

Aerospace Fuels from Nonpetroleum Raw Materials

B.A. Palaszewski¹, A.F. Hepp², M.J. Kulis³, and D.A. Jaworske⁴
NASA Glenn Research Center, Cleveland, OH, 44135

Recycling human metabolic and plastic wastes minimizes cost and increases efficiency by reducing the need to transport consumables and return trash, respectively, from orbit to support a space station crew. If the much larger costs of transporting consumables to the Moon and beyond are taken into account, developing waste recycling technologies becomes imperative and possibly mission enabling. Reduction of terrestrial waste streams while producing energy and/or valuable raw materials is an opportunity being realized by a new generation of visionary entrepreneurs; several relevant technologies are briefly compared, contrasted and assessed for space applications. A two-step approach to nonpetroleum raw materials utilization is presented; the first step involves production of supply or producer gas. This is akin to synthesis gas containing carbon oxides, hydrogen, and simple hydrocarbons. The second step involves production of fuel via the Sabatier process, a methanation reaction, or another gas-to-liquid technology, typically Fischer-Tropsch processing. Optimization to enhance the fraction of product stream relevant to transportation fuels via catalytic (process) development at NASA GRC is described. Energy utilization is a concern for production of fuels whether for operation on the lunar or Martian surface, or beyond. The term “green” relates to not only mitigating excess carbon release but also to the efficiency of energy usage. For space, energy usage can be an essential concern. Other issues of great concern include minimizing impurities in the product stream(s), especially those that are potential health risks and/or could de-grade operations through catalyst poisoning or equipment damage; technologies being developed to remove heteroatom impurities are discussed. Alternative technologies to utilize waste fluids, such as a propulsion option called the resistojet, are discussed. The resistojet is an electric propulsion technology with a powered thruster to vaporize and heat a propellant to high temperature, hot gases are subsequently passed through a converging-diverging nozzle expanding gases to supersonic velocities. A resistojet can accommodate many different fluids, including various reaction chamber (by-)products.

Nomenclature

<i>CI</i>	= generic term for simple one-carbon (CO, CO ₂ , CH ₄) compounds
<i>CH₄</i>	= chemical symbol for methane
<i>CO</i>	= chemical symbol for carbon monoxide
<i>CO₂</i>	= chemical symbol for carbon dioxide
<i>ΔG</i>	= Gibbs free energy change
<i>ΔH</i>	= Enthalpy change, related to Gibbs free energy change: $\Delta G = \Delta H - T\Delta S$
<i>F-T(S)</i>	= Fischer-Tropsch (synthesis)
<i>H₂</i>	= chemical symbol for molecular hydrogen
<i>H₂O</i>	= chemical symbol for water
<i>ISRU</i>	= In Situ Resource Utilization
<i>PAG</i>	= Plasma assisted gasification
<i>Syn-Gas</i>	= Synthesis gas: Hydrogen/carbon monoxide gaseous mixture, typical ratio is 2-3:1
<i>WTE</i>	= Waste-to-energy technologies

¹Leader of Advanced Fuels, Aero Propulsion Division, Mail Stop 5-10, AIAA Associate Fellow.

²Electrical Engineer, Research and Technology Directorate, Mail Stop 302-1.

³Combustion Scientist, Research and Technology Directorate, Mail Stop 110-3.

⁴Physicist, Space Environment and Experiments Branch, Mail Stop 309-2, AIAA Member.

I. Introduction and Background

AS NASA moves forward with plans to support human exploration of the solar system, a critical need arises to supply basic raw materials such as food, other life support, energy and propellants, and other materials (radiation shielding, clothing, etc.).¹ Thus far, NASA has relied on materials brought from Earth; this conservative approach, while quite costly, minimizes risk to crews. As mankind ventures farther from Earth and for greater periods of time, it becomes imperative to develop technologies and mission architectures that utilize local resources such as Lunar regolith or Martian atmosphere, referred to as *in-situ* resource utilization or ISRU.² For a terrestrial analog, efficient utilization of raw materials and energy often involves recycling: re-use or recovery of hydrocarbons (or syn-gas, *vide infra*) from waste plastics.³ These relate to in-flight utilization of waste and trash to produce essential materials such as water, fuel(s), and oxygen. Lighter elements such as oxygen, nitrogen, and particularly carbon and hydrogen are either not readily available or strongly bonded to metal or metalloid atoms in rocks and minerals (especially oxygen) requiring significant energy for extraction.⁴

We have previously discussed specific technologies (catalysts, reactor technologies, solar energy and other green power sources) being developed at NASA GRC and through the efforts of partnering contractors and university collaborators to utilize nonpetroleum raw materials.⁵ In this paper, we discuss the problem at hand, recycling waste and trash into useful raw materials, from a systems level with a view towards integration of sub-systems, energy utilization, human factors, mission applicability, and opportunities for insertion of disruptive technologies, to enable specific missions.

The organization that we will adopt is based upon Fig. 1 below. The major concerns and issues that we will address are broken down into three areas that define the organization of the paper: pre-processing, waste and trash breakdown, and re-formation of products, and all will be addressed in the next section. Balance-of-system issues, energy efficiency, and related concerns will be addressed in a follow-on section. Insights to be gained from modeling and theoretical consideration of components, unit operations, and sub-systems will then be discussed. We conclude by addressing potentially enabling new approaches and technologies for missions farther from Earth.

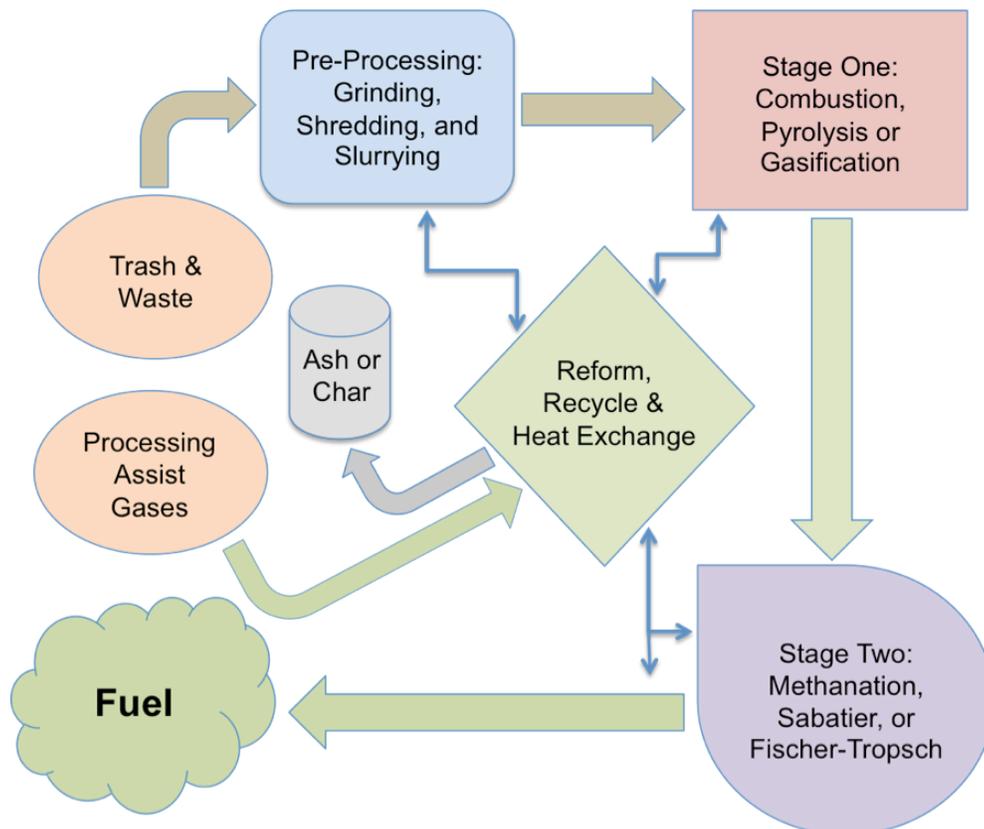


Figure 1 Overview of generic process flow diagram for a Trash-to-Supply Gas system.

II. Overview of Major Processing Sub-Systems

The general flow diagram above (Fig. 1) serves as a platform for a discussion of technological road blocks and technical solutions. This is a top-level discussion with more in-depth analyses in following sections.

A. Rationale and Goals for Modeling of Waste Materials Processing

In the Logistic Reduction and Repurposing (LRR) project, modeling of various waste conversion processes is underway. Modeling will lead to an optimized flow and production rate for each of the processes. With this information, a down-select can be made amongst competing conversion methods. Many additional factors have been identified including waste production rate, process temperature and pressure (which can affect crew safety and lengthen the processing time), the unusable matter that may accumulate in the process components, and the time needed from the astronauts for charging and cleaning the process components. The complexity, safety, and the time scales for processing the waste materials may be a very strong influence on the selection process.

B. Stage One: Production of Supply Gas and/or Hydrocarbons via Waste-to-Energy Technologies

Plastic solid waste can be recycled or utilized via four major classes of processes, designated as primary to quaternary, respectively, as physical and/or chemical breakdown increases. These include recycling (primary) and mechanical recovery (secondary) that are not discussed further, chemical recycling (tertiary), and energy recovery (quaternary).³ Commercial processes including incineration (to directly produce electricity)⁶ and biologically-assisted digestion⁷ are outside of the scope of this discussion and will also not be addressed.

There have been numerous excellent reviews that summarize and analyze in detail the various technologies, products, energy balance, and economics of several mainstream waste-to-energy (WTE) technologies. Several example tertiary or quaternary processes include: chemical recycling via pyrolysis (thermal or catalytic cracking) to produce mostly higher hydrocarbons; gasification (thermal cracking in air and/or steam) to produce CO₂ and syn-(thesis) gas (CO and H₂) and small amounts of oxygen, water, and methane, sometimes called producer gas;⁸ and plasma-assisted gasification (also a quaternary process)³ that relies on a very high temperature plasma torch to produce primarily syn-gas.

A comparison of relevant technical details as well as energy utilization and the infrastructural requirements that determine suitability for a variety of space missions is detailed in Table 1 and includes thermal cracking, flash cracking, steam reformer/Sabatier, and plasma assisted/Fischer-Tropsch (F-T)⁹ reactors. The processes previously discussed⁵ being developed by Polyflow (tertiary) and Pioneer Astronautics (quaternary) are typical of these technologies that use heat in a variety of environments to break down polymers into a product soup. The Pioneer Astronautics process involves an integrated Sabatier process to produce methane but requires a hydrogen source. The rather complex plasma-assisted gasification process relies on quite high temperatures with a significant balance-of-system to recover thermal energies.

Table 1. Comparison of Relevant Metrics for Tertiary and Quaternary WTE Processes

Process (Class)	Temperature Range	Approximate Pressure (MPa)	Product Output	Technical Complexity	Approach to Energy Efficiency or Utilization	Infrastructure Needs
Thermal Cracking (Tertiary)	400-450 °C	4-6.9	C1-C5 and Mostly > C ₆ Hydrocarbons	Low	Burning C1-C5 Fraction Supplies 80% Energy	Large
Flash Cracking (Tertiary or Quaternary)	400-600 °C	0.1-1.0	Flexible: C1- C10 depending upon T, P, catalyst	Medium	Designed to be Low Energy; Potential Solar Energy Use	Modest
Steam Reforming (Quaternary)	~850 °C	0.3-0.7	Syn-Gas (CO + H ₂), CO ₂ , CH ₄	Medium	Balancing Endothermic and Exothermic Reactions	Modest
Plasma Assisted Gasification (Quaternary)	Typically 5,000 °C	0.1	Primarily syn-gas	High	Recovery of Thermal Energy from > 1000 °C Syn-Gas Stream	Significant

While it is difficult to make direct comparisons regarding scale of infrastructure required, a typical plasma system requires significant balance-of-system hardware in order to enable self-sustaining electrical power.⁹ An energy-efficient system will include reusing otherwise wasted thermal energy from stage-one products (i.e. syn-gas at > 1000 °C) to drive turbines to generate electricity. This would then be followed by a F-T operation to convert syn-gas (CO and hydrogen) into a product soup of saturated and unsaturated hydrocarbons as well as some oxygenated products such as alcohols of C5 to C20 or so with some waxy materials. The balance-of-system technology requirements drive up the complexity (and cost),⁹ and minimize suitability for space applications; in fact, these issues eliminate PAG technology from further consideration.

The three remaining technologies to be compared include a chemical recycling technology being developed by (among others) an Akron, OH-based start-up company (Polyflow),⁵ flash cracking or pyrolysis (simple or catalytic),¹⁰ and an SBIR-funded steam reforming process.⁵ The Polyflow pyrolytic process is quite simple but scalability may be an issue.⁵ A flash cracking reactor is quite flexible from a process perspective, and is represented by a system discussed in the literature; the final product mix can be tailored depending upon the temperature and pressure as well as the presence of a catalyst.¹⁰ The lower energy demand for this process can be met by solar thermal and photovoltaic sources, as discussed below. Pioneer Astronautics has combined two unit operations that work in tandem to produce methane and oxygen. The process is quite scalable and available in 2013 as a prototype unit from a Phase II program. One issue is the need for an external hydrogen source for a Sabatier reactor: this would most likely come from splitting water.⁴ Solar energy as well as efficient thermal energy utilization will be required if this technology is to be considered as a serious flight candidate.

In summary, we have briefly compared four WTE processes to assess their suitability for ISRU: chemical recycling via pyrolysis or flash cracking, combined steam reformation/Sabatier, and plasma assisted gasification followed by (likely) Fischer-Tropsch synthesis. Because of the moderate cost, scalability for space applications, energy utilization and technology heritage of the Sabatier process, two tertiary and one quaternary WTE steam processes appear to have potential for further development. There are still balance-of-system issues remaining such as the need for hydrogen to drive the hydrocarbon production processes, safety concerns, and integration of the candidate technology into the mission architecture. The pyrolysis process, a tertiary chemical recycling methodology is technically quite straightforward but has some scaling issues due to the impact of dimensions on process kinetics. Plasma assisted gasification at the trade-study analysis level⁹ appears to present some fundamental scaling issues that preclude this technology from being further considered for LRR applications.

C. Stage Two: Processing Supply Gas into Fuels

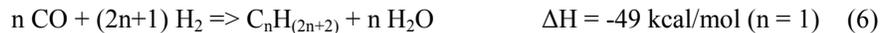
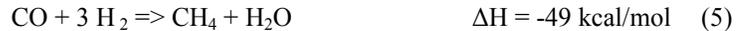
A brief consideration of C1 and related chemistry provides a context for beginning a discussion of the relevant processing options, systems issues and related technologies that will be addressed below.¹¹ C1 chemistry refers to a number of reactions including those that convert simple carbon-containing gases from “Stage One” processing of trash and waste (mostly carbon dioxide or carbon monoxide) into green and/or ultra-clean aerospace fuels. The enthalpy (ΔH) change which is related to total Gibbs free energy change of the reaction ($\Delta G = \Delta H - T\Delta S$) is an indication of whether the transformation releases energy (exothermic, negative ΔH) or requires energy input (endothermic, positive ΔH).

Depending upon the application or desired products, combining endothermic and exothermic reactions minimizes the energy that must be added to the overall system. Several endothermic reactions are available to produce synthesis gas (1) or supply gas (3) from methane, for example. Reactions (1) and (3) are related by combining reaction (1) with the slightly exothermic water gas shift (WGS) reaction (2). These are simplified “model systems” that stand in for carbon-containing waste and/or trash raw materials as discussed above.



In “stage two,” three exothermic reactions are available to produce hydrocarbons from CO or CO₂ and hydrogen. The Sabatier process (reaction (4)) is the reverse of reaction (3) and is typically catalyzed by Ni, Ru, or Rh on oxide supports; and has been a candidate technology for space habitat air revitalization.¹² In fact, a commercial Sabatier reactor was delivered to the International Space Station by mission STS-131 on April 5,

2010. Methanation^{13,14} (5) and the thermodynamically-related Fischer-Tropsch synthesis (FTS)^{15,16} (6) are also reverse reactions of steam reforming of methane (1); these reactions are catalyzed by Ni (methanation only), Co, Fe, and Ru on various oxides. All three reactions are quite exothermic and can be used to improve the energy balance in an overall system when producing fuels from waste or trash. The recycler/heat exchanger in Fig. 1 is a “black box” with several unit operations including a series of systems for the transfer of thermal energy from exothermic processes in stage two to provide heat to stage one.¹⁷ Unlike methanation, Fischer-Tropsch catalysis produces a range of products, both pure hydrocarbons and oxygenated products, depending upon the catalyst and reaction temperature and pressure.



D. Catalytic Wet Air Oxidation

Catalytic methods such as wet air oxidation or photocatalysis⁵ may serve as the basis for a system of waste and trash processing, or could be used as part of a suite of supporting or auxiliary technologies to boost the hydrogen content of various gas streams, or in using energy-efficient methods to reduce the volume and/or increase the utilization of solid or by-product streams. In catalytic wet air oxidation, Ru serves as the catalyst for the decomposition of polymers and produces mostly CO₂ and H₂, and offers additional beneficial functionality.

Catalytic wet air oxidation (CWAO) is an attractive method for the treatment of waste streams that are too dilute to incinerate (< 40%)⁶ and too concentrated for biological treatment (> 1%).⁷ The method involves the oxidation of organic substances in an aqueous suspension by means of air at elevated temperatures and pressures. Heterogeneous catalysts are used to oxidize refractory compounds in the aqueous phase and produce desired products in the gas phase. Typical conditions range from 200 °C and 2 MPa to 320 °C and 20 MPa.

NASA GRC is currently investigating CWAO as a method to produce methane from waste simulant using various catalysts in a one step process. Kulis et al., have demonstrated that significant amounts of methane can be produced using CWAO of polyethylene terephthalate with ruthenium as a catalyst.¹⁸ In addition, concentrated solar energy is being investigated as a thermal source, and photocatalysis is being investigated as a supplementary method that would be used to split water in order to produce additional hydrogen for methane production. Though CO₂ formation and departure from the catalytic surface is crucial, the kinetics may be dictated in part by such factors as surface tension, surface roughness, and gravity, where a practical understanding of bubble formation and departure may guide design of the CWAO process under reduced gravity conditions.

III. Balance-of-System Concerns and Resistojet Technology for Gas Utilization

There are a variety of issues related to the integration of the re-use technologies with the rest of the spacecraft. This section addresses some of those concerns and highlights some NASA GRC capabilities, facilities, and expertise in this area.

A. Energy Efficiency Issues

Energy must be considered at a system level, where heat is added to the system for driving the endothermic reactions and heat is harvested from the exothermic reactions for improving overall system efficiency. Overall heat rejection must also be considered. Electric power derived from spacecraft photovoltaics is the most likely source of process energy, including the electrical energy needed for running pumps and splitting water. In certain cases there may be merit in considering solar thermal to augment the process energy, particularly for the stage 1 endothermic and gas shift reactions. Given a sun-tracking requirement, solar thermal augmentation may best be suited for treatment facilities that are anchored to the lunar or Martian surface rather than part of a spacecraft rotating about its axis for thermal control. Numerous studies have been completed on the various types of solar thermal concepts available for possible use, ranging from ridged structures having facets with high quality optical surfaces and concentration ratios of the order of 8000:1, to concepts that tout light weight inflatable structures, light pipes, and trough systems with lesser efficiency and lesser concentration ratios.^{19,20} Perhaps the ideal concept is one where a sun-tracking trough style solar concentrator anchored to the lunar surface heats the carbon-containing waste and/or trash raw materials in a carrier stream of oxidizer, optimized such that the

residence time in the trough enables the heating of the mixture to the desired temperature prior to entering a reaction chamber. Small diameter thick walled tubing coated with a high absorptance coating and located at the focus of the trough would enable high pressure high temperature operation, particularly for the catalytic wet air oxidation process.

Initial research is now underway to consider solar thermal augmentation for process energy and selected on-sun testing has been performed on a test article that simulates a stainless steel tube at the focus of a high efficiency concentrator. The concentrator utilized here is of a cassegrainian design and is described in detail elsewhere.²¹ The concentrator was located on a platform equipped with sun-tracking hardware. The test article consisted of a thick-walled stainless steel tube which offers the advantage of pressure containment, however, thermal conductivity is a problem. The use of a copper jacket to distribute the heat around the perimeter of the tube was considered here, and the stainless steel tube was purposely surrounded by a press-fit copper jacket. The test article was instrumented with thermocouples and was purposely surrounded by multilayer insulation to minimize heat loss. In practice, the tubing would be sized to accommodate the flow of carbon-containing waste and trash, and the mass rate of flow along with any endothermic reactions would serve to draw heat away from the region illuminated by the concentrator. Here, the test article here was open to the air. The copper jacket was painted black, to enhance solar absorption and Fig. 2 summarizes the fabrication of the test article, reveals the concentrated sunlight as a spot on the surface of the black paint, and shows an excerpt of the on-sun heating data.

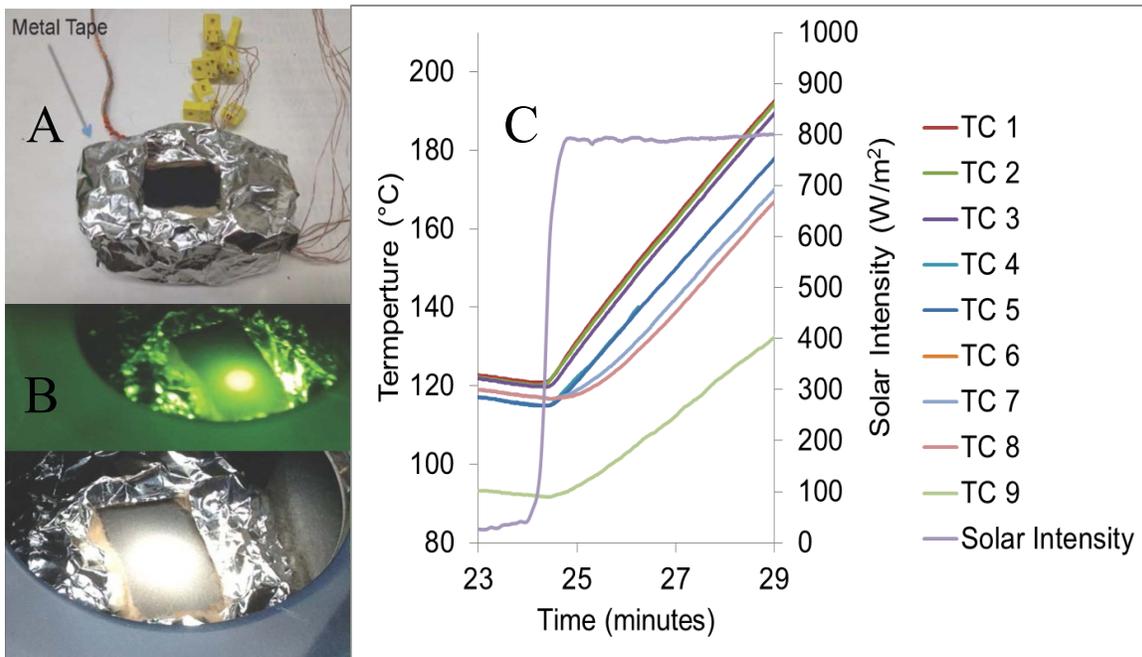


Figure 2. Copper-jacketed stainless steel test article, a) painted, instrumented, and enclosed in insulation, b) under concentrated sunlight (the glare is removed by viewing through a filter), and c) an excerpt of the on-sun data. Note: the majority of the energy impinging on the copper is within a small spot.

Conclusions from the on-sun testing are summarized here, briefly. The test article had been on-sun for several minutes, though the day was partly cloudy and the excerpt shows the sun beginning to impinge on the test article again after being cloud-covered. Thermocouples 1 and 2 were located on one side of the copper jacket, 5 and 6 were on the opposite side (6 malfunctioned), 3 and 4 were on the back, and 7 and 8 were on the exterior of the stainless steel tube some distance from the copper jacket. Thermocouple 9 was located inside the stainless steel pipe. Under ideal system-level operation, the solar thermal augmentation would ideally reach steady state, such that the energy entering the system from the impinging sunlight just equals the amount of energy departing the illuminated region in the form of mass flow and endothermic reactions. The results from the on-sun testing revealed 1) the copper jacket was only partially successful at distributing the heat around the tubing and 2) the

interior temperature lagged behind due to the thick-walled nature of the stainless steel. As can be seen, it takes many tens of minutes for the test article to heat under the influence of the concentrated sunlight. All these observations suggest that the ideal system will need an adequate solar tracking system as a minimum, a trough concentrator is likely preferred in order to avert the need for distributing heat utilizing a copper jacket, and perhaps the most important need is a well anchored solar concentrator.

The shuttling of excess heat from exothermic reactions to power endothermic reactions may be possible utilizing conventional heat pipes or heat exchangers designed to deliver such energy from one location to another. However, a temperature gradient is needed in such systems, the processing temperatures may limit such a concept, and losses are inevitable. Heat pumps are available to shuttle excess heat from one location to another, with the added feature of increasing the temperature at the outlet. Of course, heat pumps represent an electric load on the system and must be incorporated into any energy balance study. Perhaps the ideal concept is one where sufficient electrical power is provided to the reactor into which reactants are provided to overcome the sensible heat of the reactor mass and the energy needed to initiate stage 1 endothermic reactions during transient start up operations, and electrical power is throttled back as new solar thermal heat sources are brought on line during steady state operation. Repeated transient and steady state operation should be expected for either batch or continuous processing, though far fewer cycles would be anticipated for a continuous reactor.

Table 2. Comparison of Methods for Separation of Impurities from Gas Streams

Process	Energy Requirements	Impurity(ies)	Products	Comment(s)	Literature Reference(s)
Centrifugal > 30,000 rpm	Electrical – large	H ₂ S and CO ₂ in CH ₄	H ₂ S and CO ₂ removed	Not suitable for space station	[22]
Biofilters in aqueous media: bacterial, wood, textile, sand, or combination	Electrical – minimal	NH ₃ (and H ₂ S) in air	NH ₃ (and H ₂ S) removed	Must be crew bio-compatible	[23-25]
Filtering by zeolites	Thermal – minimal to reactivate	Volatile organic compounds (VOCs) in air	VOCs removed	May require heating to reactivate active adsorbants	[26]
Oxide catalyst & Metal/zeolite filter	Thermal – moderate for Temp > 400 °C	Carbon, VOCs, NO _x , and CO in air	CO ₂ and N ₂	Useful process for recycling by-products	[27]
Photocatalysis TiO ₂ /aluminum silicate fiber	Solar Energy with UV photons	SO ₂ , NO and Hg ⁰ in air	Pollutants removed	Passive relies on ambient solar irradiation	[28]
Catalytic H ₂ S splitting by solar thermal, photochemical, electrochemical, or combination of methods	Solar Energy to provide photons, heat, or electricity; geared towards renewable energy usage	H ₂ S	H ₂ + sulfur	Very flexible family of methods; details dependent upon catalyst and available energy	[29,30]

B. Methods of Handling Heteroatom Impurities

Upon consideration of the recycling of trash and waste materials, a technological hurdle that must be surmounted is separation and storage of impurities. In our previous paper, we discussed specific technologies being addressed by several co-authoring organizations to remove metals, nitrogen, sulfur, and halogens present in packaging materials and human wastes.⁵ If not removed, these materials pose potential health hazards to the crew and destructive impact on various components and sub-systems in the closed waste and trash re-processing system by material corrosion and catalyst poisoning.

There are basically two approaches to the removal of impurity compounds (oxides, hydrides, sulfides, halocarbons): methods involving little or no power that consist of adsorbing and long-term storage of impurities, possibly including recharging or re-activation of sorbent materials, or active methods involving solar, electrical and/or thermal energy to decompose impurities to simpler species, one or more of which can be re-used such as water, oxygen, or hydrogen. Table 2 summarizes and compares several methods to recycle a variety of impurity materials from gas streams of both types.

Of the six methods compared in Table 2, the first two methods are the most problematical owing to potential impact on a closed system from mechanical or biological impact on the environment. They are also difficult to integrate into a processing system (Fig. 1). The four methods that primarily rely on catalytic processes and/or adsorbent materials use lower amounts of limited power supplies and could be more readily integrated into a recycling function in a processing system. Utilization of solar energy directly or indirectly through electricity generated by photovoltaics would also have advantages in the energy balance as discussed above.

C. Resistojet Propulsion Option

As part of the LRR project, the production of fluids (liquids and gases) from the waste materials aboard a space vehicle may be many and varied. These fluids can be used in a propulsion option called the resistojet. The resistojet is a form of electric propulsion known as an electrothermal thruster, where power is provided to the thruster to vaporize and heat the propellant to high temperature, and then the hot gas is passed through a converging-diverging deLaval nozzle, expanding the gas to supersonic velocities.³¹⁻³⁷ The heating of the fluid provides much higher exhaust velocity (or specific impulse) than if the fluid were used in the cold gas mode without heating. The resistojet can accommodate many different fluids.

1. 1970s resistojet research

During the study phase of several space station concepts, the idea of using the waste fluids from the space station was considered. Resistojet propulsion was investigated and the extensive design showed some benefits and drawbacks. Fig. 3 shows an overall configuration of the resistojet system. The integration of the propulsion system with the station layout of the components is noted. The design model of the Space Station resistojet system uses environmental control life support system (ECLSS)-produced biowaste gases (CO_2 and CH_4) as propellants.^{31,32} The gases are used separately, and water is employed as a propellant supplement. The system minimizes resupply requirements, furnishes a useful method of biowaste disposal, minimizes contamination, and permits near-zero acceleration, reducing the thruster disturbances on the Station.

The resistojets have a thrust level of 0.1 Newton (0.025 lb-f) and are operated in a high-duty-cycle mode (25 to 80 percent) for Space Station orbit-keeping and control moment gyroscope (CMG) desaturation. The thrusters are mounted in modules. Four modules are located at each end of the Space Station, and the gas storage tanks are housed in the pressurizable forward compartment.³¹

The major components of the system are compression pumps, heat exchangers, accumulators, propellant tankage, thrusters, and the necessary valves and switches for control and checkout. The system weighs 259 kg (570 lb-m), occupies a volume of 2.78 m³ (100 ft³), and requires 100 to 400 watts of electrical power.³¹

The Space Station Biowaste Resistojet Propulsion system was required to operate automatically, with little or no crew participation except for maintenance and repair, etc. Thus, system control was required to acquire stabilization and attitude control (S&AC) data, calculate impulse requirements, determine propellant utilization and provide the necessary operating commands; typically once per orbit. Furthermore, the interface with the ECLSS (propellant supply) and the high duty cycle and usage (25 to 80 percent each orbit) makes operational control significantly different and more complex than conventional systems.³¹

2. 1980s resistojet research

As space station concepts moved toward reality, many propulsion options were considered. Resistojet propulsion seemed a natural choice in that many gases were produced by the many systems on Space Station Freedom. A detailed set of all waste gases and fluids were identified: from life support systems, cooling systems, and cryogenic experiment gases the resistojet could use those fluids for space station orbital reboost.³³ Extensive engineering model testing was conducted and detailed requirements were developed for resistojet propulsion for Space Station Freedom. Figure 4 depicts the orbital replacement units (ORUs) for the resistojet propulsion system. Figure 5 shows the resistojet engineering model tested by NASA for the space station. Extensive testing of the engineering model engine with the various waste gases helped identify the platinum and yttria alloys needed to survive the oxidizing and reducing environments.³⁴⁻³⁷

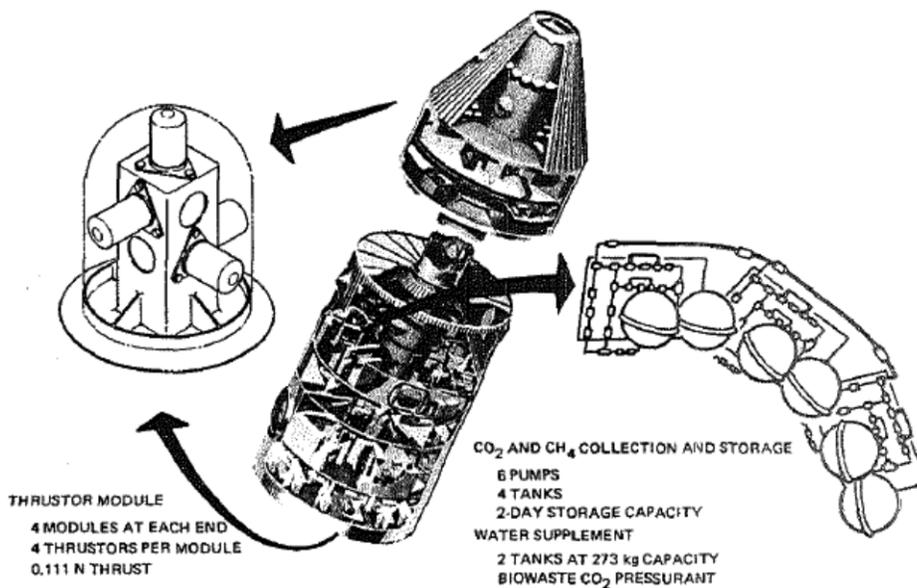


Figure 3. Diagram of resistojet propulsion technology from 1970s (Ref. 31 and 32).

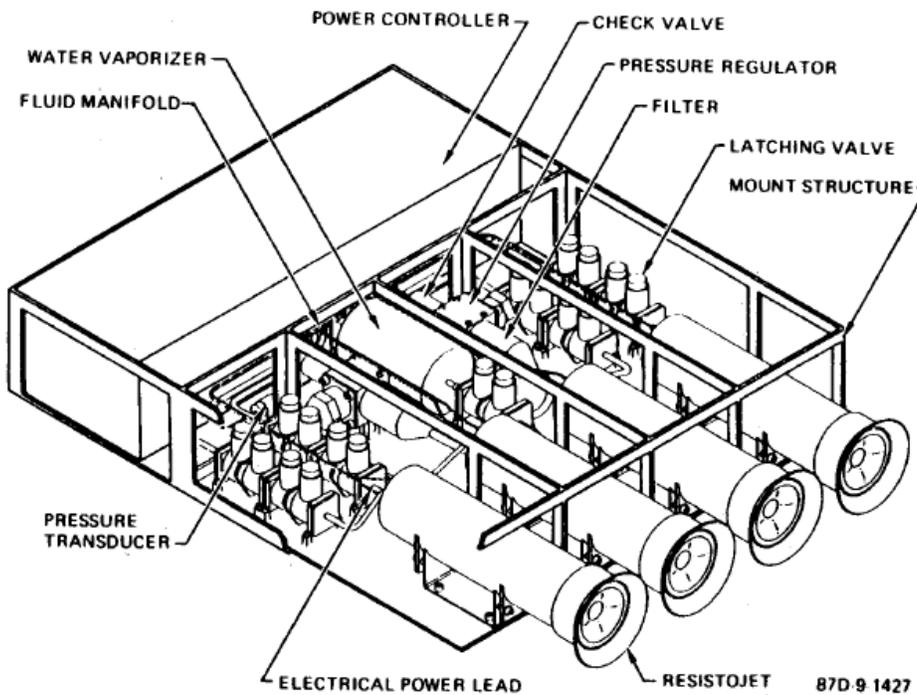


Figure 4. Resistojet orbital replacement unit (ORU, Ref. 33).



Figure 5. Resistojet thruster engineering development model (Ref. 34).

Fig. 6 shows the numerous bio-waste propellants that the resistojet can use. Their engine specific impulse and other performance parameters (heater power level, thrust levels, etc.) are noted. The cold gas specific impulse for the hydrogen resistojet is approximately 380 seconds at a power level of 329 watts. In comparison, the cold gas hydrogen performance (with no heater power) is 250 seconds.³⁵

3. Gateway propulsion needs

While the Gateway vehicle is still at the preliminary design stage, several options have been discussed. Figure 7 depicts a configuration and provides a mass summary of two such preliminary designs for 60 and 500 day stays in space. These mass estimates show all of the vehicle subsystems but not the required propulsion system masses. Based on the final mission design, additional masses for the propulsion system dry mass (tankage, feed systems, etc.), the required propellant mass and other vehicle interfaces will be required.

4. LRR and resistojet propulsion

While the planned human space vehicles are not as ambitious as Space Station Freedom, the propulsion system use of the waste gases on such future vehicles can still be advantageous. Aboard the Gateway (Earth-Moon libration point station) or other space vehicle a heat melt compactor (HMC), or other waste processing technologies, operated by the astronauts would process the waste materials. The fluids that may be produced would be water, methane, methanol, oxygen, etc. Past resistojet propulsion studies and experiments have shown that the resistojet can use a wide range of fluids and also mixtures of those fluids. By eliminating the need to separate specific fluids, the use of the waste material fluid products can be simplified significantly.

IV. Conclusion

Plastic solid waste can be recycled or utilized via four major classes of processes with increasing physical and/or chemical breakdown. Relevant to this discussion are chemical recycling (tertiary) and energy recovery (quaternary). Depending upon desired products and mission, combining endothermic and exothermic reactions minimizes energy that must be added to the overall system. A technological hurdle that must be surmounted is separation and storage of impurities. On future space vehicles, an array of potential waste fluids has been identified. These fluids may be produced using innovative processes such as heat melt compactors, catalysts, reactor technologies, solar energy, and other green power sources, for solid waste processing. Other than fluids for life support and cooling, many propulsion requirements can be met with the more energetic fluids. The delta-V and other propulsion requirements can use the captured waste fluids effectively in a low-thrust rocket engine such as a resistojet. This form of electric propulsion can accommodate many types of fluids or mixtures of fluids. While there are many processes to consider, the final selection will be based on a combination of efficiency, complexity, astronaut safety, and consumption of the astronauts' valuable time in space.

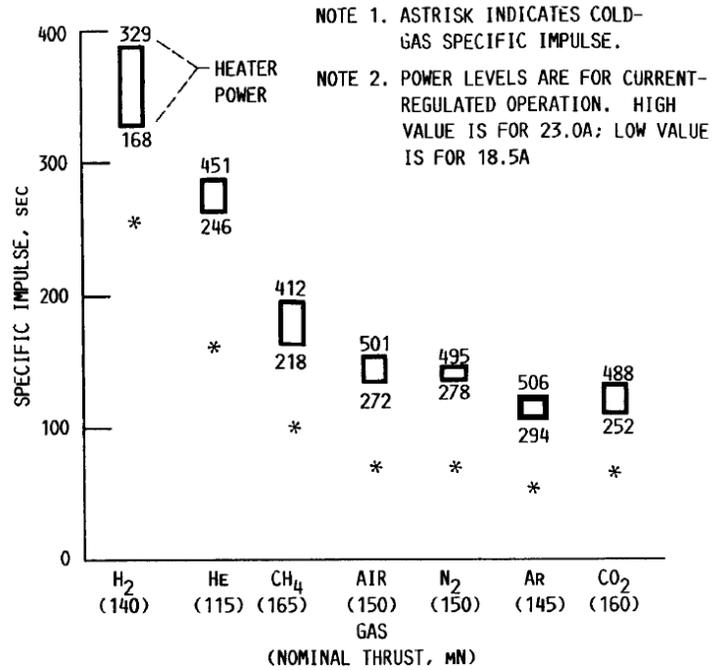


Figure 6. Resistojet propulsion performance, experimental data (Ref. 35).

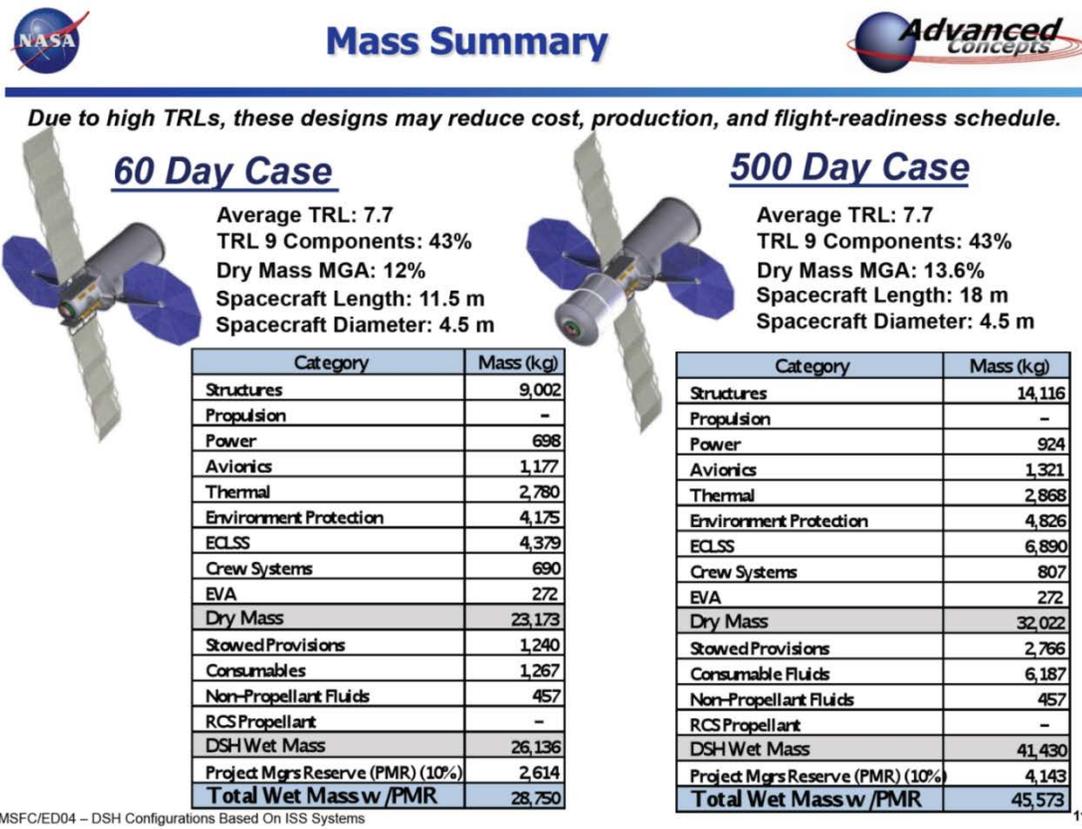


Figure 7. Notional design for Gateway vehicles (Ref. 38).

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