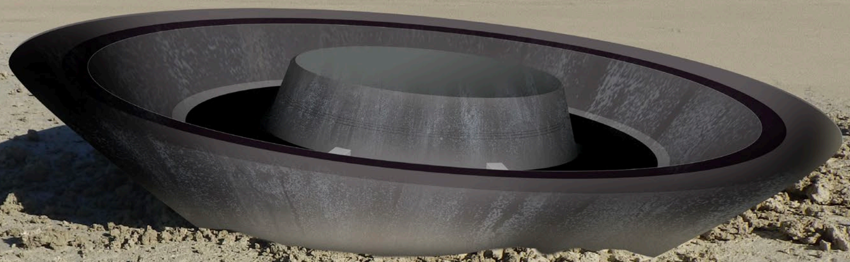
Protecting the Mars Return Samples: Landing on Earth

Shape of EES provides inherent deceleration and aerodynamic stability, without any need for a parachute



The EES makes it final approach inside restricted air space and lands on government-controlled land in Utah about 100 miles (161 kilometers) west of Salt Lake City

The redundant vessels inside the EES are designed to maintain containment during and after the landing



The EES landing zone covers over 150 square miles (388 square kilometers) of consistently flat and soft sandy clay soils that naturally cushion the landing at speeds up to 105 mph (169 kph), validated by real-life drop testing

Adopting UV Sterilization for MSR

Key Steps to Adopting a UV Sterilization Approach

- **Internal and external review**
  - Maintain information flow to key stakeholders through regular topical reviews
  - Provide review opportunities by non-advocate subject matter experts
  - Publish process development results and conclusions in peer-reviewed research journals
- **Preliminary system design**
  - Establish margined system requirements
  - Scope feasibility of meeting initial requirements (power, mass, timeline)
  - Develop preliminary design
- **Independent definition or verification of process parameters**
  - Identify biological indicators – organisms highly resistant to the sterilization treatment
  - Establish organism inactivation test capability
  - Demonstrate predictable dose-effect outcomes under relevant conditions

UV Sterilization - Independent Review

- NASA's Science Mission Directorate identified the need for an initial review of the proposed UV sterilization approach for MSR

- NASA's Office of Planetary Protection requested an independent review be coordinated by the Office of the Chief Scientist

- The Independent Study Team, after reviewing plans and information from the MSR Program, issued a July 2023 report that supported the use of UV light for sterilization
  - Recommendations were provided on biological scope, in-flight dose verification, contingency planning and dust modeling

- The MSR Program, in collaboration with the Office of Planetary Protection, has outlined how planned work and design elements will address the recommendations
  - Responses to the Independent Study Team recommendations will be formalized in upcoming life cycle reviews and tracked along with system and process developments

UV Sterilization - Internal Review

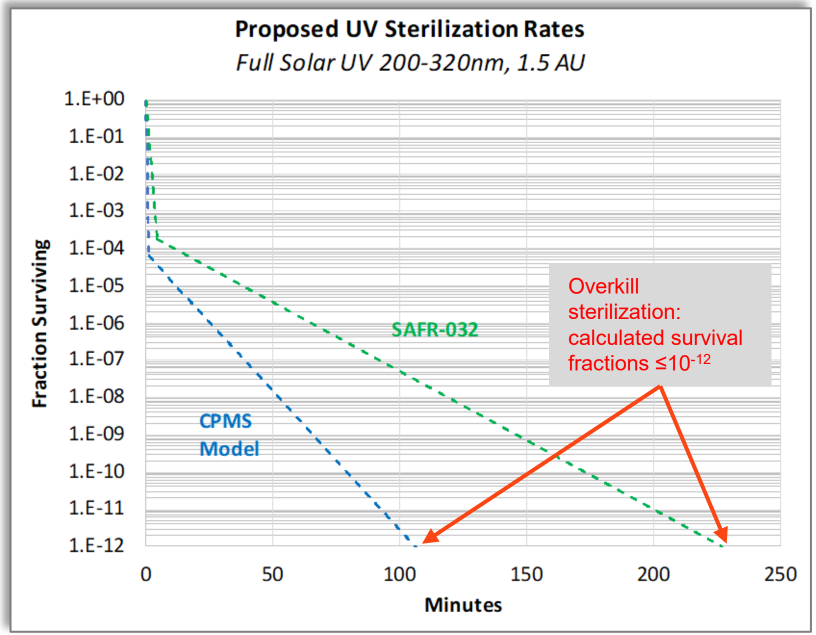
- MSR’s Planetary Protection approach is evaluated as part of the standard life cycle reviews
  - Planetary Protection reviews are held in advance of the Program-level review to provide the review board with detailed information
  - Review outcomes are presented at the Program-level review

- Specific subject matter experts and stakeholders serve as reviewers or observers on the Planetary Protection Review Board (PPRB)
  - Included are a germicidal UV expert, a member of the Program’s Standing Review Board, members of the individual projects and the Planetary Protection Officers from both ESA and NASA

- Special topics are discussed either in reviews or informational workshops/seminar as needed by either the PPRB or other stakeholders
  - UV sterilization approach has been presented to the MSR Campaign Science Group and the ESA Re-entry Safety Panel

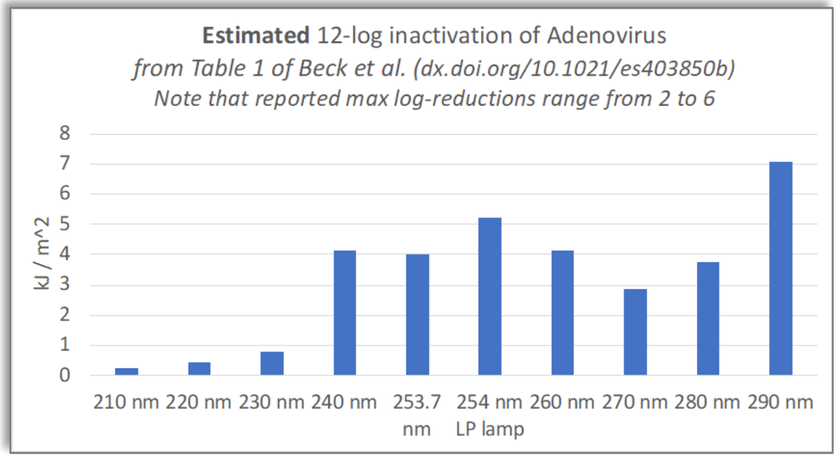
Preliminary System Design: Solar UV Sterilization Requirements

- Sterilization doses for system design are based on overkill for *Bacillus pumilus* SAFR-032
  - SAFR-032 is considered the most UV-resistant bacterium, requiring 161 kJ m^{-2} of solar UV for sterilization (integrated over 200-320nm, 225 min at 1.5 AU)
  - Data at right are adapted from Schuerger et al. (doi:10.1016/j.icarus.2005.10.008)
  - MSR's preliminary value exceeds that of the Cruise Phase Microbial Survival Model (Schuerger and Moores, 2019)
- Primary limit on Solar UV sterilization for MSR hardware is OS spin axis during orbit
  - Initial OS spin direction can rapidly precess into an orientation that may leave one side in shadow for long periods
- **MSR will utilize Solar UV sterilization to mitigate free-flying particles**



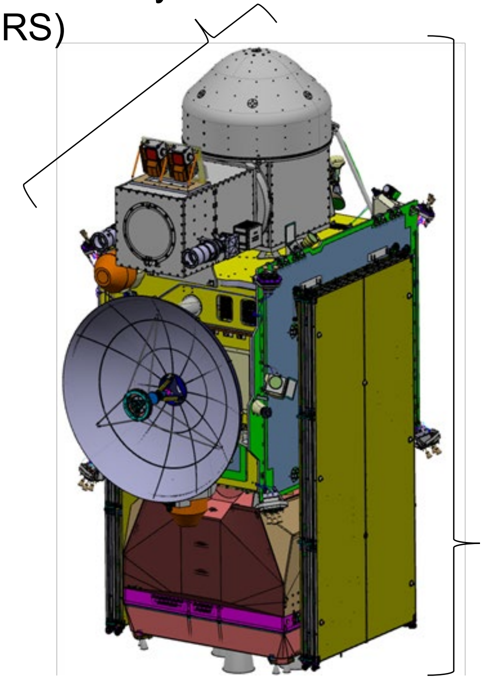
Preliminary System Design: Active UV Sterilization Requirements

- Working sterilization dose for Active UV is also based on *B. pumilus* SAFR-032
  - 20 kJ m^{-2} or ~2 times reported values at 254 nm
    - *Zammuto (2018) reported LD90 = 0.345 +/-25 kJ m^{-2} (0.370 * 12 = 4.4 kJ m^{-2}) w/ dried spores*
    - *Link et al. (2004) reported 4-log reduction at 3.4 kJ m^{-2} (3.4 * 3 = 10.2 kJ m^{-2}) w/ spores in liquid suspension*
    - *4-log disinfection for adenovirus in water treatment is ≤1.7 kJ m^{-2} per Beck (2014) and Gerba (2002)*
  - Planned implementation is LED illumination with a peak wavelength of 280 nm
- **Active UV process has been baselined for sterilizing the exterior of the Orbiting Sample container**



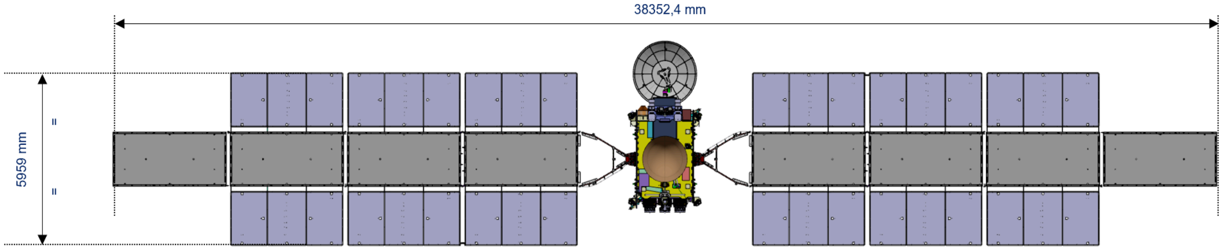
Preliminary System Design: Active UV Sterilization for the Capture, Containment and Return System (CCRS)

Capture Containment and Return System (CCRS)



Earth Return Orbiter (ERO)
launch configuration

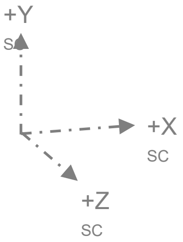
Earth Return Orbiter (ERO)
flight configuration

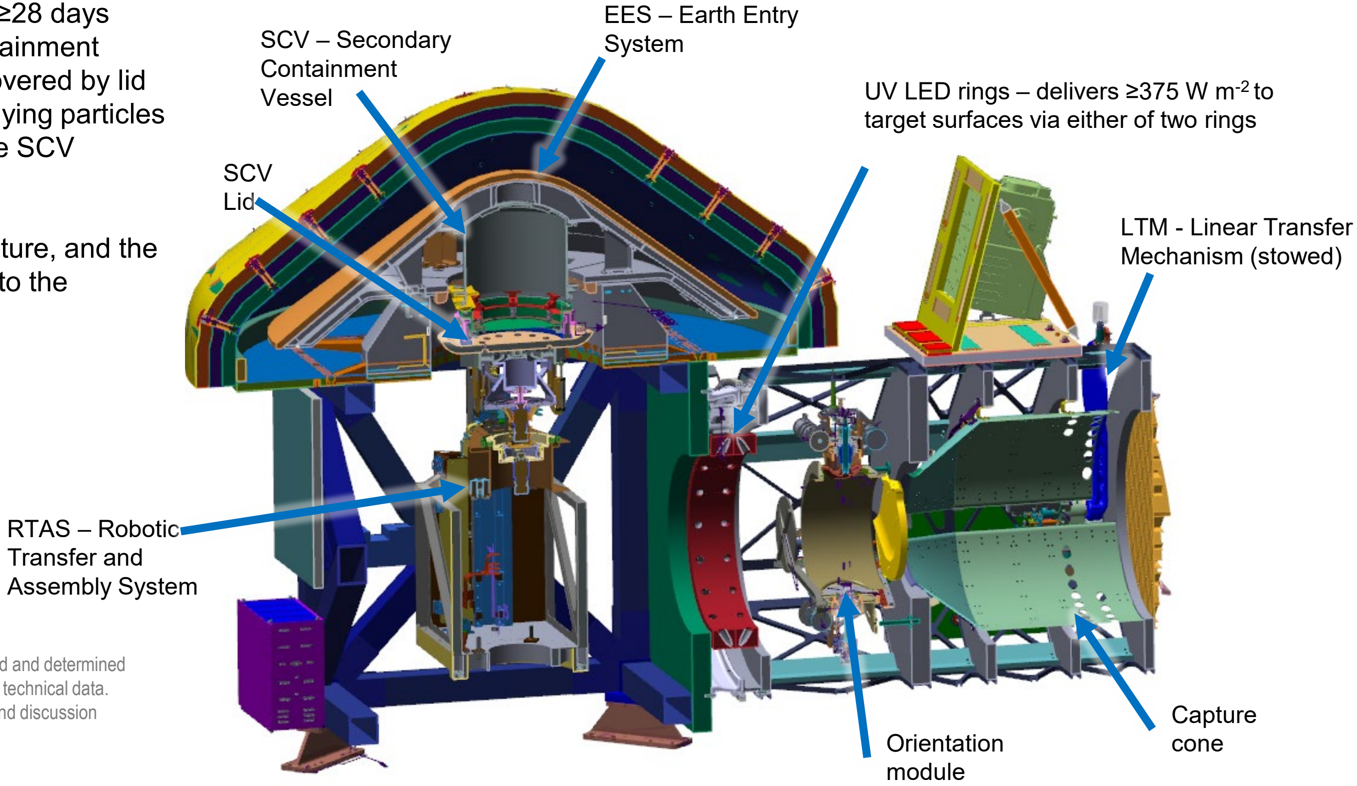


Preliminary System Design: Active UV Sterilization for the Capture, Containment and Return System (CCRS)

Initial state for capture:
- Orbiting Sample container (OS) in orbit for ≥28 days
- Secondary Containment Vessel (SCV) covered by lid to prevent free-flying particles from entering the SCV

Next :
- ERO effects capture, and the OS is brought into the capture cone





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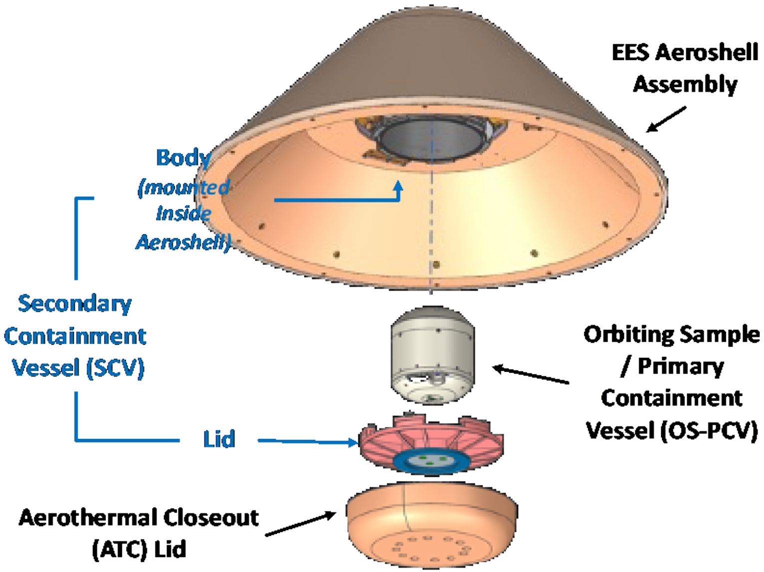


The MSR containment system is robust to the undetected failure of any one of the three containment elements: the primary container, the sterilization process or the secondary container

MSR’s UV Sterilization Process Definition

Defining a Sterilization Process

- NASA Technical Standard 8719.27, *Implementing Planetary Protection Requirements for Space Flight*, states that Restricted Earth Return missions shall either contain or sterilize returned material

- Sterilization processes are to be implemented in according to industry standards
  - “Sterilization and inactivation of samples may be achieved by leveraging overkill levels of terrestrial sterilization or inactivation of bioactive molecules through implementation of sterilization industry standards (e.g., ISO 11138-1:2017, ISO 14937:2009, ISO 22442 3:2007)” – Tech-STD-8719.27

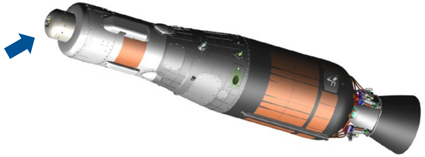
- Per ISO 14937 and ISO 11138-7, the preferred method for a conservative approach to sterilization is overkill
  - Equates to twice the dose required to inactivate 10^6 of the most resistant organisms under identical conditions
  - Does not require advance knowledge of the amount of biology present

Sterilization Process Definition: Key Inputs

- What assurance level is desired?
  - Sterility assurance level (SAL) refers to the probability an organism survives a sterilization treatment; a dose that kills 10^7 targets applied to a population of 10^6 organisms would yield a SAL of 10^{-1}
  - MSR intends to use an overkill process, producing a sterility assurance level (SAL) of 10^{-6} or a dose sufficient to kill 10^{12} of the most resistant organism
- Where is the material to be sterilized and what is the appropriate approach?
  - Deeply penetrating methods (heat, gamma irradiation) access entire volumes, such as packages and their contents
  - Surface methods (UV light, chemical treatments) penetrate only a short ways into an item, leaving the interior untouched
- How much material and how is it distributed?
  - Large quantities of target material may not be amenable to all methods
- What are the environmental conditions and materials?
  - Worst-case estimates of environmental parameters and material interactions are used to identify the required dose

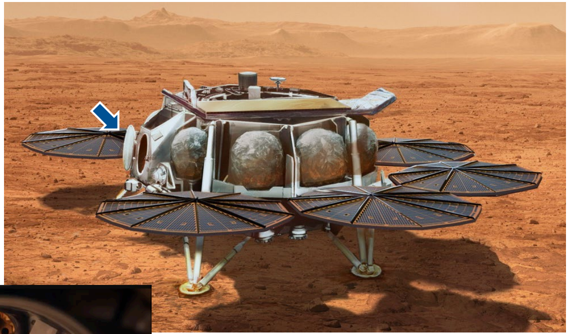
How much material and how is it distributed?

- Dust accumulation on the Orbiting Sample Container occurs when the sample access door is open during sample tube installation
  - Expected to be ≤60 hours for 30 tubes
  - OS is recessed in the Mars Launch System Bay, limiting vertical dust fall
- The uncontained Mars material requiring sterilization would be widely dispersed
  - Over 800 hours (13-fold more than expected) of door-open time would be required to exceed the allowable dust loading
  - Allowable dust loading is 4000 particles per mm^2, a mean inter-particle distance 20 times the mean particle diameter
- **The expected loading is approximately 4 milligrams of dust, roughly the mass of 4 grains of table salt**
  - Worst case loading, which is used for BPP analyses, is 36 milligrams of material



At left - A sample tube and the Orbiting Sample container (OS) and lid in which tubes would be launched from Mars. Above – the Mars Launch System with the closed OS on the front (arrow)

At Right – The Sample Retrieval Lander with the door open (arrow) for sample tube installation. Just beyond the opening, the open OS can be accessed by the Sample Transfer Arm. The OS is on the front of the Mars Launch System, which is stowed horizontally in a bay that runs across the body of the lander.



At Left – Close up of sample tube installation into the OS by the Sample Transfer Arm. During installation, the OS exterior and interior are exposed to wind blown Mars dust. When tube loading is finished, the particle-tight OS lid is installed, containing the samples and much of the dust inside the vessel. Exterior dust is later subjected to sterilization in space.

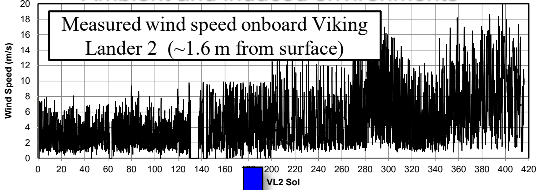
What are the environmental conditions?

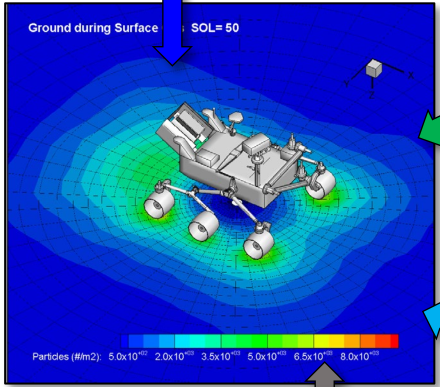
- Dust deposition on Mars is driven by the wind and dust particle parameters

- Direct Mars observations and models have previously been assessed for planetary protection
  - The mean Mars dust particle size is less than 1 micron
  - Wind effects have been both observed and successfully modeled

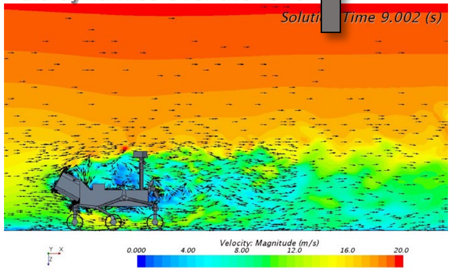
- Particle transport physics from laboratory experiments are utilized to bound predictions of dust accumulation and behavior
  - Key transport pathways to Earth's biosphere are assessed

Ambient and induced environments

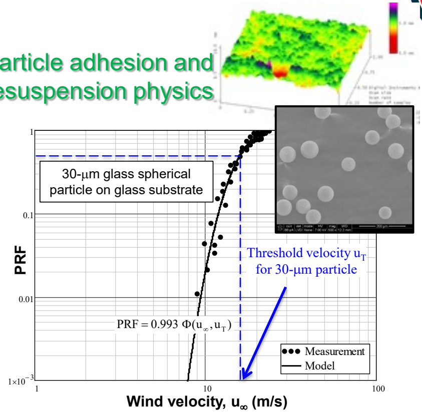


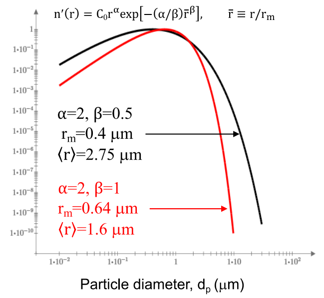


Fluid dynamics over the rover



Particle adhesion and resuspension physics

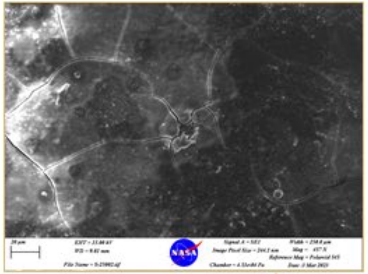




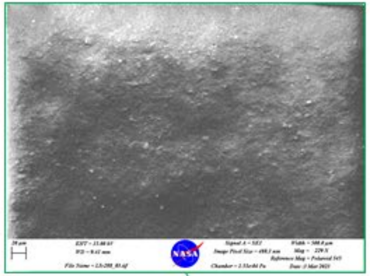
Suspended particles in the Mars atmosphere are of diameter $d_p \lesssim 10$ μm. The bounding distributions used in the MSR Campaign's analyses are shown here derived from a few widely used size distribution models in the literature. See backup slides for details.

What are the materials?

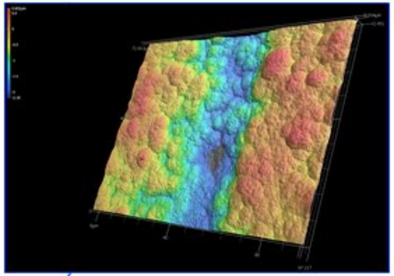
Coating A



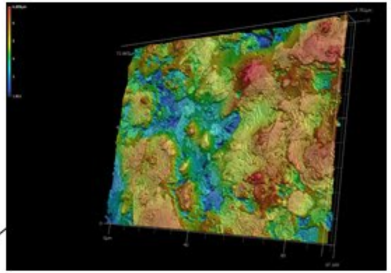
Coating B

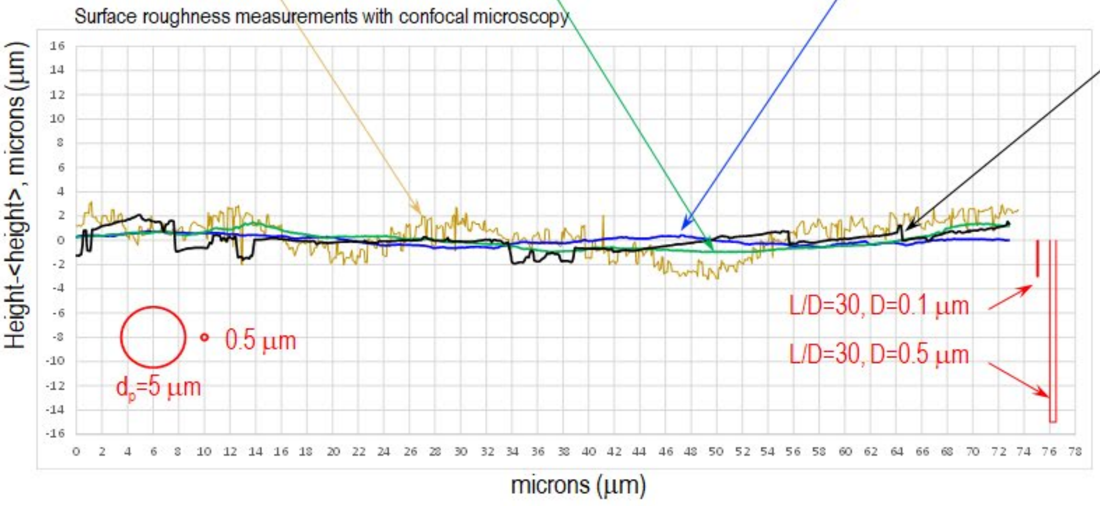


Coating C



Coating D





- Material properties are critical to UV sterilization
- Smooth, reflective OS coatings ensure dust particles are fully treated with UV
- Multiple candidate coatings are smooth enough to be compatible with the proposed process

Sterilization Process Definition: Experimental Programs

- Sterilization processes are formally defined by data derived under application-specific conditions
  - Organisms are exposed to varying UV light doses to assess dose-effect correlations and demonstrate robust inactivation of large organism populations (e.g., 10^6 per test)
  - Exposures will be done on coupons identical to the OS surface in the presence of light filtered through dust at space vacuum and flight temperatures
- Key process definition considerations include
  - Selection of target organisms (a.k.a. bioindicators)
  - Independent development or verification by laboratory not otherwise involved in the mission
  - Achieving inactivation of 10^6 organisms under application-specific conditions
- MSR has established a three-track program to establish the correct conditions for developing and confirming a robust UV sterilization process

MSR UV Process Definition Tracks

Key

Ongoing work	Future work	Completed work
MSR	*MSR*	*MSR*
Independent Lab 1	*Independent Lab 1*	*Independent Lab 1*
Independent Lab 2	*Independent Lab 2*	*Independent Lab 2*

Track 1 – UV transmissibility through relevant materials (through June 2024)

UV transmission of OS coating components

UV transmission of OS coating fragments

UV transmission of Mars dust

Track 2 – Solar UV sterilization process definition (through April 2024)

Establish contract

Establish protocols

Estimate sterilization threshold (fail fast)

Determine sterilization doses for two most UV-resistant organisms

Determine protective effect of Mars-analog particles

Demonstrate solar UV lethality on OS-like surface with Mars-analog particles

Estimate and publish lethality model for Low Mars Orbit

Track 3 – Active UV sterilization process definition (through October 2024 [TBC])

Establish Preliminary test system

Estimate Active UV sterilization doses under ambient conditions

Scope independent study

Independent lab study initiated, test unit built

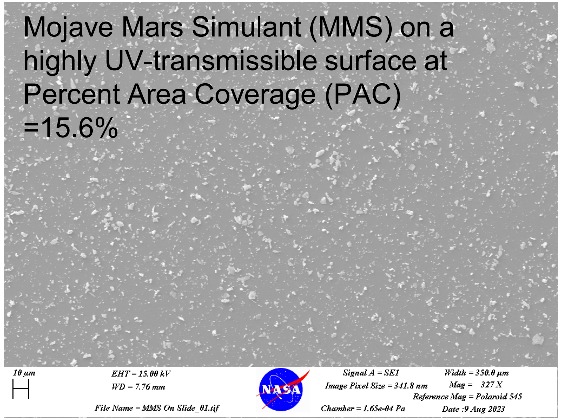
Establish flight environment test capability

Determine Active UV sterilization doses for flight conditions

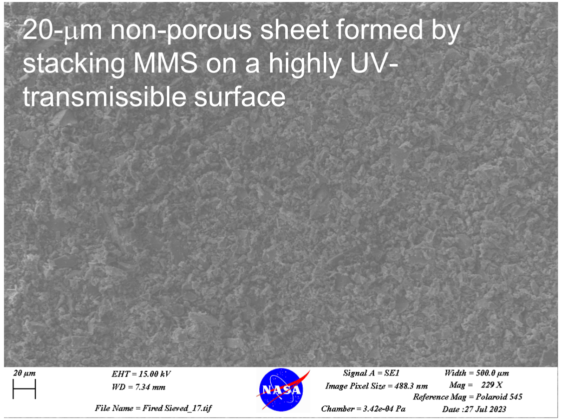
Demonstrate Active UV lethality on OS-like surface with Mars-analog particles

UV transmissibility of Mars dust

- Mars dust presents a possible constraint to UV light accessing potential Mars biological entities
- Primary experimental goal is to determine UV flux through Mars-like minerals of relevant sizes
- Secondary goal is to assess how well measured values match theoretical predictions
- Experimental approach
  - Mars simulant fired to 350˚C to remove contaminants then sieved to emulate Mars aerosol size distribution (<0.02% of particles <15 μm)
  - Measured UV transmission in sparsely-deposited and confluent monolayer particle configurations
- Both the methods and data will be used in other experiments to ensure the final process definition is relevant for flight conditions



Mojave Mars Simulant (MMS) on a highly UV-transmissible surface at Percent Area Coverage (PAC) =15.6%



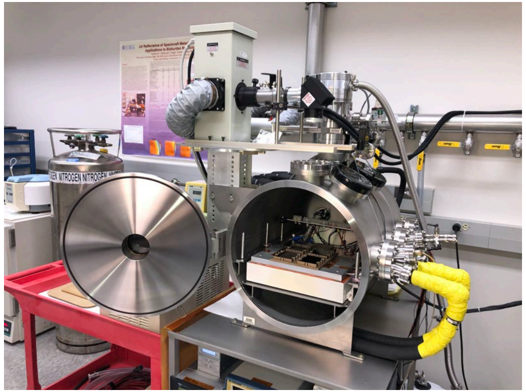
20-μm non-porous sheet formed by stacking MMS on a highly UV-transmissible surface

Solar UV sterilization process definition

Establish contract → Establish protocols → Estimate sterilization threshold (fail fast) → Determine sterilization doses for two most UV-resistant organisms → Determine protective effect of Mars-analog particles → Demonstrate solar UV lethality on OS-like surface with Mars-analog particles → Estimate and publish lethality model for Low Mars Orbit

Completed | Ongoing work | Future work

- Goal is to establish time-to-sterilization for solar fluxes at Mars-Sun distances under flight conditions
- Environmental chamber provides space-like UV light (Xe source), vacuum (4e-6 mbar) and thermal conditions
- Protocol development included establishing cell monolayer prior to exposure to mimic sparsely deposited Mars dust while still testing with 10^6 organisms per exposure.
- Currently identifying the two most resistant organisms among the test species; next will identify solar UV-C dose for a sterility assurance level (SAL) of 10^{-6} for each
- Future work will incorporate effects of Mars dust particles on solar UV-C SALs with aluminum coupons (free-flight sterilization)
- Additional work may determine effects of aeolian Mars particles on OS surface coupons to understand time required in orbit to achieve sterilization



Test strains:
Bacillus pumilus SAFR-032
Aspergillus fumigatus ISSFT-021-30
Geobacillus stearothermophilus
Naganishia onofrii DBVPG 5303

Active UV sterilization process definition

Establish benchtop Active UV light exposure system

Estimate Active UV sterilization doses under ambient environment

Scope study

Independent lab identified & on contract

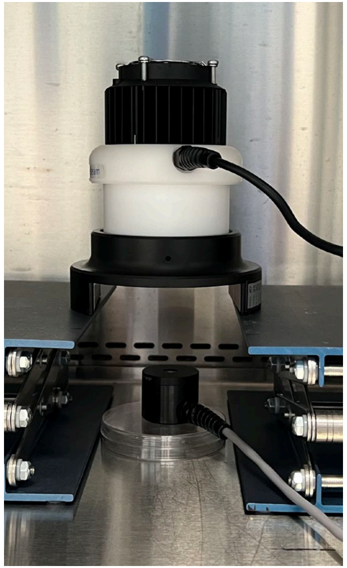
Establish flight environment test capability

Determine Active UV sterilization doses for flight conditions

Demonstrate Active UV lethality on OS-like surface with Mars-analog particles

MSR	*Completed*	*Ongoing work*	*Future work*
Independent Lab 2	*Completed*	*Ongoing work*	*Future work*

- MSR preliminary work utilizes an off-the-shelf UV LED instrument
- Initial data will identify two most-resistant strains for process definition by an independent lab
- Test unit will utilize the same LED light sources as flight system
- Independent lab workplan includes:
  - Testing in relevant flight environment conditions
  - Determine effects of aeolian Mars particles using process from JPL
  - Determine SALs for active UV in multiple organisms



UV Sterilization and Backward Planetary Protection for Mars Sample Return - Summary

- The MSR Program has established a robust approach to breaking the chain of contact with Mars utilizing containment and UV sterilization
- Efforts are underway in support of both adopting UV sterilization as an approach and developing a formally defined process
- In conjunction with with NASA’s Science Mission Directorate and Office of Planetary Protection, MSR is working to establish external consensus on UV sterilization effectiveness
- A baseline UV illumination system design, informed by literature values for UV lethality, is in development
- Ongoing laboratory experiments will define the final values for implementing in-flight UV sterilization

Thank you

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