National Aeronautics and Space Administration

NASA

EXPLORE MOON to MARS

Plasma for Crewed Transit and Planetary Habitation

NASA – Kennedy Space Center

ICOPS (International Conference on Plasma Science)

Sept 12th-16th, 2021

Human Logistics of Moon-to-Mars

- **Human Life Support**
  - Atmosphere leakage
  - Gaseous compounds of concern
  - CO_2 control (<8%)
- **Waste Management**
  - Trash management
  - Human metabolic processes
  - Science waste
- **Food and Nutritional Needs**
  - Water recovery
  - Space crop production
- **Fuel Aspects**
  - Fuel production off planet

Table 7 – Crew Consumables Mass Results for Mars Mission

Item	Mass Required (kg)			
	600-Day Transit	400-Day Mars Vicinity	30-Day Contingency	*Total*
Oxygen	-	-	99	99
Nitrogen	4	3	1	8
Water	-	-	362	362
Food	4,394	2,930	220	7,544
Personal Stowage	200	-	-	200
Operational Supplies	100	-	-	100
Personal Hygiene Kit	29	22	-	51
Hygiene Consumables	190	126	10	326
Healthcare Consumables	216	144	11	371
Wipes & Towels	468	312	23	803
Trash Bags	26	18	1	45
Clothes	528	352	26	906
WC - fecal canisters	540	360	27	927
WC - urine prefilters	150	100	8	258
Total Mass	6,845	4,367	788	12,000

*Partially closed loop. Does not include spares or maintenance items. Basic operations only. [1]

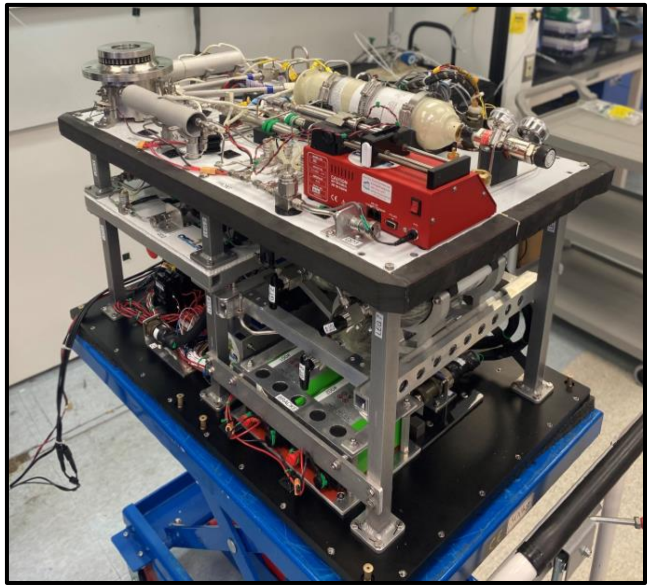
Current State-of-the-Art

- **Waste Management**
  - **De-orbit burn-up**
  - **“On-site” storage**

- **Nutritional Needs**
  - **Long-term storage**
  - **Resupply**

- **Fuel Production**
  - **Earth-based only**

- **Resupply Logistics**
  - **Sanitation**
  - **Food**



KSC Trash-to-Gas:

OSCAR

Orbital Syngas Commodity Augmentation Reactor

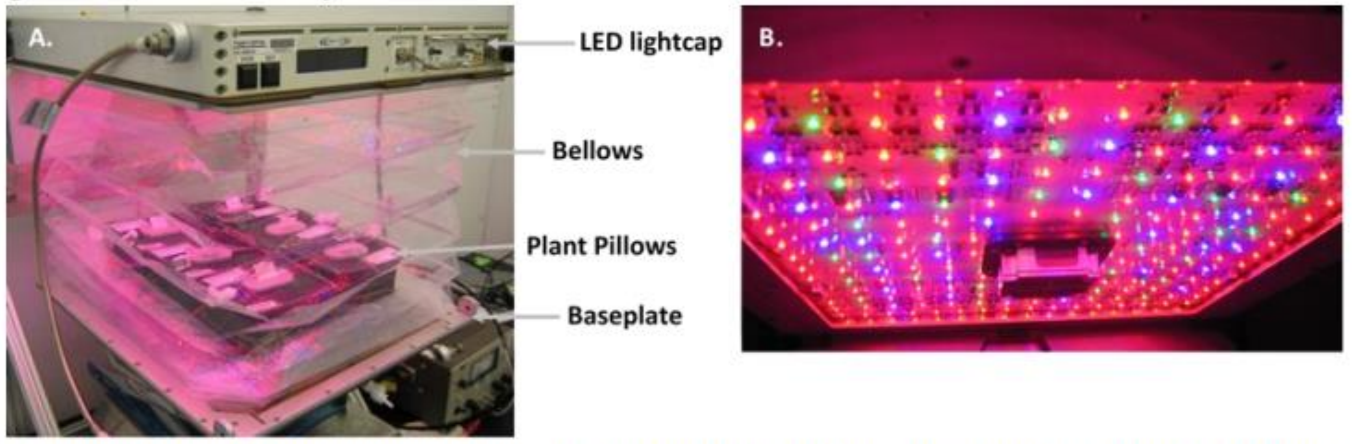


Figure 1. A) The Veggie vegetable production system, B) Close-up view of the Veggie lightcap.

Images of the Veggie vegetable production system taken from Conference paper. [2]

Plasma can be a versatile tool for crewed space exploration

Need for Plasmas in Space

Logistics of Waste Management

- Waste conversion processing
  - Mitigates need for resupply
- Electrical power and gases as consumable
- Abatement of gaseous VOCs
  - Possible reuse

Biohazard Mitigation

- Eliminate chemical storage and handling
- Reduce microbial risks
- Ensure reuse of 3D printed medical equipment

Space Crop Production

- Nitrogen fixation of water
- Microbial mitigation
- pH adjustments
- Growth enhancement

In-Situ Resource Utilization

- On-demand advanced chemical processing

Plasma Projects at Kennedy Space Center

- **Waste Gasification**
  - **Reduce waste volume**
  - **Gaseous resource production**

- **Plasma assisted nutrient recovery via ash leaching**
  - **Closing the Space Crop Cycle**

- **Lunar Regolith Reduction**
  - **H_2 plasma for oxygen extraction**

- **Plasma Agriculture (sanitation)**
  - **Mitigate biohazards of seeds and produce**

- **Plasma activated water**
  - **Agriculture, sanitation, acid-base production**

- **Plasma cleaning**
  - **Space systems processing and production**

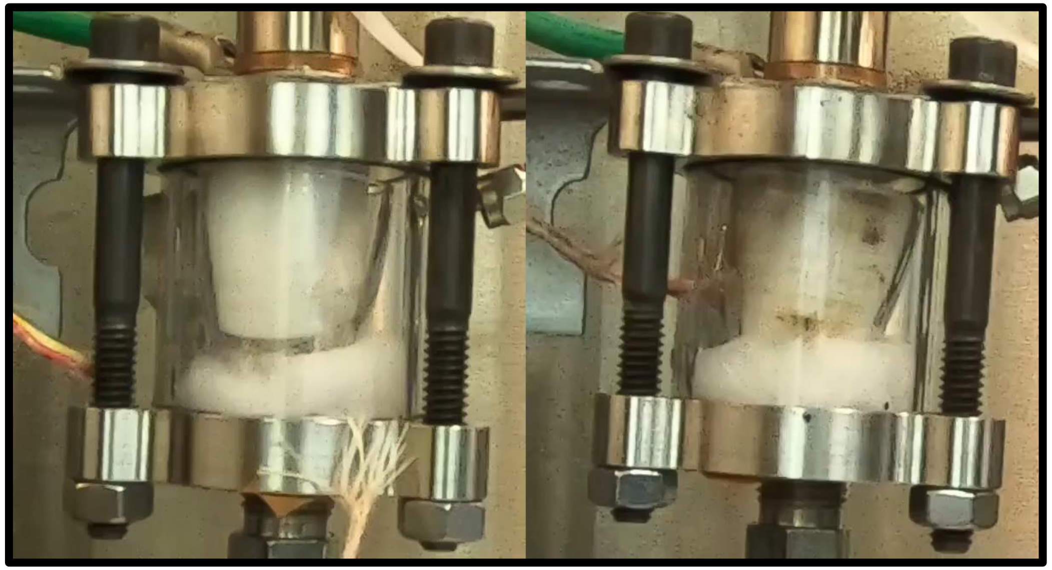
Planning to continue plasma work at KSC

Plasma Waste Gasification

- Current practice
  - Apollo
    - Waste “Dump” Sites
  - Artemis
    - Developing Trash-to-Gas Systems
    - TCPS (Trash Compacting and Processing System)
    - Mission Storage
  - ISS
    - Trash burn-up
    - Water Reclamation System

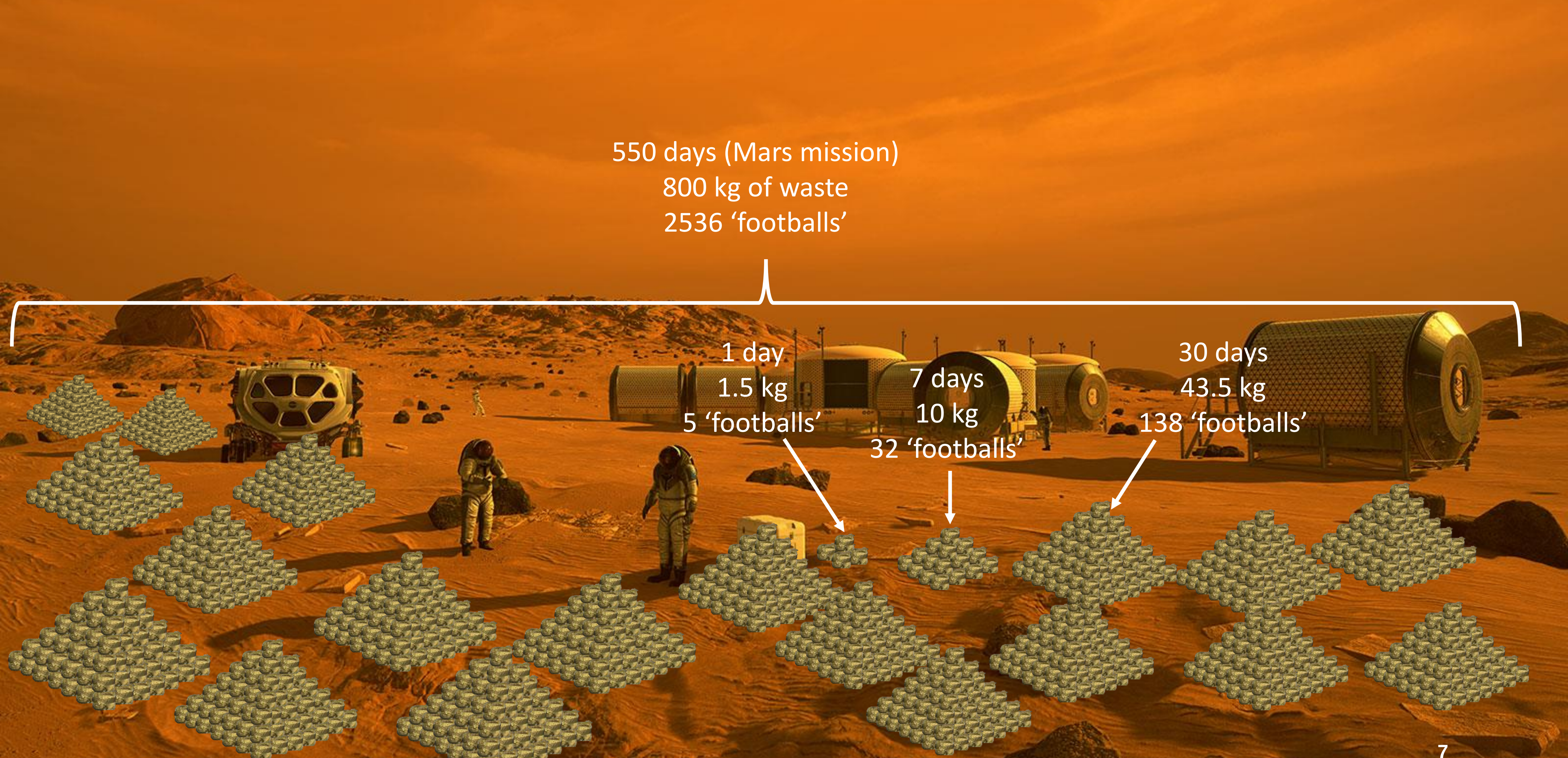
- Plasma as a solution
  - Electrical consumption ~ 200-400 Watts
  - Ability to recirculate gas (removal of commodity usage)
  - Able to achieve 74-87% gasification (air, CO_2 respectively) at KSC

Image from nasa.gov



Air-foam CO_2-foam

Plasma Waste Gasification: One Astronaut’s Trash Production

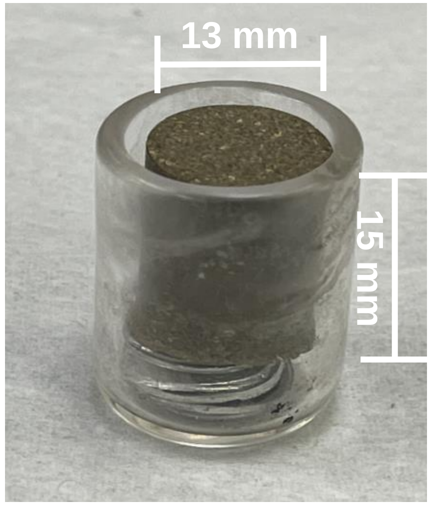


Slide Credit: Dr. Joel Olson; KSC Trash-to-Gas Team; ICES 2021 [3]

Plasma Assisted Nutrient Recovery Via Ash Leaching

- **Thermal plasma treatment**
  - **300 Watts**
  - **Thermal degradation**
  - **≈ 3g pellet size**
- **Closing the crop production cycle**
  - **Acid leaching remaining nutrients**
    - **K, Na, Ca, Mg, P**
- **Plasma treat with air, CO_2, N_2**
  - **Modify plasma parameters**
  - **Modify reaction chemistry**
  - **Explore different commodities**

CO_2 plasma plume



Crucible with pellet and Al shims

Experimental set-up

Plasma Processing

Air Plasma processed pellet

CO_2 Plasma processed pellet

Lunar Regolith Reduction

- H_2 plasma produces H^+ ions
  - Readily reduces oxides
  - Enables silicate reduction
  - H_2O -> O + H_2 via electrolysis
  - H_2 recycled
- Promising In-Situ Resource Utilization Technology

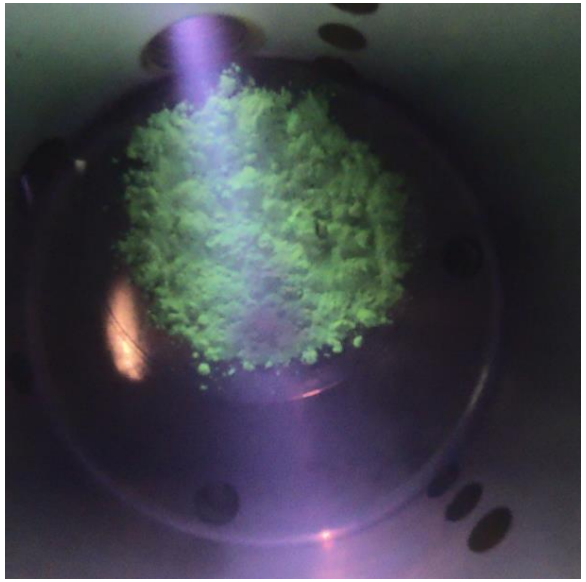
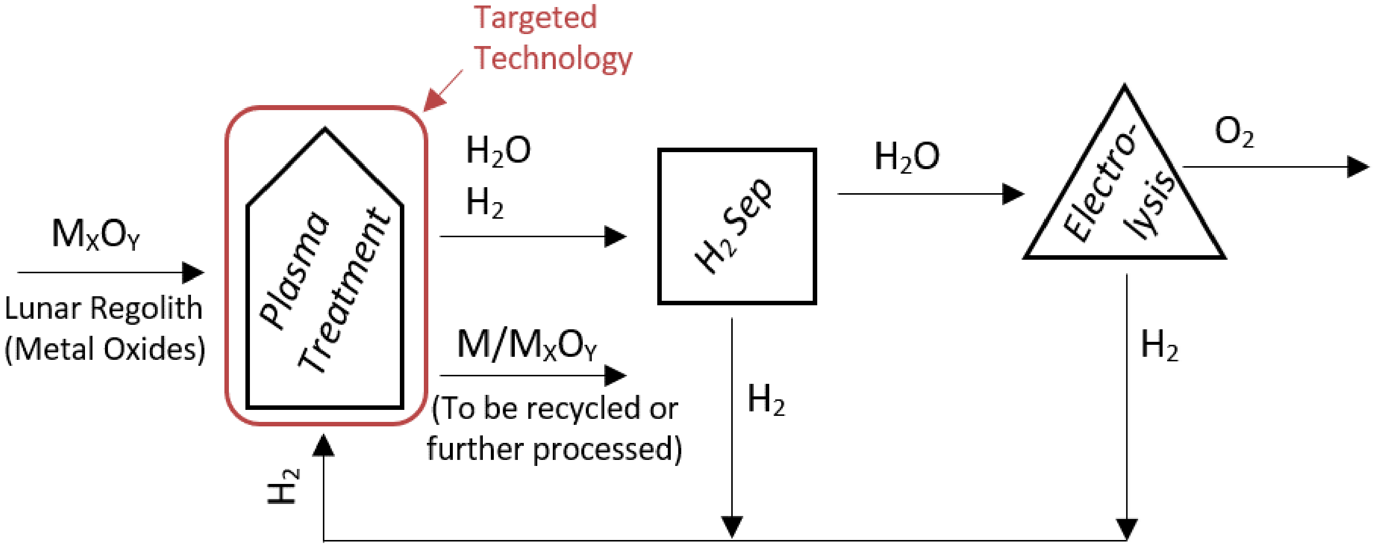


Image of regolith treatment with plasma



A schematic of the concept is shown above.

Agriculture: Sanitation

- **Plasma produces reactive oxygen and nitrogen species**
  - **In surrounding gas and at seed surface**

- **Oxygen species deactivate and reduce microbial loads**

- **Key reactions are localized to plasma-contact region**
  - **Oxygen species are short-lived**

- **RF, AC, and DC Jet plasmas used at KSC**

Image of air plasma discharge in RF sub-atmospheric system at 150mTorr.

Agriculture: Seed Treatment

- Reactive species can help enhance plant growth
  - Nitrogen act as direct fertilizer
  - Oxygen species force stress responses
  - Improve germination rates and times
- Timing of treatment important, can oversaturate and damage seeds

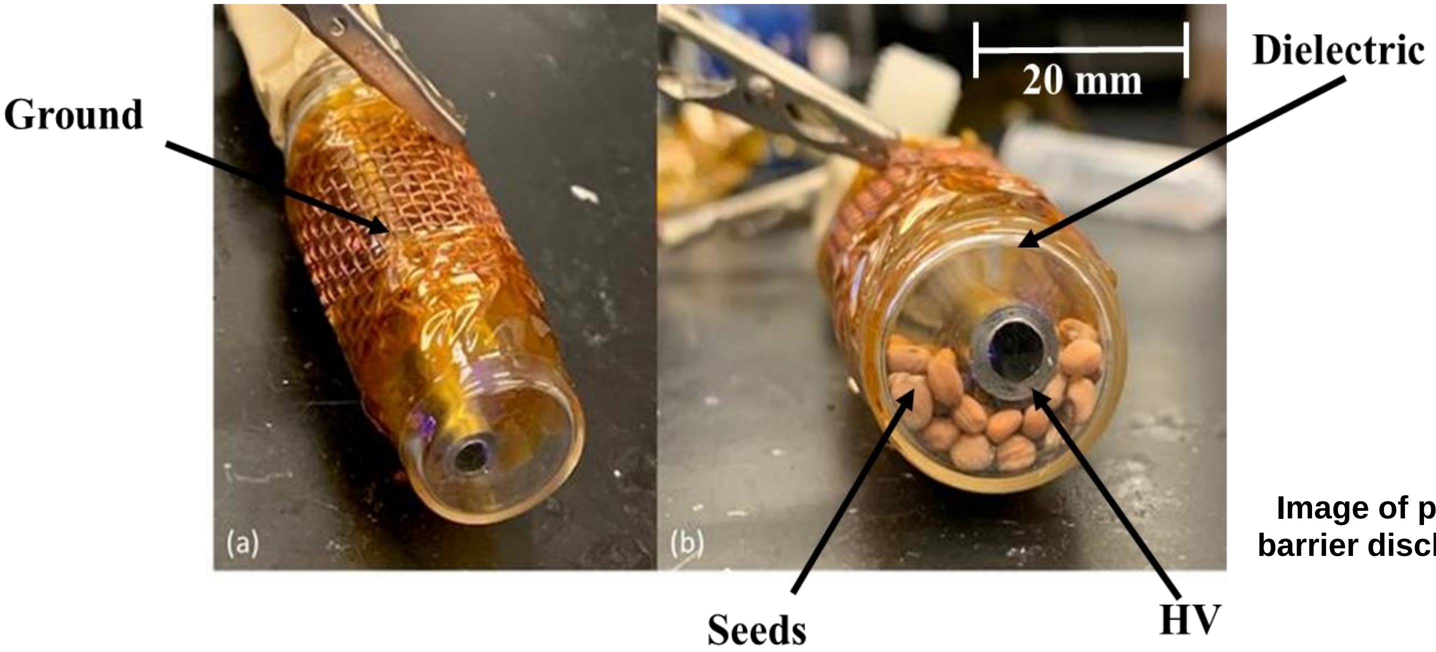


Image of packed bed dielectric barrier discharge of radish seeds

Plasma Activated Water

- **Ionizing different gases produces a plethora of reactive species**
  - **Argon increases UV**
  - **pH adjustments**
  - **Conductivity changes**

- **Air plasma interaction with H_2O**
  - **O_2 species**
    - **OH, O_3, H_2O_2, etc.**
  - **N_2 species**
    - **NO_2^-, NO_3^-, etc.**
- **Fixate nitrogen for Space Crop Production**
- **Acid-base production for chemicals**
- **Sanitizer production for biohazard mitigation**

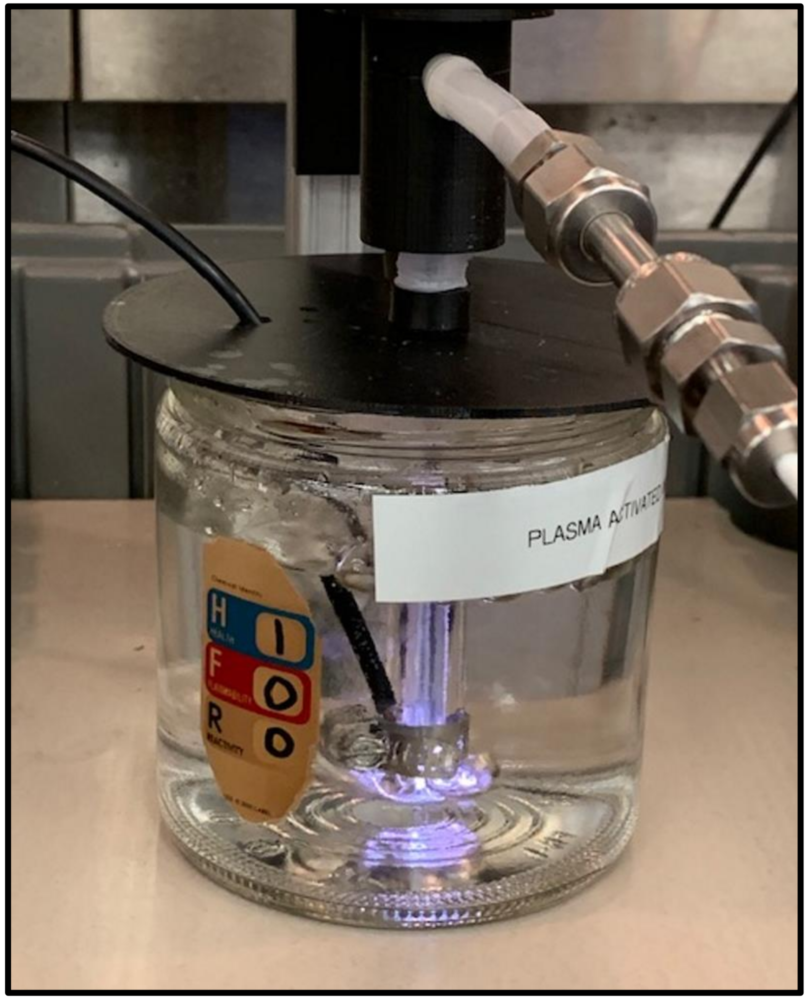


Image of argon plasma discharge in water.

Plasma Cleaning

- **Diener atmospheric plasma generator**
- **Grease and nonvolatile residue**
  - **Explore alternative precision cleaning**
    - **Environmentally friendly method**
    - **KSC uses blend of fluorinated and chlorinated solvents**
  - **Tested on coupons**
    - **300 Watt, air plasma Diener tech. PlasmaBeam**
    - **Varied height, speed, distance, step-over**
- **Did not meet most severe cleanliness standards for aerospace components**

[4] Image from Diener website

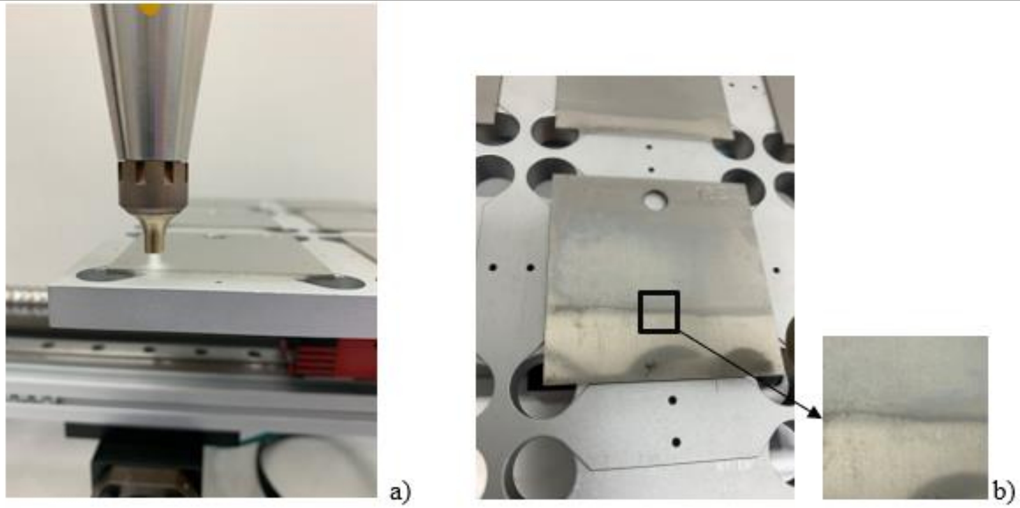


Figure 8: a) Plasma system during coupon cleaning with a 4 mm height; b) Cleaned (bottom) vs. contaminated (top) portions of the coupon

Images of the plasma cleaning system taken from NASA internal report.

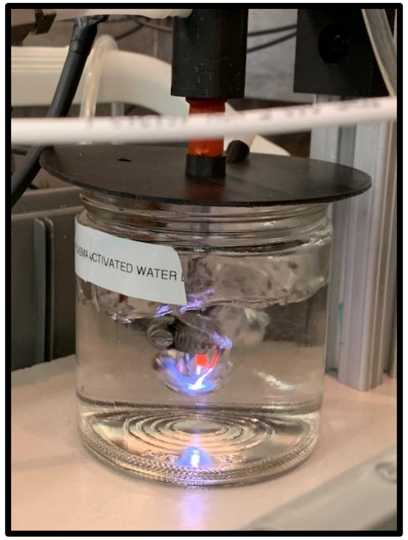
Challenges of Plasma in Space

- **Plasma not well understood**
- **Complex technology**
  - **Expensive or hard to replace components**
  - **Finicky processes and systems**
- **Electrically expensive**
  - **Scale up of processing can be costly**
- **Lacking electrical infrastructure**
  - **Electrical grounding and EMI**
  - **Dissipation of charge build-up**

CO_2 Jet in air

N_2 DC ‘Torch’

N_2 Pellet Processing



DC Argon Jet

AC Argon Jet

Waste Management Financial Comparisons

- **Power aboard ISS and Commercial Cost – Waste Gasification Example**
  - **44 kW aboard the ISS**
  - **NASA proposed Private Astronaut Mission (PAM) cost ($42 per kW-hr) – (June 2019)[5]**
  - **Trash disposal on ISS ($3,000 per kg with 35 kg max per company per year)[5]**

Feedstock Gas	Conversion %	Power (W)	Time/gram (sec)	[6] $/kg (Earth)	$/kg (ISS)
Air	88.74	200	101	0.59	236.65
CO_2	74.39	300	242	2.10	846.89

$$\text{External Handling: } 35\ kg\ (PAM)\ x\ \frac{\$3{,}000}{1\ kg} \approx \$115{,}000\text{: } 35kg\ for\ private\ company$$

Or

$$Air\ Plasma\text{: } 35\ kg\ (PAM)\ x\ \frac{\$236.65}{1\ kg} \approx \$8300\text{: } 35kg\ for\ private\ company$$

$$CO_2\ Plasma \approx \$30{,}000\text{: } 35\text{kg}$$

Crop Production and CO_2 Expenses

- **Shipping Logistics Examples for Comparable items**

  - **Hoagland nutrient solution**
    - ≈ $60,000 per kg, then dilute with water

  - **florikan: polymer coated, controlled release fertilizer (100-180 days)[7]**
    - Different polymer fertilizer required for each plant type

  - **Prosan ® wipes for sanitation**
    - 10 wipes per produce harvest
    - 120 ct/box ≈ 0.786 kg -> $21,000 ≈ 12 ‘sanitations’

  - **CO_2 scrubbing Unit**
    - Lithium hydroxide need replaced over time
    - 450 lbs unit = 202 kg = $552,000 ‘shipping’ cost
    - Less reliance on a single unit

Plasma technologies could mitigate resupply needs

The Moon and Beyond

- **Logistics for Lunar Missions and Operations**
  - **Power Requirements**
  - **Infrastructure volume**
  - **Resupply chains**

- **Logistics beyond LEO, Gateway, and Lunar Operations**
  - **Price increases for Mars transit per kg**
  - **Chemical storage and shelf-life**

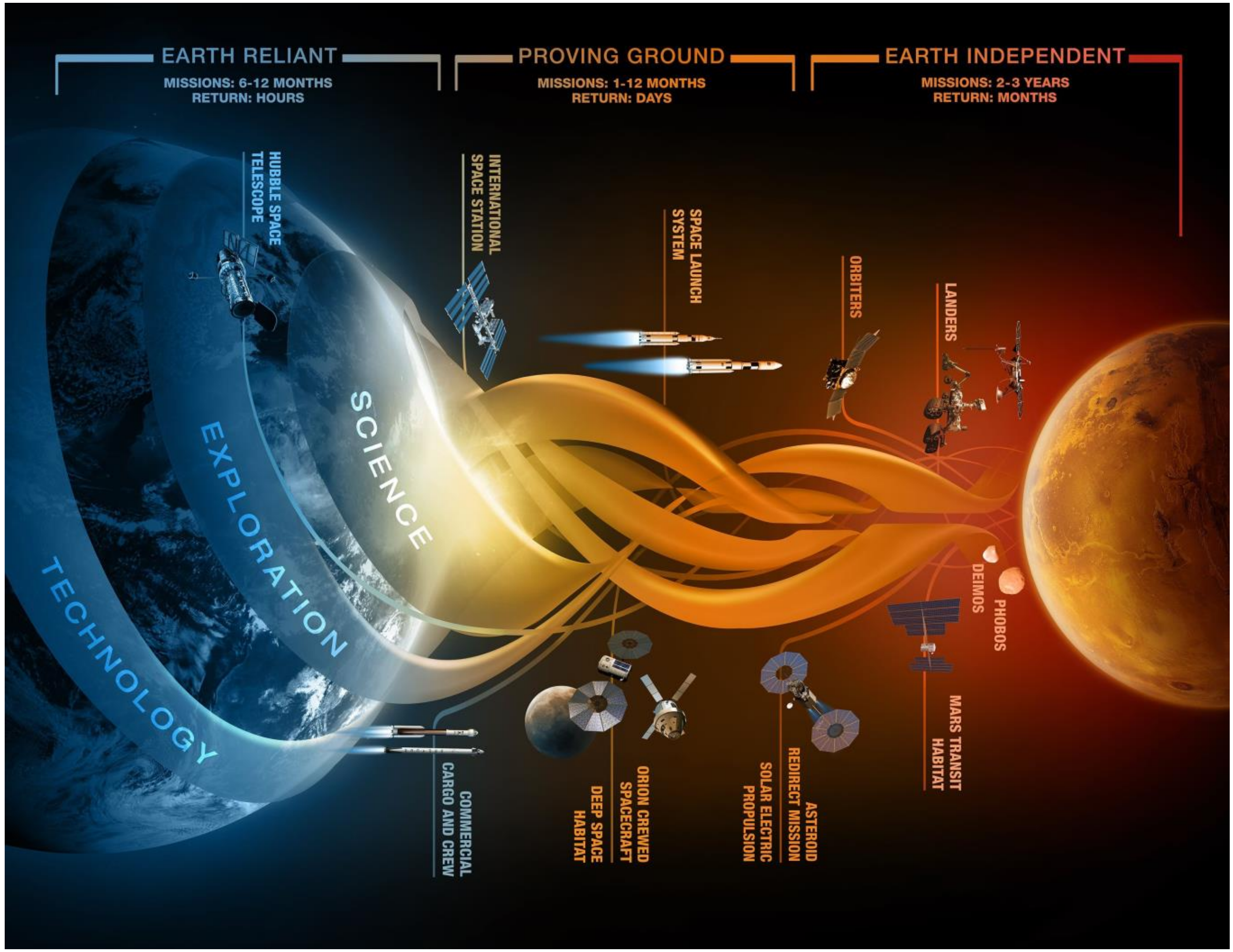


Image from nasa.gov

Technology Gaps for Plasma to Address

- Biofilm Mitigation
  - Water systems
  - Hydroponic systems
- Dusty plasma for lunar surface operations
  - Plume effects
  - Dust cleaning of panels and equipment
- Sanitation
  - 3-D printed items
  - Medical equipment
- Space Crop Productions
  - Plasma activated water
  - Seed and produce treatment
- Environmental Control and Life Support Systems
  - Brine Processing
  - VOC removal (gas/liquid)

NASA Technology Taxonomy - 2020

Image from nasa.gov

Concluding Remarks

Plasma in Space

- Paradigm shift for life support systems
  - Advance processing with little to no consumables

- Pioneering new technologies
  - Not yet developed for space applications
  - Development now leads to infusion into crewed missions

- Break away from traditional chemical production means
  - New off-planet manufacturing
  - Less reliance on industrial processing and infrastructure

Plasma processes are cost-effective solutions in extra-terrestrial environments to support human life and exploration

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References

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[2] G. Massa, R. Wheeler, R. Morrow, and H. Levine. “Growth Chambers on the International Space Station for Large Plants,” International Symposium on light in horticulture. East Lansing, MI May 2016

[3] J. Olson, D. Rinderknecht, D. Essumang, M. Kruger, C. Golman, A. Norvell, and A. Meier.. “A Comparison of Potential Trash-to-Gas Waste Processing Systems for Long-Term Crewed Spaceflight,” 50th International Conference on Environmental Systems. July 12th, 20201. (Virtual)

[4] Diener electronic – plasma treatments - Plasma.com ; https://www.plasma.com/en/ (accessed Aug. 10th, 2021)

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[7] florikan company website. https://www.florikan.com/ (accessed Aug. 11th, 2021).

Questions?