Far-UVC light to reduce microbial bioburden during spacecraft assembly

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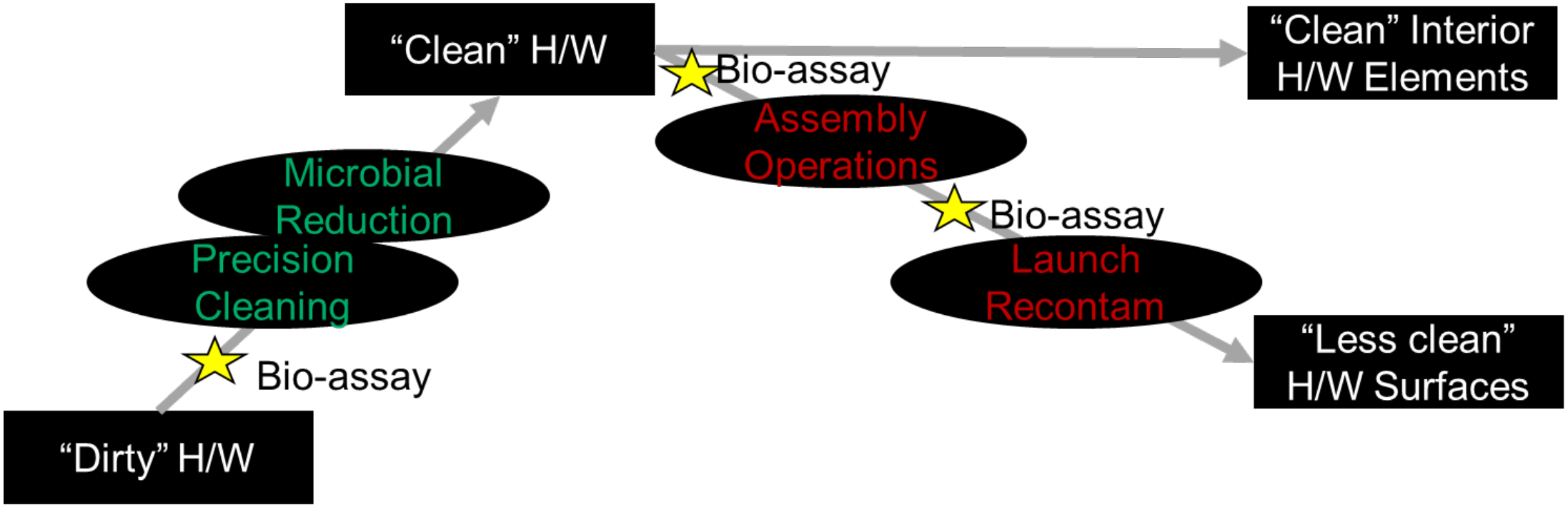
A role for far-UVC

- Current methods for microbial reduction do not mitigate on-going microbial contamination associated with assembly and launch activities



What is far-UVC?

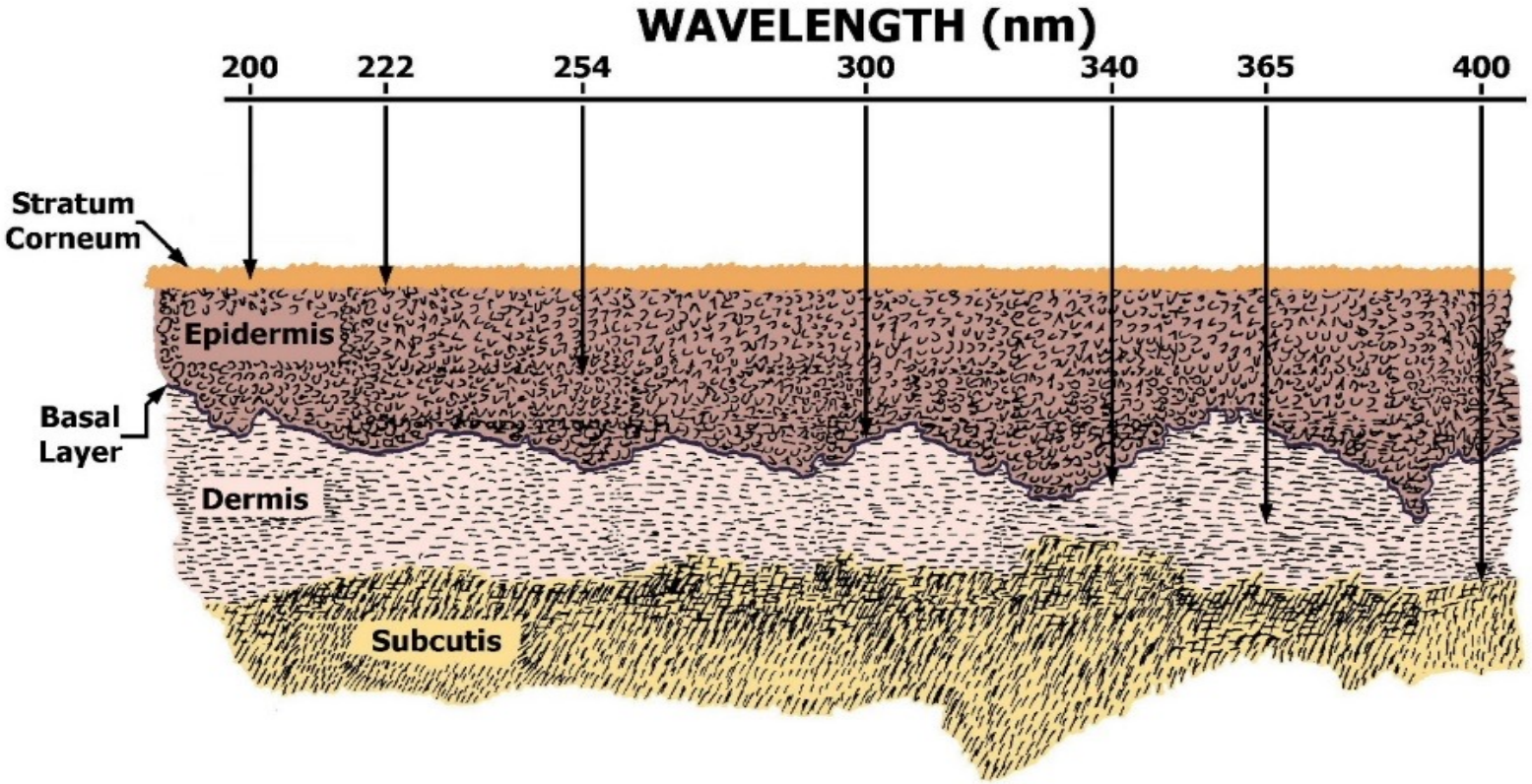


Image adapted from Sliney & Wolbarsht, 1980

- Far-UVC sources are limited
  - KrCl excimer lamps at 222 nm – filtered for safety!
  - LED technology for far-UVC is still on the horizon

Key questions with far-UVC:

- Is it safe?
- Does it work?

Far-UVC safety

- Biophysical principals
- Growing number of peer-reviewed studies
- Existing national and international regulatory frameworks

Biophysics of Far-UVC safety

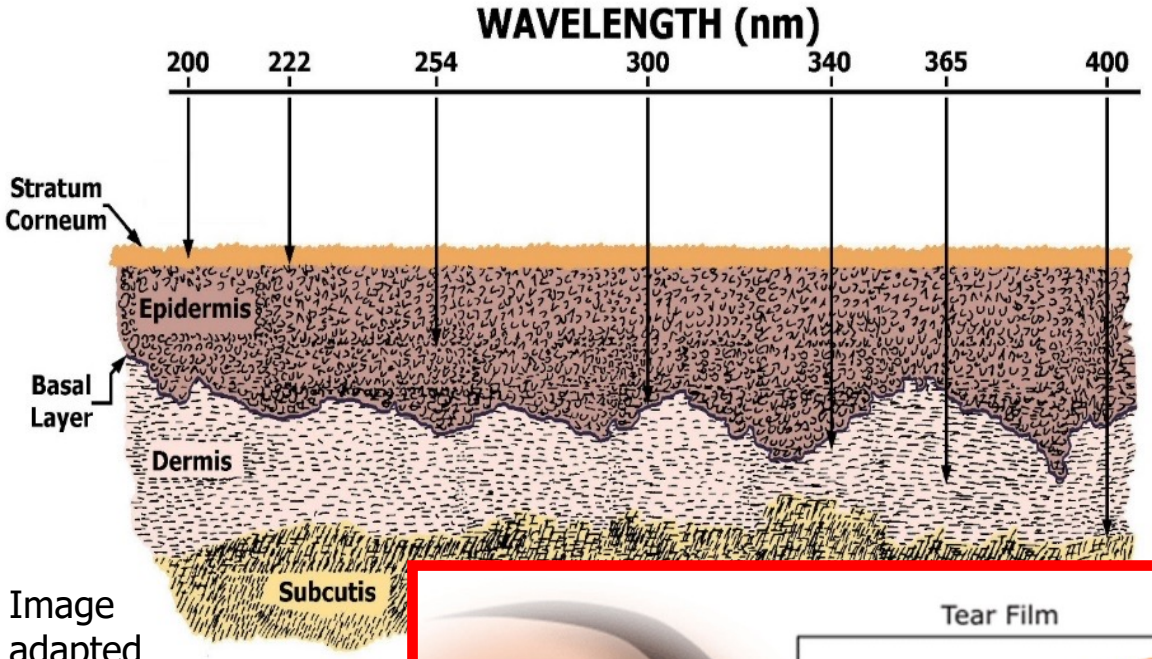
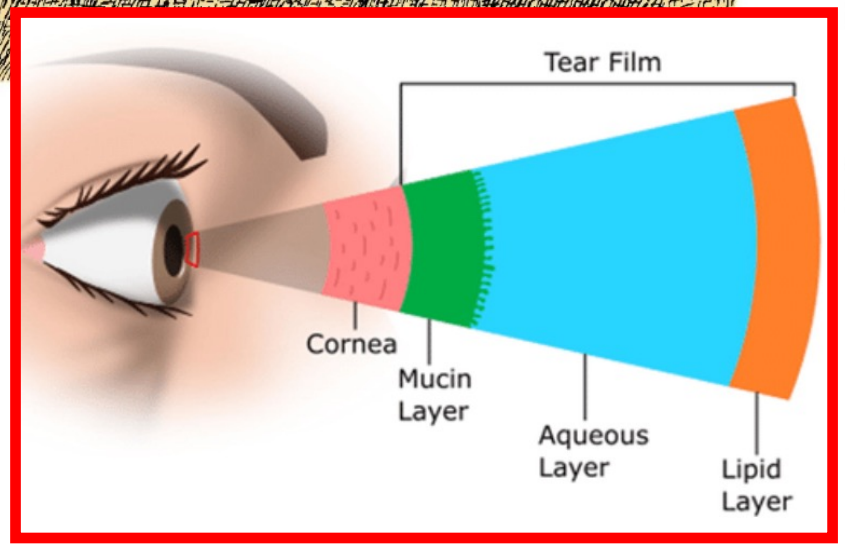
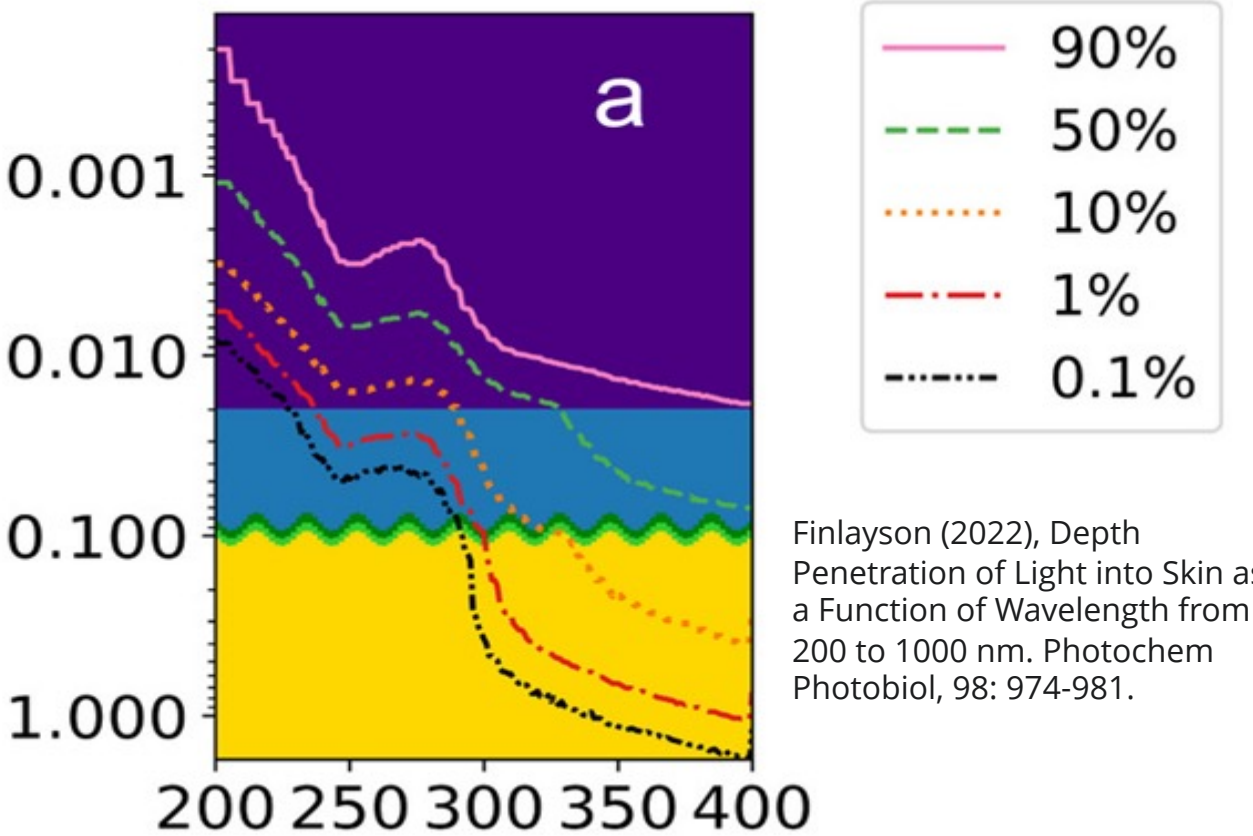


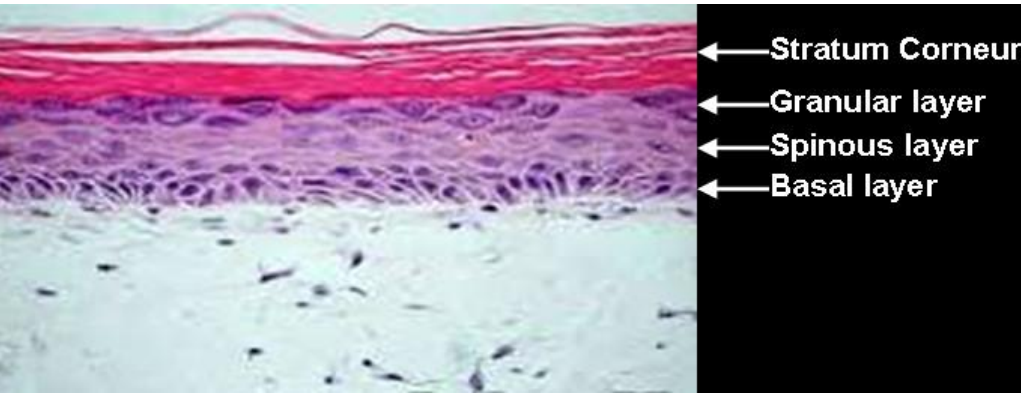
Image adapted from Sliney & Wolbarsht, 1980

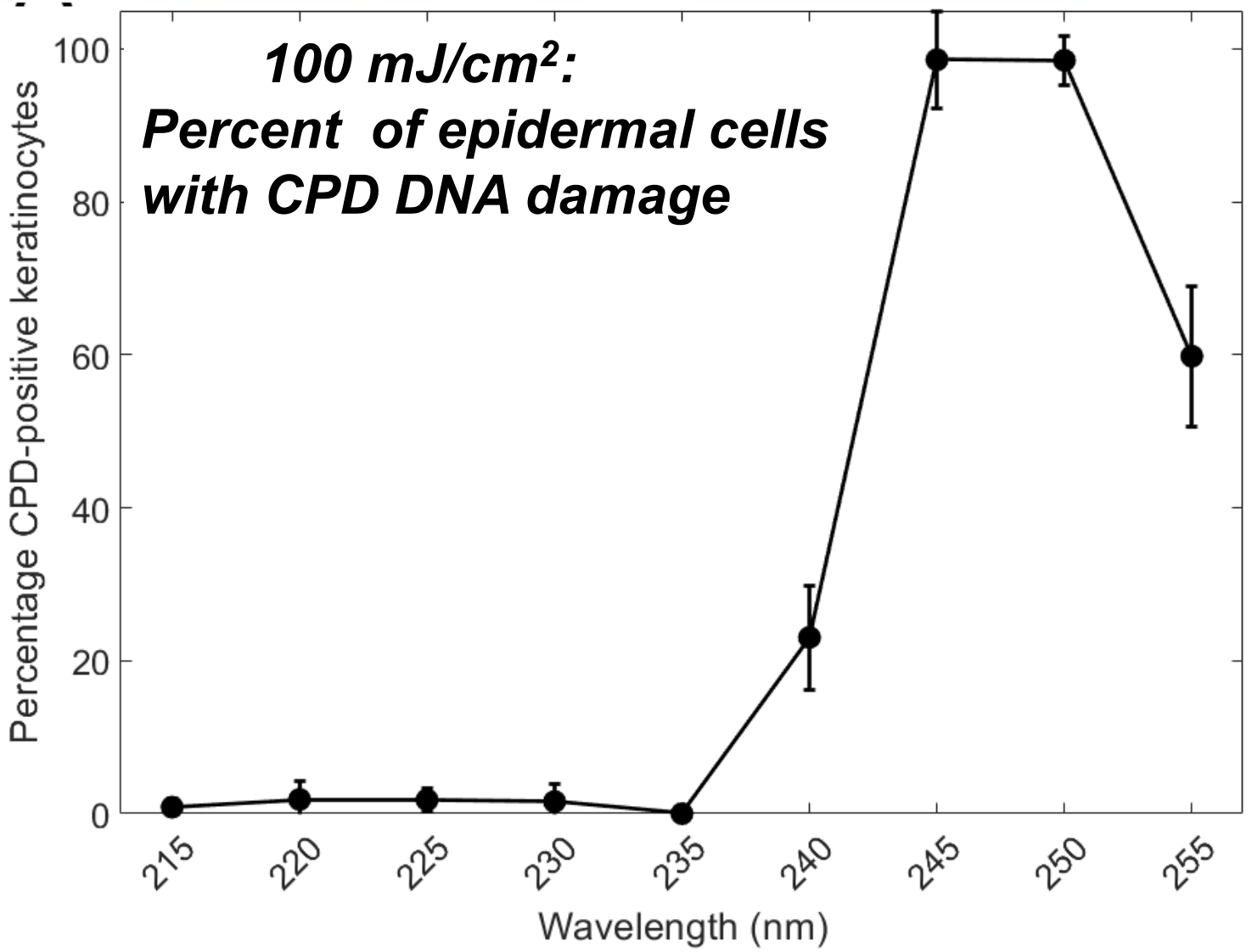




Finlayson (2022), Depth Penetration of Light into Skin as a Function of Wavelength from 200 to 1000 nm. Photochem Photobiol, 98: 974-981.

Human skin model for far-UVC safety

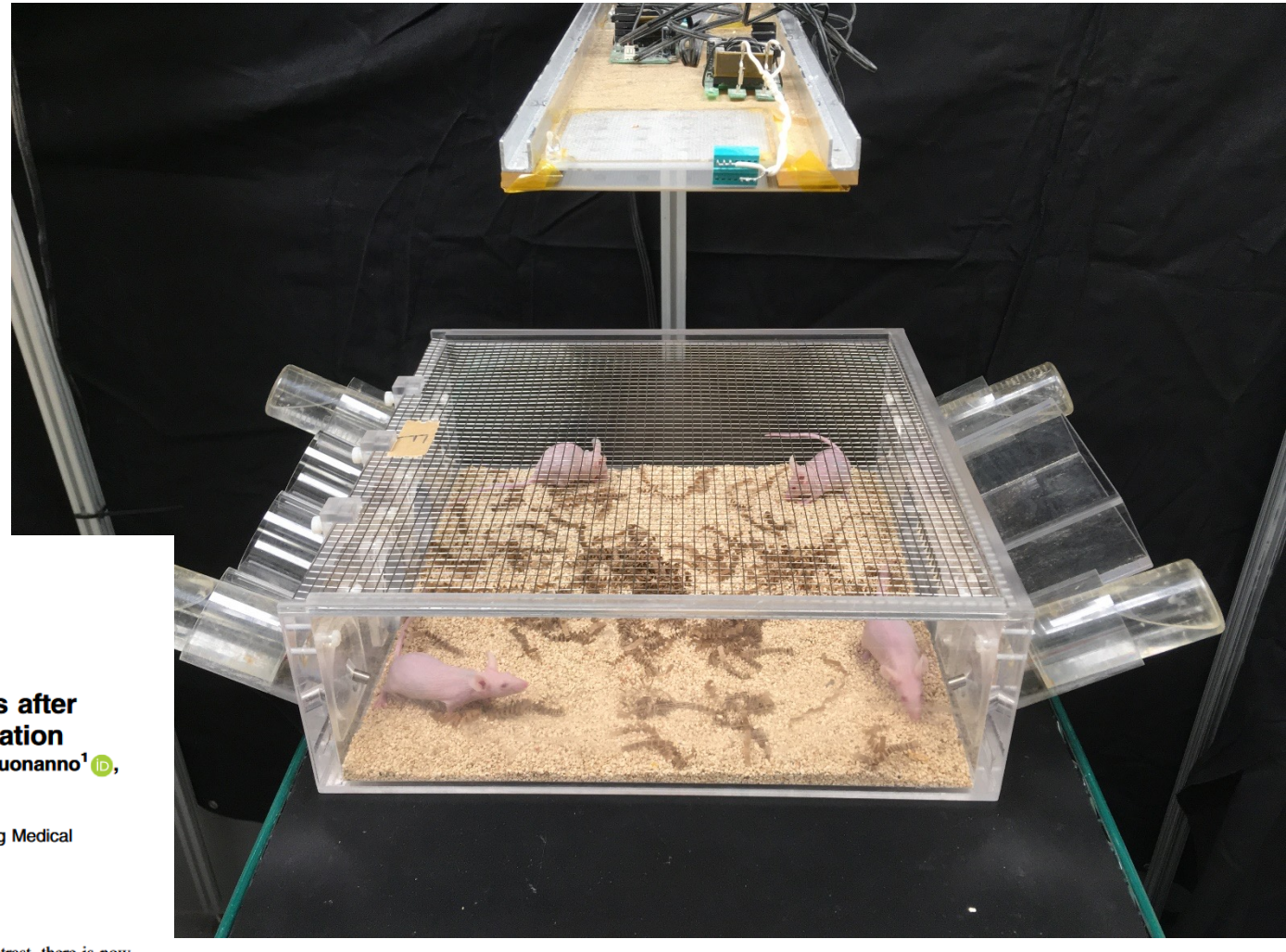




Welch et al 2022

Long-term far-UVC safety

- Commercial 222 nm filtered excimer lamps
- 96 hairless SKH-1 mice given continuous daily exposures: (0, 50, 125, 400 mJ/cm^2 / day)
- 8 hours / day, 5 days / week
- 66 weeks total



Photochemistry and Photobiology, 2023, 99: 168–175

Research Article

No Evidence of Induced Skin Cancer or Other Skin Abnormalities after Long-Term (66 week) Chronic Exposure to 222-nm Far-UVC Radiation

David Welch[1,†,*], Norman J. Kleiman[2,†], Peter C. Arden[2], Christine L. Kurylа[2], Manuela Buonanno[1], Brian Ponnaiya[1], Xuefeng Wu[1] and David J. Brenner[1]

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ABSTRACT

Far-UVC radiation, typically defined as 200–235 nm, has similar or greater anti-microbial efficacy compared with con-

acute damage to the skin and eye (2,3). By contrast, there is now compelling evidence that far-UVC radiation, commonly defined as wavelengths between 200 nm and 235 nm, is likely to be safer for direct human exposure (4–8), and also exhibits similarly

Welch et al 2023

Safety Recommendations

- American Conference of Governmental Industrial Hygienists (ACGIH)
- Threshold Limit Values (TLV)

222-nm values

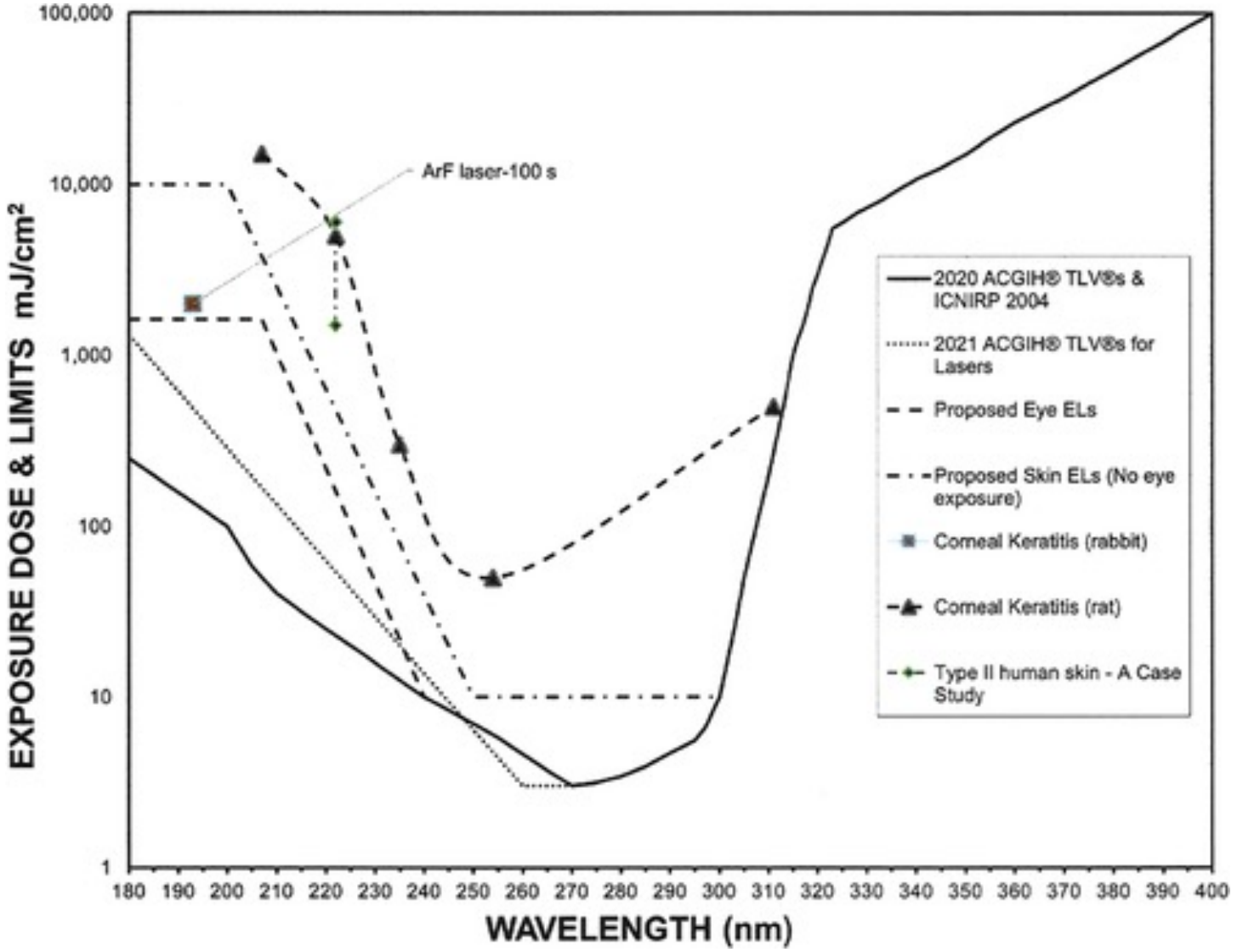
ACGIH (pre 2022) & ICNIRP

23 mJ/cm²/ 8-h day

ACGIH (2022)

Eye: 160 mJ/cm²/8-h day

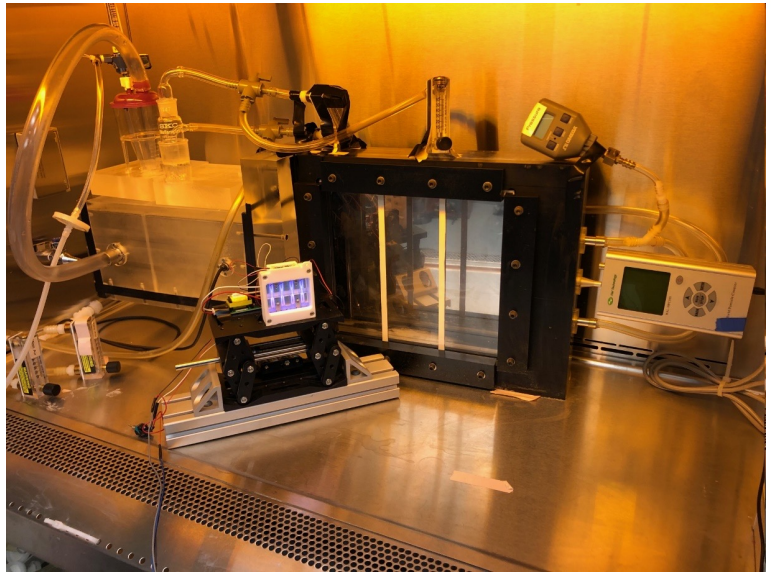
Skin: 480 mJ/cm²/8-h day

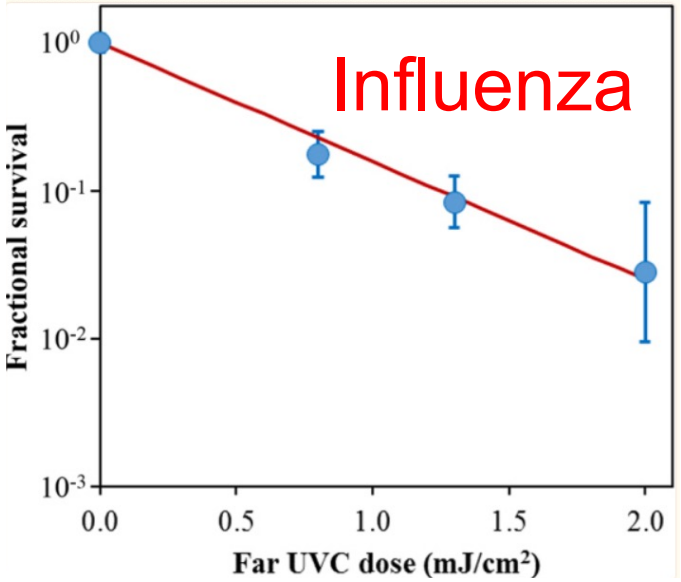


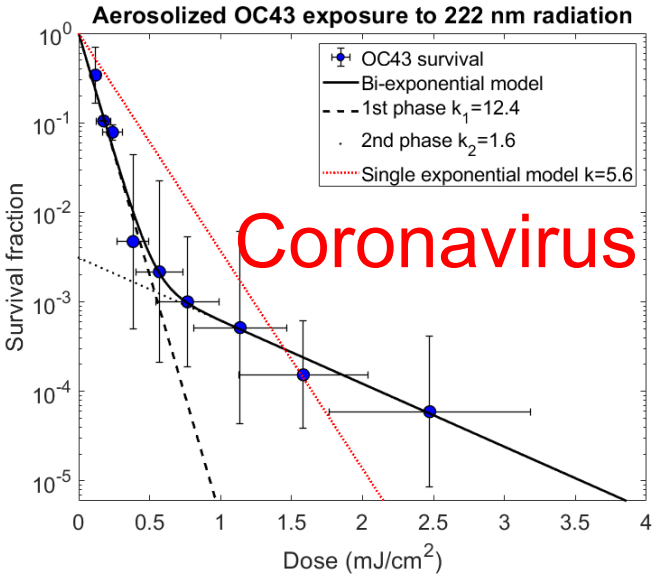
Key questions:

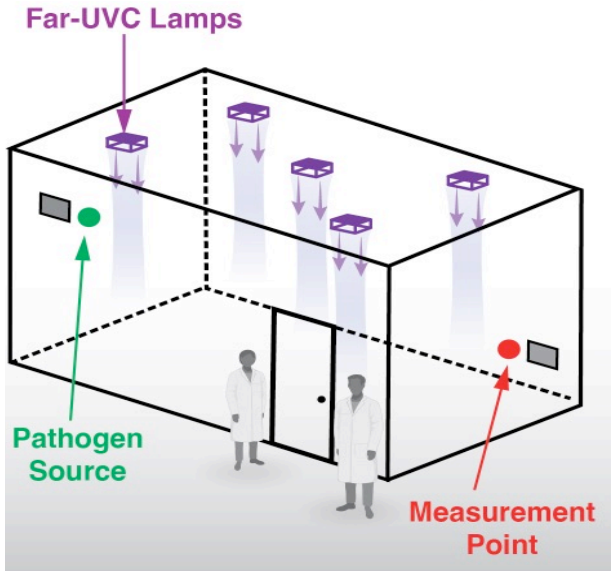
- Is it safe?
- Does it work?

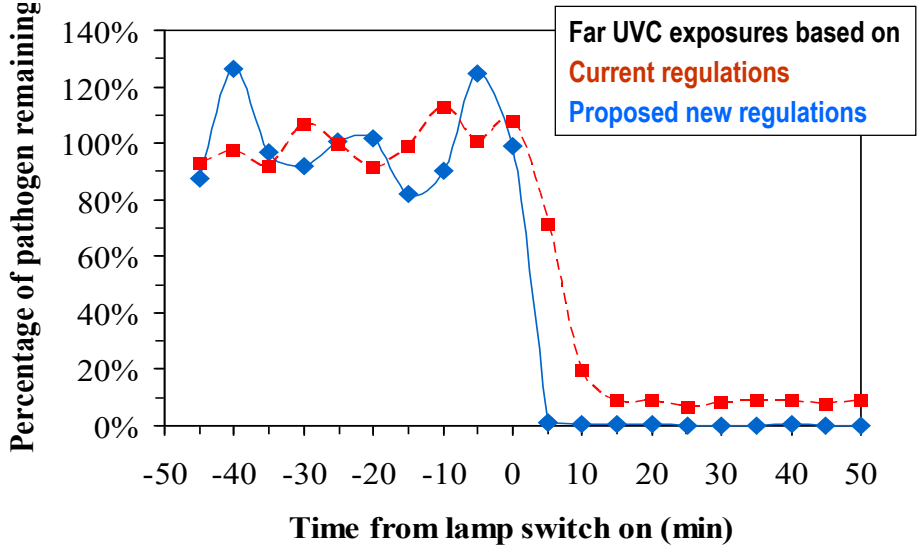
Far-UVC inactivation of aerosolized viruses and bacteria









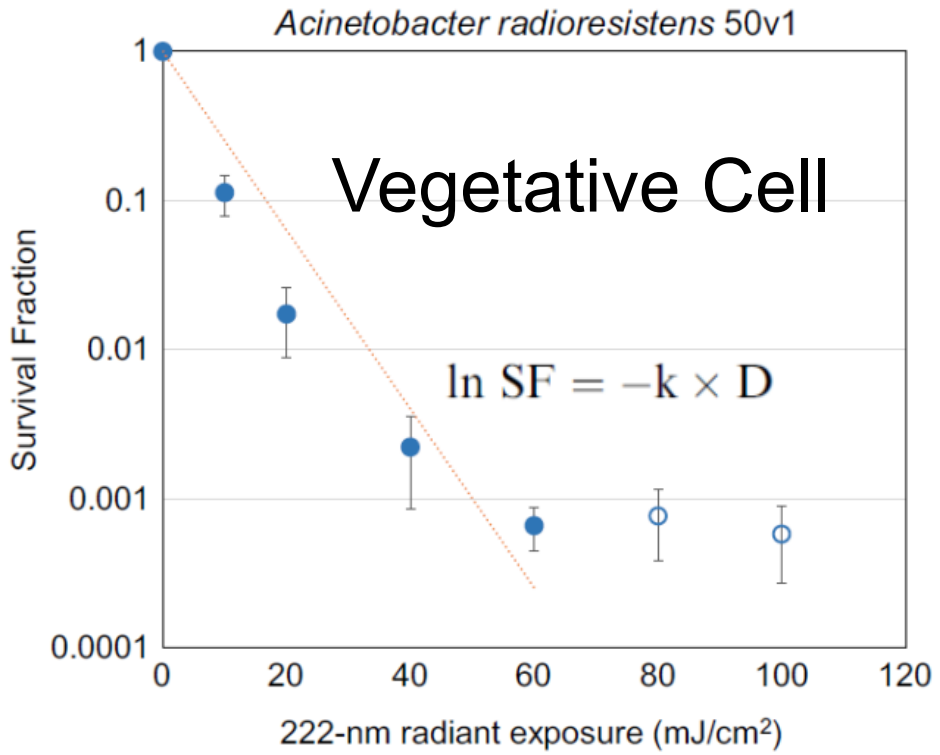


Far-UVC efficacy testing for Planetary Protection

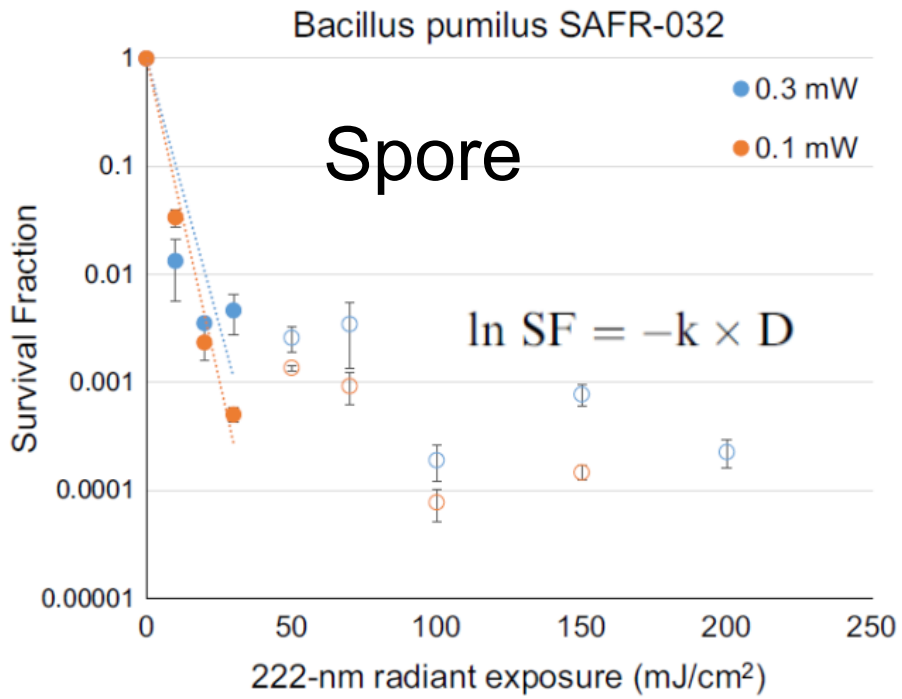
- Test microbes:
  - Acinetobacter radioresistens 50v1 (vegetative cells)
    - Isolated from cleanroom surfaces where the Mars Exploration Rovers were built
    - Previously shown to tolerate desiccation, hydrogen peroxide, and radiation
  - Bacillus pumilus SAFR-032 (spores)
    - Isolated from the spacecraft assembly facility at JPL
    - Previously shown resistance to desiccation and UV

Far-UVC efficiently inactivates bacteria on surfaces

- Expose on aluminum coupons using a filtered KrCl lamp (222 nm)



k= .14 cm²/mJ
D90 = 16.9 mJ/cm²

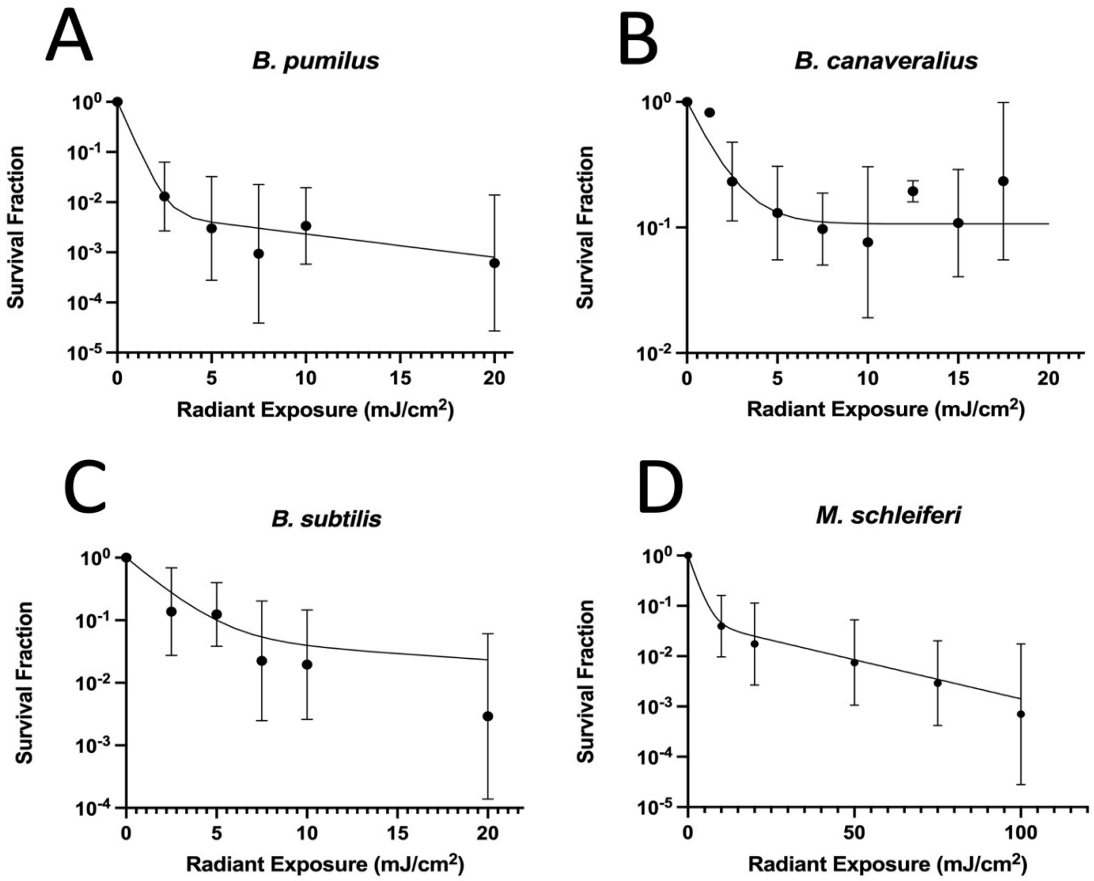


k= .23 cm²/mJ
D90 = 10.2 mJ/cm²

Testing hardy microbes

- *Bacillus pumilus* SAFR-032 (vegetative and spore)
- *Bacillus subtilis* (vegetative and spore)
- *Deinococcus radiodurans* (vegetative)
  - Not recovered from SAF yet
  - Polyextremophile (cold, dehydration, vacuum, and acid), very radiation resistant, including ionizing radiation (>>5 kGy)
- *Microbacterium schleiferi (*vegetative)
  - Isolated from SAF
  - Alkalophilic and high UV (254 nm) resistance
- *Bacillus canaveralius* 29669 (vegetative and spore)
  - Isolated from a spacecraft cleanroom environment in KSC
  - Highly tolerant to dry heat

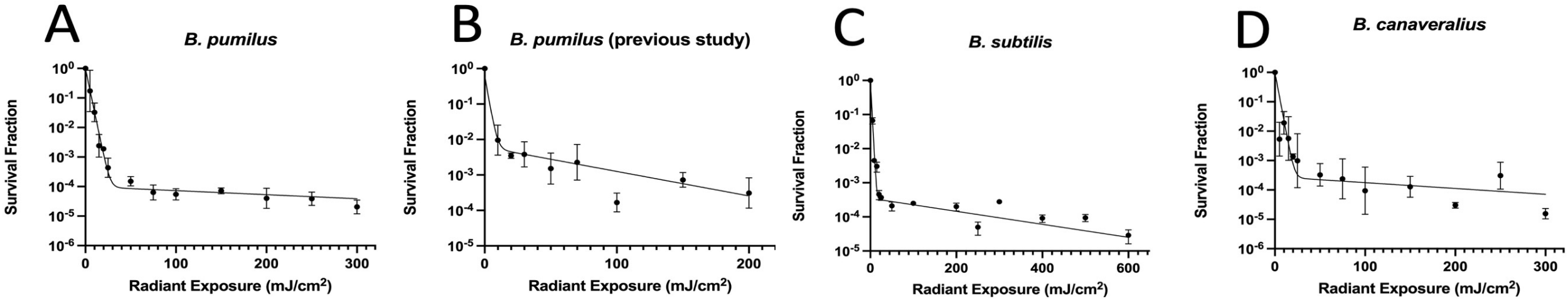
Far-UVC efficacy for vegetative cells



Species	$k_1 \pm$ SE (cm^2/mJ)	$k_2 \pm$ SE (cm^2/mJ)	D_{90} (mJ/cm^2)	f ± SE
B. pumilus	1.9 ± 6.8	0.11 ± 0.099	1.2	$6.8 \times 10^{-3} \pm 7.6 \times 10^{-3}$
B. canaveralius	0.72 ± 0.54	0.0 ± 0.038	3.2	0.11 ± 0.12
B. subtilis	0.57 ± 0.23	0.045 ± 0.14	4.0	0.058 ± 0.10
M. schleiferi	0.45 ± 0.42	0.036 ± 0.013	5.1	0.051 ± 0.046
†*A. radioresistens*	0.22 ± 3.3×10^{-3}	0.026 ± 1.4×10^{-3}	11	$6.1 \times 10^{-3} \pm 6.9 \times 10^{-4}$
D. radiodurans	0.021 ± 7.2×10^{-3}	$1.8 \times 10^{-3} \pm 1.0 \times 10^{-3}$	112	0.18 ± 0.097

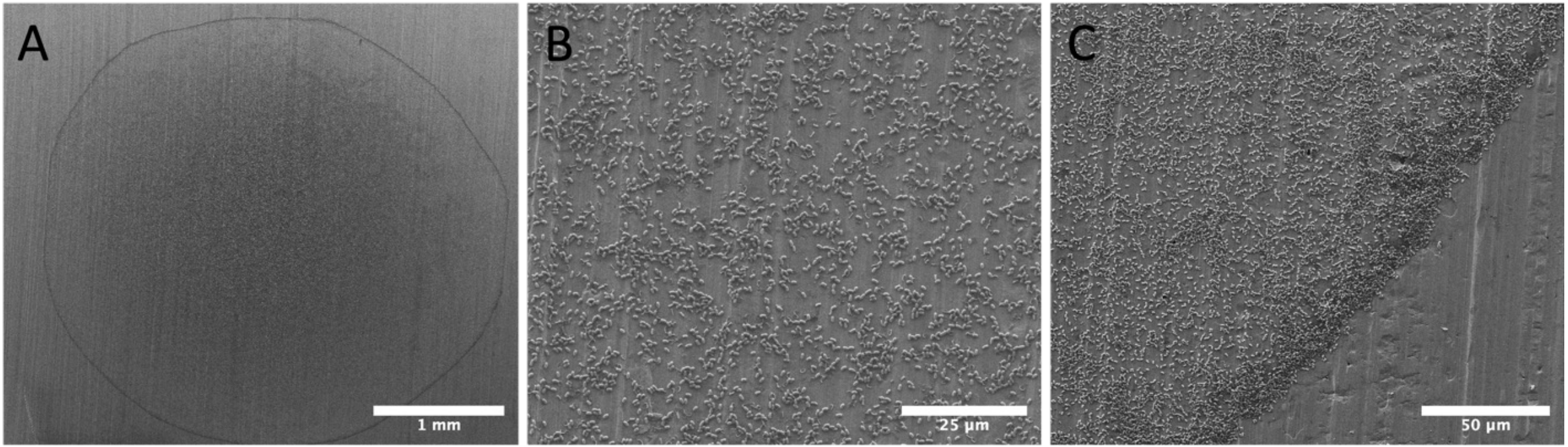
$$S = (1 - f)\, e^{-k_1 D} + f e^{-k_2 D}$$

Far-UVC efficacy for spores



Species	$k_1 \pm SE$ (cm^2/mJ)	$k_2 \pm SE$ (cm^2/mJ)	D_{90} (mJ/cm^2)	$f \pm SE$
B. subtilis	0.54 ± 0.031	$4.4\times10^{-3} \pm 5.5\times10^{-4}$	3.8	$3.5\times10^{-4} \pm 7.0\times10^{-5}$
†*B. pumilus*	0.48 ± 0.070	$0.016 \pm 2.5\times10^{-3}$	5.9	$6.3\times10^{-3} \pm 1.7\times10^{-3}$
B. canaveralius	0.38 ± 0.045	$4.6\times10^{-3} \pm 1.7\times10^{-3}$	6.1	$2.8\times10^{-4} \pm 1.3\times10^{-4}$
B. pumilus	0.34 ± 0.015	$3.2\times10^{-3} \pm 6.1\times10^{-3}$	6.8	$1.0\times10^{-4} \pm 2.0\times10^{-5}$

SEM images of spore exposure condition



Far-UVC efficacy summary

Species	Cell type	$k_1 \pm SE$ (cm^2/mJ)	$k_2 \pm SE$ (cm^2/mJ)	D_{90} (mJ/cm^2)	$f \pm SE$
B. pumilus	Vegetative	1.9 ± 6.8	0.11 ± 0.099	1.2	$6.8\text{x}10^{-3} \pm 7.6\text{x}10^{-3}$
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D. radiodurans	Vegetative	$0.021 \pm 7.2\text{x}10^{-3}$	$1.8\text{x}10^{-3} \pm 1.0\text{x}10^{-3}$	112	0.18 ± 0.097

Exploring material effects

- Spacecraft:
  - Aluminum
  - Kapton – polyimide
  - Stainless steel
  - Black and white paints
- Facility:
  - Flooring
  - Formica countertops
  - PVC sheets

Thank you

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Questions?