A Summary on Cutting Edge Advancements in Sterilization and Cleaning Technologies in Medical, Food, and Drug Industries, and Its Applicability to Spacecraft Hardware

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Agenda

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– Currently Approved Sterilization Protocols
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Introduction

• Issued primarily by COSPAR (the Committee On SPAce Research), international planetary protection policies mandate that all spacecraft hardware in contact with extraterrestrial environments “of chemical evolution and/or origin of life interest and for which scientific opinion provides a significant chance of contamination which could compromise future investigations” * be sterilized
  – These policies seek to limit the (forward) biological contamination of the target body by terrestrial microorganisms on the spacecraft, so that future missions to the target body will provide accurate and reliable scientific results
  – Also these policies seek to prevent the (backward) biological contamination of the Earth by a sample returned from the target body

• Bioburden reduction is an integral part of current space missions and its importance will magnify as sterilization requirements become more stringent in the future

• Since life detection and sample return procedures require a sterile in situ environment (to protect scientific results), subsystems and instruments which will be in contact with extraterrestrial matter must be sterilized

Introduction

• Since the first Viking mission, Heat Microbial Reduction (HMR) has served as a well-understood common practice for sterilization

• More recently, NASA and ESA have approved a standard protocol for Vapor Hydrogen Peroxide (VHP) sterilization to address some of the drawbacks of HMR by lowering operating costs and decreasing schedule impacts
  – However, even VHP has certain pitfalls that do not make it an all-encompassing sterilization modality for spacecraft (S/C) hardware (H/W)
Introduction

• Therefore, the team investigated the state-of-the-art sterilization and cleaning techniques used in other fields, such as in the medical, food, and drug industries, for application to flight hardware
  – Major techniques covered include Cold Atmospheric Plasma, Electron Beam Irradiation, and Gamma Irradiation
  – Some techniques have proven to be good candidates for adaptation for future NASA S/C missions, such as gamma irradiation (γ rad), can broaden the scope of NASA-approved protocols and expand the currently limited toolkit

• Cleaning is also an important aspect of bioburden reduction; despite the best sterilization technologies, dead microbes can interfere with and potentially invalidate the results of biosignature models of relevant celestial bodies
  – Therefore, cleaning techniques, such as carbon dioxide snow, can significantly contribute to the bioburden reduction process
Currently Approved Sterilization Protocols

• Heat Microbial Reduction is an environmentally friendly technique that uses high heat for an extended period of time to sterilize both surfaces and bulk materials (by penetration) of an object
  – Primary issues with HMR include materials compatibility, cost, and schedule impact due to the length of chamber time – particularly the high operating costs of high heat and long duration of time baking the materials
  – If testing identifies a need to rework previously HMR-processed H/W, then a repeat of HMR process following rework can cause unacceptable schedule slip

• Therefore, a new method for sterilization, VHP, was developed to increase efficiency, and address some of the pitfalls of HMR
  – VHP is lower cost, ideal for heat-sensitive parts, more efficient processing time
  – However, VHP is only able to sterilize surfaces

• As a result, it is necessary to investigate additional sterilization and cleaning techniques in order to expand the scope of hardware treatments
Other Sterilization Techniques Investigated

• Physical Methods:
  – Autoclave Steam Sterilization
  – Pressure Vapor Sterilization

• Chemical Methods:
  – Ethylene Oxide Sterilization (ETO)
  – Formaldehyde Sterilization
  – Chlorine Dioxide Gas Sterilization
  – Peracetic Acid Sterilization
  – “Cold Atmospheric Plasma” Sterilization (CAP)
    • Dielectric barrier discharge (DBD)
    • Atmospheric pressure plasma Jet (APPj)
    • Surface Micro-Discharge (SMD)
Other Sterilization Techniques Investigated

• Irradiation Methods:
  – Ultraviolet (UV) Sterilization
  – High energy X-ray Sterilization
  – Electron Beam (E-beam) Sterilization
  – Gamma Ray Sterilization
Cleaning Techniques Investigated

• Single-Wafer Spin Cleaning with Repetitive Use of Ozonated Water and Dilute Hydrogen Fluoride (SCROD)
• Low-Pressure Chamber Vapor Cleaning
• Carbon Dioxide Methods:
  – Super-critical CO₂
  – CO₂ snow
  – Liquid CO₂
  – Dry ice pallets
• Other Cleaning Techniques:
  – Multi-Tank Immersion RCA Cleaning
  – Cryogenic Aerosol-based Cleaning
  – Laser Cleaning
### Conclusions

**Techniques with NASA-Approved Protocols**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>HMR</td>
<td>Repeatability</td>
<td>Time Consuming</td>
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<tr>
<td></td>
<td>Volumetric Reduction</td>
<td>High Temperature</td>
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<td></td>
<td>Non-Corrosive</td>
<td>Slow Rate of Heating Penetration</td>
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<td></td>
<td>Non-Toxic</td>
<td>Incompatibility with some Plastics</td>
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<td></td>
<td></td>
<td>Facility cost</td>
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<tr>
<td>VHP</td>
<td>Cost</td>
<td>Surface Microbial reduction</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>Reactive with certain materials</td>
</tr>
<tr>
<td></td>
<td>Repeatability</td>
<td>Pre-conditioning</td>
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<td></td>
<td>Low Temperature</td>
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Conclusions
Techniques without a NASA-Approved Protocol

- Some techniques were definitely not compatible with S/C H/W, the following techniques were investigated in greater depth:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Advantages &amp; Disadvantages Dependent on Technique</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAP</td>
<td>Low Temperature</td>
<td>Time</td>
<td>Cost</td>
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<td></td>
<td>Multiple Sporicidal Agents</td>
<td>Sporicidal Effect</td>
<td>Toxic</td>
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<td>Geometry</td>
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# Conclusions
## Techniques without a NASA-Approved Protocol

<table>
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<tr>
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<th>Disadvantages</th>
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<tbody>
<tr>
<td>Gamma Irradiation</td>
<td>Volumetric</td>
<td>Facility cost</td>
<td></td>
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<td></td>
<td>Low Temperature</td>
<td>Radiation safety (for humans)</td>
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<td></td>
<td>Time</td>
<td>Polymers &amp; glasses can be affected</td>
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<tr>
<td></td>
<td>Predictable and Repeatable</td>
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<tr>
<td></td>
<td>No Radiation Byproduct or Residual</td>
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<td>No Further Process</td>
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## Conclusions

Techniques without a NASA-Approved Protocol

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<tr>
<td>E-beam</td>
<td>Low exposure time</td>
<td>Facility Cost</td>
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<td>Sterilization of polymers</td>
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<td>High dose necessary</td>
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<td>Ozone generation</td>
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<td>Carbon Dioxide</td>
<td>Low Temperature</td>
<td>Surface cleaning</td>
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<td></td>
<td>Time</td>
<td>Non-hydrocarbon group</td>
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<td></td>
<td>Not Toxic or Corrosive</td>
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<td>Possibility to clean MEMS and CMOS</td>
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Conclusions
Technique Chosen for Development

• The team chose gamma irradiation sterilization as the next technique to develop into a standard protocol for NASA
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract through JPL’s Research and Technology Development Strategic Initiative Program. The JPL team contributing to this study were: Fei Chen, Raffaele Gradini, Laura Newlin, and Richmund Tan.