Considerations For Waste-to-Base Future Research Paths

Steve Sepka[1]
NASA Ames Research Center, USA

Andrew A. Shapiro[2]
HeroX, Glendale, CA, 91206, USA

Michael Ewert[3]
NASA Johnson Space Center, Houston, TX, 77058, USA

and

Jeffrey M. Lee[4]
NASA Ames Research Center, USA

Developing innovative technologies to reprocess low value waste into high value base products will enable a new "Waste-to-Base" (WtB) capability leading to innovative approaches to space mission design. Systems engineers and mission architects will work together under a new paradigm in logistics planning. Equipment, components, packaging, storage, and structures will be understood not only by functional requirements, but also in terms of useful lifetimes and materials of construction. The advent of a new technical discipline - reprocess engineering - will grow from the intersection between chemical, mechanical, and systems engineering, mission design, and logistics planning. A crowdsourcing approach was employed to gather low Technology Readiness Level (TRL) concepts into workable solutions for issues in trash management, CO_2 processing, foam reprocessing, and fecal processing. The results of the crowdsourcing activities are summarized along with a discussion for future technology development work.

Nomenclature

EGaIn = Eutectic Gallium-Indium
ESA = European Space Agency
HDPE = High Density Polyethylene
MELiSSA = Micro-Ecological Life Support System Alternative
MeOH = Methyl Alcohol (Methanol)
NASA = National Aeronautics and Space Administration
PEEK = Polyether Ether Ketone
PLA = Polylactic Acid
PVDF = Polyvinylidene Fluoride
TRL = Technology Readiness Level
WO = Wet Oxidation
WtB = Waste-to-Base

I. Introduction

A thousand-day mission to Mars, which includes travelling to and from the planet along with orbit and any surface activities, will generate a significant amount of waste [1,2]. Developing innovative technologies to reprocess low

[1] Physical Scientist, Bioengineering Branch, MS 239-131, NASA Ames Research Center
[2] Technical Consultant for HeroX
[3] SE&I Lead, Exploration Capabilities Logistics Reduction Project, Crew & Thermal Systems Div. NASA JSC
[4] Physical Scientist (Retired), Bioengineering Branch, MS 239-15, NASA Ames Research Center

value waste into high value base products will enable a new “Waste-to-Base” (WtB) capability that can spawn innovative approaches to mission design. Systems engineers and mission architects will work together under a new model of logistics planning. Equipment, components, packaging, storage, and structures will be understood not only in terms of functional requirements, but also in terms of useful lifetimes and materials of construction. A new technical discipline - reprocess engineering - will grow from the intersection between chemical, mechanical, and systems engineering, mission design, and logistics planning.

Consider a human spaceflight mission to Mars as illustrated in Fig. 1. At launch, the foam packing used for cushioning cargo becomes useless when in space. Furthermore, during the mission, trash is produced from a variety of sources such as food containers, leftover drinks, food waste, used hygiene items, soiled clothes, washcloths, tissues, and human metabolic waste. Mechanical parts will break and systems will become functionally obsolete. These items - once useful and now useless – become a burden to the flight in terms of both non-useful mass that must be propelled and volume that could be used for other storage or crew activities. With a WtB capability, useless trash is processed back into useful products. WtB is defined as processing any waste into a compact, non-toxic, storable base material that is available for future use. A polymer is an example of a base material. This base material can be used with 3D printers to make replacement parts, structures, and tools. The polymer could also be printed into augmented radiation shielding tiles during the flight to Mars. Then, when the spacecraft approaches Mars, the tiles could be further processed, if needed, by breaking down the polymer into a fuel such as methane, or the polymer could be used as propellant for hybrid, pulse plasma [3], or resistojet thrusters. Storing polymers with the ability to provide spacecraft thrust or 3D printing is far more beneficial than just simply jettisoning the dead mass into space. This reprocessing is repeated many times during the flight to Mars and return to Earth. For example, upon approaching Earth some of the transport vehicle can be processed as the journey nears its end of life. Crew cabin privacy walls, storage containers, surplus supplies, and radiation tiles that were once necessary during the flight but are no longer needed are reprocessed into structural supports or additional propellant for spacecraft maneuvers and reentry.

Fig. 1 also identifies the processing steps that could enable WtB, and Table 1 summarizes each step with its corresponding technology and current Technology Readiness Level (TRL). The processing steps are: 1. oxidize waste and trash with a steam reformer, 2. reduce the CO_2 (carbon dioxide) with a Sabatier reactor thereby recovering oxygen and producing methane, 3. pyrolyze the methane to produce ethylene and recover hydrogen, 4. polymerize ethylene to produce solid polyethylene and other polymers that can be, 5. extruded into filament for 3D printing and be formed into tiles for radiation shielding, which can eventually be used as propellant for thrusters, i.e., hybrid, resistojet, or pulse plasma.

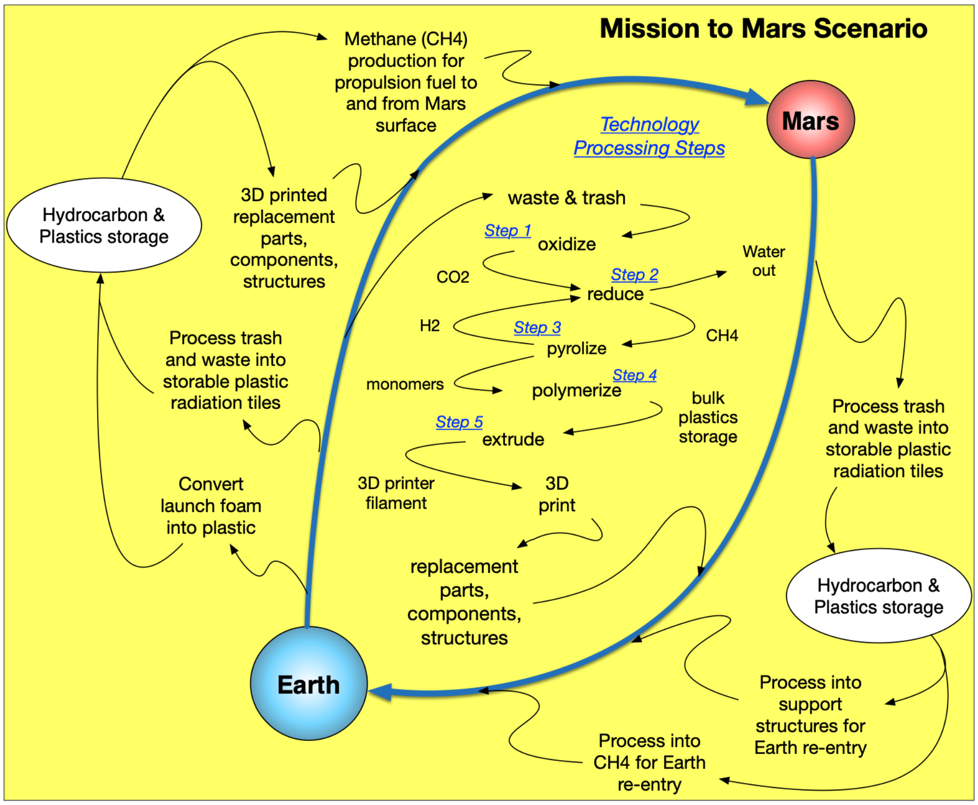

Figure 1. Illustrated Waste-to-Base scenario for a mission to Mars and return to Earth

Table 1. Technologies to enable a Mars Mission architecture using a Waste-to-Base process

Process	Step	Technology	Purpose	TRL
Decompose trash and waste	1	Steam Reforming	Oxidize waste into CO, H2, CO2, H2O	3-4
	2	Sabatier Reactor	Reduce CO2, CO to CH4 (methane)	7
Synthesize polymers	3	Methane pyrolysis, non-thermal plasma	Convert CH4 into C2/C3 monomers	1-2
	4	Ziegler-Natta and metallocene catalysis	Heterogeneous solid phase polymer synthesis of PE, PP, EPM, and PLA	1
Form feedstock	5	Thermal extrusion	Produce filament feedstock for 3D printer; form polymer tiles for radiation shielding	1-2

A. Crowdsource Approach

A crowdsourcing approach was employed to gather low TRL concepts into workable solutions for issues in trash management, CO_2 processing, foam reprocessing, and fecal processing. Any salvaged material is a bonus for the mission rather than having it discarded. There is no existing capability to reprocess many of these materials, although repurposing for in-space manufacturing is being explored [4, 5].

To host crowdsourcing activities, NASA Open Innovation Services 2 requests for proposal were released under NASA's Space Technology Mission Directorate NASA Tournament Lab. These contracts were announced in June of 2020 and enabled 19 companies to compete using NASA's crowdsourcing toolkit. The toolkit allows for an expanded set of crowdsourcing tools that includes prize competitions, freelance and micro-task projects, and additional crowd-based methods. The 'Waste to Base Materials Challenge: Sustainable Reprocessing in Space' was one of these contracts awarded to find innovative ways to convert waste into base materials during future manned Mars transit missions and Lunar and Mars surface operations. HeroX was the selected company for managing the crowdsourcing challenge.

The project synopsis provided by NASA for the competition was as follows: "A new mission architecture that addresses sustainability as a core principle will naturally lead to the question of what to do with all the trash and waste that is generated during a mission to Mars? The answer to dealing with all this "dead mass" is to reprocess waste into useful products, such as replacement parts, structures, shielding, and propellant thereby reducing the initial launch mass and thus saving billions of dollars in launch costs."

II. Crowdsource Challenge Guidelines

The WtB challenge consisted of four categories. They are trash, fecal waste, foam packaging, and CO_2 processing. Submissions were gathered from participants world-wide. Here is the solicitation that was provided in the challenge:

A. Trash

Trash consists of food, drink pouches, wet wipes, cotton clothes and towels, hygiene products, plastics and Ziploc® bags, VELCRO®, and nitrile gloves. These items are primarily composed of carbon, hydrogen, oxygen, and small amounts of nitrogen. Water is also often present, and its recovery is valuable. In fact, water is already recovered from humidity condensate and urine on the International Space Station.

We are interested in processes that can recover water. We are also interested in ways to convert dry trash into materials that can become the base material for making new things, like feedstock for 3D printing of broken or needed components, such as gears, elastomers, gaskets, storage containers, tools, etc. Keep in mind that a spacecraft has limited volume and no gravity, so any process that converts dry trash into reusable base materials must meet constraints around volume, mass, power consumption, waste heat, and the avoidance of highly reactive or hazardous reagents. Outgassing is a particular concern. Common recycling approaches that shred mixed waste and then separate different components for material-specific reprocessing are not currently practical onboard, but process modifications might change that. Novel approaches to recycling are of interest, as are approaches that might start with a new base material for clothing and packaging. In the case of proposing new base materials, remember that the required performance properties of a polymer used to make gears or tools are likely very different from those used to make clothes or storage containers.

B. Fecal Waste

Fecal waste needs to be made biologically safe, is composed generally of the same elements as trash, and has significant amounts of water.

In addition to water, fecal waste is rich in microbes. We want to recover the water, and we are also interested in processes that can harness the microbial activity inherent in this waste stream. Urine falls in this waste category too. What are the possible uses for the urine brine and salts left after water removal?

C. Foam Packing

Foam packing is used to protect items from the force of high acceleration during launch. After launch the foam is not needed, and it takes up valuable open volume in the spacecraft. Most foam used for this purpose is ZOTEK®, Plastazote®, or a similar highly crosslinked material, which can be difficult to reprocess. These are lightweight, high-performance materials that are easily fabricated into complex shapes. They are made without chemical blowing agents and are top-rated for both flame and outgassing performance.

Although space missions currently use ZOTEK® or Plastazote®, other new foams can be proposed if they meet the needed performance specifications (launch, landing, and fire resistance requirements), and if a compelling case can be made for how they contribute to the spacecraft's integrated materials lifecycle. For example, if a foam can be processed into feedstock for 3D printers, that would be a tremendous advantage since the feedstock would occupy significantly less volume than the foam, and feedstock for 3D printers wouldn't need to be carried onboard separately. Another approach would be to consider the lifecycle of foam usage in a mission. For example, after launch, foam is then compacted into radiation shields to be used for radiation storm shelters during Mars transit. Upon arrival at Mars, foam is re-transformed into packing foam to protect delicate instruments sent to the Mars surface, and foam is also converted into propellant for the Mars descent vehicle. On the return trip to Earth, the remaining foam is used as propellant for ion thrusters and as gas for resistojet thrusters for spacecraft maneuvering.

D. Carbon Dioxide (CO_2) Processing

CO_2 is exhaled by astronauts and then extracted from the air. The Environmental Control and Life Support System then processes the CO_2, with the addition of hydrogen, to recover oxygen while producing by-product hydrocarbons like methane, ethylene, and acetylene. These hydrocarbons are currently vented to space, but they also are potential resources.

How can we extract value from those hydrocarbons? We are interested in processes that convert them into propellants, usable materials, or starting materials for other onboard processes.

III. Summary of Awarded Concepts

This section is a summary of the winning crowd-sourced concepts. The governing metrics of the winners include power, mass, volume, reliability, ease of use, creativity/novel solutions, and safety. The winning concepts are listed in no particular order.

A. Trash

The trash-based WTB submissions span a wide range of ideas. These include clothing manufacturing, clothes washing, shredding, composite production for additive manufacturing, and trash sorting mechanisms.

One concept has cotton-based clothing pulped, mixed with microgreen seeds, and pressed into paper. Here cotton fabric is cut into small pieces and blended in water, forming a pulp. Microgreen seeds such as radish, broccoli, or kale are then mixed in and grown from the mixture. This application may not be very useful while in transit because of space limitations but could become important for surface habitat ecology.

In another idea, supercritical carbon dioxide is used in a clothes washing machine. The process is shown schematically in Fig. 2. Here, only a small amount of soap/detergent is needed along with supercritical CO_2. Operating conditions are 31.3°C and 72.9 atm. After washing, the pressure and temperature are returned to standard conditions. The CO_2 vaporizes leaving the clothes clean and dry. There is concern with the equipment needs, safety, and power required to reach these high pressures, but it is an interesting concept.

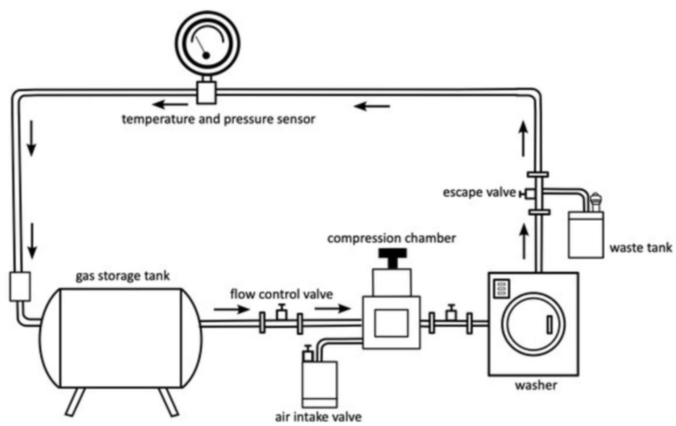

Figure 2. Supercritical CO_2 washing machine

One idea proposes a powerful shredder to consume nearly any type of solid waste, shredding it into tiny particles. Then 3D printing is accomplished using the resulting particles with a UV resin to create a composite object. The shredder can be used with plastic, papers, packaging, soft metals, and trash. However, there is concern with using shredders because they consume a lot of power, may become jammed, and have high mass and volume requirements. This submission provided successful examples of these processes on Earth.

Another entry has tracer-based sorting separating different material even after shredding. Tracer-based sorting uses inorganic tracer substances that are added to a material when it is formed. The substances fluoresce when excited with electromagnetic radiation. The fluorescence can be quickly detected and can be used to identify an article or material. A sorting mechanism is then used. This might be a good way to sort the trash for recycling.

B. Fecal Waste

The submissions that were deemed as most promising for fecal processing usually included composting, anaerobic decomposition, or fermentation methods.

One entry has the metabolic and food waste streams combined in a holding tank, then ground while on its way to an anaerobic decomposition chamber. The novelty of this approach is that the remains were then separated by use of a centrifuge.

Another approach has metabolic waste stored in bioplastic bags that break down when composting. Bokashi composting is proposed, which uses a substrate traditionally fermented from wheat bran or many other kinds of waste materials to harvest biodiverse microbes. Solid and liquid waste streams are later separated.

Wet oxidation (WO), also called sub-critical water oxidation, was proposed for metabolic waste. WO is a process in which organic material is oxidized (typically by air) in the presence of liquid water. The critical point of water is at 374°C and 21.4 MPa (3104 psi). The WO reaction occurs at moderate temperatures of 150-370°C [6, 7], below supercritical values. WO typically does not have 100% oxidation conversion efficiency, which can result in nitrogen remaining in solution as ammonia. This may be beneficial because ammonia can be used as a fertilizer. If full oxidation occurs, the resulting N_2 gas might be more difficult to further process or it could be used as a make up gas for other processes.

One submission heat sterilizes feces prior to composting. The sterilization allows for the safe transport of fecal containers to proposed vertical composting reactors. Once fully decomposed, the remains are used as fertilizer.

Feces contains about 10% fiber. One idea calls for breaking down the fiber (cellulose) into the simpler sugar, glucose. The fiber is broken down by hydrolysis with boiling water and perhaps a small amount of mild acid. Glucose is then converted to starch and then to polylactic acid, PLA. PLA is a thermoplastic monomer suitable for 3D printing.

Metabolic waste fermentation has been closely studied by the European Space Agency (ESA) project MELiSSA (Micro-Ecological Life Support System Alternative). MELiSSA is an ESA program to create a closed-loop ecosystem to recycle waste into oxygen, water, and food with only the input of energy to drive the process. By using a variety of microbes to decomposes feces and brine, a complete re-use of all materials by fermentation can ideally be accomplished.

Another approach for feces decomposition is by alkaline hydrolysis. Here, feces are placed in a solution of water and alkaline chemicals, for example potassium hydroxide. The strong base solution will rapidly react with the feces when pressurized and heated to 150°C. A sterile solution of water, salt, and simple sugars will result.

A dry-distillation method has also been proposed. Here the fecal matter is first dehydrated. Then it is heated using microwave radiation. Hydrogen, methane, carbon monoxide, and sulfuric acid gases are extracted in sequence, and this heating and gas extraction process is repeated five to ten times. Pure carbon results, which is then converted to graphene by acoustic treatment.

Another approach is to use an induction furnace to control pyrolysis heat-treatment temperatures. At lower temperatures (torrefaction), water is boiled off from the feces. As temperatures increase, methane gas is recovered. By using a variable temperature induction furnace, valuable resources of water, methane, and other gases can be recovered.

Feces can also be consumed by microbes. The waste material is broken down by microbes while also producing biomass. The biomass is further processed into an edible (palatable) form for consistency, taste, and smell. While not being fed to humans, perhaps it can be used as an animal feedstock.

Another approach uses anaerobic digestion for metabolic waste, but further uses algae to remove CO_2 and nutrients. An eventual food source is developed. A schematic diagram of the proposed process is given in Fig. 3.

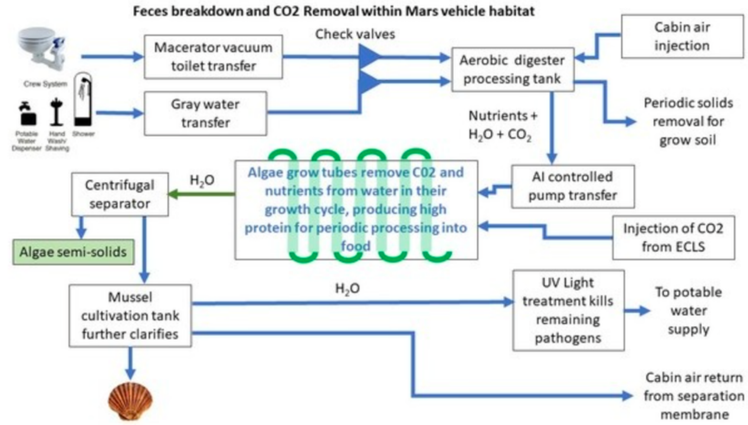

Figure 3. Feces and Gray Water recycling process

The final winning entry in this category combines dried fecal matter with all other organic waste. The mixture is then inserted into mushroom grow bags. The mushrooms can be eaten and whatever remains is used to fertilize plants.

C. Foam/Plastics

The most used foam for spacecraft hardware protection is ZOTEK® F30 (density 30 kg/m^3) and is distantly followed by Plastazote® LD45FR (density 45 kg/m^3). Both are thermoset, heavily cross-linked polymers that typically have no useful applications after being used as packing materials because they are so difficult, if not impossible, to decompose. This section investigates ways to find a new material or novel uses of existing ones.

There is much research going into developing high-strength foam polymers that can be easily decomposed back to monomers for 3D printing. [8, 9]. One technique is to use substitution or addition of a molecule in the polymer chain that easily breaks its bonds resulting in depolymerization. However, monomer recovery is often energy-intensive, costly, and incompatible with complex mixtures. For spacecraft applications, the need for polymer stability above 100°C is minimal. Also, depolymerization without the need for strong acids is beneficial due to having to carry additional materials in flight.

Another appealing approach [10] has plastics polymerized using dynamic covalent diketoenamine bonds. Recovery of monomers occurs at ambient temperature in 5.0 M H_2SO_4 or HCL solutions. Complete depolymerization occurs in less than 12 hours, with pure triketone and amine monomers recovered with >90% yield. Depolymerization also works well with a wide spectrum of additives, including dyes, pigments, inorganic fillers, fiber reinforcing fabrics, and flame-retardants.

Another interesting concept [11] is to make high density polyethylene (HDPE) with a small amount of in-chain functional groups added as recycling break points. Mechanical properties remain nearly identical to pure HDPE. Typically, chemical recycling of pure HDPE occurs at temperatures above 600°C with a recovery yield of ethylene less than 10%. However, the modified HDPE can be completely depolymerized in MeOH within 12 h (or in 2 h with catalyst) at 150 °C with a recovery rate of more than 96%.

One very novel idea for making reusable plastic products is by using polyvinylidene fluoride (PVDF) in string form and weaving it into useful materials. When the material is no longer needed, it can be untangled and knitted for reusability.

If a shredder could be developed that uses low mass, volume and power, then 3D printing from thermoplastics, fiberglass, metal, ceramics, and ice can occur directly by use of interchangeable heads on the printer. Although not common, ice printing would be useful if a low-friction surface was needed.

A novel approach to reduce packing material volume is with Orbeez™. These small, jelly-like balls are super-absorbent polymers and are commonly used as a children's toy. They can grow up to 100 times their original size when submerged in water. Desorption commonly occurs by heating in direct sunlight or in an oven. Depending upon the amount of heat applied, desorption occurs in about an hour to a few days. When filled they provide shock protection, radiation shielding, and a recoverable water source. They can also be used as a plant's water supply when placed in soil.

One way to repurpose material is to use a commercially available thermoplastic reforming machine to remake plastic into containers for hydroponics, as shown in Fig. 4. For Mars applications, a soft-walled system would be developed. In a similar manner, Plastazote® plastics are ground up with cotton clothes and towels to make a filament suitable for 3D printing.

Figure 4. Hydroponics drip application system.

If polyether ether ketone (PEEK) is used as an alternative thermoplastic foam packaging material, it could later be recycled for 3D printing. Existing Essentium 3D printers accept it as feedstock.

Finally, a novel idea is to use a corn-based packing foam that's edible. While it seems unlikely the physical properties of such a foam could meet all the stresses of spaceflight, the idea's novelty is that it can easily be converted to a powder by a shredder, or perhaps more importantly, dissolved in water.

D. CO_2 Processing

Removal of carbon dioxide by absorbents is a well-known technology. However, the use of a catalyst to split carbon from CO_2 is a relatively new approach. A Royal Melbourne Institute of Technology research group [12] is using the catalyst Eutectic Gallium-Indium (EGaIn) as a liquid at 100 - 120°C to split carbon from CO_2 gas into solid carbon flakes. An equivalent portion of the metal gallium is consumed as gallium oxide. The use of gallium oxide in industry is well-known, but for spacecraft its applicability is much more limited. There is significant concern to not allow liquid gallium to contact aluminum, thereby severely weaking the aluminum's structural strength. In a similar approach, [13] a small amount of metallic cerium is mixed into liquid Galinstan. A small voltage potential is applied to facilitate the removal of carbon from CO_2 as flakes.

A very novel technique [14] to split carbon from CO_2 uses an inductively coupled plasma at 2 mTorr to ionize the CO_2. Then the ionized CO_2 is accelerated in an electric field until it hits a gold surface to cleave off the carbon. So far, the yields produced have been small.

In another entry, a photobioreactor is proposed that uses algae with artificial lighting to convert organic waste and CO_2 into oxygen and excess algae. The organic waste is contained in a media, and the airborne algae is circulated around it in a mushroom-shaped container. Another approach uses seaweed for CO_2 processing, similar to how it is naturally processed on Earth.

Finally, one approach is to let CO_2 concentration increase and use its greenhouse effect as a Martian solar heating source. This approach is not intended to remove CO_2 but make use of its optical properties. Further study is needed to determine the amount of solar heating that can be developed with the expected concentration levels.

A list of the all the awards by name is given in Table 2.

Table 2. Waste-to-Base Awarded Submissions

Category	Submission Name
Trash	Make – Break - Make Again - Plastic Recycling.
Trash	Supercritical Fluid Carbon Dioxide Washing Machine.
Trash	Nibbler: Tomorrow's Objects with Today's Trash.

Trash	Fashion Your Feast: Clothing as Growing Medium.
Trash	Tracer-Based-Sorting for Maximum Water Reuse.
Trash	3-D print with polymers, metals, ceramics, and ice.
Fecal	Toilet to table. Mechanizing Natural Recycling.
Fecal	💩🍄🌾 Poop-Mushroom-Plant Cycle.
Fecal	Better Tomorrow - No Waste in Space.
Fecal	Biota Chamber: Fecal Waste Converter.
Fecal	Alkaline Hydrolysis: Biowaste Become Inert Liquid.
Fecal	Slingin' Space Sludge!
Fecal	Fire Under Water.
Fecal	What ! Fecal Waste Can be Used in this Way?
Foam	InnoPacking: Innovative Knitted Payload Packing.
Foam	Packing Material Recycling.
Foam	Recycling of Packing Foam, Urine for Hydroponics.
Foam	Creating Building Materials from Trash.
Foam	Orbeez In Orbit - Recover Water, Shock Protection.
Foam	Using PEEK as Alternative Foam Packaging Material
CO_2	Algae Oxygen Generator Mushrooms and Panels.
CO_2	Let's Get It Done CO_2 Processing.

IV. Summary and Conclusion

Twenty-two winners received awards for this crowdsourcing effort. The ideas are very low TRL concepts that can hopefully be developed. The novelty of ideas is excellent. For processing trash, concepts varied from repurposing materials as a growing medium, grinding materials for 3D printing, ways to sort them, and oxidize (react) to simpler materials. For fecal processing, many of the entries used some form of anaerobic digestion and heat treatment. NASA is currently investing in an organic processing system [15], but specialty microbes that have been proposed here might aid in processing. For plastics, many concepts propose ways to chemically break down polymers into 3D printable monomers. Much of this technology will be driven by recycling needs on Earth, but space applications should also be considered. For CO_2 processing, very novel ideas have been presented to cleave carbon from O_2. These technologies are still in their infancy but show promise.

Overall, it has been a very rewarding experience to gather and compile these ideas. It is hoped that other researchers will be able to gain from them and help bring them to maturity.

Acknowledgments

The authors thank the many involved for their assistance in judging the numerous entries for this crowdsource challenge, and to Ryon Stewart for much valuable insight, and finally to HeroX and Shane Jenkins for hosting the challenge.

References

[1]M. K. Ewert, et. al., "Comparing Trash Disposal to Use as Radiation Shielding for a Mars Transit Vehicle," 47th International Conference on Environmental Systems, ICES-2017-178, 16-20 July 2017, Charleston, SC.

[2]Broyan, J. L., Schlesinger, T., and Ewert, M. K., "Exploration Mission Benefits From Logistics Reduction Technologies," 46th International Conference on Environmental Systems, paper# ICES-2016-140.

[3]Pulse plasma thruster," Wikipedia Foundation, 6 January 2023, https://en.wikipedia.org/wiki/Pulsed_plasma_thruster

[4]Moraguez, M., and de Weck, O., "Benefits of In-Space Manufacturing Technology Development for Human Spaceflight," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-11, doi: 10.1109/AERO47225.2020.9172304

[5]Prater, T., Werkheiser, N., Ledbetter, F., and Morgan, K., "In-Space Manufacturing at NASA Marshall Space Flight Center: A Portfolio of Fabrication and Recycling Technology Development for the International Space Station," AIAA SPACE Forum, 17-19 September 2018, Orlando, FL, 2018 AIAA SPACE and Astronautics Forum and Exposition, doi: 10.2514/6.2018-5364

[6]Johnson, C.C., Wydeven, T., "Wet Oxidation of a Spacecraft Model Waste," Paper 851372, SAE Technical Paper Series, Fifteenth Intersociety Conference on Environmental Systems, San Francisco, CA July 15-17, 1985

[7]Takahashi, Y., Wydeven, T., and Koo, C., "Subcritical and Supercritical Water Oxidation of CELSS Model Wastes" Adv. Space Res.Vol.9, No.8,pp.99—110,1989

[8]B. A. Abel et al. "Chemically Recyclable Thermoplastics From Reversible-Deactivation Polymerization of Cyclic Acetals" Science 13 August, 2021; pp. 783- 789. DOI: 10.1126

[9]Sathe, D. et al. Olefin metathesis-based chemically recyclable polymers enabled by fused-ring monomers' Nat. Chem. 13, 743–750 (2021). https://doi.org/10.1038/s41557-021-00748-5

[10]Christensen, P. R., Scheuermann, A, Loeffler, K et al. Closed-loop recycling of plastics enabled by dynamic covalent diketoenamine bonds ' Nat. Chem. 11, 442–448 (2019). https://doi.org/10.1038/s41557-019-0249-2

[11]Häußler, M., Eck, M., Rothauer, D., Mecking, S., "Closed-loop recycling of plastics enabled by dynamic covalent diketoenamine bonds" Nature, Vol 590, 18 February 2021, pp Nature, Vol 590, 18 February 2021 pp 423-427

[12]Zuraiqi, K., Zavabeti, A., Clarke-Hannaford, J., Murdoch, B.J. Shah, K., et. al. "Direct conversion of CO_2 to solid carbon by Ga-based liquid metals" J. Energy and Environmental Science, Issue 2, 2022,

[13]Esrafilzadeh, D., Zavabeti, A., Jalili,R., Atkin, P., Choi, J., Carey, B.J., et al. "Room temperature CO_2 reduction to solid carbon species on liquid metals featuring atomically thin ceria interfaces" Nature Communications volume 10, Article number: 865 (2019)

[14]Yao, Y., Shushkov, P., Miller, T.F., and Giapis, K.P., "Direct dioxygen evolution in collisions of carbon dioxide with surfaces" Nature Communications volume 10, Article number: 2294 (2019)

[15]Smith, A., Bullard, T., Saetta, D., Hoque, B., Devito, C., et al. "Management of Fecal Waste Utilizing a Hybrid Organic Processor Assembly Unit Designed for Resource Recovery" 51st International Conference on Environmental Systems, 7/10/2022