Foods for a Mission to Mars: Equivalent System Mass and Development of a Multipurpose Small-Scale Seed Processor

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Description of the problem

The candidate crops for planetary food systems include: wheat, white and sweet potatoes, soybean, peanut, strawberry, dry bean including lentil and pinto, radish, rice, lettuce, carrot, green onion, tomato, peppers, spinach, and cabbage. Crops such as wheat, potatoes, soybean, peanut, dry bean, and rice can only be utilized after processing, while others are classified as ready-to-eat (Levri et al. 2003). To process foods in space, the food processing subsystem must be capable of producing a variety of nutritious, acceptable, and safe edible ingredients and food products from pre-packaged and re-supply foods as well as salad crops grown on the transit vehicle or other crops grown on planetary surfaces. Designing, building, developing, and maintaining such a subsystem is bound to many constraints and restrictions. The limited power supply, storage locations, variety of crops, crew time, need to minimize waste, and other equivalent system mass (ESM) parameters must be considered in the selection of processing equipment and techniques. Equivalent System Mass (ESM) is a metric developed by NASA to describe system and sub-system influences on closed loop networks in terms of a single parameter, mass (Levri et al. 2003). The food system of a Mars mission may use a large percentage of total mission ESM, potentially up to 50% (Hanford, and Ewert 2002), and any decrease in this ESM would be extremely beneficial to the success of a mission. The non-crew time ESM, or so called crew-independent ESM, is calculated as shown in Equation 1:

$$ESM_{NCT,i} = M_i + \gamma_V \cdot V_i + \gamma_P \cdot P_i + \gamma_C \cdot C_i$$

Equation (1)

Where:

ESM is the Equivalent System Mass value of the technology / equipment *i* in **kg**

M_i is the mass of the technology / equipment *i* in ***kg***

V_i is the volume of the technology / equipment *i* in m^3

P_i is the power drawn by the technology / equipment *i* in ***kW***

C_i is the cooling requirement of the technology / equipment *i* in ***kW*** (assumed to be equal to power)

The γ's are defined as conversion factors or cost equivalencies used to convert the non-mass parameters into mass measurements. These constants are calculated based on the mission, design of the vessel, power supply, and cooling system (Levri et al. 2000). Hanford and Ewert (2002) computed equivalencies for advanced missions. Several researchers have calculated ESM of select types of food processing equipment to compare ESM for individual food types; however, a survey of ESM parameters for a wide variety of currently available food processing unit operations and packaging materials has not been completed.

Conversion of highly processed crops into palatable food products will require a variety of processing operations that include mixing, cooking, and solid-liquid separation. Due to the ESM restraints, multi-purpose equipment specifically designed for minimum ESM, minimum crew-time involvement, and maximum versatility for food production is needed. A survey of available equipment and current ESM parameters is a starting point, but ideally targeted equipment would be designed for NASA missions. The proposed seed processor offers all of these processing operations in a single compact and lightweight equipment, able to produces multiple foods and food ingredients and work in a low gravity environment with minimal crew time and energy for operation and cleaning. The multi-purpose nature of the seed processor could reduce the equivalent system mass (ESM) of equipment necessary to perform a variety of essential food processing operations by reducing the amount of equipment that must be sent and reducing crew time necessary to process and prepare foods.

In addition, there is a non-NASA demand for very low capacity extruders to process high value seed materials available only in small quantities. The smallest Insta-Pro extruder is 300 kg/hr in capacity. For small agribusiness in developing countries, a lower capacity extruder is desirable. Research and development organizations involved in biotechnological innovations concerning new cultivars also demand very low capacity extruders compatible with the limited supply of the experimental seed materials. The proposed small-scale multipurpose seed processor is directly relevant to meet these demands.

Objectives:

1. To collect the parameters needed for calculating the ESM of processing and packaging scenarios for a mission to Mars and prepare spreadsheets of ESM information for different scenarios.

2. To design and manufacture a small scale multipurpose seed processor that is able to provide the crew of future long duration space flights with a variety of nutritious, safe, and palatable foods similar to those produced by industrial extruders.

Findings to date

Equivalent system mass of food processing equipment

Gandolph et al. (2004) compiled ESM-parameter information (mass, volume, and power) for currently available, small-scale food processing equipment and to provide average, high, and low ESM values for each class of equipment (hand-held and bench-top mixers, etc.) that performs the following unit operations: mixing, size reduction, heat transfer (heating and cooling), and extraction (water, oil, and juice). In this study, each piece of equipment was assumed to perform a single task, the power required for cooling was set equivalent to the power needed to operate the equipment, and the crew-time was not considered in the preliminary ESM estimates. These values could serve as a reference for comparing ESM parameters of other equipment not considered in this document, for evaluating effects of multi-purpose use (multiple functions or food products), and for evaluating effects of different crew-time requirements on ESM related to food processing scenarios.

Equivalent system mass of bread production

Weiss et al. (2003, 2004) investigated the impact of grain mill type on the ESM of producing yeast and flat breads and collected ESM data for producing yeast and flat breads from commercial mixes or raw ingredients (flour, etc.). Wheat is a candidate crop for the Advanced Life Support system, and cereal grains and their products will be included on long-term space missions beyond low earth orbit. While the exact supply scenario has yet to be determined; some type of post-processing of these grains must occur if they are shipped as ingredients or grown on site for use in foods, and equipment capable of processing grains must be evaluated. There were significant differences in ESM values for making breads, and production methods, milling methods, and baking methods all contributed to these differences. The need to develop multi-use equipment simultaneously with product formulations and menu rotations is necessary due to the high cost of launching materials into space and the need to minimize the food system contribution to total mission ESM.

Food Packaging Waste Scenarios

Because handling unusable package waste in an enclosed, bioregenerative life support environment will be difficult, it is imperative to investigate alternate packaging scenarios that will both minimize waste and maximize product quality (barrier properties are essential). Using the Baseline Values and Assumptions Document (BVAD) waste assumptions (Hanford and Ewert 2002), package waste mass for the 1080 day mission to Mars would be between 1555 kg and 1750 kg. All comparisons of other packaging options obtained from a survey of literature/commercial products were made to reference values from Levri (2001), adapted and shown in Table 1.

Table 1. Packaging waste estimates for a mission to Mars.

Packaging Type	Mass per clean package (g)	Number of packages consumed per person per day	Waste (package mass, g) per day for 6 crew members	Package waste (kg) for 1080 day mission with 6 crew members
Rehydratable	16.61	6.29	627	677
Thermostabilized(1-serving)	8.61	3.71	192	207
Beverages (+ straw)	14.56	3.43	300	324
Irradiated	8.00	0.43	21	23
Natural form/IMF	6.93	3.57	149	161
Fresh foods (tortillas)	10.50	1.57	99	107
			Total package waste (kg) =	1499 (some estimates up to 1750 kg)

Based on these estimates, spreadsheets were developed to predict packaging waste generated for a variety of food storage and consumption scenarios (Snuffin et al. 2005). To summarize conclusions, removing the rehydratable foods following the 240 day outbound flight has the greatest single impact on package waste, reducing the waste by

~17% if irradiated, IMF, and/or thermostabilized foods are substituted. Removing 90% of single-serve beverages during the 600 day surface stay reduced package waste by ~11% Biodegradable packaging may not be a viable option for space foods due to barrier property limitations and strict control of food quality and safety. Impact of biodegradable packages on solid waste handling systems is unknown. Depending on amount of mass reduction over current package formats, lighter-weight high-barrier package materials that meet NASA constraints could reduce package waste (with an average 1 gram per package reduction, the total package waste would be reduced by ~8%). More work is needed in the design of high-barrier package formats for a mission to Mars, considering ESM, multi-use formats, and integration with waste-processing and other subsystems in the enclosed habitat.

The small scale multi-purpose seed processor (MSP)

The developmental stages for modeling, designing, and constructing a small scale multi-purpose seed processor are described in the following five sections: 1) design and fabrication of a prototype extruder; 2) testing the prototype; 3) designing an oil press; 4) designing a (on line?) slit die viscometer; and 5) downscaling and design of the small scale multi-purpose seed processor (MSP).

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1) Design and fabrication of a 30kg/hr prototype dry extruder

A 30 kg/hr extruder has been designed and fabricated. The design was the result of a 10-fold scale-down of the smallest commercial extruder manufactured by Insta-Pro International (Des Moines, Iowa). This was the first step in a proposed gradual scale-down of the commercial extruder to a size suitable for the NASA application. The design and construction of the 30 kg/hr prototype extruder (shown in Figure 1) was intended to validate the mathematical model used for the scale-down process (Chen et al. 2005) and to demonstrate that the machine is functional at this level of downscaling.

Figure 1. The 30kg/hr Prototype Dry Extruder

2) Testing the 30kg/hr extruder

The functionality of this prototype was tested with raw materials selected from the NASA candidate crop list. The machine was tested for its functionality in processing full fat soybeans. The commercial process of full fat soy is designed to deactivate the endogenous protease inhibitors and release the oil for its subsequent extraction in an oil press. The adequacy of the thermal deactivation process was determined by measuring the urease activity of soybean at the beginning and end of the process. The target was to deactivate urease activity by 90% of initial value.

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The machine was able to successfully process full fat soybeans, and no major troubleshooting was necessary. Trials showed that it was possible to attain similar temperature profiles in the prototype to those observed during the commercial process. The process temperature at the discharge end of the extruder was approximately 300° F. The throughput rate of the extruder was 31 kg/hr. These results were useful for validating the mathematical models used for the extruder scale-down. The urease activities in the raw bean and the processed full fat soybean were 2.13 pH units and 0.02 pH units, respectively. This represents a 99% deactivation of urease activity.

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When rice was introduced with soy, the temperature profile was in excess of the desired target, which indicated that the screw configuration must be changed for processing different cereal-based products. Further development will focus on the design of a universal screw for processing a variety of cereals.

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3) Development of the oil press

The design of the oil press, which has been based on principles similar to those used in the design of the prototype extruder, has been completed. Engineering drawings for the fabrication of the press have also been finished, and the press fabrication is on-going.

4) Design of the (on line?) slit die viscometer

One of the important tasks in development of the multipurpose extruder is the study of rheological behavior of various raw materials of NASA interest (e.g. candidate crops or bulk ingredients) during the extrusion process. These studies are necessary to optimize the extrusion process and ensure that the products will have acceptable physical and sensory characteristics. For this purpose it was proposed to design an on-line slit die viscometer to characterize the rheology of extrudate melts which have been previously subjected to extrusion. The design and engineering drawings of this viscometer have been completed, and the fabrication of the viscometer is on-going.

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5) Downscaling and design of the small scale multi-purpose seed processor (MSP)

In summary, a mathematical model used for the scale-down of food extruders has been validated by successful design of the 30 kg/hr prototype extruder. It has been demonstrated that the machine is functional at this level of downscaling. In the next step, the same downscaling method will be applied to the design of the small scale multi-purpose seed processor (MSP) which will minimize the mass, volume, power consumption and other ESM metrics while satisfying a set of constraints. These constraints, such as residence time distribution and specific mechanical energy, will be imposed to guarantee a final product quality comparable to products produced in industrial size extruders.

The primary NASA application of the designed MSP will be for performing a variety of processing operations including size reduction, cooking, liquid extraction, dehydration, stabilization, and texturization for long duration ALS system. These operations will convert seeds grown on planetary surfaces or shipped as bulk ingredients into a variety of nutritious and safe food products, such as pasta, vegetable oil, dense and expanded snacks, breakfast cereals, and texturized meat-like vegetable proteins without requiring external heat supply. Because different food products require different operating conditions (such as temperature, pressure and shear rate), the MSP is designed to allow the (inter?)changing of some parts, e.g. screws, and the motor rotation speed to meet processing requirements of different products. Additional applications of the MSP include using the seed processor as a press for phase separation of solid and liquids, in particular oil - and water in a low gravity environment. Another potential use of the MSP include dehydration and volume reduction for wet solid wastes, as well as microbial and enzyme inactivation to reduce biological hazards.

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Research needs.

There is a dual need to both characterize the ESM of currently available food processing equipment and to develop new multi-purpose equipment to fit within NASA mission constraints. ESM considerations must also include crew-time, equipment capacity or throughputs, actual power draw, equipment wear and tear, behavior of foods and processes in reduced gravity, and differences in crew-time needed to operate, for example, one type of food processor versus another. Also important to note is that, for foods, ESM does not take into account product quality as defined by nutritional value, sensory characteristics, diet cycle, and chemical or physical food stability. Interdisciplinary research efforts are needed to develop an integrated food subsystem for NASA missions beyond low Earth orbit.

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