Logistics Materials for Reuse

ICES-2026-250

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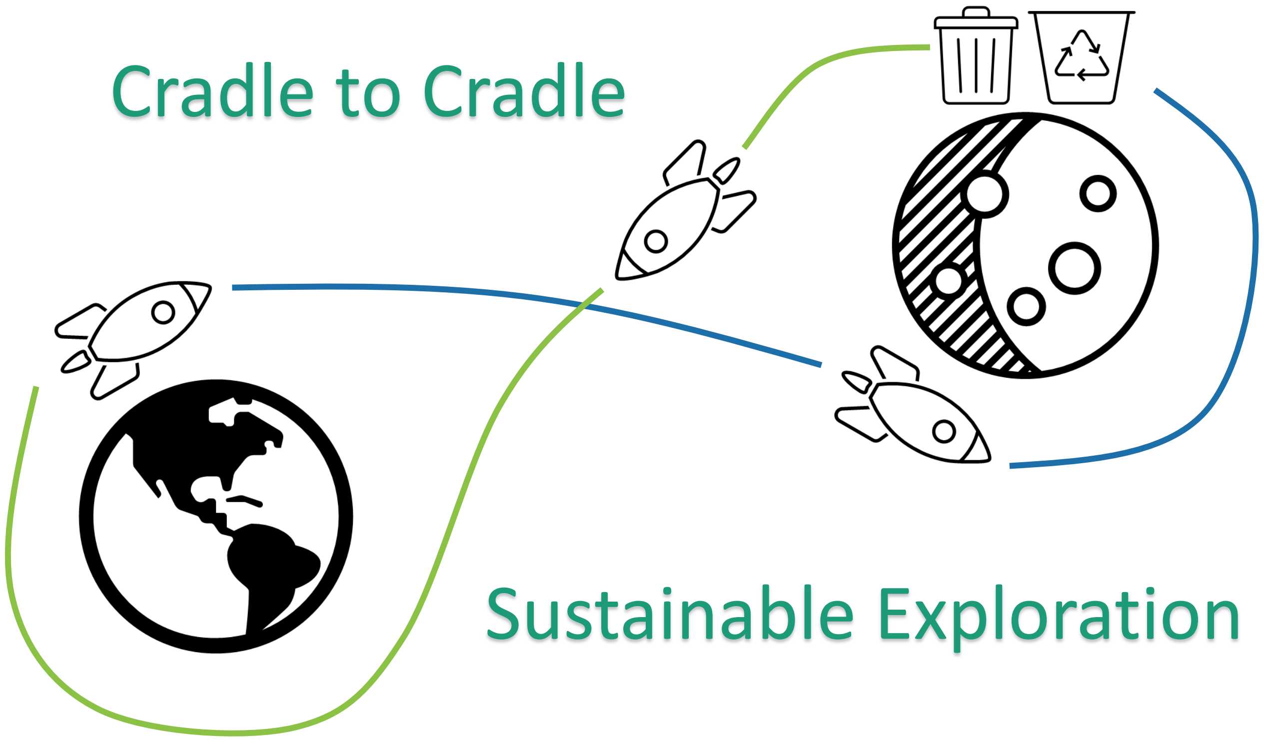
Project Goals

Timeline: March 2023-September 2024

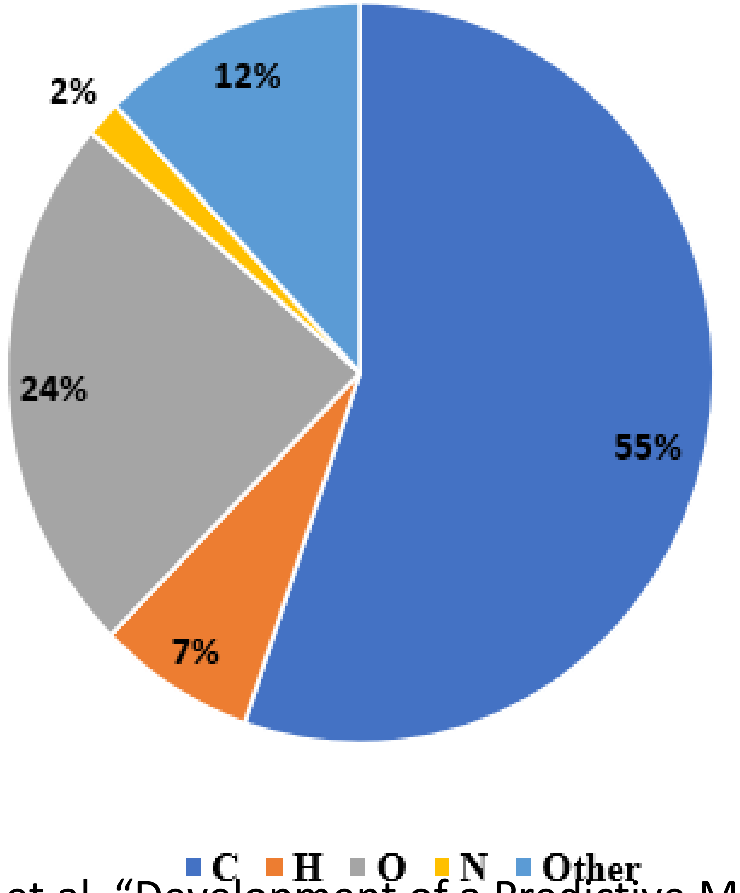
1. Evaluate requirements for selected logistics materials, cargo packaging, and restraint systems for deep space missions.
2. Identify commercially available materials that can meet NASA's requirements and serve as feedstock with easier recycling or follow on use applications such as trash-to-gas or additive manufacturing feedstocks.
3. Down select the materials and test: flammability screening, mechanical testing, combustion, and water and oxygen permeation.

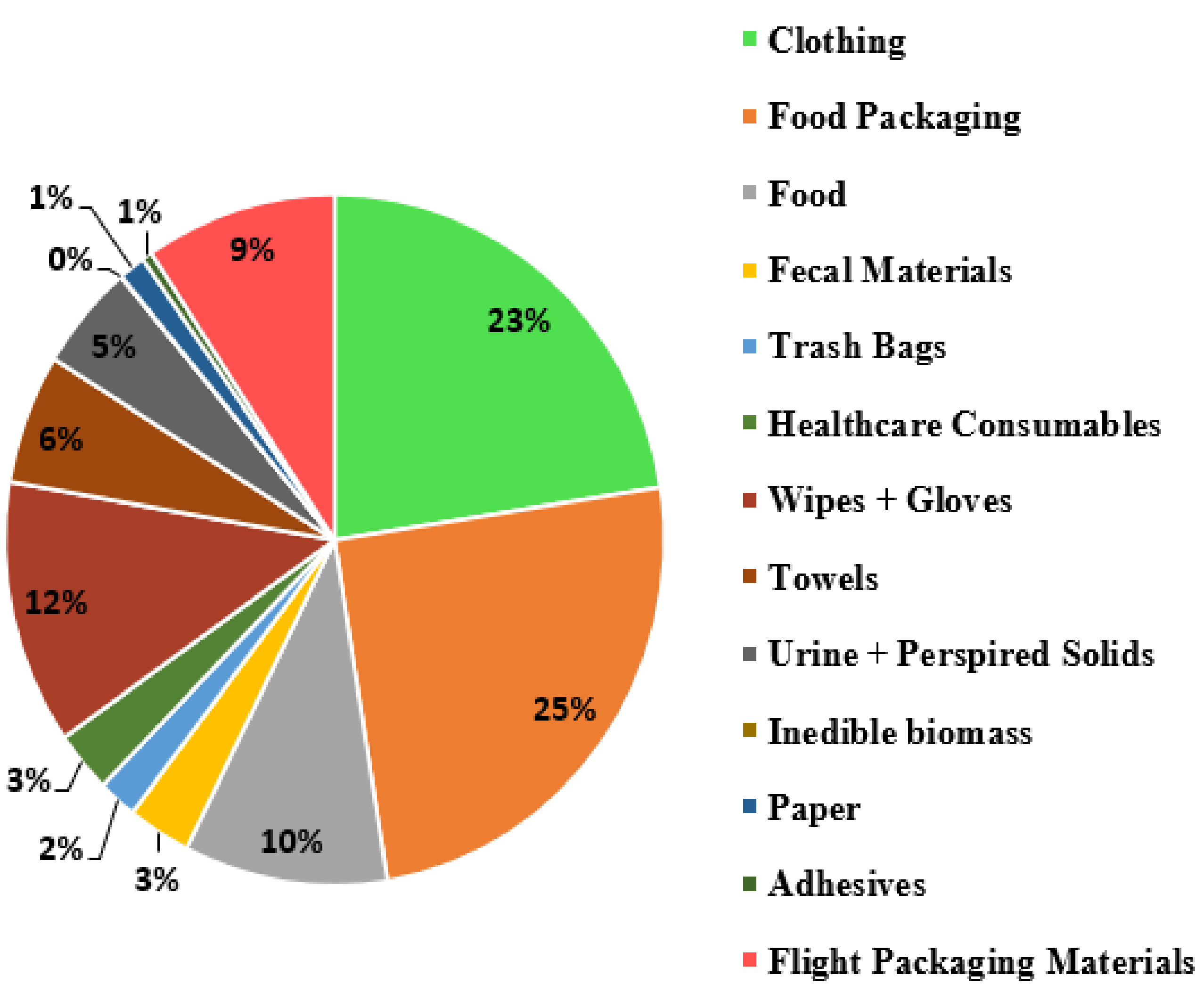


<u>Moon 2 Mars Objectives</u>

- **Waste Repurposing and/or Recovery considers NASA's sustainable architecture for recycling/reuse of on-orbit M2M Objectives:**
  - **OP-12:** Establish procedures and systems that will <u>*minimize the disturbance to the local environment*</u>, <u>*maximize the resources available to future explorers*</u>, and allow for <u>*reuse/recycling*</u> of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.
  - **RT-5:** Maintainability and Reuse: when practical, design systems for maintainability, <u>*reuse*</u>, and/or <u>*recycling*</u> to support the long-term sustainability of operations and increase Earth independence.
  - **RT-6:** Responsible Use: Conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for <u>*responsible behavior*</u> in space.
- No mission stakeholder incorporates reuse from waste (LEO, Moon, Mars)

Material and Elemental Breakdown of Space Waste





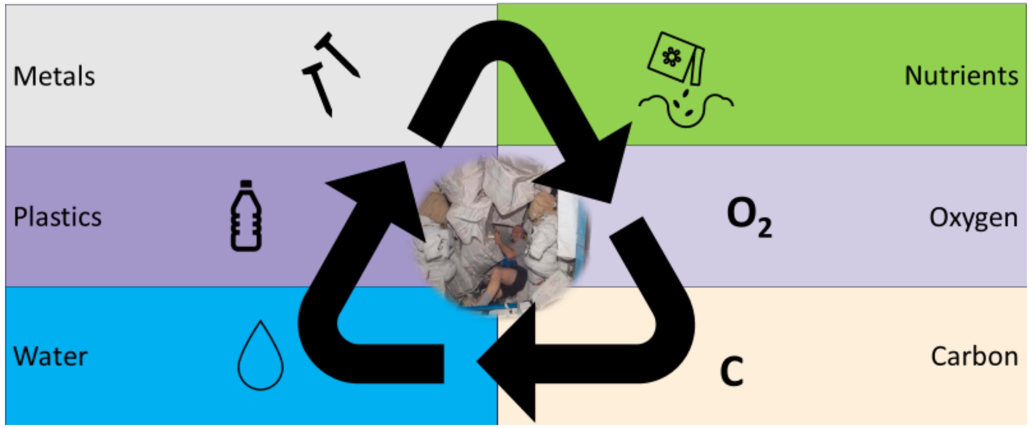
R.Pitts et.al. “Development of a Predictive Model for In-Situ Resource Utilization of Space Exploration Waste”, ASCEND 2023

One Astronaut's Trash Production

Resources Available for Two Future Mission Scenarios in Trash

850-Day Mars Mission

- Mission duration: 850 days
- Mission location: Mars
- Crew size: 4
- Trash production rate: 1.607 kg/CM-d
- Trash composition: OSCAR-FS



30-Day Lunar Mission

- Mission duration: 30 days
- Mission location: Moon
- Crew size: 4
- Trash production rate: 1.607 kg/CM-d
- Trash composition: OSCAR-FS

Resources Available in (Crew Consumable) Waste Stream (kg)								
Mission Type	Trash Total	Oxygen	Water	Polyethylene	Polyester	Polypropylene	Nylon	Aluminum
850-Day Mars	5463.8	1148.9	628.3	968.7	535.4	299.6	916.6	173.6
30-Day Moon	192.8	40.6	22.2	34.2	18.9	10.6	32.4	6.1

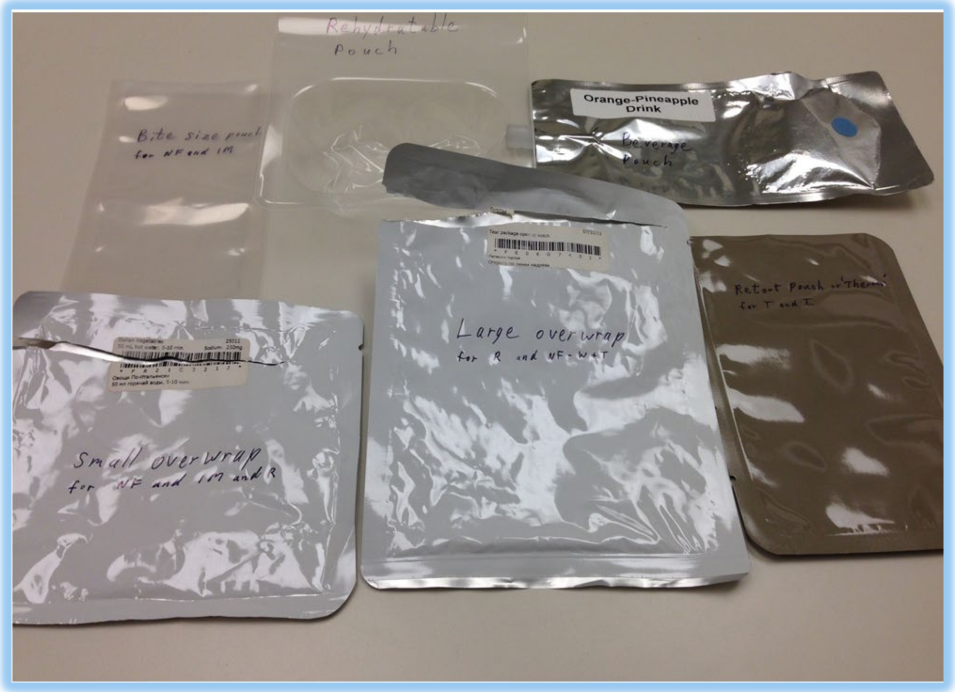
R.Pitts et.al. "Development of a Predictive Model for In-Situ Resource Utilization of Space Exploration Waste", ASCEND 2023

Material Requirements Search

- **What qualifies certain logistic materials for flight?**
  - Initial requirements focused on the applications of food packaging, foam, and textiles.
  - Heritage use, flammability, mechanical strength, and permeability.

- **Food packaging:** one of the largest sources of plastic trash in logistical items.
  - Permeability of O2
  - Water permeability
  - NASA-STD-3001: [V2 7001] The food system shall maintain food safety and nutrition during all phases of the mission.
    - shelf life and microorganism levels are main concerns.
    - Packaging microorganism tolerance: 3000 CFU per Pouch, Septum, 25 cm2 or base

- **Foam**: used to protect payloads during launch



Types of packaging: Natural form (NF), thermopouch packaging (T), beverage (B), irradiated (I), rehydratable (R), intermediate moisture (IM)

Alternative Materials Search

- **Meet or exceed current use requirements AND infusion into future** *waste management capabilities based on NASA technology investment portfolio*

1. **TrashPRO (NASA ARC + Sierra Space)**
   - Assorted trash volume reduction
   - Water extraction
   - Radiation protection potential
2. **Trash-to-Gas (NASA KSC)**
   - Assorted trash mass and volume reduction
   - Water extraction
   - Fuel or other syngas production (CO_2, CH_4, H_2, etc.)
   - Solid carbon and/or biochar production
3. **Reuse/Recycle In-space Manufacturing (NASA MSFC)**
   - Metal and/or polymer additive manufacturing
4. **Bioreactor / composting (NASA KSC)**
   - Crop nutrient extraction
   - Volume reduction of waste

Current NASA investment (items 1)

Past and/or planned future investment (items 2–4)

Three logistics material categories assessed:

1. Foam/filler cargo packaging
2. Food packaging
3. Other packaging (hardware packages, etc.)

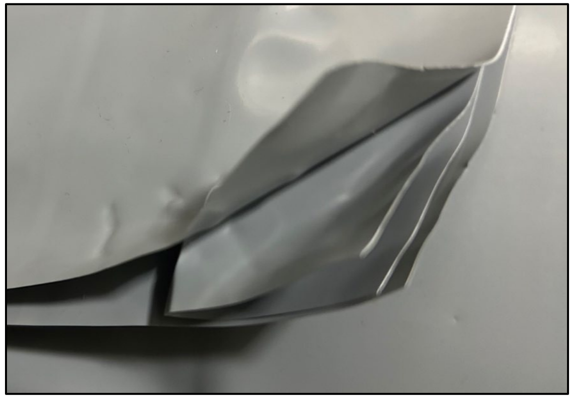
85 Materials Surveyed, 19 Tested

Table 2. Material Test Matrix for Commercial Materials with Completed Testing.

Material Information				Testing			
ID	**Manufacturer**	**Material**	**Test Classification / Vendor use case**	**Tensile**	**Permeation Testing**	**Flammability**	**Combustion (grams combusted)**
3	**Design Packaging**	LDPE	Ethafoam®/ Foam packaging				X (10)
4	**Eco by Naty®**	Plant fiber + wood pulp	Baby wipes				X (10)
5	**Eco Products®**	Cellulose Film	Film	X			
8	**Starch E**	Cassava Starch WR	Film	X	X		
11	**Starch E**	Cassava Starch	Film	X			
12	**Starch E**	Cassava Starch	Film	X	X		
16	**Starch E**	Seaweed	Film	X	X		
17	**Follus**	LDPE	Film / Trash bag				X (10)
20	**Goyunwell**	PSM Starch	Film	X			
23	**Petocat**	PLA +PBAT + Corn Starch	Film/Trash bag		X		X (8)
24	**SuperBio®**	PLA + PBAT	Film/Trash bag				X (8)
25	**Weavabel®**	rHDPE	Film	X	X	X	
26	**Weavabel®**	Sugarcane PE	Film	X	X		
27	**Weavabel®**	PLA + PBAT	Film	X	X	X	
29	**Weavabel**	rLDPE	Film	X			
34	**GreenCell Foam®**	Starch	Foam packaging				X (10)
36	**LLDPE B**	50:50 LLDPE + HDPE w/ Biodeg. Add.	Film/Plastic liner		X		X (10)
38	**LLDPE B**	LLDPE w/ Biodeg. Add.	Film		X		
46	**BASF/Azelis**	Ecoflex + Small Amt. PLA	Pellets	X		X	
47	**BASF/Azelis**	Mineral Filled PLA	Pellets, Ecovio® IS1335	X		X	X (8)
48	**BASF/Azelis**	Ecoflex + 80% PLA	Pellets - Ecovio® T2308	X		X	X (10)
49	**BASF/Azelis**	Compostable Polyester	Pellets	X		X	
50	**Blend D**	Proprietary	Pellets				X (10)
51	**Mycell C**	Mushroom mycell	Foam Packaging/Foam				X (10)
52	**PrimaLoft®**	Cotton + biodegradable additive	Clothing				X (10)
53	**PE A**	Polyethylene	Film/ Food packaging	X	X	X	X (10)
57	**TekPak®**	Proprietary	Film	X	X		

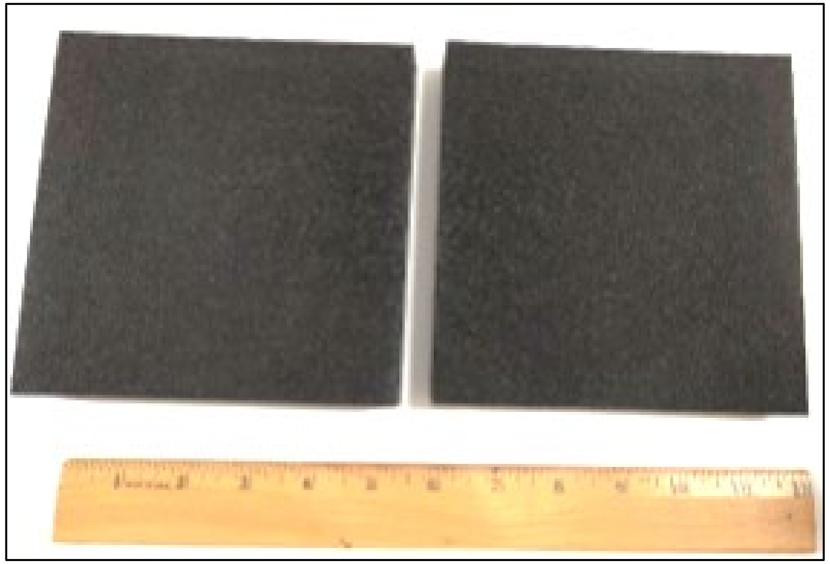
Alternative Materials Search – Films and Pellets

- Several biodegradable materials were found to be feasible for testing
  - Additive added allows microbes to break it down faster
  - Customizable biodegradable LLDPE, HDPE, and PE blends
  - Biodegradable plastic additives allow microbes consume C-C bonds increasing surface area, enabling plastophilic microbes to attach to the polymer's newfound cavities
- Compostable plastics derived from renewable materials such as corn, potato and tapioca starches, cellulose, soy, protein and lactic acid
- PET, PVC, PP, PS
- PLA + cellulose + lining + starch + PHAs
  - Sustainable for food contact, flexible and tough
  - special aliphatic-aromatic copolyester and a small amount of polylactic acid (PLA)
  - Anti-blocking and slip agents for easy extrusion and film conversion
- Proprietary blends



Alternative Materials Search – Foams

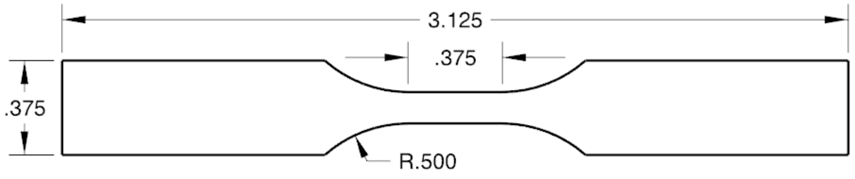
- Odorless non-crosslinked foam from polyethylene resin
- Non-toxic, plant-based formula
    - Mushroom Packaging – combination of agricultural feedstock and mycelium
- Compostable and biodegradable fibers, recycled content



Test Methods

1. **Compression Molding**
2. **Tensile**
3. **Flammability Screening**
4. Permeability and Moisture Uptake
5. Thermochemical Testing (Trash to Gas)
    - 100% Combustion, goal: >90% solid to gas conversion

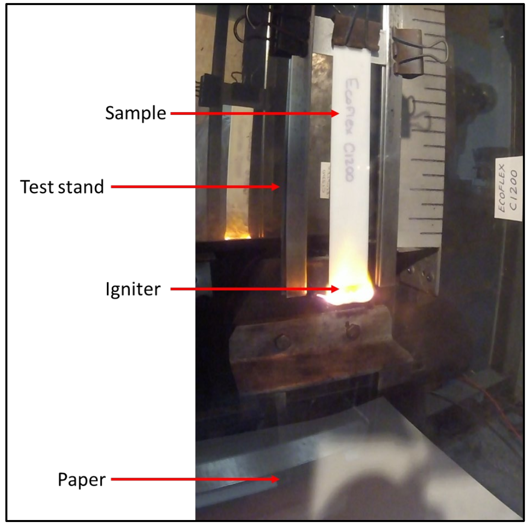
Compression Molding



Tensile Test Standards and Dimensions

MATERIAL TYPE	TEST	STANDARD	LENGTH [IN]	WIDTH [IN]
FILM	Tensile	D882 Tensile Properties of Thin Plastic Sheeting	6.000	0.500
COMPRESSION/CAST MOLDED	Tensile	D638 Tensile Properties of Plastics	3.125	0.375
INJECTION MOLDED	Tensile	D638 Tensile Properties of Plastics	6.500	0.750
FILM/MOLDED	Flammability	NASA 6001	6.000	1.000

Flammability Test Set-up

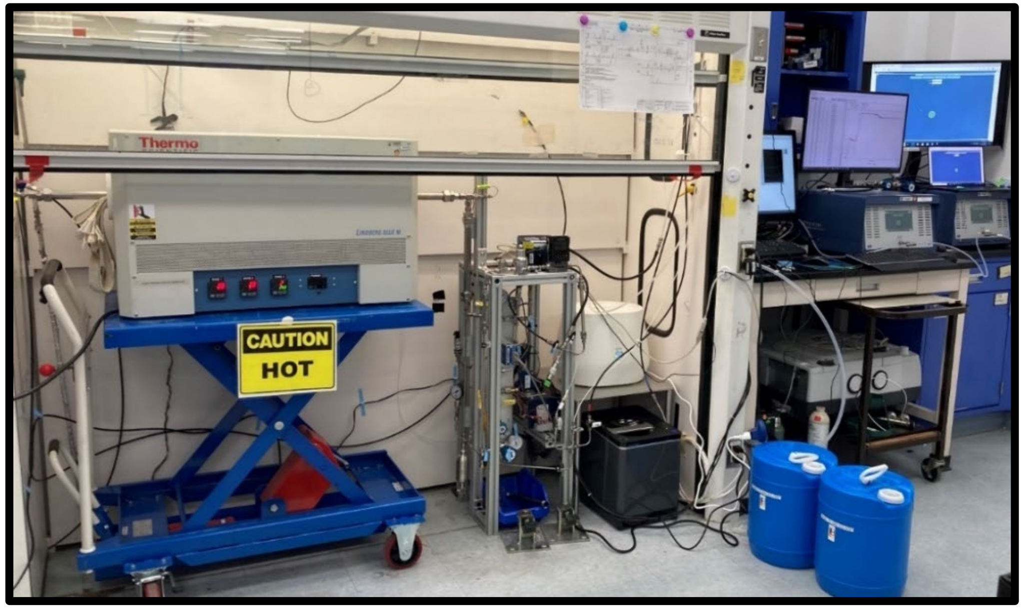


Flammability screening testing based on NASA STD-6001B.

Test Methods

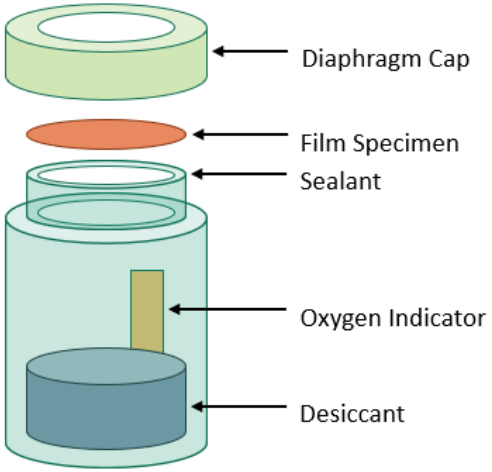
1. Compression Molding
2. Tensile
3. Flammability Screening
4. **Permeability and Moisture Uptake**
5. **Thermochemical Testing (Trash-to-Gas)**
   - **100% Combustion, goal: >90% solid to gas conversion**

Thermochemical Testing (Trash-to-Gas)



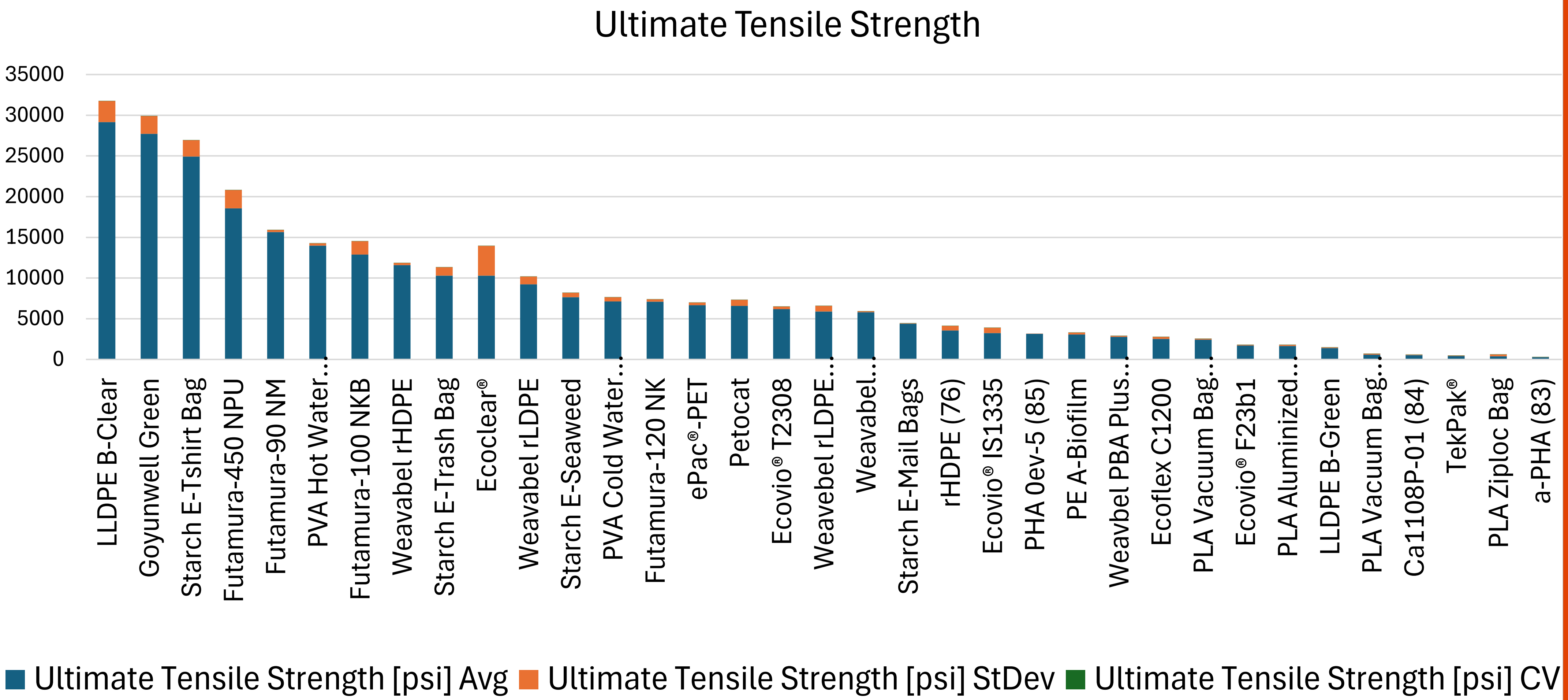
Left: Moisture and Oxygen Barrier Test.

Right: actual test sample, disassembled for demonstration purposes.

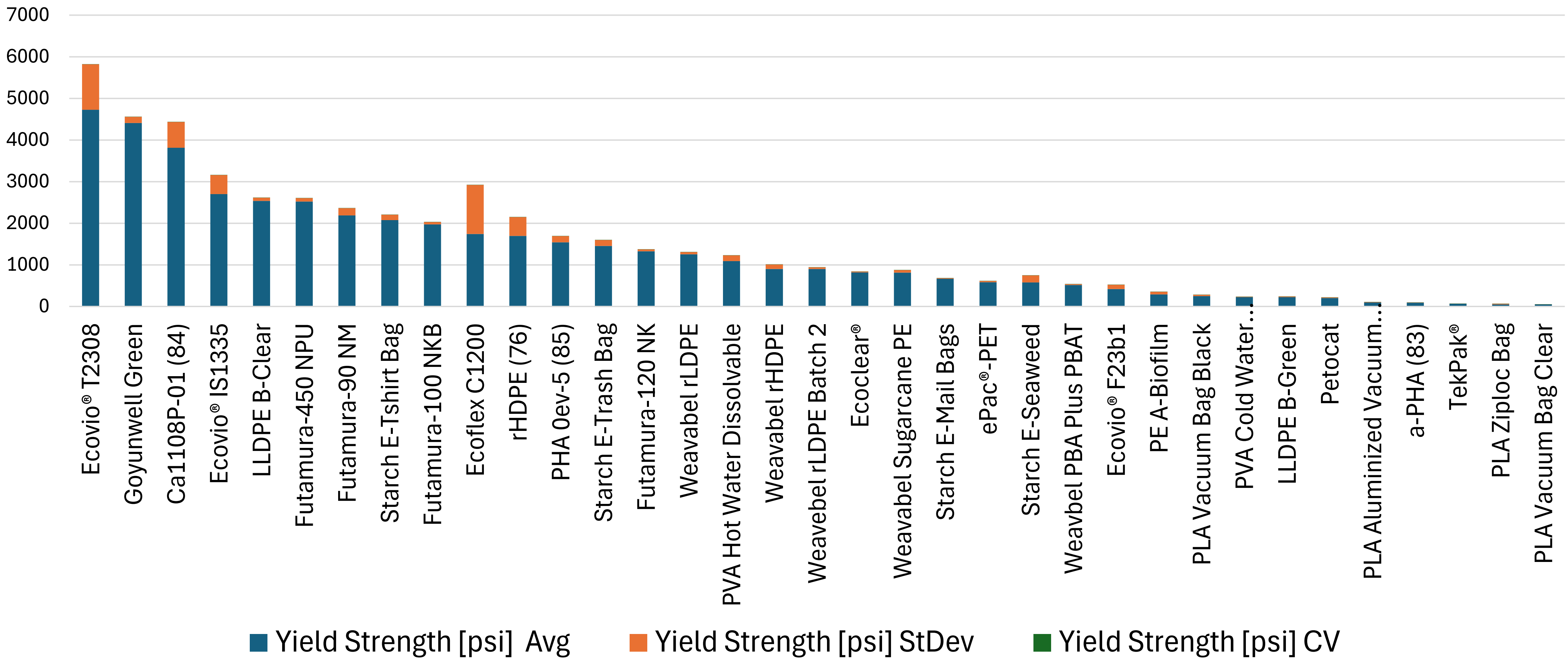


Tensile Testing

$$\sigma_{UTS} = \frac{P_{max}}{A}$$



Yield Strength

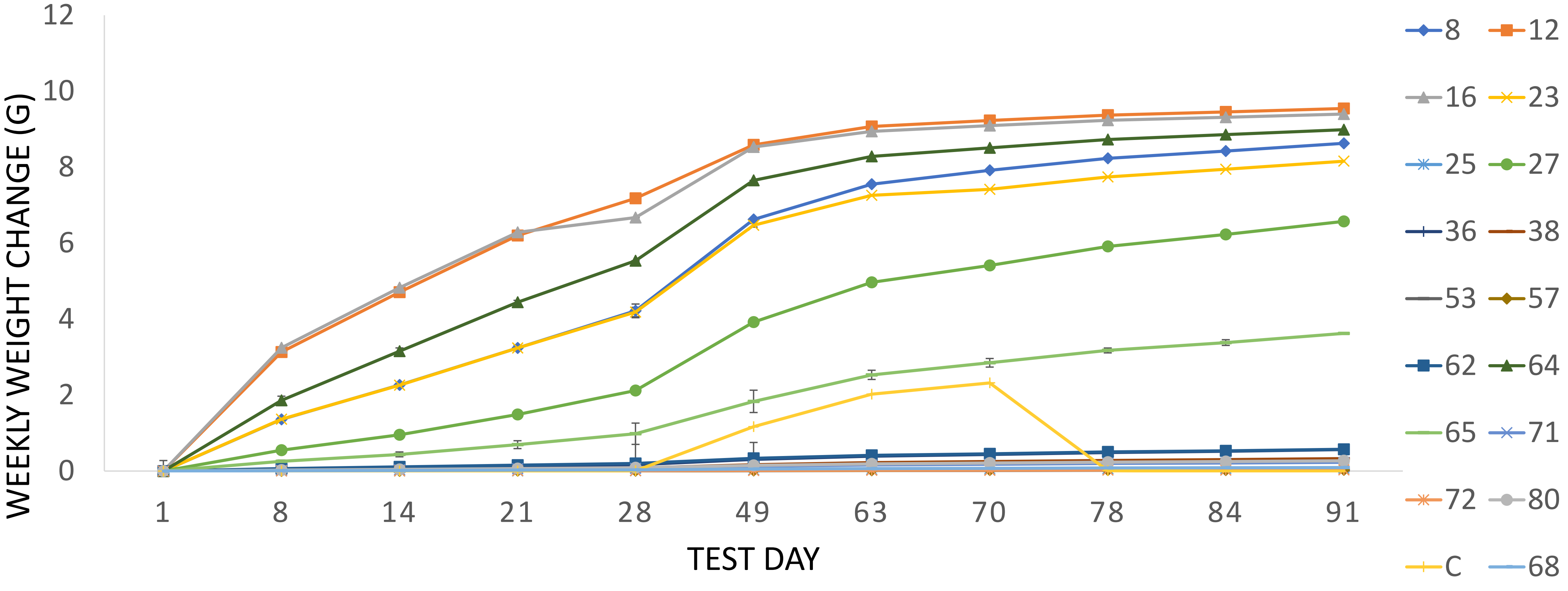


Flammability

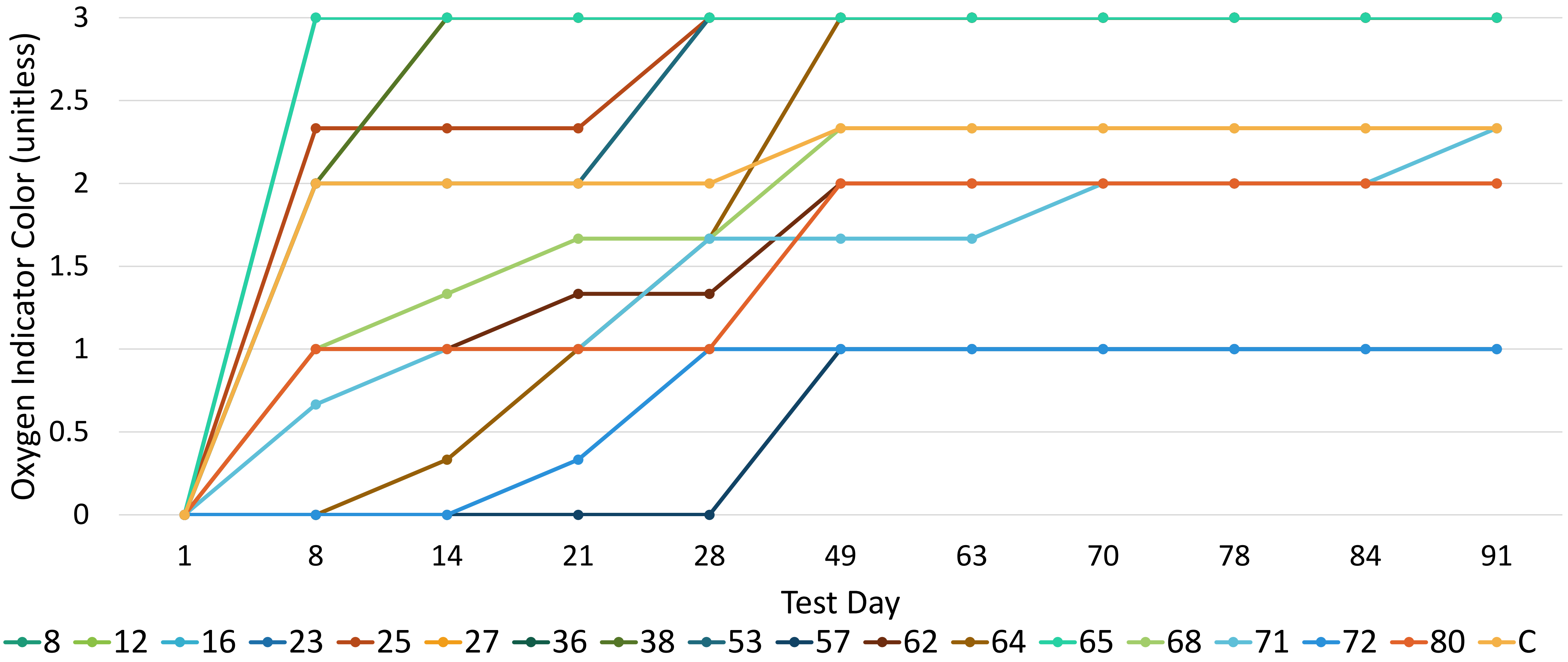
Material Name	Sample Burned (Y/N)	Burning Debris (Y/N)	Sample Extinguished (Y/N)	Notes	Rating
Ecovio® C1200	Y	Y	Y	Sample extinguished after 80 seconds, debris that dripped down set paper underneath on fire. Continued to burn after sample extinguished	X
Ecovio® T2308	Y	Y	Y	Sample and paper extinguished after 37 seconds but hot plastic continued to drip/pool onto paper underneath until ~45 seconds after ignition	X
Ecovio® IS1335	Y	Y	N	Entire sample was consumed in burn, debris that dripped down set paper on fire. Continued to burn after sample was consumed	X
Ecovio® F23B1	Y	Y	N	Sample was completely consumed in burn, debris that dripped down set paper on fire. Continued to burn after sample was consumed	X
LX175 PLA	Y	Y	Y	Sample extinguished after 75 seconds, debris that dripped down set paper underneath on fire. Continued to burn after the sample extinguished	X
rHDPE	Y	Y	N	Entire paper under sample was burned up and sample continued to burn and drip flaming debris	X
Weavebel rHDPE	Y	Y	Y	Sample burned quickly to halfway mark then extinguished at 14 seconds, a couple drops of burning debris fell but did not ignite paper underneath	C
Weavebel PLA + PBAT	Y	N	Y	Almost entire sample consumed in 15 seconds, extinguished after 32 sec but only very edges of sample remained	C
PE A	Y	Y	N	Entire sample burned up by ~40 sec	X
Bioplastics PLA Ziploc	Y	N	N	Entire sample burned up by ~18 sec	C
Bioplastics PVA	Y	N	N	Entire sample burned up by ~18 sec	C
Futamura 90 NM	Y	N	N	Entire sample burned in ~9 sec	C
Futamura 450 NPU	Y	N	N	Entire sample burned in ~9 sec	C

Flammability Key	
A - Burn length of <= 6in and no ignition of K-10 paper	S - Special test
C - Burn length >6 in and no ignition of K-10 paper	I - less than 3 samples but meet condition A
X - Moderate or large drip burning with K-10 ignition	U - Unacceptable data

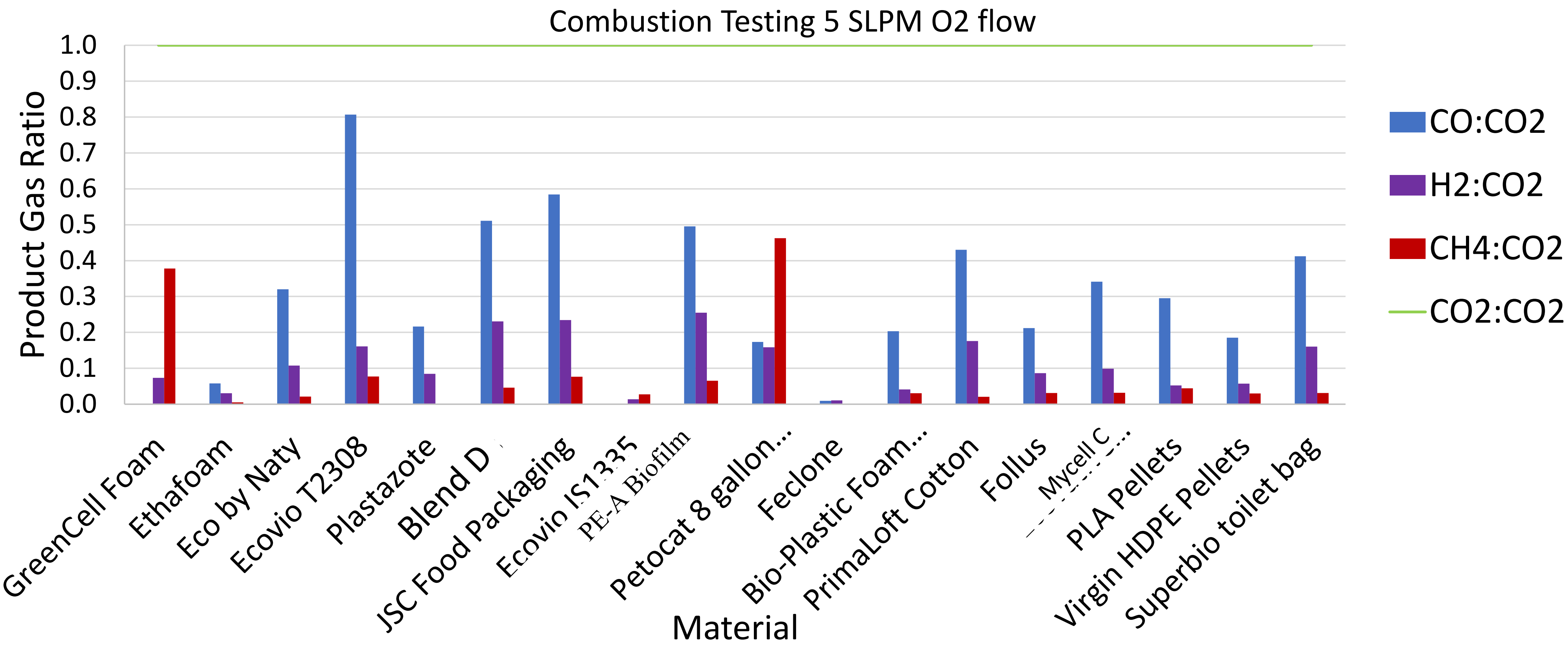
Moisture Absorbed



Oxygen Permeability Results



Primary Gas Product Ratios (Relative Production of Major Gas Constituents)

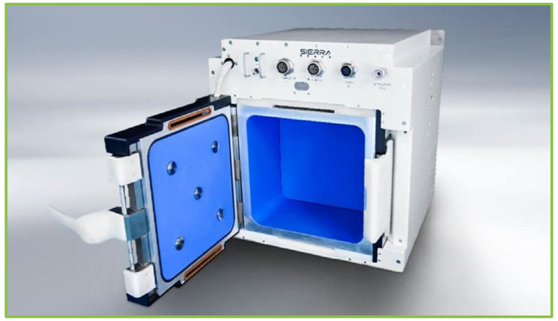


Conclusions

- **In-space manufacturing PLA material** in order of performance: BASF Azelis Ecoflex (46), Corbio (PLA) (80).
- **Foam recommendation:** Any could possibly be a good choice from a combustion standpoint (3, 34, 51, 59) however permeation and flammability testing would need to be performed.
- **Films with high performing moisture and strength:** CFutamura (71) (cellulose base), and Weavabel (25) rHDPE
- What do we really gain in the space 'recycling' efforts if we then need to bring a processing unit (M/P/V). The material change must be very convincing to programs.
- Will we really get 'cleaner' product in TtG with these materials? – GC MS not performed. Only qualitative.
- Continued investment in this line of research supports the broader goal of developing material systems that meet functional performance requirements, while meaningfully reducing environmental impact across the full material lifecycle.
- At this time, there is no clear path for materials and their reuse in space. It is known that these materials hold high carbon amounts, are carefully sourced and characterized for launch, and therefore can be reused.
- We must be stewards of our home and solar system, striving to consider how to reuse all materials from cradle to grave, or until an absolute 'end-of-life' material exhaustion occurs. Therefore, upfront material selection and requirements for flight are needed, and this document hopes to serve as a steppingstone for that mentality.

Continue Investing in Sustainable Approaches

- Future work should prioritize closed-loop evaluation of the highest-performing candidates under mission-relevant conditions, cost evaluations, including optimized combustion environments, repeated cycling, and long-term barrier durability assessment.
- Expanding the material matrix to include additional bio-based polymer families, recycled-content composites, and novel compatibilized blends will further advance the understanding of structure-property-performance relationships in sustainable packaging and film materials.
- REMADE – Work that followed on from this 2023/2024 effort.
- LUNARECYCLE CHALLENGE – DEMOS in AUGUST 2026!
- Waste/Trash Logistics Investments are important!



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- Gino Carro, Matthew Hernandez, Casey Kindel and Brian Cheshire for providing fluids analysis, oxygen compatibility analysis, flammability and tensile testing.

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- Gateway Logistics Program members: Bianca Rhym and Jeff Smith. Financial support was also provided by KSC CESO program and the KSC Chief Technology Office.

Explore Sustainably ☺

Backup

85 Materials Surveyed, 19 Tested

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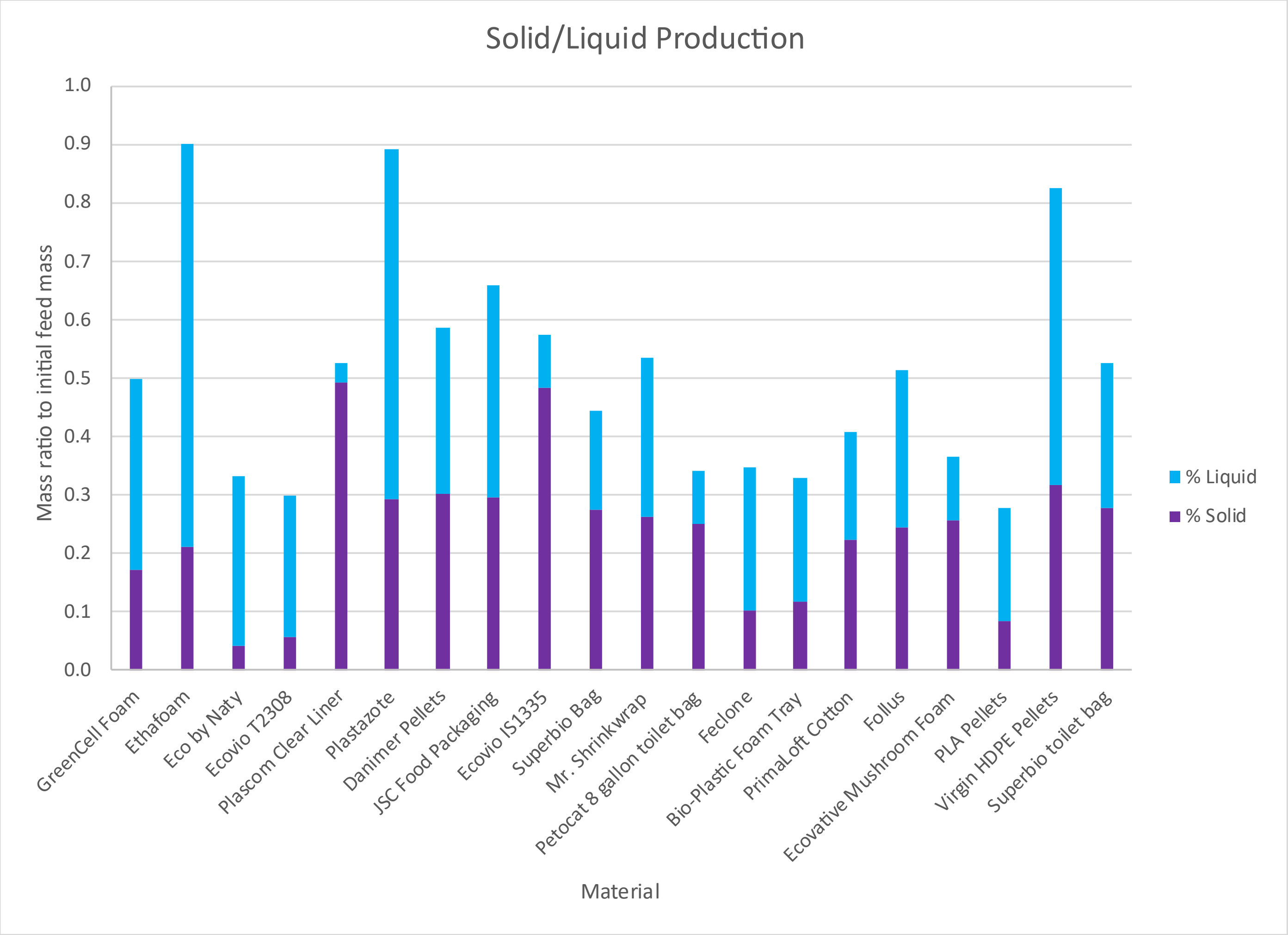
5	Eco Products®	Cellulose Film	Film	X			
8	Starch E	Cassava Starch WR	Film	X	X		
11	Starch E	Cassava Starch	Film	X			
12	Starch E	Cassava Starch	Film	X	X		
16	Starch E	Seaweed	Film	X	X		
17	Follus	LDPE	Film / Trash bag				X (10)
20	Goyunwell	PSM Starch	Film	X			
23	Petocat	PLA +PBAT + Corn Starch	Film/Trash bag		X		X (8)
24	SuperBio®	PLA + PBAT	Film/Trash bag				X (8)
25	Weavabel®	rHDPE	Film	X	X	X	
26	Weavabel®	Sugarcane PE	Film	X	X		
27	Weavabel®	PLA + PBAT	Film	X	X	X	
29	Weavabel	rLDPE	Film	X			
34	GreenCell Foam®	Starch	Foam packaging				X (10)
36	LLDPE B	50:50 LLDPE + HDPE w/ Biodeg. Add.	Film/Plastic liner		X		X (10)
38	LLDPE B	LLDPE w/ Biodeg. Add.	Film		X		
46	BASF/Azelis	Ecoflex + Small Amt. PLA	Pellets	X		X	
47	BASF/Azelis	Mineral Filled PLA	Pellets, Ecovio® IS1335	X		X	X (8)
48	BASF/Azelis	Ecoflex + 80% PLA	Pellets - Ecovio® T2308	X		X	X (10)
49	BASF/Azelis	Compostable Polyester	Pellets	X		X	
50	Blend D	Proprietary	Pellets				X (10)
51	Mycell C	Mushroom mycell	Foam Packaging/Foam				X (10)
52	PrimaLoft®	Cotton + biodegradable additive	Clothing				X (10)
53	PE A	Polyethylene	Film/ Food packaging	X	X	X	X (10)
57	TekPak®	Proprietary	Film	X	X		

59	**Bioplastics Int'l.**	PLA + PBAT	Foam Trays				X(10)
61	**Bioplastics Intl.**	Modified PLA, Aluminized	Film	X			
62	**Bioplastics Intl.**	PLA	Film	X	X	X	
63	**Bioplastics Intl.**	PVA	Film	X			
64	**Bioplastics Intl.**	PVA	Film	X	X	X	
65	**Futamura**	Cellulose + Coating + Metallized Surface	Film	X	X	X	
68	**Futamura**	Cellulose + PVdC Coating	Film	X	X		
69	**Futamura**	Cellulose	Film	X		X	
60	**Bioplastics Intl.**	Modified PLA	Film				
71	**Futamura**	Cellulose + Moisture Barrier/Heat-seal Coating	Film	X	X		
72	**ePac®**	PCR PE+PET	Film		X		
73	**ePac®**	PET	Film	X			
76	**Control**	HDPE	LDPE				X (8)
79	**Control**	LDPE	Foam packaging/Plastazote®				X (10)
80	**Control/Corbion**	PLA	Pellets	X	X	X	X (8)
81	**Control**	Experimental Food packaging, JSC	Multi-layer film				X (10)
82	**Control**	Fecal Simulant (Feclone)	Fecal mix				X (g)
83	**CJ Group**	aPHA	Pellets	X			
84	**CJ Group**	PLA/aPHA	Pellets	X			
85	**CJ Group**	PHA	Pellets	X			

Conversion percentages into gas and liquid for various trash materials. Solid portion is a combination of dried tars and ash.



Trash-to-Gas systems evaluated Mars transit propellant requirements

TtG System Name, Year of Operational Report	Thermal Process Technology	Total Vehicle Mass (kg)	Total Mass Reduction (kg)
Baseline (Stowage Model)	n.a.	309,296	--
NASA Incinerator/Gasifier (Inc-Gas), 2014 [23]	Incineration and Gasification	303,074	6,222
NASA Plasma Gasification [30] (Plas-Gas), 2019	Plasma-Induced Incineration and Gasification	303,145	6,151
Advanced Organic Waste Gasifier (AOWG), Pioneer Astronautics, Inc. (developed under NASA SBIR.) 2020 [23]	Oxygen-Enhanced Steam Reforming	303,391	5,905
Orbital Syngas Commodity Augmentation Reactor (OSCAR), 2021 [28], [48]	Oxygen-Enriched Combustion	303,141	6,155
Microwave Assisted Pyrolysis (MAP), (Advanced Fuel Research (AFR) Corporation (developed under NASA SBIR)) 2014 [23]	Microwave-Induced Pyrolysis	303,430	5,866
(Plas-Pyro), 2020 [45]	Plasma-Induced Pyrolysis	303,511	5,785
Torrefaction Processing Unit, (TPU), AFR Corporation (NASA SBIR), 2019 [40]	Torrefaction	305,597	3,699

J. A. Olson, P. Chai, D. Rinderknecht, and A. J. Meier, “A Comparison of Propellant Requirements for Crewed Mars Missions Incorporating Different Waste Processing Technologies,” presented at the ASCEND, Las Vegas, Nevada & Virtual, 2021. doi: 10.2514/6.2021-4080.

Testing Details – Flammability

- Testing to NASA Standard 6001, Upward Flame Propagation Test
- Film samples: 2.5” x 12”
- Pass criteria requires materials to be “self-extinguishing”
- Screening test, one sample burned to determine if further testing is warranted