Food Production and Solid Waste System for Advanced Life Support on Long-Term Space Missions

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ABSTRACT

This paper describes further development of a bio-regenerative food and waste management system concept for long-term space travel. The concept proposes a system by which sufficient food and fiber could be taken along for a six-person crew on a 3-year round trip mission to Mars by lifting off with only a 6-month supply of pre-packaged shelf-stable food and fiber products on board (sufficient for one-way transit to the planetary base). During residence time on the planetary base, daily food production would include repackaging and reprocessing a daily excess of prepared shelf-stable ready-to-eat meals with recycled retort pouches that were accumulated during transit for this purpose.

Technical feasibility of such a system was addressed beginning with selection of a specific realistic scenario that could be supported with available data from recent NASA-funded research in space agriculture, advanced food technology, and solid waste management. The paper reports on a preliminary attempt to track mass balances of daily food intake requirements from crew consumption and metabolism, recovery of organic wastes, and bioconversion of those wastes and residues to compost through anaerobic digestion for return to plant growth media.

INTRODUCTION

Man's never-ending quest for exploration throughout world history leaves us with no surprise that our National Aeronautics and Space Administration (NASA) has persistently held fast to the long-term goal of launching a successful manned mission to the planet Mars, considered to be the next "frontier".

The very arrival of the roving robots on Mars' surface is evidence that NASA has developed the needed rocket science technology to lift off and propel a spacecraft from Earth to Mars (and presumably back, again). The challenge seems to be the lack of technology needed to provide for human life support on a three-year adventure to a non-inhabitable environment with no roadside rest stops along the way. It is unrealistic to expect a vehicle to lift off from earth's surface carrying the mass of water, food and fiber to be consumed by a crew of 6 persons over a period of 3 years. Assuming minimum per capita consumption of 2 kg/day of food and water (not including packaging materials and disposable paper/fiber products), this amounts to well over 12 metric tons. In addition to food and water, other consumables, such as absorbent fiber products in the form of paper toweling, bathroom and facial tissue, and sanitary wet wipes will need to be consumed daily by crew members in maintaining personal hygiene, and will significantly add further to prohibitive vehicle weight and volume (Teixeira et al. at ICES-2004).

On earth, essentially all food and absorbent paper products are fabricated from agriculturally grown raw materials, and early pioneers relied upon establishing agricultural production systems to "regenerate" their food supply for their continued life support at remote outposts. An agriculturally based "bio-regenerative" system in which organic nutrients are continually recovered, recycled, regenerated and reused is likely to have greater technical feasibility than a "backpack" system. This paper attempts to further explore the potential for technical feasibility of such a "bio-regenerative" system and its component sub-systems and their integration.

METHODS

SYSTEM CONCEPT DESCRIPTION - The concept described in this paper was presented earlier by Teixeira et al. (2004). It proposes an advanced life support (ALS) system in which sufficient food and fiber can be provided for a six-person crew on a 3-year round trip mission to Mars with only a 6-month supply initially brought on board. The assumption of a 3-year time span stems from the understanding that transit time between Earth and Mars when the two planets are closest will be approximately 6 months, and that once reaching Mars, an 18-month stay will be required until the two planets once again come closest together from their elliptical orbits. The overall ALS system would consist of seven fully integrated subsystems consisting of air revitalization, water recovery, solid waste treatment, biomass production, food processing, paper production, and crew consumption.

System architecture and mode of operation would be based upon the following assumptions:

- The ALS system would operate as a “closed” system, conserving mass and energy to the extent possible; all input and output flow streams would remain in a closed loop.
- No gravity field would be available during outbound and return transit missions. Therefore, little food/fiber production or processing would occur during transit; but air, water and solid waste treatment systems would remain fully operational.
- Once on Mars, a planetary base would be established in which gravity-dependent subsystem operations would be carried out, and production and processing subsystems could operate at full capacity.
- The solid waste system would be based upon bioconversion of organic wastes into compost for use in plant growth chambers for biomass production.
- Appropriate food processing and paper making technology would be available to convert the edible portion of biomass production into acceptable ready-to-eat food products, and the inedible portion into fiber and absorbent paper products for crew hygiene.
- All food, paper and human waste would be biodegradable, and converted into compost by the bio-regenerative waste treatment process.

SYSTEM MODE OF OPERATION - Since little food production and processing would occur during the 6-month outbound transit mission, the food and fiber systems during that time would consist of pre-packaged shelf-stable foods in retort pouches and paper goods in sufficient quantity to support the crew during transit to the planetary base, where a bio-regenerative plant/crop production system would gradually take over daily production of food and fiber. Plant growth chambers with porous media beds would be prepared from the 6-month accumulation of compost produced from the anaerobic digestion of solid organic waste generated by crew consumption of food and fiber in transit. During residence time on the planetary base, daily food and fiber production would include repackaging and reprocessing a daily excess of prepared shelf-stable food and fiber products with recycled packaging materials accumulated during transit for this purpose. This would continue until sufficient stockpiles had accumulated to support the return trip to Earth.

TECHNICAL FEASIBILITY – The work reported in this paper is an attempt at estimating preliminary mass balances between food consumption and waste treatment as a first step toward establishing technical feasibility. The approach to this part of the work was begun with selection of a specific realistic scenario that could be supported with available data from past and recent NASA-funded research in space agriculture, advanced food technology, and solid waste management. This included selection of a sample menu made up of ingredients from planned biomass production that would be processed into palatable meal entrees with planned on-board equipment, and deliver essential macro-nutrients to the crew (protein, fat and carbohydrate).

Subsequent work consisted of qualitatively following the transfer/transport of organic mass from plant growth media through crop development to edible food ingredients and inedible fiber products, food processing and preparation, crew consumption and metabolism, recovery of organic wastes and inedible biomass/fiber residue, and finally bioconversion of those wastes and residues to compost through anaerobic digestion for return to plant growth media. From these assessments, estimates were made of the mass of prepackaged food and packaging material that would be required on board at lift-off, and how much porous growth media would be produced weekly from anaerobic composting of the solid organic waste routinely generated by the 6-man crew. These estimates were prepared from baseline data found in Bourland (1998), Vodovotz (1999), Verostko et al. (2001), Chynoweth et al. (2002) and Perchonok et al. (2002).

RESULTS

MENU SELECTION– In order to be consistent with requirements for a feasible scenario, menu selection was based upon use of food crops and ingredients that had already been selected for study by NASA’s Advanced Food Technology (AFT) Group at the Johnson Space Center. Perchonok (2003, 2004) identified selected crops being considered for advanced life support on long duration space missions. These are listed in Table 1, and grouped under salad crops that provide micro- nutrients, and staple crops such as rice, beans, and starchy tubers that provide macronutrients. For purposes of this study, a menu of rice and beans served in a Spanish-style tomato sauce seasoned with green onion and bell pepper was chosen as a suitable meal entrée that would be feasible on a daily basis with equipment systems currently being developed by NASA’s AFT group. Rice and beans provide complementary amino acid profiles, such that when eaten together, both profiles combine to provide the complete protein required in human nutrition. They also provide adequate amounts of fat and carbohydrate to complete the daily requirements for macronutrients. Micronutrients would be provided by the daily consumption of fresh salad crops accompanying each meal entrée.

Planetary Food System Selected Crops

Salad Crops	Staple Crops
(MICRO-NUTRIENTS)	(MACRO-NUTRIENTS)
– Tomato	• Potato
– Carrot	• Sweet potato
– Spinach	• Wheat
– Cabbage	• Soybeans
– Green Onion	• Peanut
– Lettuce	• Rice
– Radish	• Dried beans
– Herbs	
– Bell Pepper	
– Strawberry	
CAN BE USED FRESH	NEED PROCESSING

TABLE 1 - Planetary Food System Selected Crops (Perchonok, 2003).

CREW CONSUMPTION – Much of the food consumed by the crew during the 6-month outbound transit mission would be in the form of the fully prepared meals-ready-to-eat (MRE's) in flexible retortable pouches. These are "thermostabilized" or retorted canned foods with the rigid metal can replaced by a flexible laminated pouch of much less weight and volume. In this system scenario as the meals are being consumed, the empty pouches would be wiped clean, sanitized, and flattened for compact storage until needed by the food processing system when operating on the planetary base. Once the planetary base is established, the 6-month supply of MRE's should be nearly all consumed. At that time the crew should begin to enjoy freshly prepared meal items from harvested grains and vegetables grown in the biomass production system, such as the selected menu of beans and rice in tomato sauce chosen for this scenario.

In addition to food consumption, the crew will also be consuming a variety of absorbent paper products, such as paper napkins, towels, wet/sanitary wipes, and facial and toilet tissue. The 6-month supply of these products should also be nearly consumed once the planetary base is established. At that time the crew will be expected to begin utilizing counterpart products fabricated on-site from fibers recovered from the inedible portion of biomass production. During planetary base operations, both food and fiber processing would operate with sufficient overcapacity so as to gradually rebuild the 6-month stockpile of prepackaged food and fiber products needed for the return trip to Earth.

BIOMASS PRODUCTION – Considerable work has been underway for several years in the development of biomass production systems for food and fiber production in support of long-term space missions. Design of plant growth chambers for this purpose is the goal of on-going research and development activity at the Kennedy Space Center (Sager, 2004). Kloeris (2003) presented a concise summary of current and past space food systems under consideration, while Perchonok (2003) discussed the challenges in the development of food systems for long duration space missions, and identified many of the specific types of crops under consideration and the rationale for their selection. For the system concept proposed in this paper, the biomass production system would be designed to produce crops with both edible components needed for food processing, and inedible components from which suitable fiber could be extracted for fabrication of absorbent paper products.

At lift off, plant beds would be fully prepared with appropriate growth media, seeds and seedlings, sufficient to support the need for daily food consumption of the crew during the long stay on the planetary base. Additional empty bed area would also be available at lift off to accept weekly deposits of stabilized compost discharged from the waste treatment system digesters during the 6-month outbound transit. Once the planetary base is established, this extra bed area would provide the overcapacity needed to produce the extra quantity of food and fiber daily so as to gradually rebuild the 6-month stockpile of prepackaged food and fiber products needed for the return trip to Earth. In a very simplistic way, we are suggesting that the food consumed by the crew on the 6-month outbound voyage converts back into organic nutrients used to regenerate a new food supply for the return voyage to Earth.

FOOD PROCESSING – Perhaps most impressive of all is the rate of progress being made in food process technology development specifically directed toward long term space missions. Nutritionists know full well that vegetarian diets offering "complete" protein (containing all essential amino acids) can be readily achieved with appropriate mixtures of selected grains, beans and seeds. Therefore, these are likely to be the mainstay of crops grown in the biomass production system (rice, beans, lentils, etc.). A variety of taste and texture sensations can be achieved by different methods of preparation and combination with flavorful sauces and condiments, the most useful of which would be tomato-based products.

Among some of the food processing equipment currently under development for this purpose is the "STOW" processor developed by Johnson Engineering to take raw soybeans and process them into soy milk, tofu, and okara. It is designed to be fully computer controlled. Similarly, a miniaturized tomato processing plant is currently under development at the University of California, Davis (Singh, 2004). Although the unit is suitable for processing a host of different fruits and vegetables, tomatoes will likely constitute the majority of its use. Fresh whole tomatoes enter the small hopper at top, and can come out sliced or diced. They can also be processed further by passing through the finisher into tomato juice, or processed further through a reverse osmosis (RO) membrane system to produce tomato sauce and/or paste up to various levels of concentration. Meanwhile, the clear sterile permeate can be recovered as safe potable water. The resulting juice, sauce or paste can also be heat pasteurized through the ohmic heating unit at the bottom for aseptic filling into appropriate containers for subsequent storage. The ohmic heater component is currently under development at The Ohio State University (Sastry, 2003).

With rice, beans, herbs and tomato sauce available, completely balanced nutritious casserole-type meals could be made suitable for retort processing in the reusable flexible retortable pouches that were stored away on the outbound transit mission. The pouches would have been initially designed so as to be capable of being refilled resealed and reprocessed at least once subsequent to being opened for the first time. Thermal processing (or retorting) would be carried out by ohmic heating within the food pouch, it self. The pouches would be fabricated with electrode strips down opposite sides and seated in a strong block mold. The mold would engage the electric contact to begin internal heat generation, while also holding the pouch from expanding, thus building the internal product vapor pressure producing "steam sterilization" of the product within the pouch. Thus, the pouch and mold would serve as a miniature self-contained steam retort. This technology is also currently under development at Ohio State University (Sastry, 2004).

PAPER PRODUCTION - Since the dawn of civilization, fiber-based materials have been used to make paper, clothing, rope, building materials, as well as disposable hygienic tissue products (Soroka, 1999). The ability to produce such materials during long duration missions may offer opportunities to reduce initial payloads, but may also enhance productivity of the overall mission. Immediate examples of useful applications of paper products include, but are not limited to toilet paper, absorbent towels, and disposable/recyclable clothing. Researchers at the USDA/ARS Western Regional Research Center in Albany, CA have determined that wheat and rice straw are good sources of cellulose fiber, and can be used for manufacturing absorbent paper products (Wood, 2002).

SOLID WASTE TREATMENT – Extensive work is currently underway at various institutions aimed at exploring bio-regenerative waste treatment technologies capable of biologically converting organic wastes into stable reusable resources. Among those under consideration is a process for odorless bioconversion of organic solid wastes to methane and compost by anaerobic digestion patented by the University of Florida (Chynoweth and Legrand, 1993). Known as Sequential Batch Anaerobic Composting (SEBAC), the process can potentially serve as the solid waste management (SWM) component subsystem in a bio-regenerative advanced life support (ALS) system for long-range NASA space missions and planetary bases (Chynoweth et al, 2002).

Anaerobic digestion is an attractive option for stabilization of organic wastes and conversion of energy crops and paper wastes to methane and compost. In fact, that is the method used in nature under the anaerobic conditions that prevail in sites of concentrated organic matter. Teixeira et al. (2003, 2004) have recently reported on the design, development, fabrication, installation, and start-up of a full-scale prototype solid waste management system to support a 6-person crew on long-term space missions. The system consists of five reactors and two gas-liquid separators designed for operation under conditions of micro-gravity. During any week of operation, one reactor is used for feed collection and compaction, three for stage-wise anaerobic composting, and one for post-treatment aerobic stabilization, while simultaneously serving as a bio-filter in the pretreatment of cabin air within the air revitalization subsystem. Each reactor carries its one-week charge of feedstock through all five stages of bioconversion in completing a five-week sequential batch cycle.

MASS BALANCES– The preceding sub-sections have described the sub-systems through which the organic matter passes from biomass production to edible food ingredients and inedible fiber products, through food processing and preparation to crew consumption, metabolism and recovery of organic wastes and inedible biomass/fiber residues to bioconversion of those wastes and residues to compost through anaerobic digestion for return to plant growth media in biomass production. From these assessments and the sources of data cited, estimates were made of the mass of prepackaged food and packaging material that would be required on board at lift-off, and how much porous growth media would be produced weekly from anaerobic composting of the solid organic waste routinely generated by the 6-man crew.

Table 2 summarizes a compilation of base-line data taken from Bourland (1998), Vodovotz (1999) and Perchonok et al. (2002). The table shows estimated daily food requirement per crewmember for historical and near-term space travel missions, including shuttle transport (STS) and International Space Station (Phases II and III). It was assumed that the daily requirement of 1.82 kg per crewmember during shuttle transport would also apply to the 180-day transit voyage from Earth to Mars. Based upon this assumption,

Parameter	Mass [kg/CM-d]	Volume [m^3/CM-d]	Comments	Water Content [%]
IVA Food, dw	0.674		A Reference Value	0
Space Transportation Food System				
STS Food	0.8	0.002558	Dehydrated	20
	1.591		As-Shipped, No Packaging	58
	2.227		Packaging Alone	
	1.818	0.004045	Packaged, As Consumed	
International Space Station Foods Systems				
Phase II	1.83	TBD	Packaged, As-Shipped, with Food Locker	TBD
Phase III	1.955		As-Shipped, No Packaging	66
	0.345		Packaging Alone	
	2.3	0.006570	Packaged, As-Consumed	

TABLE 2 –Historical and near-term estimated food system masses.

Table 3 summarizes the calculation steps taken to estimate the total food system mass needed at lift off, and shows that this total food system mass (for the 180-day transit), including food, packaging material (retort pouches) and storage lockers will approximate 2.7 metric tons, or approximately one-fifth of the 12 metric tons needed for the entire 3-year mission. Although this is a significant reduction in food system mass, it is still an enormously large quantity to attempt to lift off against earth's gravity with current rocket science technology leaving technical feasibility still somewhat uncertain at this time.

Mass of retortable-pouched food needed (58% MC)

1.818kg/CM-d x 180d x 6CM = 1963.44kg

or

3meals/CM-d x 180d x 6CM = 3240 individually packaged meals

Total food system mass for 180-day transit

$(24.5kg/locker_{filled} - 6.4kg/locker_{empty})/(0.606kg/meal) = 29.868$ or 29meals/locker

and

(3240meals)/(29CM-meals/locker) = 111.72 or 112lockers

so

23.974kg/locker x 112lockers = 2685.088kg or approximately 2.7mton

TABLE 3 – Mass of retortable-pouched food system needed for 180-day transit, including food, packaging material and storage lockers.

Tables 4 and 5 summarize the estimated daily solid waste streams to be expected from a 6-person crew on a 600-day exploratory mission on a planetary base, and the quantity of new porous growth media that will be produced from anaerobic composting of the organic portion of those waste streams. Table 4 shows that total daily waste from 6 persons will be approximately 10.6 kg dry weight. But, only 7.5 kg will consist of organic matter capable of anaerobic digestion for bioconversion into porous media compost. Based upon early performance data reported by Chynoweth et al (2002), Table 5 indicates that roughly 11kg of plant growth media will be produced each week from the 7.5 kg daily organic waste stream, while waste stream volume would be reduced by 86.4%. These estimates clearly support the continued interest further development of anaerobic composting technology as a technically feasible means for nutrient recovery, stabilization and volume reduction of organic solid waste streams on long term space travel.

Waste Component	Dry Weight [kg]	Ash [% dw]	Organic Matter [kg]	Moisture [%]	Part of Total [%]
Dry human waste	0.72	5	0.68	85	9.4
Inedible plant biomass	5.45	5	5.2	75	51.4
Trash	0.56	5	0.53	10	5.3
Paper	1.16	5	1.1	10	10.9
Packaging materials	2.02	5		10	19.0
Tape	0.25				2.4
Filters	0.33				3.1
Misc.	0.07				0.7
Total	**10.6**		**7.5**		**100**

TABLE 4 – Estimates of daily solid waste streams for a 6-man crew during a 600-day exploratory planetary mission (Verostko et al. 2001).

	Units	Feedstock: Rice, Paper, Dog Food
Parameter	kg dw	55.23
VS_{in}	kg dw	52.57
TS reduction	%	80.2
VS reduction	%	85
Volume reduction	%	86.4
TS_{out}	kg dw	10.94
VS_{out}	kg dw	7.89

TABLE 5 – Weekly production of porous growth media for biomass production from anaerobic composting of solid organic waste routinely generated by 6-man crew.

CONCLUSION

This paper has described further development of a bio-regenerative food and waste management system concept for long-term space travel. The concept proposes a system by which sufficient food and fiber could be taken along for a six-person crew on a 3-year round-trip mission to Mars by lifting off with only a 6-month supply of pre-packaged shelf-stable food and fiber products on board (sufficient for one-way transit to a planetary base on Mars). During residence time on the planetary base, daily food production would include re-packaging and reprocessing a daily excess of prepared shelf-stable ready-to-eat meals with recycled retort pouches that were accumulated during transit for this purpose.

Technical feasibility of such a system was addressed beginning with selection of a specific realistic scenario that could be supported with available data from recent NASA-funded research in space agriculture, advanced food technology, and solid waste management. The paper reports on a preliminary attempt to track mass balances of daily food intake requirements from crew consumption and metabolism, recovery of organic wastes, and bioconversion of those wastes and residues to compost through anaerobic digestion for return to plant growth media. Results show that total food system mass for the 180-day transit at lift-off will approximate 2.7 metric tons, or approximately one-fifth of the 12 metric tons needed for the entire 3-year mission. During planetary base operations, roughly 11kg of plant growth media will be produced each week from approximately 50 kg weekly organic waste stream, while waste stream volume would be reduced by 86.4%. These numbers, however, neglect the actual mass trade-off between transporting three years supply of food and paper against the entire food and paper production and processing system (equipment, supplies and crew time).

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