Cellular Agriculture

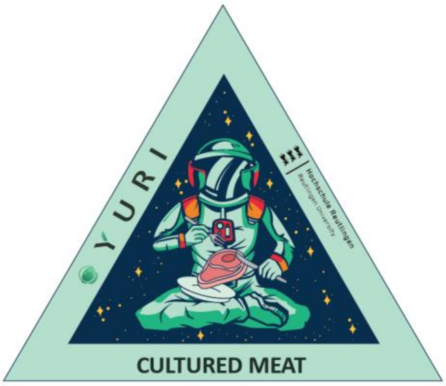
Executive Summary Report

Issue 02

Date 2023-02-16

Ref.: yuri-CLAR-RP-2023-001

ESA contract no. 4000136560/21/NL/GLC



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Issue and revision: 02

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Document Change Record

Revisions		
Issue	Changes	Date
01	Initial issue	2023-01-23
02	Adjustments based on comments from ESA review. Whole document reflects parameters for a crew of four astronauts now	2023-02-16

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List of Abbreviations

AD	*Applicable Document*
RD	*Reference Document*

1. REFERENCE AND APPLICABLE DOCUMENTS

All referenced documents (RD) are listed in Table 1.

Table 1: Reference documents

RD No.	Citation
[RD1]	F. Gòdia *et al.*, *MELISSA: a loop of interconnected bioreactors to develop life support in Space*, vol. 99. 2002. doi: 10.1016/S0168-1656(02)00222-5.
[RD2]	ESA, “MELiSSA Closed Loop Compartments.” https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Melissa/Closed_Loop_Compartments (accessed Jan. 23, 2023).
[RD3]	M. S. Anderson, M. E. Ewert, and J. F. Keener, “Life Support Baseline Values and Assumptions Document,” 2018. Accessed: Jan. 24, 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20180001338
[RD4]	O. Monje *et al.*, “Hardware Validation of the Advanced Plant Habitat on ISS: Canopy Photosynthesis in Reduced Gravity,” *Front Plant Sci*, vol. 11, p. 673, 2020, doi: 10.3389/fpls.2020.00673.
[RD5]	D. Kaschubek, “Optimized crop growth area composition for long duration spaceflight,” *Life Sci Space Res (Amst)*, vol. 30, pp. 55–65, Aug. 2021, doi: 10.1016/j.lssr.2021.05.005.
[RD6]	L. Poughon, C. Creuly, F. Godia, N. Leys, and C.-G. Dussap, “Photobioreactor Limnospira indica Growth Model: Application From the MELiSSA Plant Pilot Scale to ISS Flight Experiment,” *Frontiers in Astronomy and Space Sciences*, vol. 8, Aug. 2021, doi: 10.3389/fspas.2021.700277.
[RD7]	Stephanie Grahl, “Food product development with spirulina (Arthrospira platensis) – Sensory profiling, product perception and consumer acceptance,” Doctoral Thesis, Georg-August-Universität Göttingen, Göttingen, 2019.
[RD8]	M. G. Wiebe, “Myco-protein from Fusarium venenatum: a well-established product for human consumption,” *Appl Microbiol Biotechnol*, vol. 58, no. 4, pp. 421–427, 2002, doi: 10.1007/s00253-002-0931-x.
[RD9]	L. Li, Z. Zhao, and H. Liu, “Feasibility of feeding yellow mealworm (Tenebrio molitor L.) in bioregenerative life support systems as a source of animal protein for humans,” *Acta Astronaut*, vol. 92, no. 1, pp. 103–109, 2013, doi: 10.1016/j.actaastro.2012.03.012.
[RD10]	J. J. Cho-Lim, V. J. Caiozzo, B. P. Tseng, E. Giedzinski, M. J. Baker, and C. L. Limoli, “Satellite cells say NO to radiation,” *Radiat Res*, vol. 175, no. 5, pp. 561–568, 2011, doi: 10.1667/RR2453.1.

[RD11] Cellink, “Cellink Bioprinter BIO X,” 2022. https://www.cellink.com/bioprinting/bio-x-3d-bioprinter/ (accessed Oct. 27, 2022).

[RD12] D. Kaschubek, A. Feigel, and B. Schreck, “LiSTOT,” 2021. https://gitlab.lrz.de/listot/listot (accessed Jan. 24, 2022).

[RD13] D. R. Liskowsky and W. W. Seitz, “Human Integration Design Handbook,” 2014. Accessed: Jan. 24, 2022. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf

2. INTRODUCTION

As humans travel further and longer into the solar system the many challenges must be solved. One challenge is the adequate food supply for the crew. Currently all of the food that is consumed by Astronauts on the ISS is prepackaged on ground and transported to the ISS. This approach requires a significant investment of mass and the long-term stability of nutrients in the stored food is unclear. Especially the impact of radiation outside of the low earth orbit may have a negative impact on the stored food.

Currently ESA is researching plant and microbial based alternatives to produce food in closed loop systems [RD1] with plants and algae that are grown in space as food source, see Figure 1.

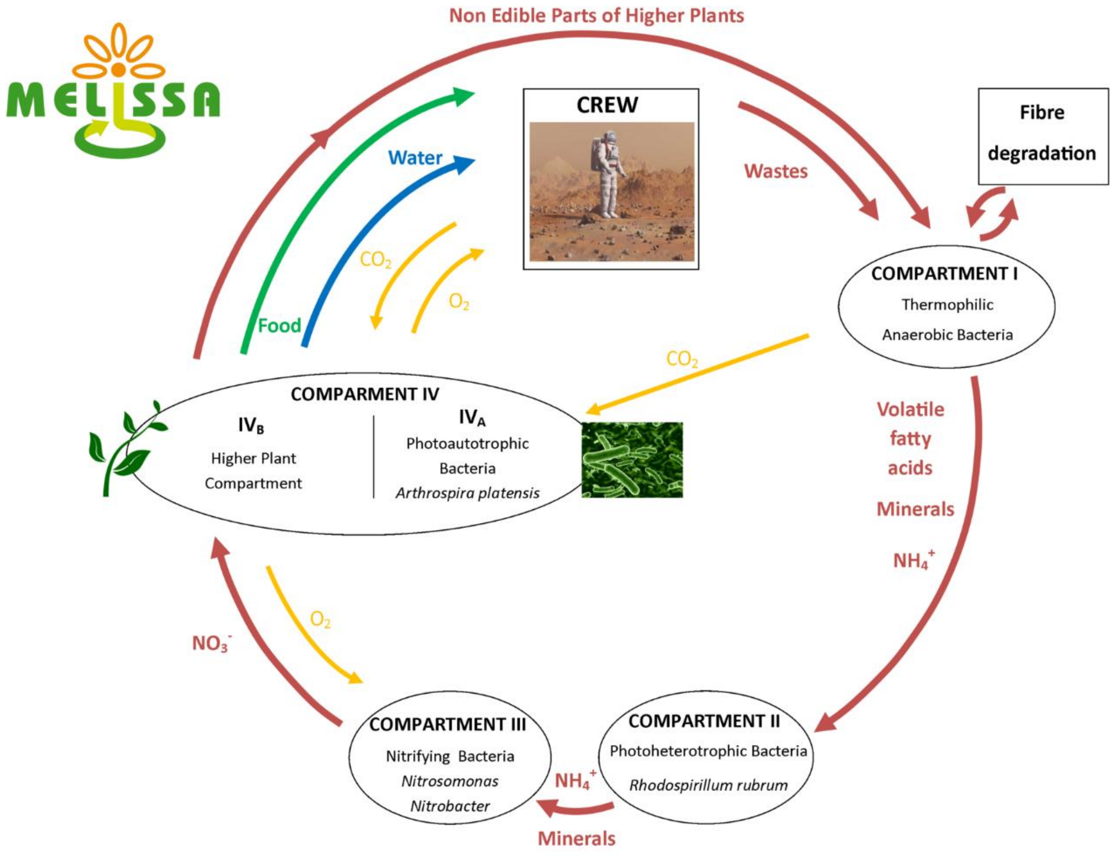

Figure 1: MELiSSA biological life support concept [RD2].

As plants with a high protein content often have lower productivity compared to plants which produce carbo hydrates [RD3] the goal of this study was to focus on the protein production and potential alternatives to plants and algae. The alternative on which this study focuses is so called cultured meat, where animal cells are grown in a lab environment to produce a meat analog without the need of rearing animals. The study therefore first compared various alternatives for protein production in space, from plants over algae and other microorganisms to cultured meat and then derived a conceptual design of a cultured meat production system for four astronauts. As expected mission an approximately 1200 day long Mars mission is assumed.

3. PROTEIN PRODUCTION ALTERNATIVES

Food production in space is a challenging task, as is evident by the current small scale systems that are used in space, like e.g. the NASA Advanced Plant Habitat [RD4] which focuses on studying the growth of plants in space and not the actual production of food, see Figure 2.

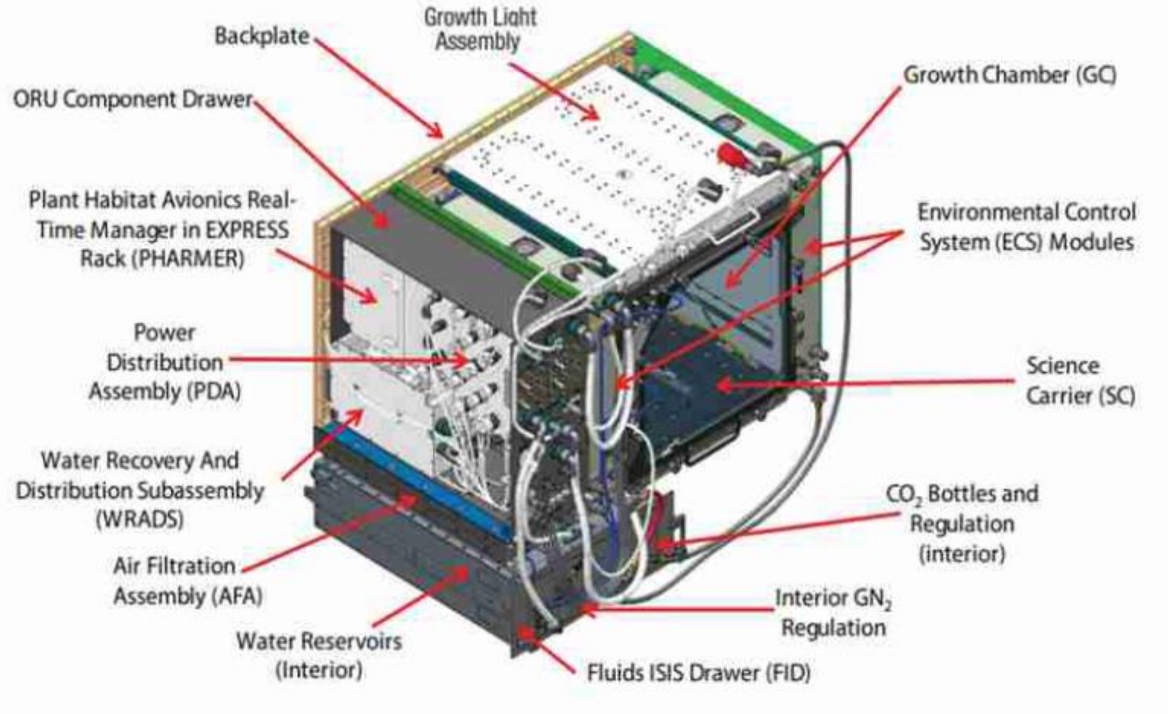

Figure 2: Advanced Plant Habitat facility for the growth of wheat in space [RD4].

Actual food production in space would require fairly large growth areas and many resources, with current estimates ranging from about 40 m² for a high carbohydrate diet, to 57 m² for a more balanced diet [RD5]. The resources required for the growth of the plants in total result in about 14 years till the plant system is more efficient than the stored food approach used on the ISS in a equivalent system mass trade-off [RD5]. Equivalent system mass is a trade-off approach where all required parameters of a system, like e.g. power demand, are converted into the mass value required to provide this parameter in the space environment.

Algae (or cyanobacteria) are currently studied in the space environment as alternative protein source [RD6] but are also developed on Earth by e.g. Solar Foods (Helsinki, Finland) as a food product called Solein. Algae can be produced more efficiently than plants but face some constraints with respect to taste which make additional post-processing necessary [RD7]. Other potential alternatives include e.g. fungi [RD8] or insects like the yellow mealworm [RD9] which are considered for biological life support. These alternatives are currently not well studied in the space application context, similar to the application of cultured meat in space. Therefore, the next step was to study the different concepts how cultured meat can be produced and compare them to the other protein production alternatives.

4. CULTURED MEAT PRODUCTION SYSTEM FOR SPACE

The initial step to derive a cultured meat production system is to compare the various options how the cells can be cultivated that are used on Earth. These include in general four different types of bioreactors:

- Microcarrier Bioreactors in which three-dimensional beads provide a large surface to volume ratio as growth surface for the cells
- Packed-Bed Bioreactors in which support structures like e.g. fibers are used as scaffold on which the cells grow
- Hollow-Fiber Bioreactors where the cells growth on hollow semipermeable microfibers
- Scaffold-Free Bioreactors where the cells do not grow attached to any structure but attach to other cells, creating spheroids

Based on publications about these concepts and the reported parameters, models were derived to compare them. In addition to the reactor types, two different operating modes were also considered, a batch mode where one batch of cells is grown over multiple days and then harvested and a continuous operating mode where the cells are continuously harvested during the growth. The model derived for the different concepts included a simplified bioreactor model as shown in Figure 3 and additional estimates for the power and thermal demands of the system based on the reported parameters. The achievable cell-growth rates were used to compare the productivity of the concepts to their demands on the system.

The bioreactor was then dimensioned to cover 60% of the protein demand of four astronauts. One astronaut was assumed to consume 1.2 g protein per kg of bodyweight with a bodyweight assumed per astronaut of 82 kg on average. Therefore, to cover 60% of the demand the bioreactor is dimensions to produce 59 g of protein from cultured meat per astronaut per day.

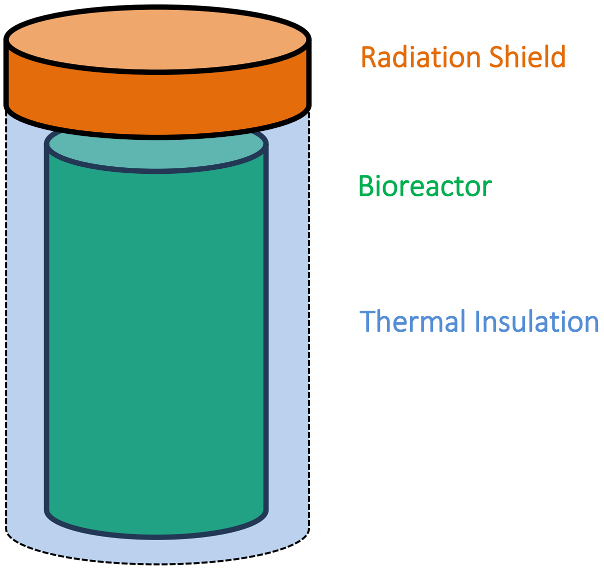

Figure 3: Simplified bioreactor model used in trade-off.

In the initial trade-off the best performing bioreactor type was the scaffold-free bioreactor operating in a continuous mode. This bioreactor only was estimated to require approximately 1.03 m^3, 1581 kg and 122 W of power for a crew of four astronauts. As the radiation shield was estimated to be a relatively large part of this mass (954 kg), although the cells have similar radiation limits as astronauts [RD10], the following trade-offs neglected the radiation shield and instead assumed that the spacecraft itself provides adequate shielding for the astronauts and the cells.

As the size of the bioreactor is still significant, further optimizations were considered which are based on reported cell growth parameters, but have not been verified in larger bioreactors yet. The key parameter assumed here is a higher achievable cell density in the bioreactor which allows the bioreactor to become smaller as more cells can fit into less volume. Under this assumption, the stand-alone bioreactor for four astronauts would require 0.2 m^3, 397 kg (of which 332 kg are radiation shielding) and 25 W power demand.

Based on this initial bioreactor trade-off a more detailed conceptual design of the whole production system was derived, which is shown in Figure 4.

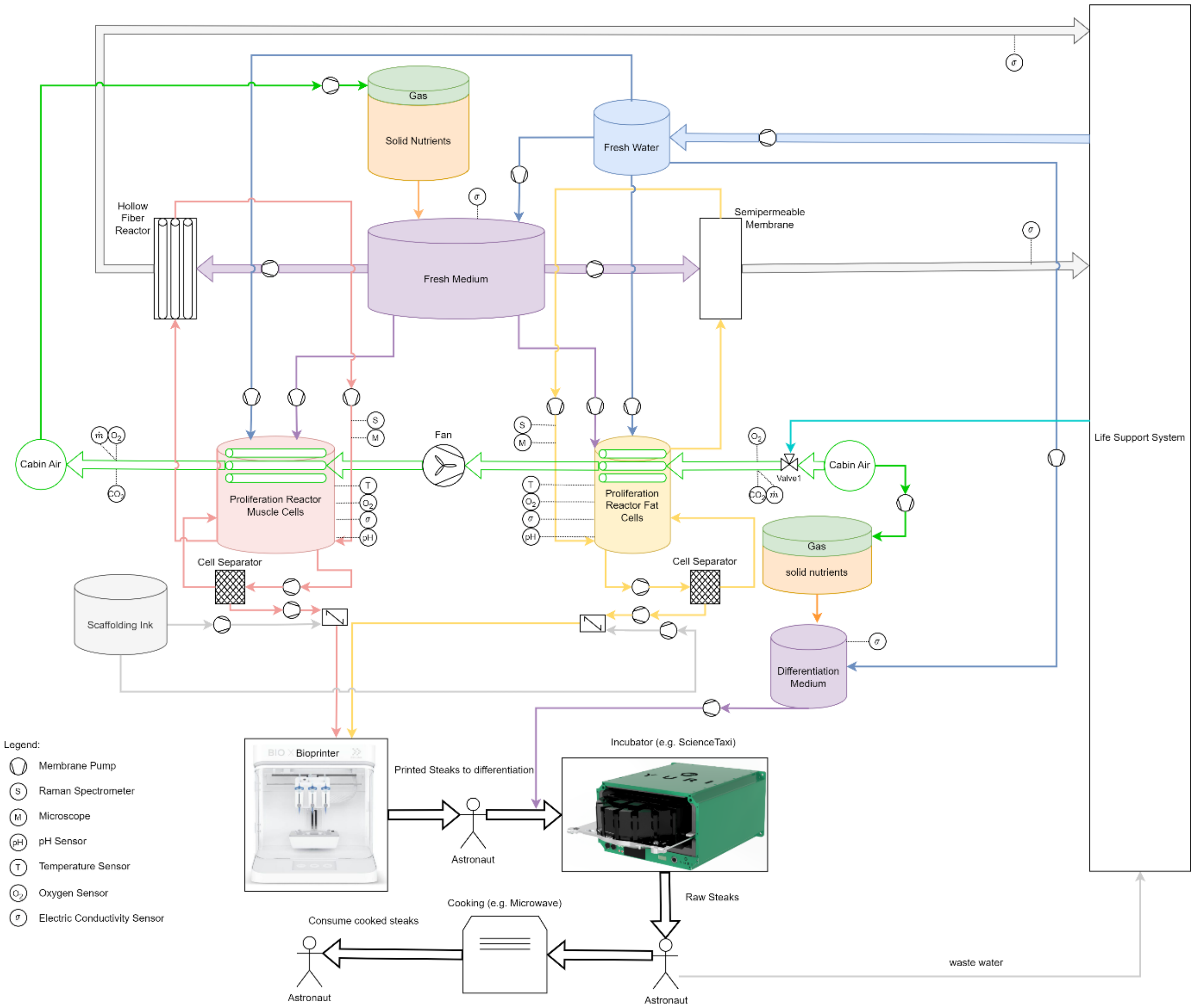

Figure 4: Cultured Meat Production System Conceptual Design. Picture of Bioprinter from [RD11].

Additionally, a simplified 3D model of the complete production system with rough estimates for the different sizes of the components in an ISS International Standard Payload Rack (ISPR) was created, which is shown in Figure 5.

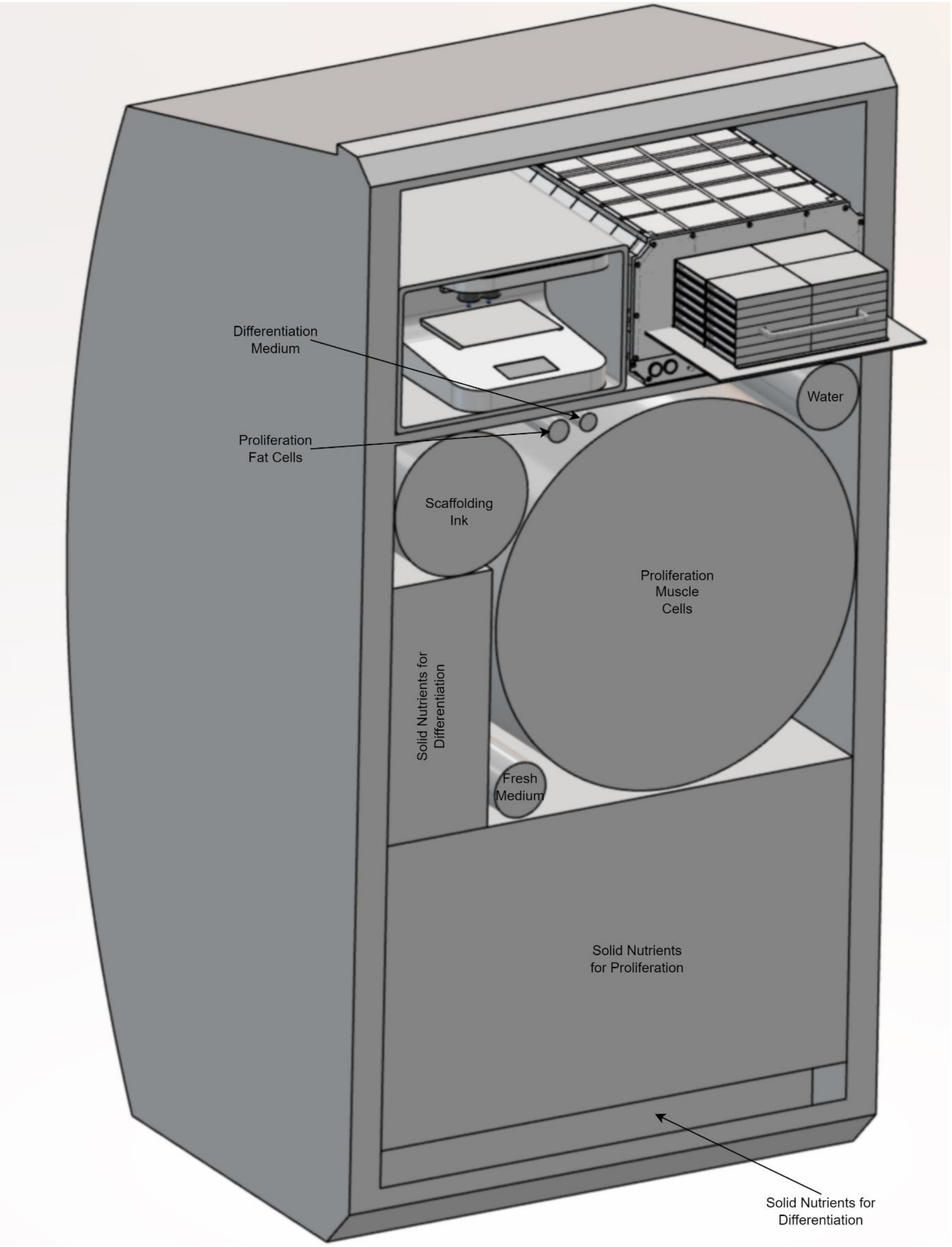

Figure 5: 3D concept of cultured meat production system for four astronauts fitted into an ISPR.

This concept was compared to the alternatives in an equivalent system mass trade-off using the LiSTOT tool [RD12] which is shown in Figure 6.

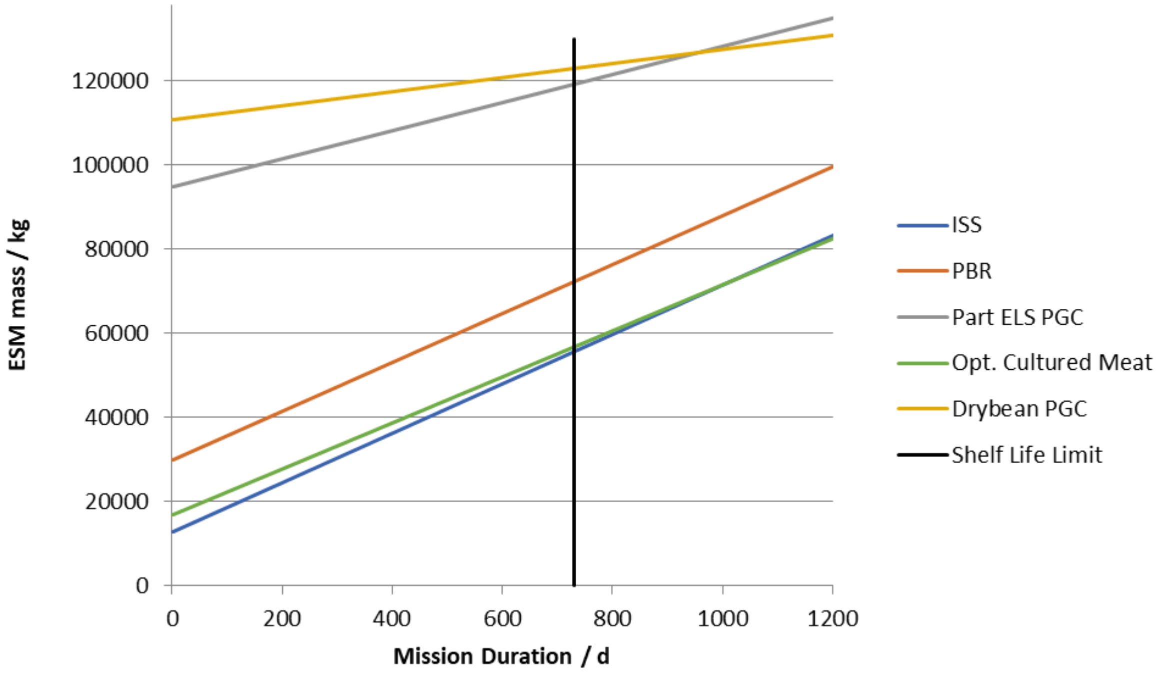

Figure 6: Equivalent System Mass of the proposed cultured meat system for four astronauts compared to the current stored food concept used on the ISS, a photobioreactor (PBR) for algae growth, a small mixed plant growth chamber (Part ELS PGC) and a protein focused Drybean plant growth chamber (PGC) which also produces 60% of the protein demand. All systems are sized for four astronauts as well. The black line shows the maximum shelf life of stored food as stated by [RD13]

The derived concept for cultured meat production can therefore be more efficient than the considered alternatives after more than 1028 days. Table 2 provides a more detailed comparison of the most promising alternatives for protein production and their individual parameters as they were estimated in this trade-off.

Table 2: Comparison of alternatives for four astronauts on a 950-day Mars mission.

	Unit	Stored Food	Drybean Plant Chamber	Cultured Meat
Mass (inlc. Spares)	kg	1159	8205.6	1243
Volume	m^3	3.06	92.84	1.955
Power	W	-	96449.8	722
Maintenance	h	-	3073.3	1178

The stored food as it is currently used on the ISS, would require a similar amount of mass but much more volume compared to the cultured meat production system. However, it would not require any power and no maintenance. For the comparison of stored food the current shelf life of the food used on the ISS of 2 years [RD13] must also be considered, as it exceeds the mission duration. The concept for cultured meat production utilized stored solid nutrients for the cell growth, as the stability of the required nutrients in solid form is expected to be longer than for the dissolved nutrients. However, the exact shelf-life of the required nutrients for cultured meat production must be studied to ensure the system is a viable alternative.

5. CONCLUSION

Overall, the conceptual design of a cultured meat production system shows promising results with a similar total mass than the equivalent amount of stored food and also a break-even with stored food after about 1028 days. Compared to the considered alternatives like plants it would provide a much earlier break-even. However, the loop closure of the cultured meat production system is not as high as the one achievable with a plant growth chamber because pre-stored nutrients are required for the cultivation of meat cells. The design is also currently based on assumptions to close some existing knowledge gaps. For example, most of the cell culture literature focuses on Chinese hamster ovary cells, which are not anticipated to be used as food product for astronauts. Instead beef (bovine cells) is expected to be the most promising type of cultured meat due to the high protein content. In addition to the benefits of mass savings for long missions, a cultured meat food product can also provide a pleasing addition to the diet of the astronauts, especially compared to some food alternatives like algae. For this reason, the design also considered the production of cultured meat which is close to the texture and taste of actual meat and therefore includes fat cells to texturize the cultured meat product. If the pure goal is protein production, the fat cells could be neglected but this would have a negative impact on the taste of the cultured meat product.

Cultured meat could therefore be a potential addition to the diet of future astronauts but before this is feasible further work is required to optimize the design and verify some assumptions.