ARCHITECTURE FOR A FARM IN A MOON VILLAGE WITH IN-SITU MATERIALS FOR INFRASTRUCTURE

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(Image Credit - ESA/Foster + Partners)

Outline

- **Coauthors**
- **Moon Village Association**
- **Moon Farm Layout**
- **3D Printing with Regolith and Binder**
- **Biopolymers from Algae and Self-Replicating Greenhouse Units**
- **Carbon Sources on the Moon**
- **Future Work**
- **Summary**

Coauthors

- **James D. Burke, The Planetary Society, Pasadena, CA**
- **Robert P. Mueller, NASA KSC, Kennedy Space Center, FL**
- **Nathan J. Gelino, NASA KSC, Kennedy Space Center, FL**
- **Bradley C. Buckles, The Bionetics Corporation, Kennedy Space Center, FL**
- **Daniel V. Tompkins, DIY Service LLC (DBA GrowMars), Tampa, FL**

What is the Moon Village Association?

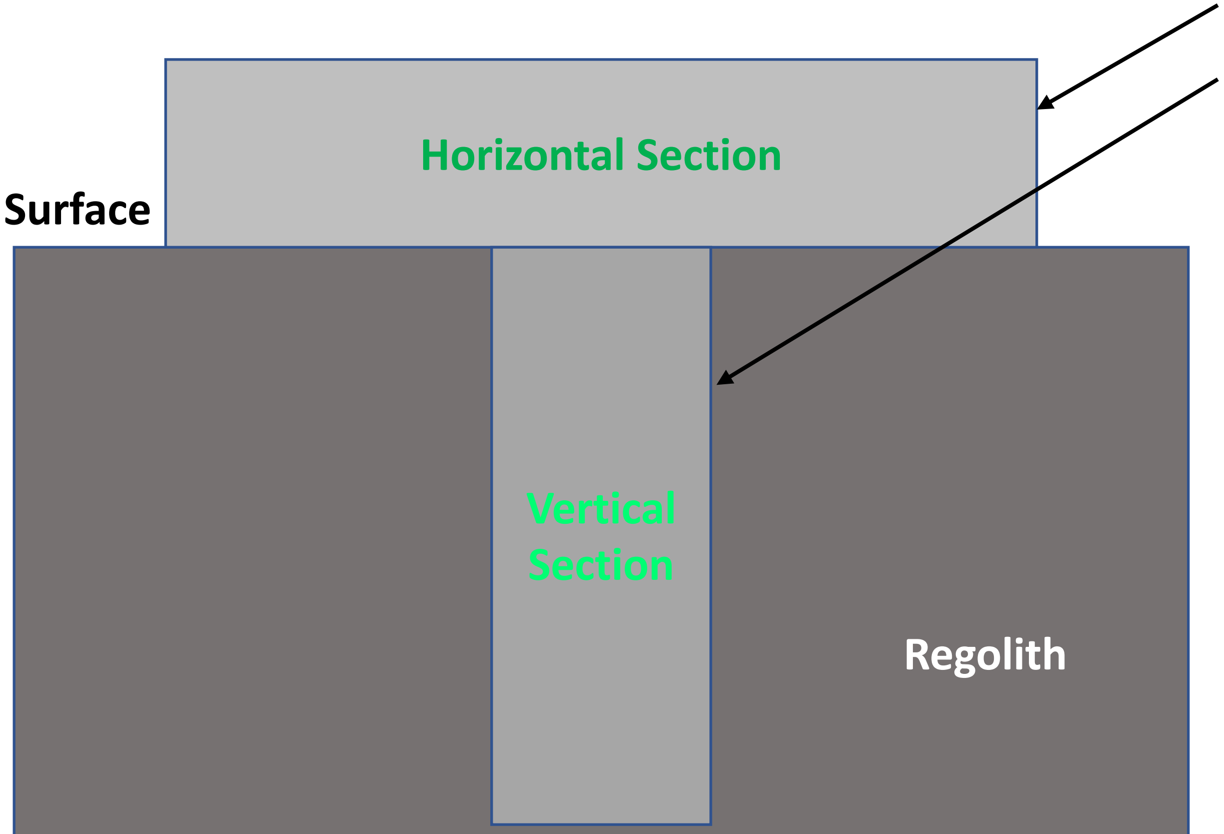
NOT a particular design of the Moon Village

(Image Credit - ESA/Foster + Partners)

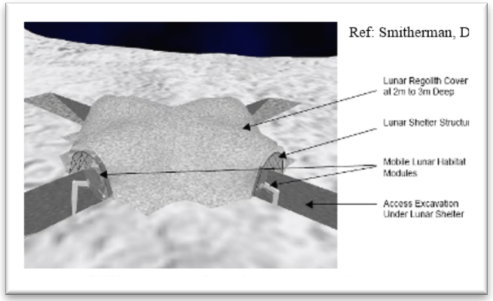
- The Moon Village Association (MVA) is an NGO based in Vienna
- Major goal is an informal forum for global stakeholders interested in the development of the Moon Village
- The MVA fosters cooperation for existing or planned global moon exploration programs
  - ~220 members from more than 39 countries and 25 Institutional members
- MVA partners with non-space organizations to promote international discussions and formulation of plans to foster the implementation of the Moon Village and is creating international, national and regional networks to engage civil society around the world.
- https://moonvillageassociation.org/

What does a Moon Village farm look like?

- Part of the farm lies horizontally on the surface
- Part of the farm is buried vertically below the surface



[See Mueller, Robert P., and Robert H. King. "Trade study of excavation tools and equipment for lunar outpost development and ISRU." AIP conference proceedings. Vol. 969. No. 1. AIP, 2008 for a candidate architecture to establish a lunar outpost that includes in-situ resource utilization (ISRU).]



Habitats with 2-3 m of Regolith Shielding

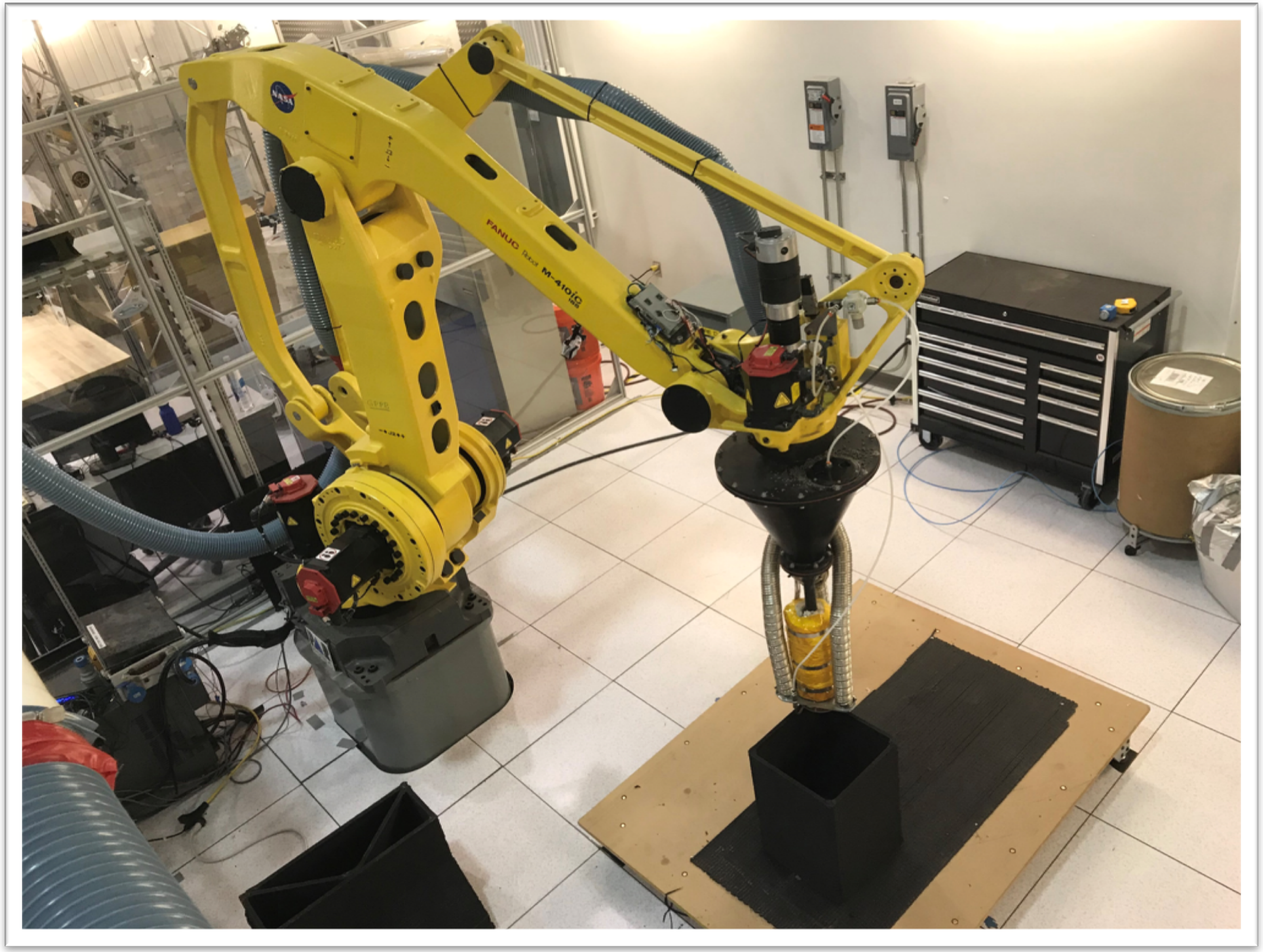
(Figure Credit, Silverman D., V. Dayal V., and Dunn D., AIP Conf. Proc. 813, 1022 (2006))

KSC RASSOR excavating a slot trench in BP-1

(Photo Credit – NASA KSC)

RASSOR 2.0 Prototype
Dry Mass ~66 Kg
Regolith Payload = 80 Kg
Counter-Rotating Bucket Drums = Zero Net Reaction Force

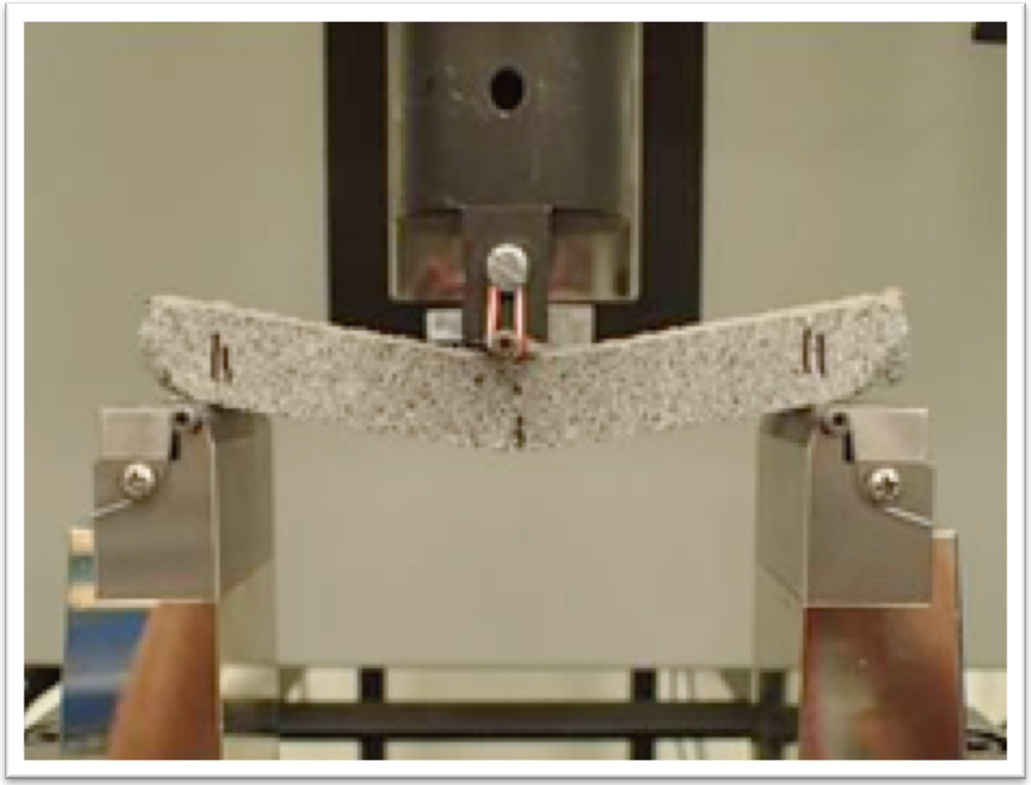
3D Printing with Regolith and Binder



(Figure Credit: NASA KSC)

- Use local materials
- Don't import large masses

Regolith/polymer mix being tested for additive construction



https://kscpartnerships.ksc.nasa.gov/-/media/KSC%20Partnerships/UB/image004.ashx?h=176&w=233&hash=00C71B1B984C1276D1DF386CFE8A6E72675748EA&hash=00C71B1B984C1276D1DF386CFE8A6E72675748EA&la=en

(Figure Credit: NASA KSC)

GrowMars Process - Bioderived Plastic Greenhouse Blocks

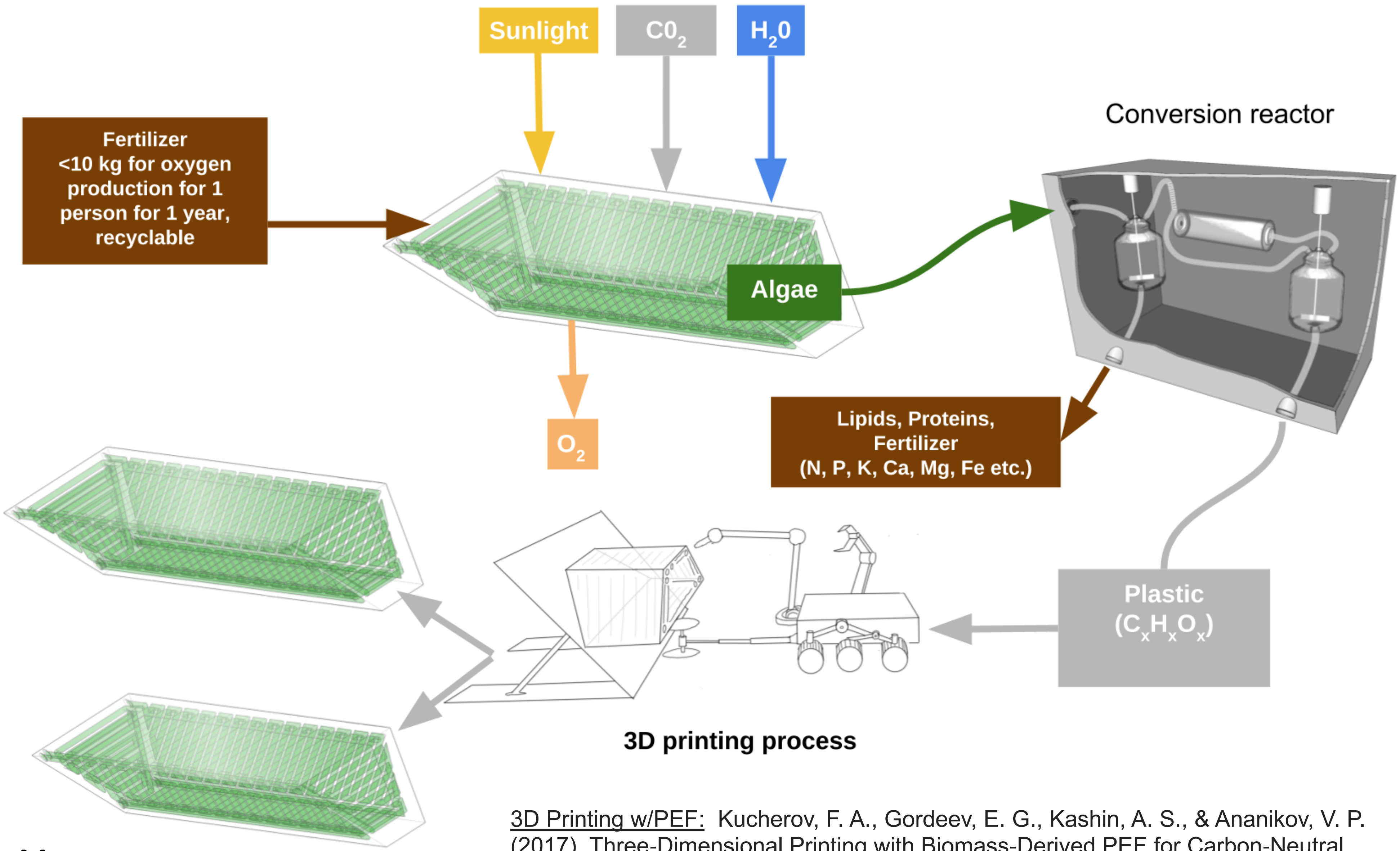
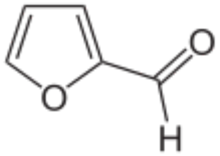
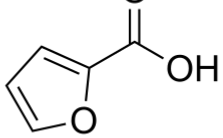


Photo Credit: GrowMars

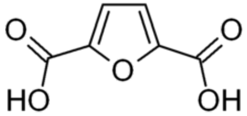
3D Printing w/PEF: Kucherov, F. A., Gordeev, E. G., Kashin, A. S., & Ananikov, V. P. (2017). Three-Dimensional Printing with Biomass-Derived PEF for Carbon-Neutral Manufacturing. *Angewandte Chemie International Edition*, *56*(50), 15931-15935.

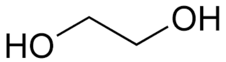
Processing Algae to Biopolymer (PEF)

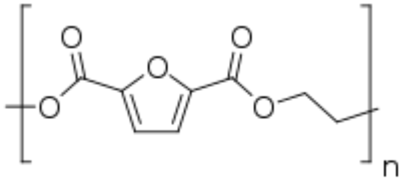
1) **Dried algal biomass distillation to produce furfural** 

2) **Furfural oxidation to 2-furan carboxylate (FC)** 

3) **Reacting 2-furan carboxylate (FC) with carbon dioxide and cesium carbonate (Cs_2CO_3) to produce furan-2,5-dicarboxylic acid (FDCA)**



4) **Producing polyethylene furan dicarboxylate (PEF) from FDCA and monoethylene glycol (MEG)** 

which can be derived from ethanol
   - **Ethanol production is an already proven process with algal culturing**
5) **Overall PEF yield is 70%** 

(Dick, G. R., Frankhouser, A. D., Banerjee, A., & Kanan, M. W. (2017). A scalable carboxylation route to furan-2, 5-dicarboxylic acid. *Green Chemistry*, *19*(13), 2966-2972.)

Solar tracking block design for increased bio-solar efficiency and increased thermal control (Mars Version)

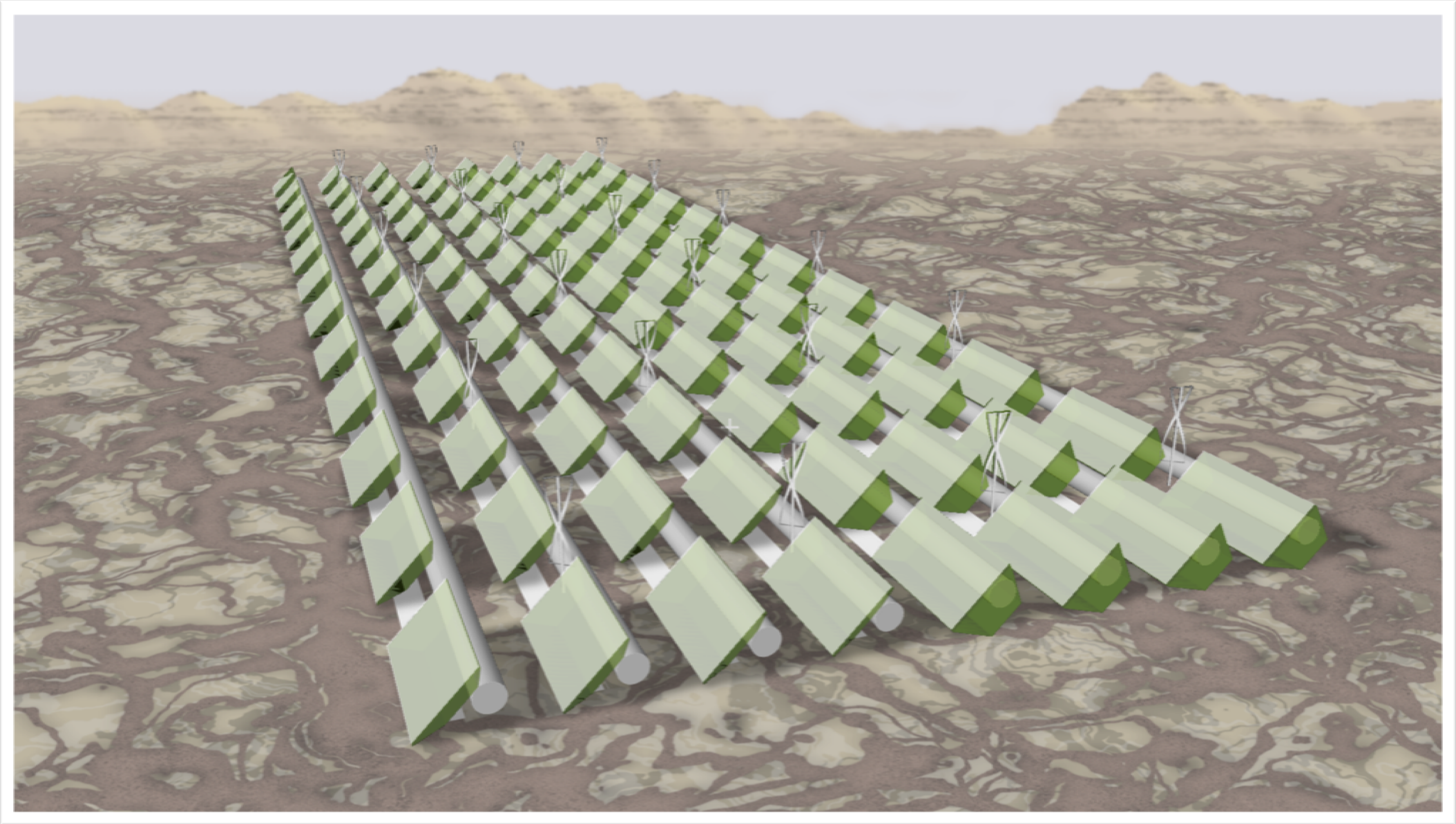


Image Credit: GrowMars

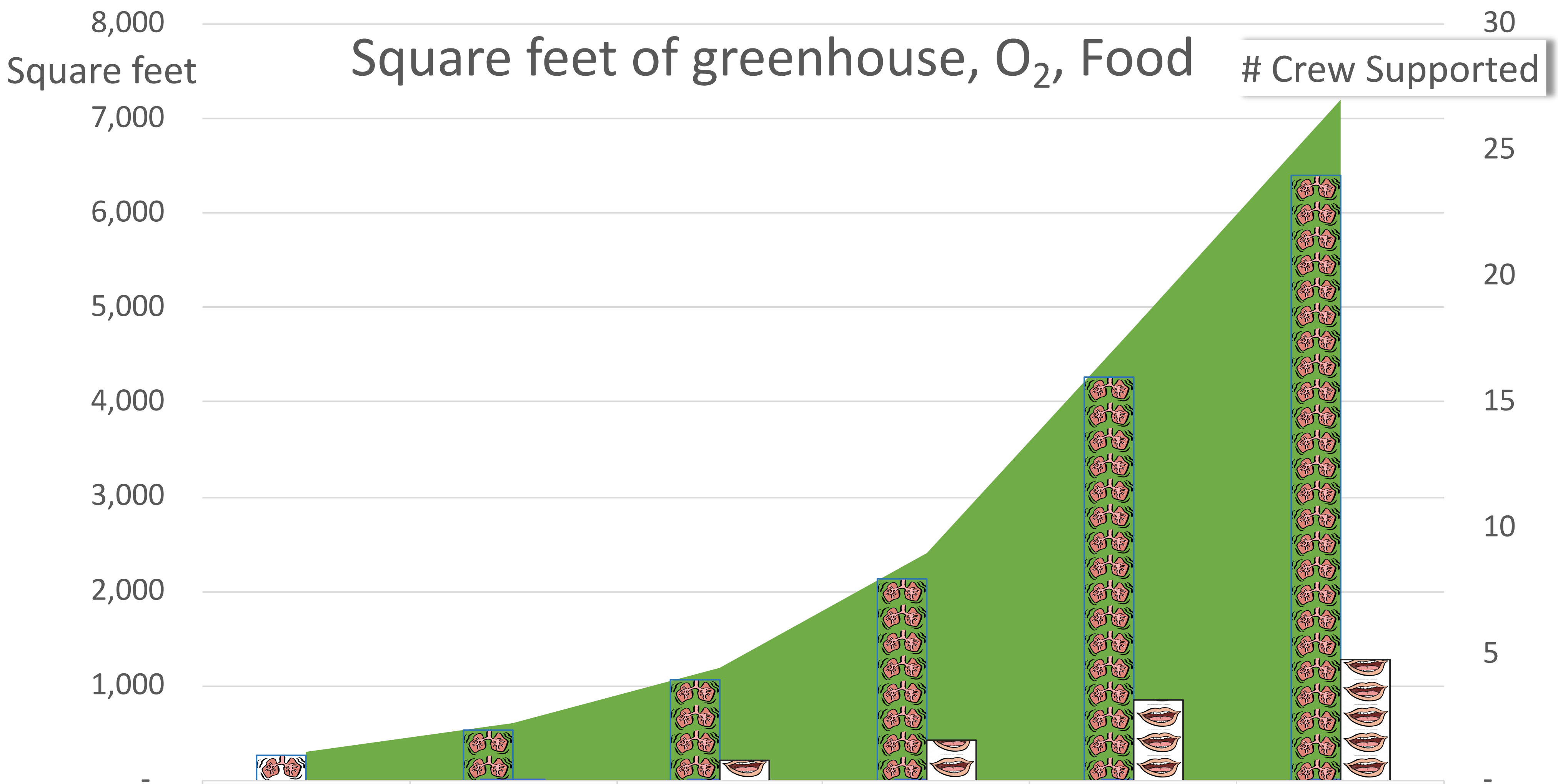
A solar reflector is needed to convert horizontal sunlight to vertical sunlight on the Moon

Tessellation compatibility

(Click to watch video)

Image Credit: GrowMars

Greenhouse area for food ~5X > area needed for biological life support



	0	3	6	9	12	15
Square feet	300	600	1,200	2,400	4,800	7,200
Year	0	3	6	9	12	15
Oxygen Supply	1	2	4	8	16	24
Caloric Food Supply	0	0	0.8	1.6	3.20	4.80

- **4,356 ft^2 (~400 m^2, 1/10th acre) for 3 crew calorically**
- **900 ft^2 (~84 m^2) Biological life support for 3 crew**

Image Credit: GrowMars

Plants in a PEF-Based Greenhouse (Mars Version)

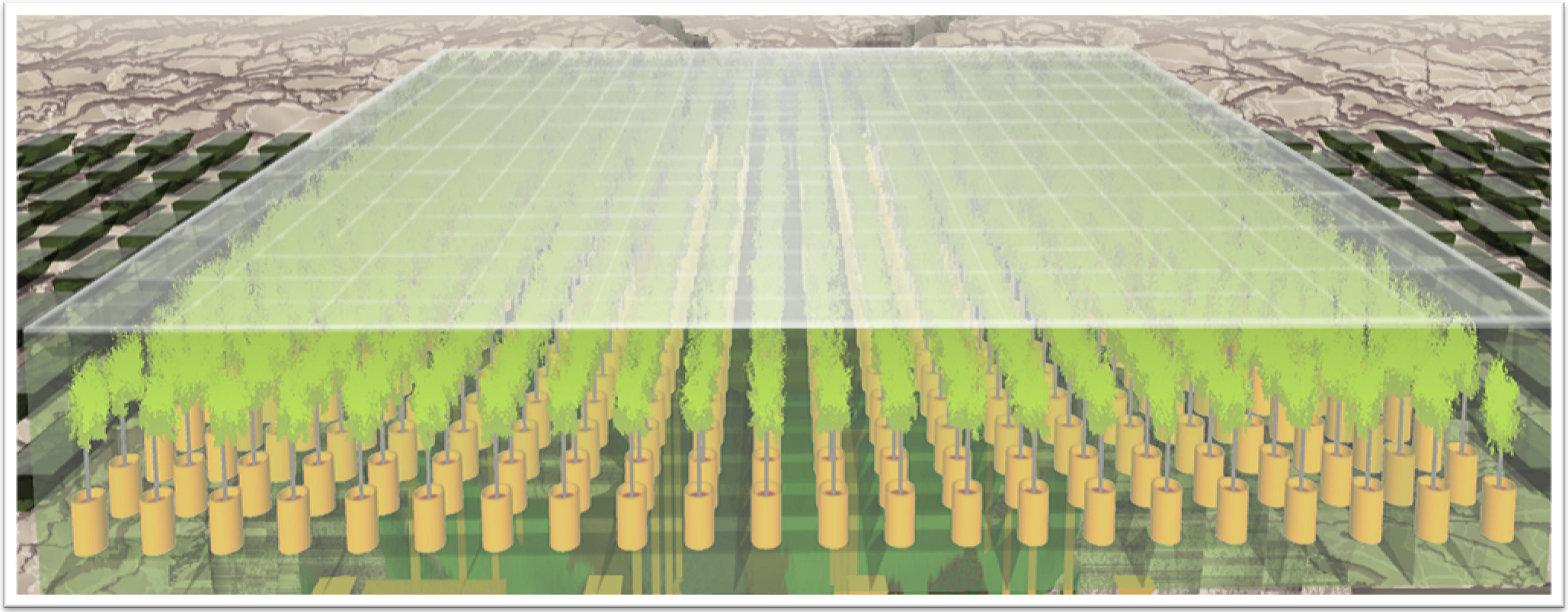
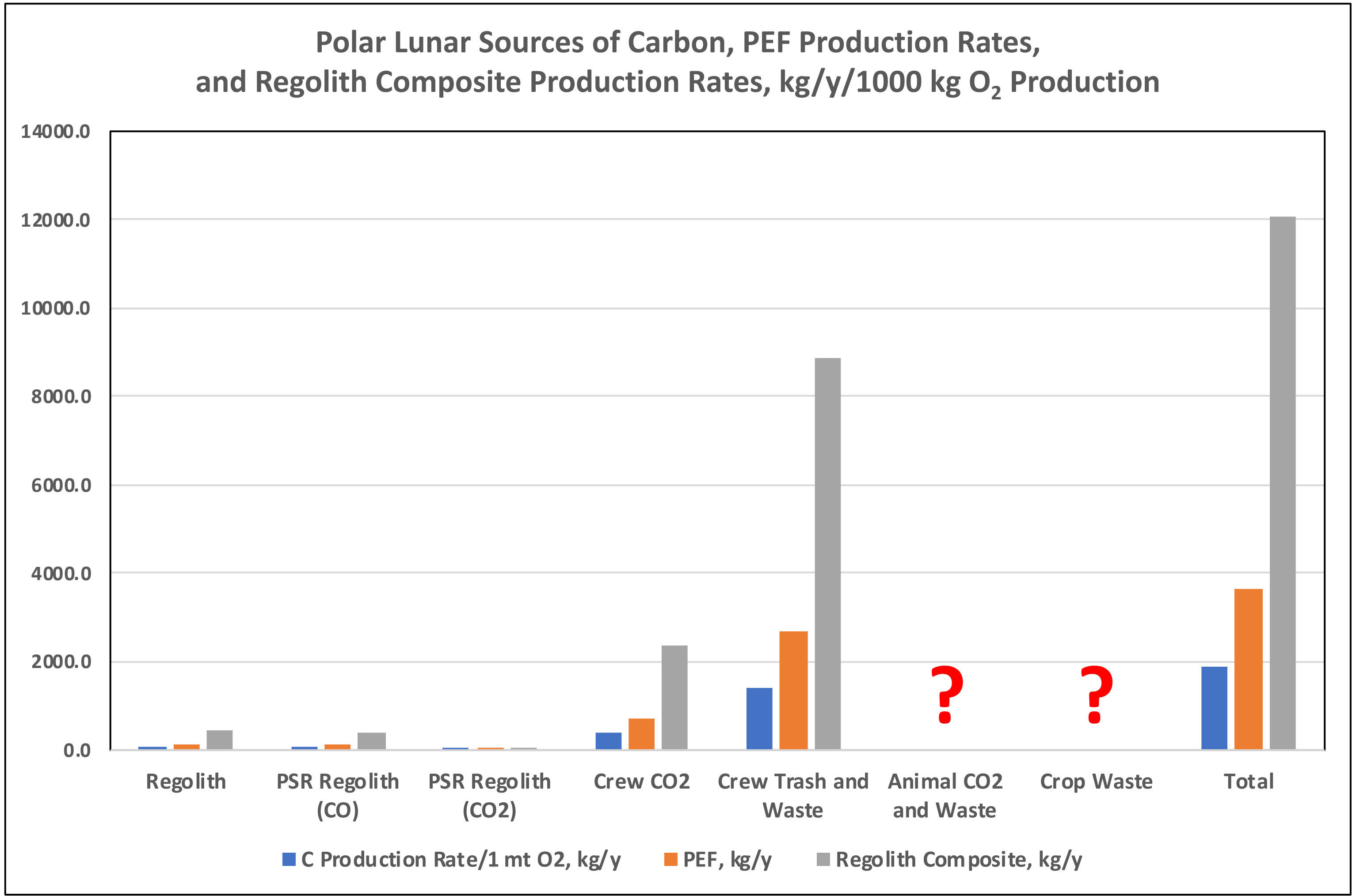


Image Credit: GrowMars

Carbon Sources on the Moon

- Carbon is rare on the Moon
- Also need 0.3 kg water/kg PEF



Polar Lunar Carbon Sources:

- **Regolith - 82 ppm Carbon (Carbothermal Reduction)**
- **PSR: 0.7% CO, 0.12% CO_2**
- **Crew CO_2 - 1 kg/Crew/d (3.76 Crew = 1 mt O_2/y)**
- **Crew Trash and Waste – 1.45 kg C/Crew/d (3.76 Crew = 1,408 kg C/y)**
- **Animal CO_2 & Waste and Crop Waste = TBD**

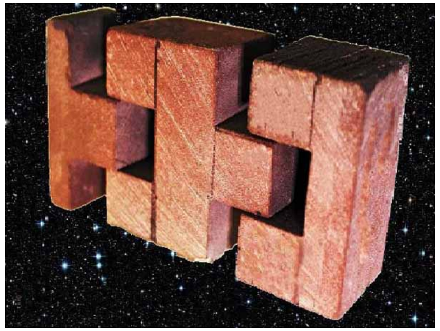
Assumes 100% Conversion of Algae to PEF Using Oxidation to Convert Residuals Back to CO_2 & All PEF Is Used for Binder, Not Greenhouses

12 tons of Regolith Composite Is ~5 m^3 at 30% PEF (Midpoint of 10-50%) (Particulate d = ~3, PEF d = 1.43)

Possible Ways to Extend PEF Usage

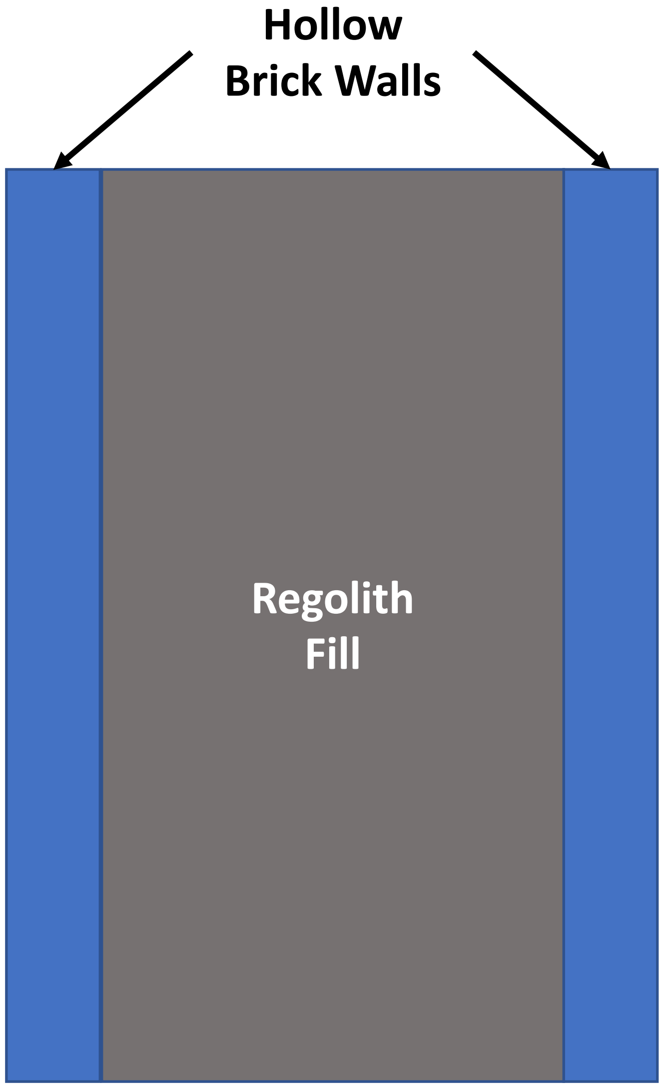
- See if <<30% PEF is still a good binder
- Instead of 3D printing solid forms w/composite, print hollow bricks or troughs and fill with regolith
  - 3D print a thin layer to bind bricks together
- For shielding, print two hollow brick walls and fill the gap with regolith
- May be able to reduce PEF needed by 80-90%
- <u>These concepts need further refinement</u>

(Photo Credit: Quality Glass Block & Window)



Planetary LEGOs

(Photo Credit: PISCES)



Future Work

- Obtain funding to demonstrate PEF production from algae for greenhouse blocks and ISRU
- Moon Village Farm inputs/outputs need much more detailed design to estimate carbon sources and sinks
- Evaluate low-binder regolith products (hollow bricks, troughs, “Legos”, etc.)
- Adapt greenhouse design for low angle polar lunar sunlight
- Further develop Mars greenhouse version (lots of CO_2 there!)

Summary

- A farm envisioned by the Moon Village Association could benefit by using PEF produced from algae in PEF greenhouse blocks as a binder for 3D printing of regolith for construction to reduce import requirements
- Carbon sources are very limited on the Moon, but sources from crew CO_2 and wastes are much more plentiful
- Alternatives to 3D printing solid objects could greatly extend the availability of construction materials using biopolymer binder
- The PEF can also be used for self-replicating greenhouse blocks to expand capacity and provide dual-use transparent building materials