Development of a Light Weight Ohmic Food Warming Unit for a Mars Exploration Vehicle

Ram Bhuwan Pandit, Romel Somavat, Soojin Jun, Brian Heskitt and Sudhir Sastry*

Department of Food Agricultural and Biological Engineering
The Ohio State University, 590 Woody Hayes Dr
Columbus, OH, USA

*Corresponding author. Tel: 1-614-292-3508 Fax: 1-614-292-9448

E-mail Address: Sastry.2@osu.edu URL: http://www.oardc.ohio-state.edu/sastry/

1. Introduction

The transit time for NASA's planned Mars mission is expected to be 180 days each way, thereby posing some challenging life-support problems. The food supply should have 3-5 years of shelf-life. In addition, mass and volume must be minimized (Levri, et al., 2003; Jones, 2001) to keep costs manageable. Other unique requirements for systems in space are low energy usage, low operation time, maximum usability, minimum waste and operability in microgravity. Each of these factors influence the key parameter: Equivalent System Mass (ESM)

Currently, US space shuttles use a forced-convention oven or hot water supply to reheat foods to serving temperature. Due to heat-transfer limitations in conventional heating, and the relatively low efficiency of indirect heat transfer, alternative heating methods are desirable. Our research group has focused on designing and developing efficient light weight ohmic food warming and sterilization units for the Mars exploration vehicle (Jun & Sastry, 2007, 2005). These studies have reported on the design of a pouch fitted with electrodes to permit ohmic heating. The pouch is used to warm food to serving temperature. The package is reused post-consumption to contain and sterilize waste.

Ohmic heating has advantages over conventional and other alternative heating methods such as microwave and radio frequency heating including uniform heating, energy efficiency, and compact design (Salengke, 2000, Sastry and Palaniappan 1992). This paper explores the feasibility of designing a light weight compact food warming unit. The specific objective of this study was to develop an ohmic heating system to warm the food for a crew of four to six persons on a crew exploration vehicle within a half-hour, and to compare the resulting ESM to that of the food warmer currently used aboard the space shuttle.

2. Materials and methods

2.1. **System design**

2.1.1. *Pouch design*: Pouches were designed with electrodes within them, and optimized to the shape of a rectangular prism. This ensured greater uniformity of heating than a conventional MRE pouch, and also improved stackability. Photographs of the pouch are presented below in Fig. 1 (a and b). Pouch development has been reported separately, and is not within the scope of the present discussion.

2.1.2. Power supply unit: A key consideration in ohmic heating on a spacecraft is the need to eliminate electrolytic gas production at the electrodes. Under zero gravity conditions, bubbles will experience no buoyant forces, and may interfere with electrical current flow, resulting in failure of the heating process. A previous study (Samaranayake, Sastry, & Zhang, 2005) had confirmed that electrochemical reactions are minimal with a square waveform of frequency 10 kHz and duty cycle (pulse widths/period) 20 to 80 %. Accordingly, an integrated-gate-bipolar-transistor (IGBT)-based power supply system was designed to convert the input power into a square waveform with the required frequency and duty cycle. Details of the power supply system can be found elsewhere in Jun & Sastry (2007). For designing the electrical instruments, two possible options were considered to meet the available power supply for the crew exploration vehicle. Schematic representations of each option are provided below with their merits and limitations.

a). *Power supply system with D.C voltage booster and IGBT module*: The main advantage of this option (shown schematically in Fig. 2) is that the voltage is boosted prior to the IGBT module. Thus, the IGBT will be switching high voltage/low current. The voltage will be boosted 3-4 times the supply voltage, so the current will be 25%-33% of what it would be without boosted voltage, resulting in cooler operation, and reduced necessity for external cooling. The main drawback is that the voltage booster is a heavy and bulky item. Although optimization studies are continuing, we consider this option as the default ohmic option in calculation of ESM.

b). *Power supply system with IGBT module and pulse transformer*: The main advantage of this option (Fig. 3) is the relatively small size and mass of the pulse transformer compared to the voltage booster detailed in option (a). However, this advantage might be offset by a bigger heat sink and fan necessary to dissipate the extra heat produced by the IGBT. The current that the IGBT will switch in this option is up to 4 times that of option (a). Since the heat loss is proportional to the square of the current, the heat generated by the electronics could be up to 16 times that of option (a). Further, the ESM calculation protocol severely penalizes energy inefficiencies; thus this option was not considered in the ESM calculation here.

2.1.3. Food heater enclosure: Another key component was the food heater enclosure. We selected carbon fiber as the base material to construct the enclosure, due to its low density, high strength and suitability for use in spacecraft. We located the food enclosure on the top of the instrument box. A metallic plate with adjusting spring was attached on both sides of the heater enclosure to provide contacts between pouch electrode tabs and the power source.

2.2. **Equivalent system mass (ESM) calculation for newly designed and currently installed heater**

The ESM concept arises from the need to design spacecraft as efficiently as possible, due to the high cost (US$ 22,000/kg) of putting materials in orbit. Each item that is placed within a vehicle occupies space, which necessitates a corresponding increase in vehicle size to accommodate it. Further, if the item uses energy, or requires cooling, this will increase the demands on the power or cooling systems, increasing their mass. Consequently, each such factor results in an increase in system size, resulting in a mass penalty for each of the key aspects of the item. Equivalent System Mass is then the sum of the masses of life support supplied commodities, plus the mass penalties for infrastructure support, especially power, volume, cooling, and crew time required to operate and maintain the life support system(Levri, *et al*., 2003).

ESM was calculated as:

$$ESM = \sum_{i=1}^{n} \left[\left(MI_i \; SF_{I_i} \right) + \left(V_{I_i} . V_{eqi} \right) + \left(P_i \, . \, P_{eqi} \right) + \left(C_i . C_{eqi} \right) + \left(CT_i . \, D.CT_{eqi} \right) + \left(M_{TD_i} \; .D. \, SF_{TD_i} \right) + \left(V_{TD_i} \; .D. V_{eq_i} \right) \right]$$

where:

i = number of subsystem consider in ESM calculation

MI_i = initial mass of subsystem i

SF_{Ii} = initial mass stowage factor for subsystems i (kg/kg)

V_{Ii} = Initial volume of subsystem i (m^3)

P_i = power requirement of subsystem i (kWe)

C_i = cooling requirement of the subsystem i (kW_{th})

CT_i = crew time requirement of subsystem i (CM-h/y)

D = duration of the mission segment of interest (y)

M_{TDi} = time-or event-dependent mass of subsystem i (kg/y)

SF_{TDi} = time dependent mass stowage factor for subsystem i [kg/kg]

V_{TDi} = Time dependent volume of subsystem i [m^3]

$V_{eqi,}$ $P_{eqi,}$ $C_{eqi,}$ $CT_{eqi,}$ are corresponding mass equivalence factors.

The total ESM for the Mars Transit Vehicle in the Independent Exploration Mission for the ohmic food warming unit was computed to compare our design with the existing suitcase type heater (Table 1). For this assessment, the computed crewtime-mass penalty was considered to be 0.728 kg/CM-h (Hanford, 2006). This ESM calculation is based upon a crew of six members consuming two meals daily. Mass of the food sample in each pouch was considered as 226 gm. Other assumptions and equivalence factors were considered similar as mentioned by Hanford (2006) for the Mars Transit Vehicle.

2.3. **Heating tests**

The system was modified to heat four pouches of food in parallel, as shown in Fig. 5. Heating tests were conducted to test the capability of the system to heat food pouches within the specified power limit (250 W). Eight ounces of sample was filled into each pouch. Temperature at the geometric center of each pouch was monitored by T-type thermocouples (Omega Engineering Inc., Stamford, CT). The target temperature was set to 65 ± 2 ^{o}C.

3. Results and discussion

Results on ESM of the ohmic food warmer are shown in Table 1, together with the assumed mass equivalence factors. The results show that the ESM for the ohmic system was much lower (839 kg) than the existing suitcase type heater (3475 kg) for the same mission (Rapp, 2006).

Results of heating tests shown in Figure 6 indicate that four pouches of salt solution with 0.4 % salt content could be heated within 25 minutes to the target temperature, at a power level of 200 W, well below the allowable 250 W. We have since tested a number of other products including tomato soup and cream of potato soup, and have been able to heat these products within the required time and power constraints. Also shown in Fig. 6 is the temperature of the heat sink used to cool the IGBT module. As may be seen, the temperatures show no overheating of this module, thus large cooling ESM penalties will not be necessary for the default design option.

4. Conclusions

Our results show the feasibility of designing a food warming device of greatly reduced ESM, while keeping heat sink temperatures at manageable levels. This performance may be expected meet the constraints of a long duration space mission. While the calculations here are based on the Mars mission, the current NASA focus is the Crew Exploration Vehicle, which is intended to establish a lunar base prior to the trip to Mars. While the ESM factors will change for such a mission, we expect major savings in ESM compared to the current suitcase heater.

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Table 1: Equivalent system mass calculation for the developed food warming unit.

Mission Segment Name														
INDEPENDENT EXPLORATION MISSION: MARS TRANSIT VEHICLE														
Mission Segment Duration (in Terrestrial years) [D]														
360 DAYS														
SUBSYSTEMS														
	Initial Mass		**Initial Volume**		**Power**		**Cooling**		**Crewtime**		**Time Dependent Mass**		**Time Dependent Volume**	
	MIi	**SFIi * MIi**	**VIi**	**VIi * Veqi**	**Pi**	**Pi * Peqi**	**Ci**	**Ci * Ceqi**	**CTi**	**CTi * CTeqi**	**MTDi**	**MTDi * SFTDi * D**	**VTDi**	**VTDi * Veqi * D**
	kg	**kg**	**m3**	**kg**	**kWe**	**kg**	**kWth**	**kg**	**CM-h/y**	**kg**	**kg/y**	**kg**	**m3/y**	**kg**
Subsystems	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*	*number/ formula*
Food Warmer	1.8	1.8	0.007	0.064	0.18	42.66	0	0	144	105.12	0	0	0	0
Food Pouches	31.92	31.92	1.44	13.22	0	0	0	0	0	0	653	644	0	0
ESM Subtotals (kg)	33.72		13.28		42.66		0		105.12		644		0	
Total ESM (kg)	**838.78**													
System Applicable Equivalency Factors														
			Volume Factor		**Power Factor**		**Cooling Factor**		**Crewtime Factor**					
			Veq		**Peq**		**Ceq**		**CTeq**					
			kg/m3		kg/kWe		kg/kWth		kg/CM-h					
			9.16		**237**		**40**		**0.728**					

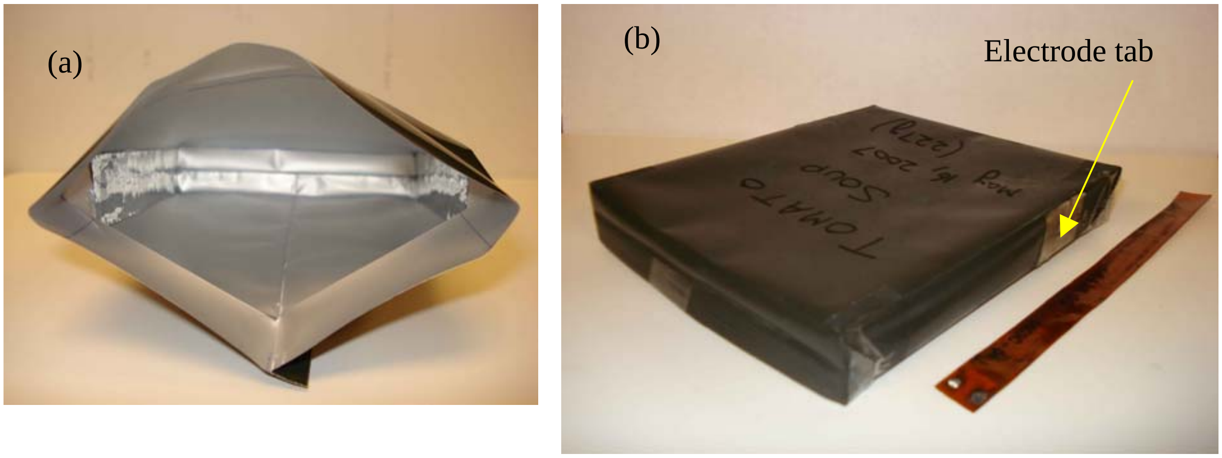

Fig. 1. (a). Pouch interior showing electrode; (b) exterior of pouch, showing one of the electrode tabs used to contact the power source.

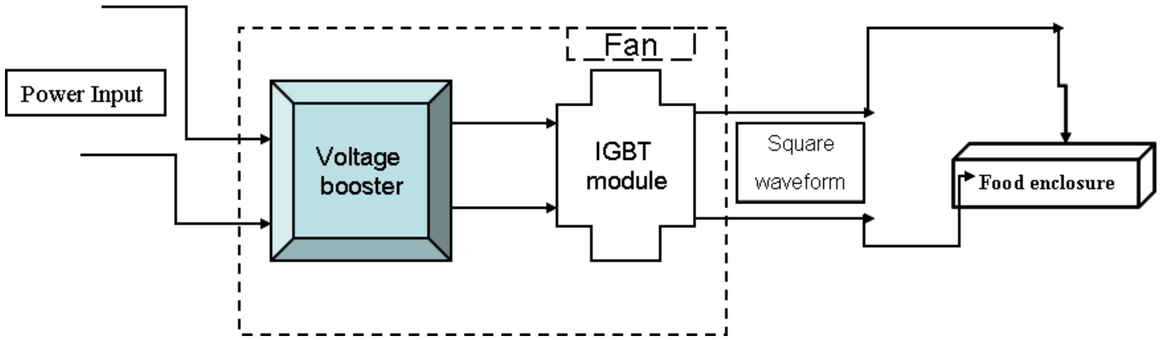

Fig. 2. Schematic diagram showing instrumentation box with D.C voltage booster and IGBT module.

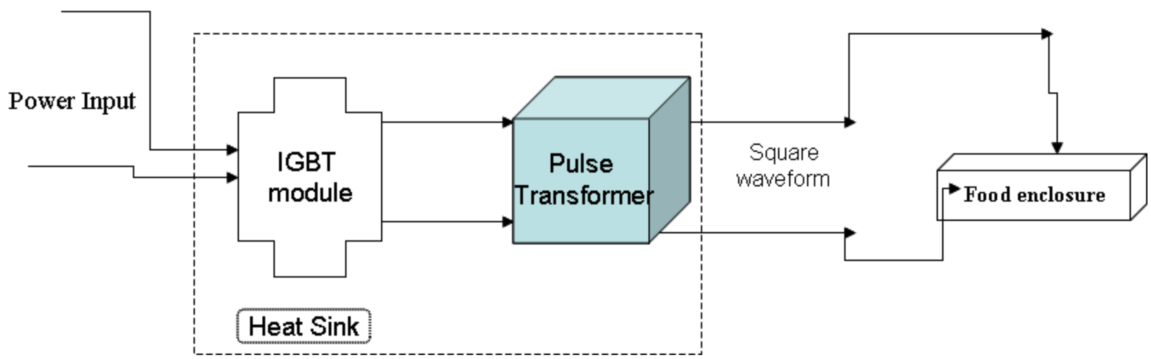

Fig. 3. Schematic diagram showing instrumentation box with IGBT module and pulse transformer.

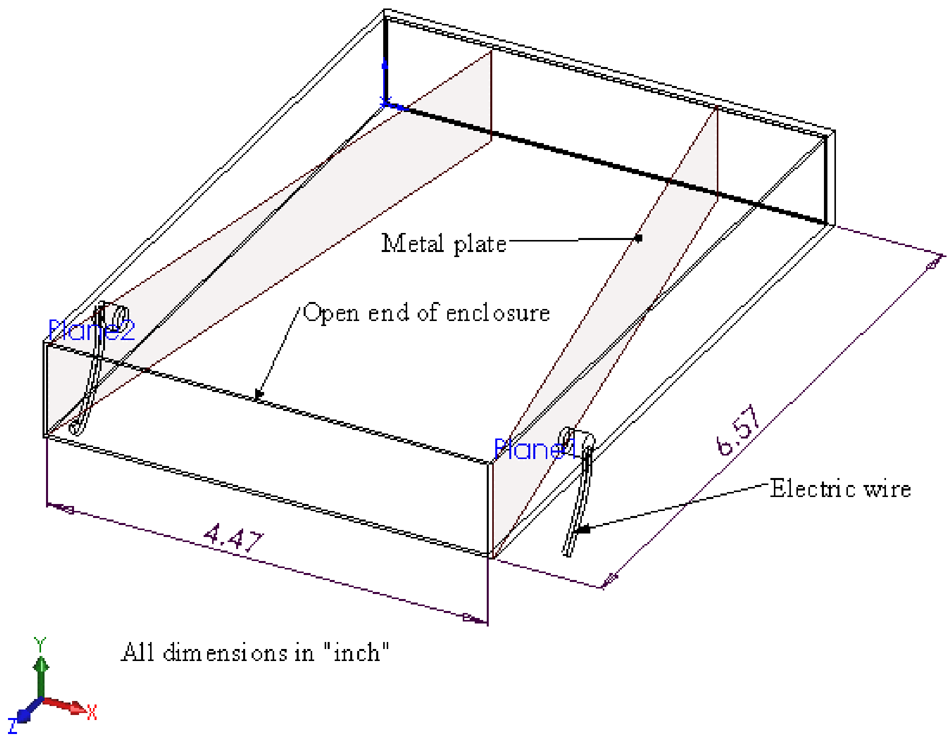

Fig. 4. Schematic of the food heater enclosure.

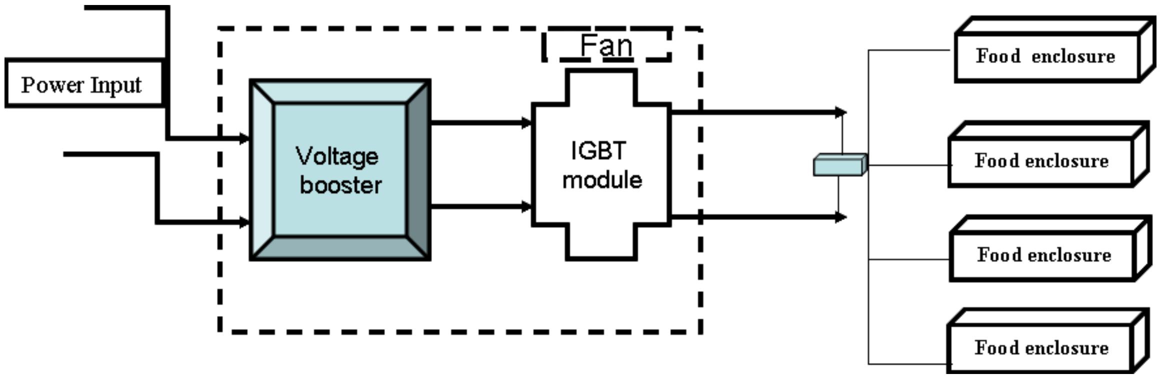

Fig. 5. Schematic showing food enclosure connected in parallel with power supply unit as mentioned in option (a) during heating operation.

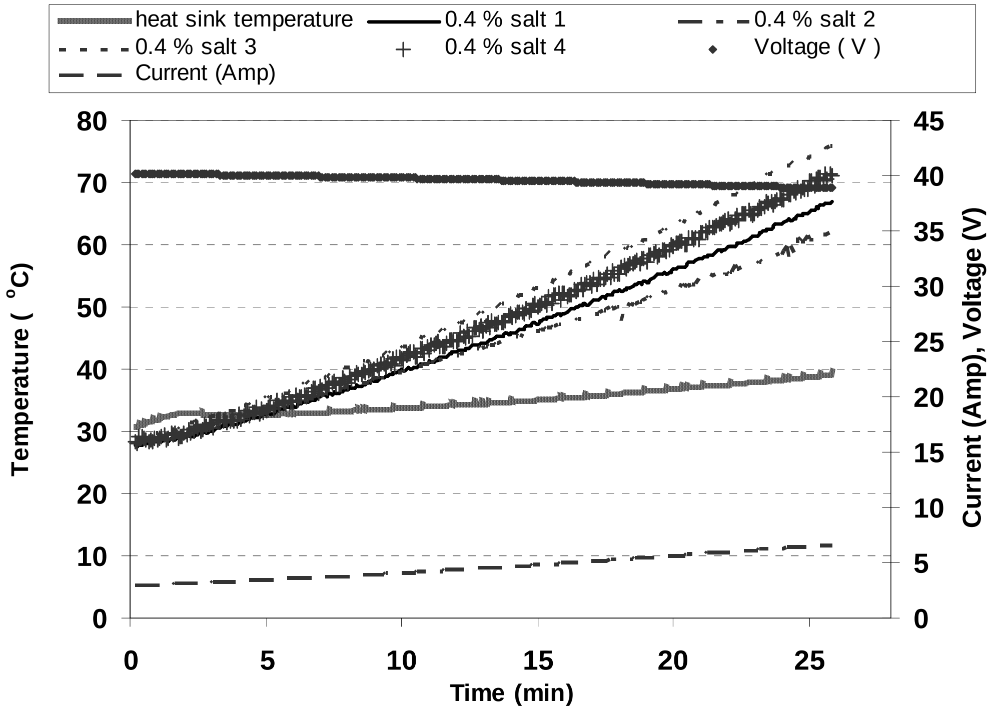

Fig. 6. Heating curves for four pouches of 0.4% salt solution, showing voltage and current curves