PeaPod - Design Brief

Submission to the NASA/CSA Deep Space Food Challenge

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1 Introduction

1.1 Purpose

The purpose of this design brief is to outline the requirements for a submission to the NASA/CSA Deep Space Food Challenge Phase 1 [1]. In doing so, it also documents the scope of a design submitted by University of Toronto Agritech (UTAG).

The goal of the Deep Space Food Challenge is for participants to "Create novel food production technologies or systems that require <u>minimal inputs</u> and <u>maximize safe, nutritious, and palatable food outputs</u> for <u>long-duration space missions</u>, and which have potential to benefit people on Earth." [2]

1.2 Framing Structure

This document achieves its purpose via "top-down" framing (Section 2), with each subsection's entries being derived from the entries of the previous[1].

- **2.1 - Opportunity**: A succinct scoped challenge statement.
- **2.2 - Requirements**: Categorical or scoping constraints.
- **2.3 - Stakeholders**: Persons and groups in consideration.
- **2.4.1 - High-Level Objectives**: Conceptual aims, DfX; derived from Requirements and Stakeholders.
- **2.4.2 - Low-Level Objectives**: Tactical goals; derived from HLOs.
- **2.5 - Metrics**: Quantitative measures of design success, fit, utility, etc; derived from LLOs.

[1] Each objective and metric has a numbered reference to the entry it was derived from (**<u>S</u>**takeholder **<u>1</u>** : S1, **<u>H</u>**igh-**<u>L</u>**evel Objective **<u>8</u>** : HL8, etc.)

1.3 Scope and Justification

Phase 1 development, testing, and assessment is scoped to terrestrial/Earth-like operational constraints [2]:

- Gravity (9.81 m/s^2);
- Ambient atmospheric pressure (101,325 Pa);
- Ambient atmospheric/"room" temperature (22 °C);
- Ambient atmospheric humidity (50 %RH);

In addition, it is important to note that the solution "need not meet the full nutritional requirements of future crews, but can contribute significantly to, and integrate with, a comprehensive food system." [2]

The three underlined criteria in the challenge statement in Section 1.1 have also helped to define the scope of this brief:

1. The longer the duration of the space mission (up to and including interplanetary travel and permanent colonization) the lesser the feasability of resupply [2].
2. The lesser the feasability of resupply, and the more minimal the input (i.e. launch mass), the more the design will need to generate net-new food grown on-board during the mission [3].
3. The minimization of inputs (launch mass), the minimization of other negative criteria such as growth time, design complexity, etc. and the maximization of safety (pathogenic and otherwise) means that food animal growth has been deemed not feasible, and is outside the scope of this brief. Thus, the design should focus on food-producing plant (or crop) growth[4].
4. Spacecraft are not good crop growth systems (lack of water access, proper lighting and nutrition, etc.), thus the design should encompass a crop growth environment that:
   (a) provides of all necessary crop growth inputs (water, nutrients, lighting, etc.)

[2] Minimal resupply is also listed as a constraint directly in the challenge details [2].

[3] Any other food production technologies would be taking advantage of existing food; as such this is the basis for the problem.

[4] This is primarily an issue in-transit; for colonization, non-plant food production systems should definitely be considered.

(b) contains or otherwise encompasses a viable crop growth environment (temperature, humidity, gas concentrations, airflow, etc.)

(c) has control over all parameters of both a) and b) (environment parameters); these together are the (crop growth) environment conditions.

5. To maximise safety (of both the crops and the crew) and redundancy, and to minimize inputs (required human interaction), the environment should be automated and isolated from the spacecraft cabin with regards to all environment conditions (thermally, water-tight, etc.) unless beneficial and efficient (i.e no loss).

6. A greater degree of nutrition and palatability of food outputs implies a greater variety of crops (incl. leafy greens, fruits/fruiting vegetables, root vegetables, algaes, etc.); as such the food production system should be able to generate a continuous variety of environmental conditions such that any number of food crops could be grown within.

7. The demand for high crop variety, automation, parameter control, etc. implies the use of a hydroponic/aeroponic/hybrid crop growth method.

1.4 Definitions

A number of useful definitions have emerged from the above scoping:

1. (Crop Growth) Environment - The environment within which the crop grows/with which the crop interacts; the environment parameters in terms of their relationship with the crop and its growth.

2. (Crop Growth) Environment Parameters - The (often quantitative) parameters of the crop environment, as well as any and all other parameters relevant to crop growth.

3. Crop Growth System - Includes the physical enclosure (containing the crops and the controlled environment; incl. isolation) as well as any infrastructure required to generate the crop growth environment and control all environment conditions; satisfies all requirements of this brief.

2 Framing

2.1 Opportunity

Design a fully automated and isolated hydroponic/aeroponic crop growth system for the Deep Space Food Challenge Phase 1[1], able to generate any environment from a combination of independent environment parameters.

2.2 Requirements

Compiled from DSFC Applicant Guide details [2] and an excerpt of NASA-STD-3001: Section 7.1 Food and Nutrition[5] [3]:

1. *Helps* fill food gaps for a **three-year** round-trip mission with **no resupply**:
   (a) Feeds a crew of **four (4)** people;
   (b) Provides the capability to maintain food safety and nutrition **during all phases** of the mission;
   (c) Provides food that is *acceptable* to the crew **for the duration** of the mission;
   (d) Produces **varied, safe, nutritious, and palatable** food outputs that can provide **all daily nutritional needs** and require **little processing time**[6] for crew members;
2. Improve the accessibility of food on Earth; in particular, via production directly in urban centres and in remote and harsh environments:
   (a) Enhance local production;
   (b) Reduce food supply chain shortages;
   (c) Reduce the impact on the resources needed for food production;
   (d) Able to operate in harsh and remote environments;

[5] Additional nutrition and caloric output constraints relative to activity level, crew details, etc. are provided; however they are not in direct consideration as of Phase 1.

[6] It is assumed that fresh (or packaged unprepared) edible plant products are already prepared on existing space missions, and that this preparation meets this requirement; thus, preparation time is outside the scope of this design brief.

3. Achieve the **greatest amount of food output** with **minimal inputs** and **minimal waste**;

Extracted from scoping:

4. Must be able to operate under Earth-like conditions (See Section 1.3);

2.3 Stakeholders

1. Food Product Consumers
2. NASA/CSA Stakeholders - Spacecraft feasability and optimization criteria
3. Crops - Crop growth metrics

2.4 Objectives

2.4.1 High-Level

1. Food Output Suitability (S1, R1, R1a, R2a)
2. Environment Control, Automation, and Optimization (S2, S3, R1b, R2c, R2d, R3)
3. Efficiency (S1, S2, R1, R2a, R2c, R3)
4. Cross-Contamination (S1, S2, R1c)
5. Safety, Redundancy (S1, S2, R1b, R2b)
6. Modularity, Repairability (S1, S2, R2d)
7. Feasability (S2)

2.4.2 Low-Level

1. Output Food Variety (HL1)
2. Output Food Palatability (HL1)
3. Nutrient Output (HL1)
4. Energy Output (HL1, HL4)
5. Air Temperature Control (HL2)
6. Air Humidity Control (HL2)
7. Gas Concentration Control (HL2)
8. Lighting Control (HL2)
9. Light Isolation (HL2)
10. Thermal Isolation (HL2)
11. Water-tightness (HL2, HL5)
12. Airflow (HL2)
13. Water Flow Rate (HL2)
14. Water Temperature (HL2)
15. Germination Success (HL2)
16. High Degree of Automation (HL3)
17. Energy Efficiency (HL3)
18. Water Usage Efficiency (HL3)
19. Plant Matter Usage (HL3)
20. Gas Exchange Incentive (HL3)
21. Number of Harvests (HL3)
22. Time-To-Harvest/-Reharvest (HL3)
23. Germination Time (HL3)
24. Growth Time (HL3)
25. Potential for Cross-Contamination (HL4)
26. Structural Safety (HL5)
27. Electrical/Power Safety (HL5)
28. Power Supply Redundancy (HL5)
29. Infrastructure Redundancy (HL5)
30. Growth Container Modularity (HL6)
31. Infrastructure Modularity Support (HL6)
32. Growth Container Repairability (HL6)
33. Infrastructure Repairability (HL6)
34. Documentation Completion (HL6)
35. Design Complexity (HL6)
36. Tool Speciality and Number (HL6)
37. Cost (HL7)
38. Size (HL7)

2.5 Metrics

#	Metric		Units
1	Number of Suitable Crop Species	(LL1)	# (per crop)
2	Quality/Palatability of Crop Output	(LL2)	1-10 (per crop)
3	Crop Nutrient Concentration	(LL3)	% (per crop)
4	Protein Output Density	(LL3)	g/kg
5	Protein Output	(LL3)	kCal/crewmember (%TDEI)
6	Carbohydrate Output	(LL3)	kCal/crewmember (%TDEI)
7	Lipid Output	(LL3)	kCal/crewmember (%TDEI)
8	Ω-6 Fatty Acid Output	(LL3)	g/day/crewmember
9	Ω-3 Fatty Acid Output	(LL3)	g/day/crewmember
10	Saturated Fat Output	(LL3)	kCal/crewmember (%TDEI)
11	Trans Fatty Acids Output	(LL3)	kCal/crewmember (%TDEI)
12	Cholesterol Output	(LL3)	mg/day/crewmember
13	Fiber Output	(LL3)	g/day/crewmember
14	Caloric Output per Day	(LL4)	kCal/24hr
15	Air Temperature Control Range	(LL5)	min, max °C
16	Air Temperature Control Rate	(LL5)	°C/sec at each °C
17	Air Temperature Control Stability	(LL5)	±°C at each °C
18	Air Humidity Control Range	(LL6)	min, max %RH
19	Air Humidity Control Rate	(LL6)	%RH/sec at each %RH
20	Air Humidity Control Stability	(LL6)	±%RH at each %RH
21	CO_2 Concentration Control Range	(LL7)	min, max ppm CO_2
22	CO_2 Concentration Control Rate	(LL7)	ppm CO_2/sec at each ppm CO_2
23	CO_2 Concentration Control Stability	(LL7)	±ppm CO_2 at each ppm CO_2
24	O_2 Concentration Control Range	(LL7)	min, max ppm O_2
25	O_2 Concentration Control Rate	(LL7)	ppm O_2/sec at each ppm O_2
26	O_2 Concentration Control Stability	(LL7)	±ppm O_2 at each ppm O_2
27	Light Spectrum Wavelength Control Range	(LL8)	min, max nm
28	Light Spectrum PAR Spectrum, Intensity Coverage	(LL8)	% (each crop)
29	Light Spectrum Intensity Control Range	(LL8)	min, max μmol m^{-2}sec^{-1} at each nm
30	Light Spectrum Intensity Control Stability	(LL8)	±μmol m^{-2}sec^{-1} at each nm
31	Light Captured by Non-Photosynthetic Surfaces	(LL9)	%
32	Outside Light Penetration	(LL9)	%
33	Heat Transfer	(LL10)	±W at each °C
34	Unintentional Water Loss due to Leaks, Evaporation	(LL11)	mL/hr
35	Internal Circulation Airflow Control Range	(LL12)	min, max m^3/min
36	Gas Exchange due to Leaks	(LL12)	m^3/min
37	Maximum Intentional Gas Exchange	(LL12)	m^3/min
38	Nutrient Solution Delivery Rate Control Range	(LL13)	min, max mL/plant/sec
39	Nutrient Solution Delivery Rate Control Rate	(LL13)	mL/plant/sec^2 at each mL/plant/sec
40	Nutrient Solution Delivery Rate Control Stability	(LL13)	±mL/sec/plant at each mL/sec/plant

2.5 Metrics (Cont'd)

#	Metric		Units
41	Nutrient Solution Temperature Control Range	(LL14)	min, max °C
42	Nutrient Solution Temperature Control Rate	(LL14)	°C/sec at each °C
43	Nutrient Solution Temperature Control Stability	(LL14)	±°C at each °C
44	Germination Success Rate	(LL15)	%
45	Required Human Intervention Time - Maintenance	(LL16)	min/day
46	Required Human Intervention Time - Setup	(LL16)	min
47	Energy Efficiency - In (Power) vs. Out (kCal + Loss)	(LL17)	%
48	Necessary Water Waste per Day	(LL18)	L/day
49	Water Recycling from Spacecraft Systems	(LL18)	L/day
50	Initial Water Requirement	(LL18)	L
51	Plant Matter Usage	(LL19)	%
52	CO_2 Capture - Fraction of Typical Reclaimer Consumption	(LL20)	%
53	O_2 Production - Fraction of Typical Reclaimer Production	(LL20)	%
54	Number of Harvests per Planting	(LL21)	# (each crop)
55	Harvest to Reharvest - Fruiting Crops	(LL22)	min (each crop)
56	Seedling to Harvest	(LL22, LL24)	min (each crop)
57	Germination Time	(LL23)	min (each crop)
58	Potential for Cross-Contamination - Germination	(LL25)	% (each event)
59	Potential for Cross-Contamination - Planting	(LL25)	% (each event)
60	Potential for Cross-Contamination - Harvest	(LL25)	% (each event)
61	Factor of Safety	(LL26)	FOS (each structure)
62	Mounting Stability - System to Surroundings	(LL26)	FOS (each mount)
63	Mounting Stability - Infrastructure to System	(LL26)	FOS (each mount)
64	Risk of Electrical Malfunction	(LL27)	%
65	Backup Power Systems?	(LL28)	Y/N
66	Incremental Power-On?	(LL28)	Y/N
67	Backup Water Systems?	(LL29)	Y/N
68	Infrastructure Failure Notification?	(LL29)	Y/N
69	Independent Crop Growth Environments?	(LL30)	Y/N
70	Support for N+1 Crop Growth Environments?	(LL31)	Y/N
71	Lighting System Swappable?	(LL32)	Y/N
72	Heating/Cooling System(s) Swappable?	(LL32)	Y/N
73	Water Delivery System(s) Swappable?	(LL32)	Y/N
74	Lighting System Swappable?	(LL32)	Y/N
75	Computer Subsystems Swappable?	(LL33)	Y/N
76	All Fabrication Procedures, Tools, and Materials Documented?	(LL34)	Y/N
77	All Assembly Procedures, Tools, and Materials Documented?	(LL34)	Y/N
78	All Repair Procedures, Tools, and Materials Documented?	(LL34)	Y/N
79	Total Fabrication, Assembly, and Startup Time	(LL35)	min
80	Total Number of Tools Required	(LL36)	#

2.5 Metrics (Cont'd)

#	Metric		Units
81	Number of New Tools Required	(LL36)	#
82	Cost	(LL37)	CAD
83	Outer Dimensions	(LL38)	m (x,y,z)
84	Outer Volume	(LL38)	m^3
85	Power Consumption	(LL38)	W

2.6 Constraints

Metric	Constraint
M4	a
M75	$\leq 2\ m^3$ [2]
M76	$\leq 2\ m^3$ [2]

References

[1] "Deep Space Food Challenge," Impact Canada, launched by NASA/CSA. [Online]. Available: https://impact.canada.ca/en/challenges/deep-space-food-challenge

[2] "DSFC Applicant Guide," Impact Canada, launched by NASA/CSA. [Online]. Available: https://impact.canada.ca/en/challenges/deep-space-food-challenge/application-guide

[3] "Excerpt of NASA-STD-3001: Section 7.1 Food and Nutrition," National Aeronautics and Space Administration, Standard, 02 2015. [Online]. Available: https://impact.canada.ca/challenges/deep-space-food-challenge/excerpt