PLASMA REACTOR WASTE MANAGEMENT SYSTEMS

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The University of North Dakota is developing a plasma reactor system for use in closed-loop processing that includes biological, materials, manufacturing, and waste processing. Direct-current, high-frequency, or microwave discharges will be used to produce plasmas for the treatment of materials. The plasma reactors offer several advantages over other systems, including low operating temperatures, low operating pressures, mechanical simplicity, and relatively safe operation. Human fecal material, sunflowers, oats, soybeans, and plastic were oxidized in a batch plasma reactor. Over 98% of the organic material was converted to gaseous products. The solids were then analyzed and a large amount of water and acid-soluble materials were detected. These materials could possibly be used as nutrients for biological systems.

INTRODUCTION

With the launching of the U.S. space station scheduled for the mid-1990s, the likelihood of longer manned missions to the Moon and Mars, and eventual lunar and martian bases, there is a need to develop more comprehensive Environmental Control/Life Support Systems (ECLSS) for use in extraterrestrial activities. Both energy and physical size requirements will dictate the type of ECLSS that will be necessary. Three options are available for extended space living, including (1) systems in which consumables such as oxygen and food are not recycled; (2) totally closed-loop systems with recovery of all consumables; or (3) partially closed systems. The decision regarding the percentage of consumable material that will be recycled will be based primarily on the size and energy requirements of the closed-loop system.

Environmental Control/Life Support Systems, as they exist in current spacecraft, are primarily concerned with subsystems that will provide life support. The raw materials for these systems have been self-contained and, to a large extent, not recycled. For larger systems, such as bases, the processing must be expanded to allow manufacturing, materials handling, and waste treatment. The interaction between the groups (biological, materials, manufacturing, and waste processing) in the closed-loop processing (CLP) resource management system is illustrated by Fig. 1.

The primary objective of this research program at the University of North Dakota is to develop the application of low-temperature plasma reactor systems to closed-loop processing. Closed-loop processes are those that require essentially no raw materials, while producing little or no by-product or waste. Typical applications of these systems are those that will be used in either remote processing or habitation communities such as isolated research communities, both terrestrially and in space.

The systems that will be used on the lunar surface will integrate the biological systems and the material processing systems as closely as possible. A plasma reactor could be a central processing unit that will serve to integrate the operation of waste treatment, biological processing, materials processing, and manufacturing, all of which are being conducted at a remote site where resupply and waste disposal are impossible, or at least difficult and costly.

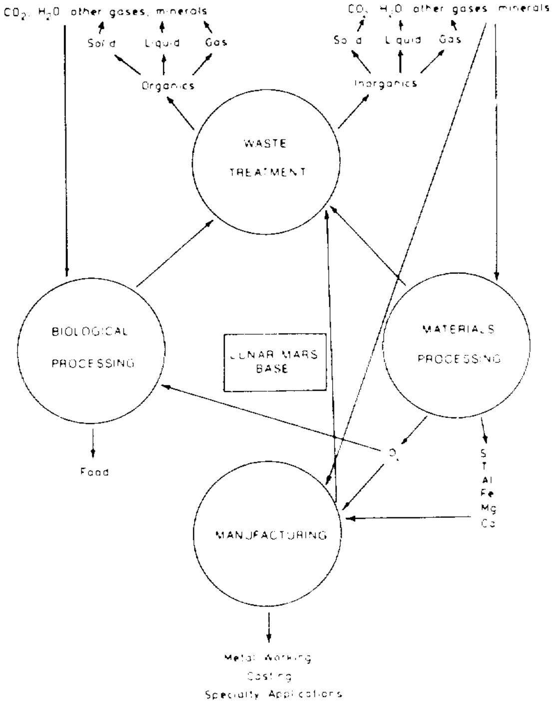

Fig. 1. Closed-loop processing (CLP) resource management system.

The intent of the project and future research is to pass products from one or more of the CLP areas to another in which they will serve as reactants.

BASIC PLASMA GENERATION

A plasma is a highly ionized gas that is electrically neutral and composed of ions, electrons, and neutral particles. The various species are formed when gas molecules acquire energy by intermolecular collisions or from electromagnetic radiation.

There are three basic methods of plasma generation: (1) direct thermal; (2) direct-current discharges; and (3) high-frequency discharges. Figure 2 is a block diagram summarizing the generation types. Each pertinent group will be discussed in the following paragraphs.

Direct-current (dc) and high-frequency discharge both produce ions by one or a combination of two mechanisms: (1) molecular absorption of photons and (2) inelastic electron-molecular collisions. These reactions occur simultaneously, in equilibrium, with the termination reactions that include (1) desorption of a photon, (2) elastic electron-molecular collision, and (3) reaction of the ion with other molecules to form new compounds.

The first initiation mechanism is the molecular absorption of a photon (i.e., the Compton Effect; *Beiser,* 1981). The activated molecule may then react with other reactants to form products, such as ions, or it can release the energy by emitting a photon. When the products of these reactions are ions, the electromagnetic field will also provide kinetic energy to the ionic molecules, which in turn will promote the production of additional ions through collisions. Because a particular wavelength activates certain molecules, selective activation of a single species in a multicomponent system may be accomplished.

The second method of ionization is by electron-molecular collisions. The kinetic energy of the molecules is then increased by elastic electron-molecular collisions, while inelastic collisions lead to excitation, fragmentation, or ionization of the molecule. In every case, the rate at which the collisions occur per unit gas volume is directly proportional to the bulk gas pressure and the electron density (*Baddour and Timmins,* 1967, pp. 1, 55-59).

Either of the two mechanisms of ion production will promote the production of more ions. The mechanism that predominates will depend on electron temperature, bulk gas temperature, electric field intensity, and the concentration of molecules in the system.

UNIQUE ASPECTS OF PLASMA REACTOR SYSTEMS

Plasma reactors offer several characteristics that make them particularly attractive for use in space applications, where the ability to control the reactor and the moderate operating temperatures and pressures contribute to relatively safe operation. While engineering details change, the overall concept will work in both microgravity and gravity fields. Particular operating characteristics that contribute to the usefulness and safety of plasma reactors are

*1. **Reaction Specificity.*** The efficiency of energy transfer from the electromagnetic source to the parent gas molecules depends on the frequency of the radiation. Therefore, when a specific frequency is used, particular molecules will ionize and cause specific reactions to occur. With the ability to vary the frequency, the plasma reactor can be used for a variety of reactions, thus providing a very versatile system.

*2. **Reaction Rate Control.*** Because the rate of ion generation is directly related to electromagnetic field strength, the concentration of activated species and, consequently, the reaction rate can be very easily controlled.

*3. **Rapid Reactor and Reaction Shutdown.*** The ion production rate in the "ion generator" is inversely proportional to the concentration of reacting molecules in the system. Therefore, a hole or leak into the generator will result in an increase in system pressure, and the rate of ion production will decrease markedly. The result would be an orderly shutdown of the reacting system.

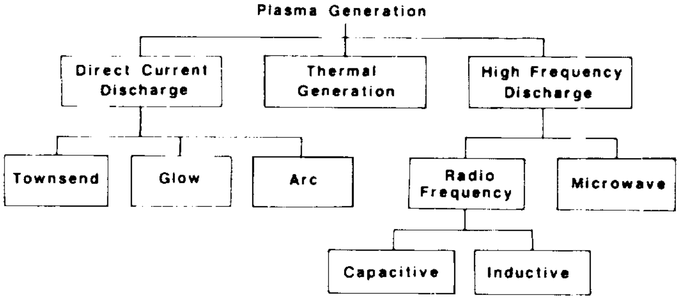

Fig. 2. Plasma generation techniques.

OXYGEN PLASMA WASTE CONVERSION (OPWC) RESEARCH

Preliminary testing of the feasibility of using oxygen plasma reactor systems for the removal of organics from waste material has just been completed. Samples of oats, sunflowers, freeze-dried human fecal waste, and a plastic bag (Baggie) were reacted in a batch oxygen plasma system. Table 1 shows an HCN (hydrogen-carbon-nitrogen) analysis of the material remaining in the reactor.

TABLE 1. Data summary for oxygen plasma waste conversion unit.

Freeze-dried Human Fecal Sample	
OPWC % Residue[*]	31.00
% Carbon	5.205 + 0.145
% Nitrogen	0.885 + 0.045
% Hydrogen	1.380 + 0.06
% Conversion[‡]	98.39
% 6M-HCl-Soluble	73.86
% Water-Soluble	32.33
Sunflower Root, Stalk, and Head Sample	
OPWC % Residue	18.52
HCN Analysis of Residue	
% Carbon	5.220 + 0.27
% Nitrogen	0.440 + 0.04
% Hydrogen	1.655 + 0.095
% Conversion	99.03
% Water-Soluble	82.36
Oat Root, Stalk, and Head Sample	
OPWC % Residue	11.15
HCN Analysis of Residue	
% Carbon	1.810 + 0.06
% Nitrogen	0.260 + 0.02
% Hydrogen	1.035 + 0.085
% Conversion	99.8
Soybean Root, Stalk, and Head Sample	
OPWC % Residue	17.45
HCN Analysis of Residue	
% Carbon	3.955 + 0.155
% Nitrogen	0.490 + 0.01
% Hydrogen	0.890 + 0.05
% Conversion	99.31
Plastic (Baggie) Sample	
OPWC % Residue	1.40
% Conversion	98.60

[*] (Weight of residue out of OPWC)/(weight of sample in OPWC).
[†] Standard HCN on a Control Equipment Corporation unit.
[‡] 1-(OPWC residue - nonorganic weight)/(OPWC sample weight - nonorganic weight).

Conversion was based on the amount of C left in the sample and was defined as one minus the weight of inorganic free residue divided by the initial inorganic free sample weight. The carbon content was determined by a standard HCN analysis (*Control Equipment Corporation*). The human and plastic samples exhibited the lowest conversions of 98.4% and 98.6%, respectively.

Figure 3 shows the results of a simple residence time experiment completed using human fecal matter. Every two hours the sample was removed from the chamber, cooled in a desiccator, weighed, stirred, and replaced in the reactor. Stirring is necessary to remove any residue formed at the surface. Conversion takes place rapidly up to approximately 80% and then the rate of conversion declines.

Processing of the waste materials included two steps: dehydration and organic conversion. Figure 4 summarizes the composition of a typical fecal sample including the mass of water, material converted, water-soluble residue, and insoluble residue. The figure gives a perspective of the percentage of material the two steps need to handle. The dehydration and organic conversion step removed 99.56% of the material.

The remaining 0.0012 lb of inorganic material was evaluated by water and acid (HCl) solubility tests and X-ray diffraction and fluorescence analysis. Figure 5 shows the results of the solubility tests and Table 2 shows the X-ray fluorescence test results. These materials have amorphous structures since the X-ray diffraction analysis did not yield any crystalline structures above 5% of the total mass.

The X-ray fluorescence results verify the solubility test results. The only component that is readily soluble in water is P_2O_5, which decomposes. The solubility test indicated approximately 32% of the residue to be soluble, while the X-ray fluorescence indicates 31.7% of the material to be P_2O_5. The acid solubility tests also correspond. Magnesium oxide, Al_2O_3, P_2O_5, SO_3, CaO, and Fe_2O_3 are HCl soluble. The solubility test (83%) and the X-ray fluorescence (81.57%) indicate this relationship. Further tests are being done to determine potential end uses for this residue.

These figures show a systematic reduction of 99.56% of the material by dehydration followed by the conversion of an organic material. Since the primary goal of determining if an oxygen plasma system could process a quantity of materials with high conversion was achieved, further analysis of the products and process development is needed to determine electrical requirements, size, residence times for fluidized beds, etc. This information will determine feasibility for space use.

The gas stream from the oxygen plasma conversion unit was not analyzed. It is assumed that most of the gaseous products were CO_2; however, the gas stream from the plastic bag probably contained some chlorine compounds.

TABLE 2. Energy-dispersive X-ray analysis.

		RESULTS			
	Weight %	Std. Dev.		Oxide %	Std. Dev.
O	37.340				
Mg	3.319	0.044	MgO	5.504	0.072
Al	0.279	0.008	Al_2O	30.527	0.014
Si	1.330	0.010	SiO_2	2.844	0.022
P	13.840	0.040	P_2O_5	31.720	0.090
S	1.809	0.008	SO_3	4.516	0.021
Ca	27.800	0.100	CaO	38.900	0.140
K	6.917	0.049	K_2O	7.465	0.059
Ti	0.471	0.010	TiO_2	0.786	0.017
Fe	0.279	0.003	Fe_2O_3	0.399	0.004
TOTAL	92.660				

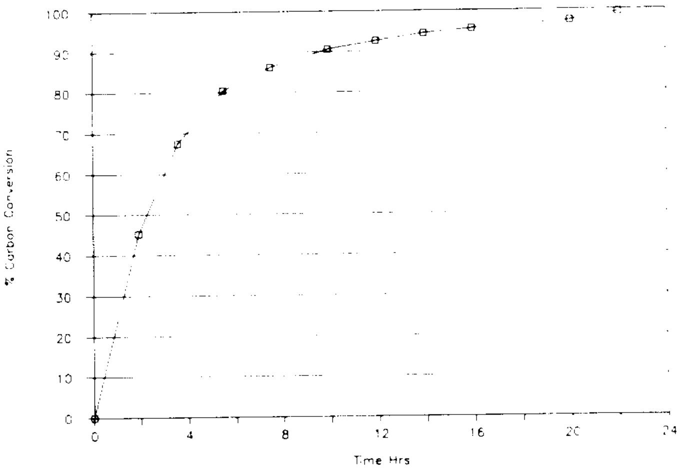

Fig. 3. Percent combustor carbon conversion.

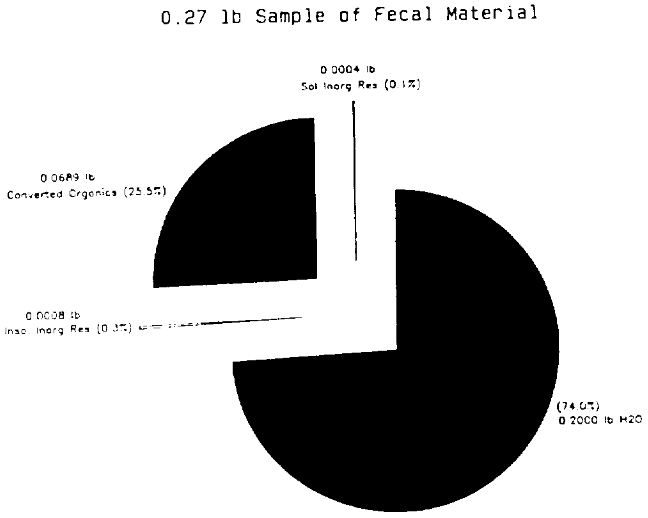

Fig. 4. Fecal sample composition.

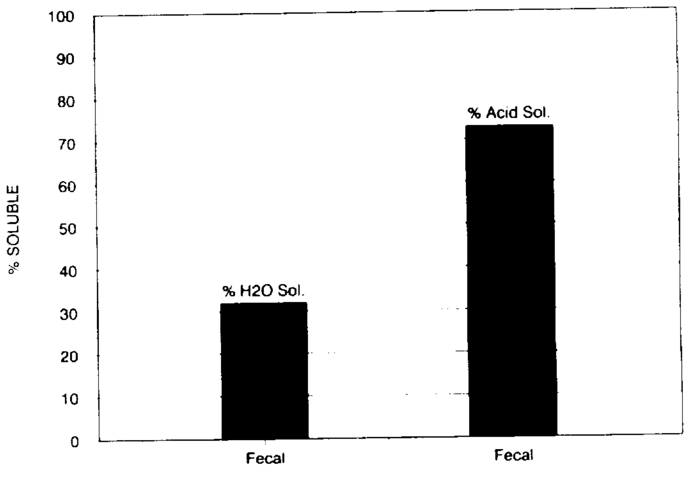

Fig. 5. Combustor residue solubility.

APPLICATIONS OF PLASMA REACTORS TO SPACE ENGINEERING SYSTEMS

A process flow diagram, as shown in Fig. 6, could be used to process waste material from a space station or lunar base. Similar processes have been proposed for terrestrial use, but because of relatively high electrical costs as compared with those of other biological processes, the systems were uneconomical. In space environments, factors other than electrical costs play important roles. This system could be either independent of a biological treatment system or in conjunction with such a system. These types of systems could complement each other because they could provide operating flexibility by changing electrical requirements, size, weight, residence time, and allow high conversion of all organic feed materials.

In terrestrial processes, the following technical and economical factors must be considered: (1) operating conditions (temperature, pressure, pH); (2) operating complexity; (3) equipment maintainability; (4) size; (5) weight; (6) electrical requirements; (7) storage of processing and processed materials; (8) location of raw materials; (9) heat rejection; and (10) safety. Due to the many operating restrictions, the plasma reactor system may have operational advantages over other schemes based on the following: (1) low operating temperatures; (2) low operating pressures; (3) mechanical simplicity; (4) can be used to process solids, liquids, and gases; (5) relatively safe operation; and (6) ease of operation.

A plasma reactor may oxidize or reduce specific components of a process stream while leaving the remainder of the stream unaffected. This, in effect, is a separation and conversion process taking place in one reactor. An example is the conversion of the organic fraction of plants, human waste, and plastics to gases while the inorganic fraction remains unchanged. The inorganic materials can then be directly recycled to other operations.

Plasma reactors are relatively simple to operate because they do not require high temperatures or pressures, or the addition of caustics or acids for chemical reactions. Aqueous solutions can be treated by using a microwave drying step before the oxidation step. Because the system operates under mild conditions, the plasma reactor may offer an alternative to high-temperature processes. The system does not require a heating or cooling period, so reactions can be very tightly controlled; this contributes to the efficiency and safety of the system.

Other applications for the use of plasma reactors could be in the reduction of lunar soils for the production of oxygen. Presently, researchers are thermally heating hydrogen to approximately 900°C and reducing ilmenite to Fe, TiO_2, and water (*Gibson and Knudsen,* 1985). The water is then electrolyzed to produce hydrogen and oxygen. Since this system requires the injection of large quantities of heat, which will require the presence of larger radiators on the lunar surface, reduction by a hydrogen plasma atmosphere may be practical. While this presents advantages in reducing process severity, there remain many technical questions that need to be addressed.

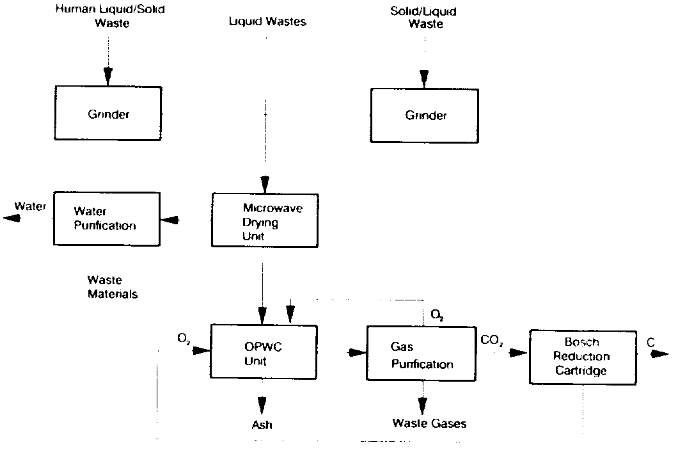

Fig. 6. Waste management process flow diagram .

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