SOLAR
FOODS

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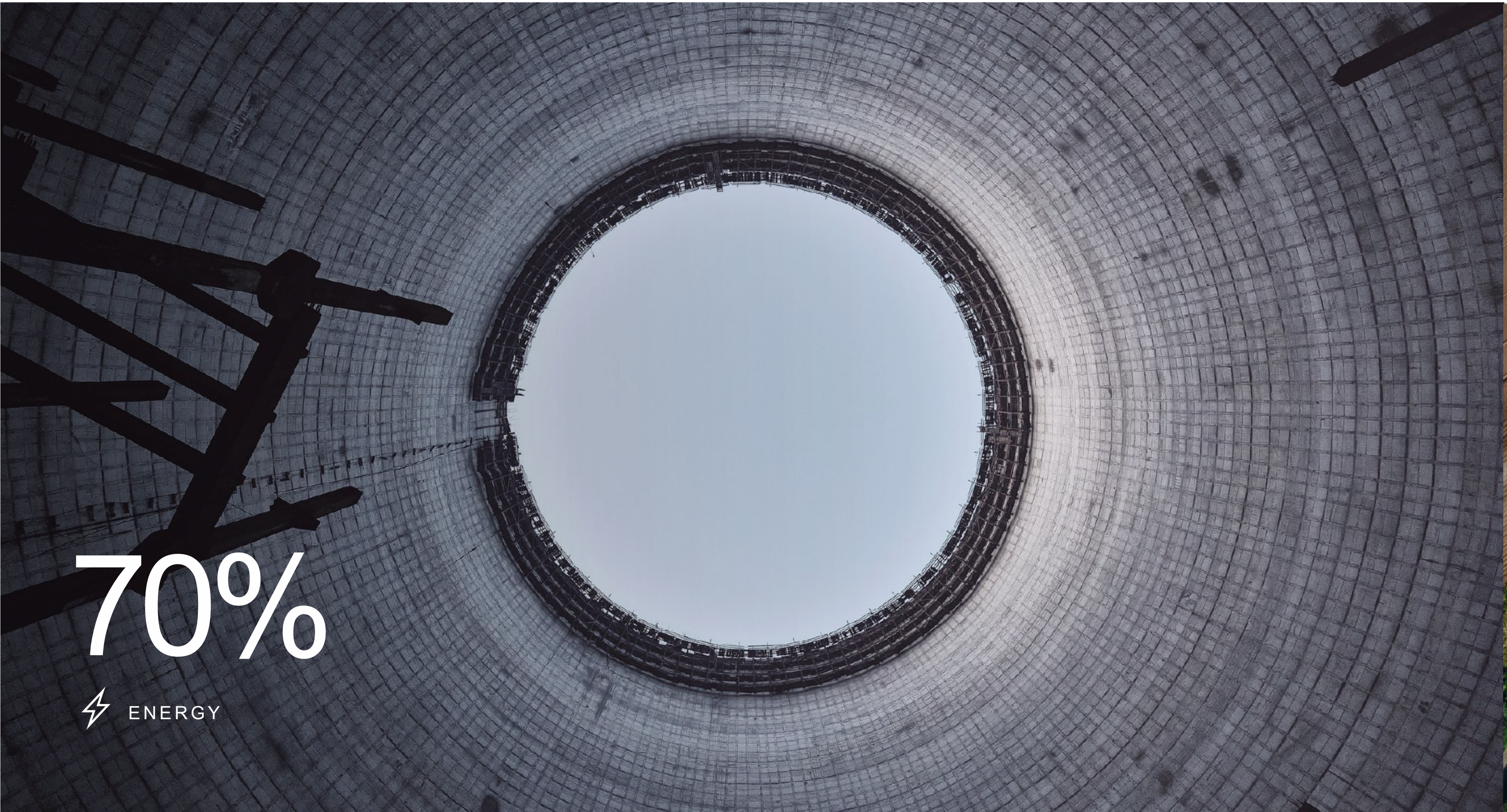
Food Out of Thin Air

Deep-space food production based on single-cell protein production by means of gas fermentation

09/10/2025

ESA Contract No. 4000140412/23/NL/GLC/OV

Sources of global greenhouse gas emissions



70%

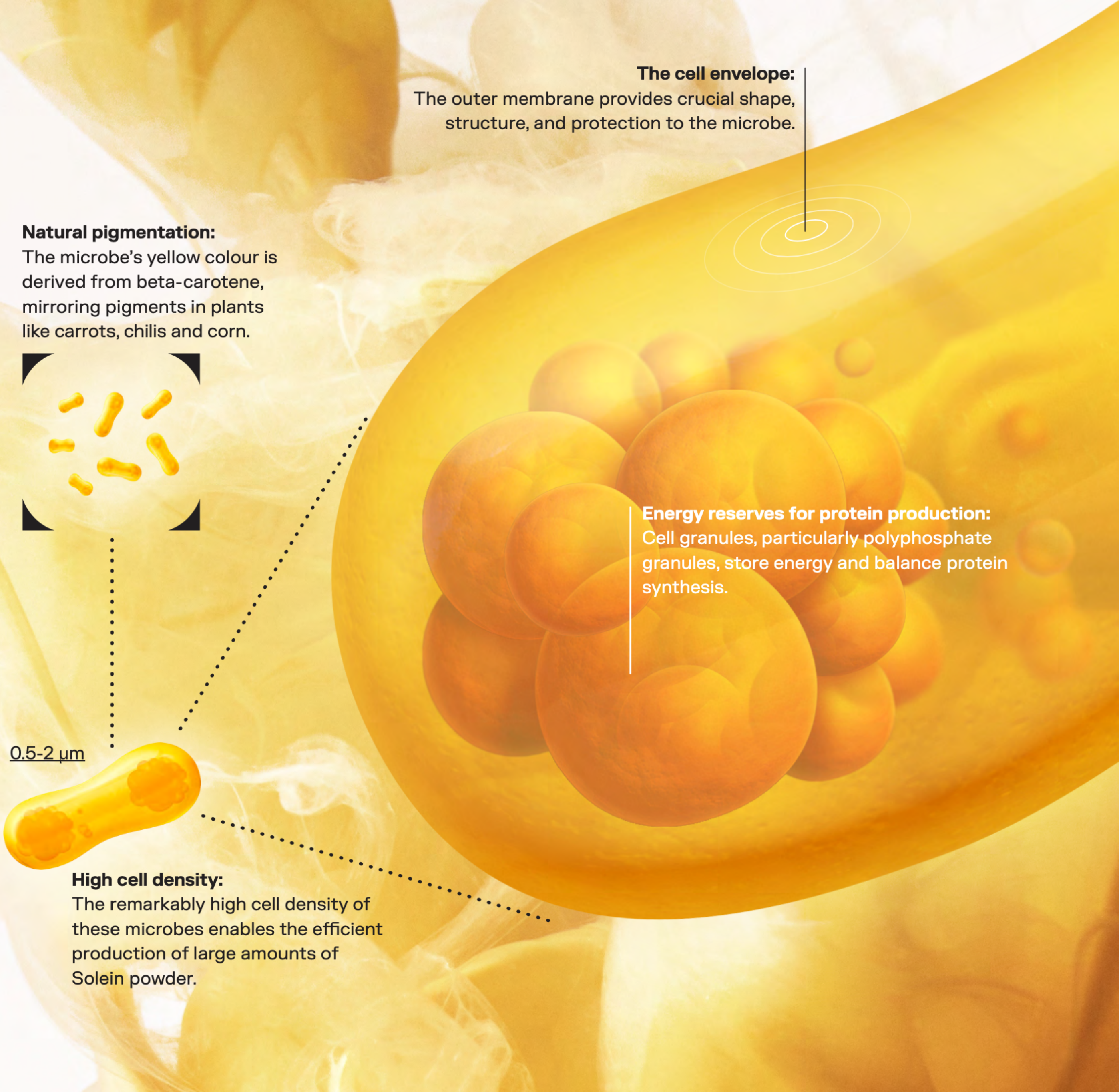
ENERGY

30%

FOOD PRODUCTION AND
LAND USE CHANGE

Solar Foods disconnects food production from agriculture

Solein uses microbes that can synthesise protein from air molecules – hydrogen and CO2, to offer an efficient, nutritious and functional alternative to traditional food sources.



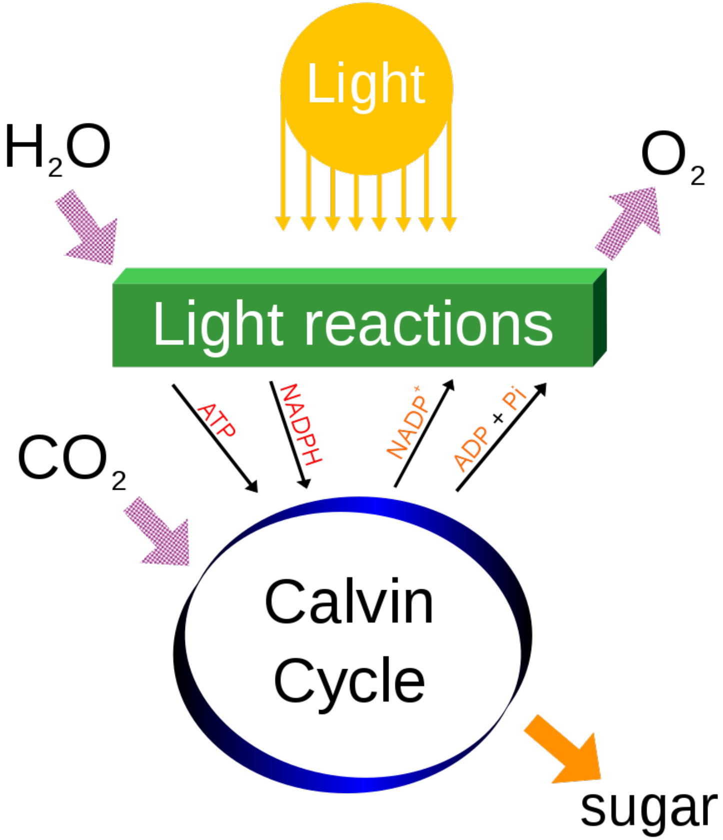
The cell envelope:
The outer membrane provides crucial shape, structure, and protection to the microbe.

Natural pigmentation:
The microbe's yellow colour is derived from beta-carotene, mirroring pigments in plants like carrots, chilis and corn.

Energy reserves for protein production:
Cell granules, particularly polyphosphate granules, store energy and balance protein synthesis.

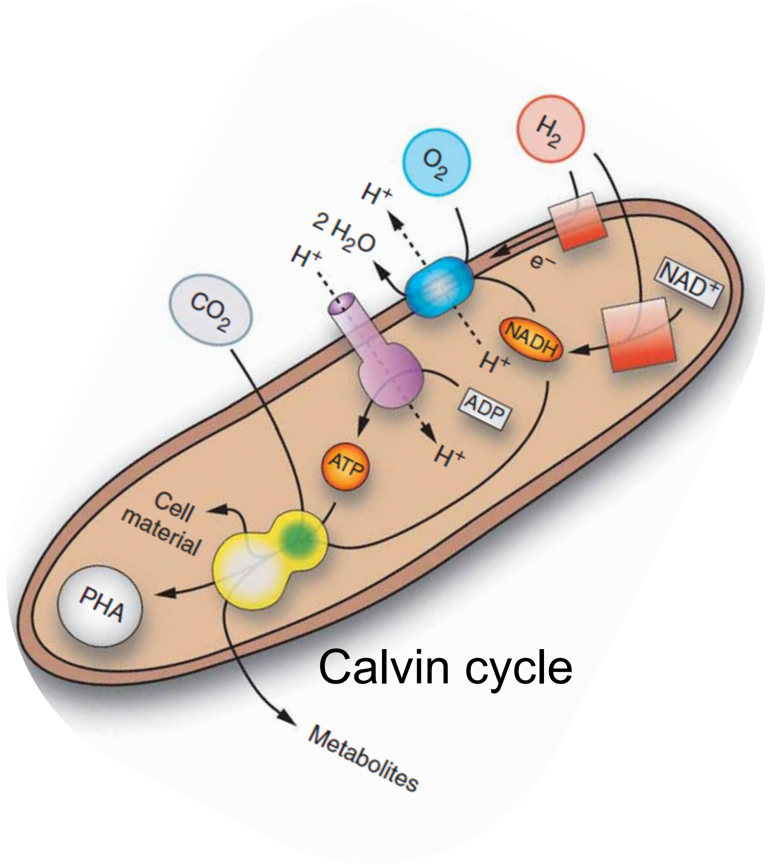
High cell density:
The remarkably high cell density of these microbes enables the efficient production of large amounts of Solein powder.

PHOTOSYNTHESIS (PLANTS)



https://commons.wikimedia.org/wiki/File:Simple_photosynthesis_overview.svg

HYDROGEN OXIDIZING BACTERIA (HOB)

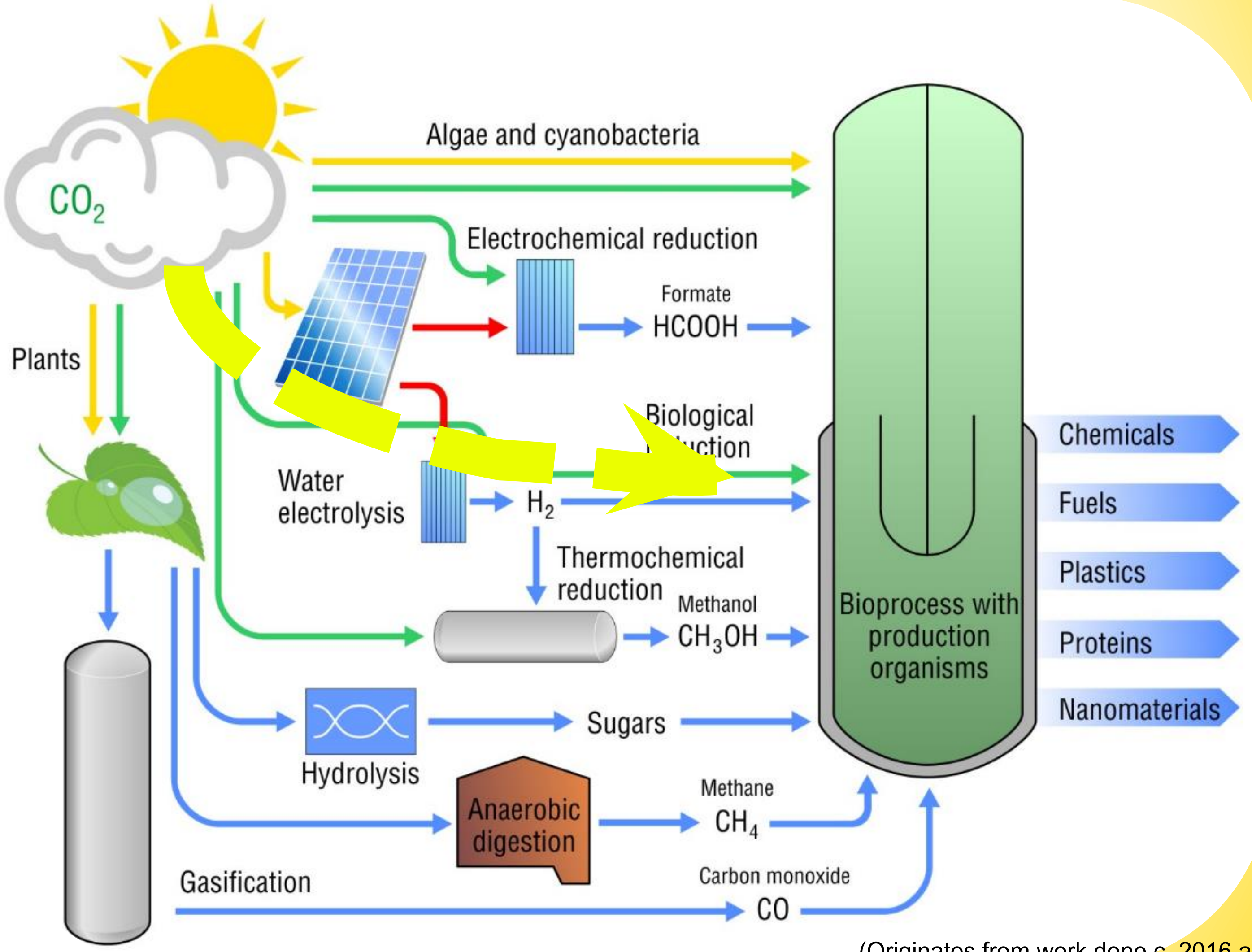


Pohlmann et al. ‘Genome Sequence of the Bioplastic-Producing “Knallgas” Bacterium Ralstonia Eutropha H16’. *Nature Biotechnology* 24, no. 10 (October 2006): 1257–62. https://doi.org/10.1038/nbt1244.3

ROUTES FROM SUNLIGHT AND CO_2 TO PRODUCTS THROUGH BIOTECHNOLOGY

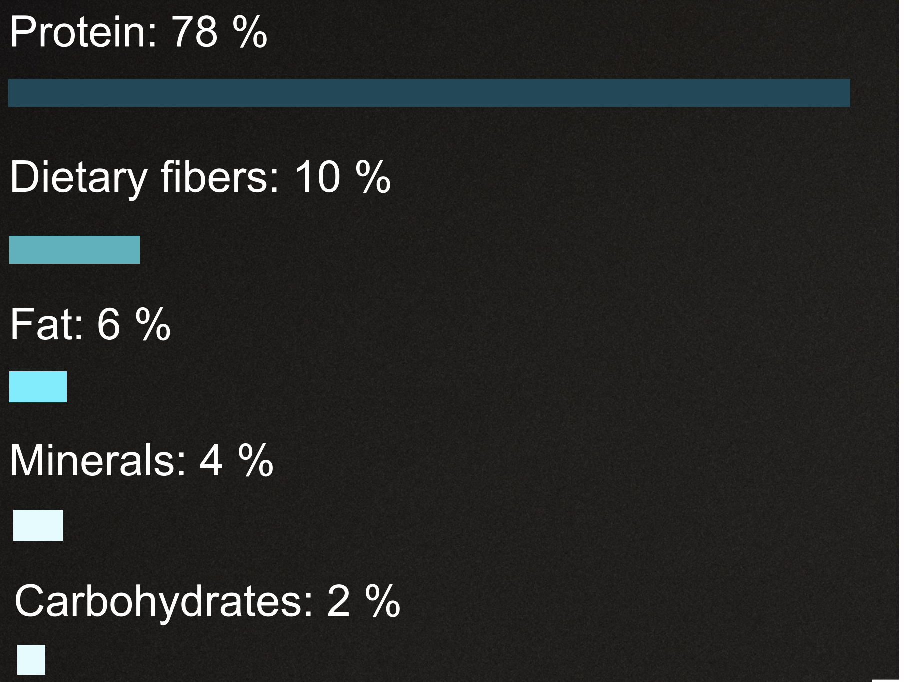
Combination of solar panels, electrolysers and Hydrogen Oxidizing Bacteria can have **~5 % energy efficiency** from sunlight to edible calories = **10x** better than plant photosynthesis (Not taking into account solar panels and artificial lighting).

This is the Solar Foods' route.



(Originates from work done c. 2016 at VTT Technical Research Centre of Finland)

Sustainable everyday protein



Protein: 78 %

Dietary fibers: 10 %

Fat: 6 %

Minerals: 4 %

Carbohydrates: 2 %

Rich in iron, B-vitamins and carotenoids
Free from allergens
Not genetically modified
Vegan

"Our mission is to solve the global food crisis and of course, Solein is primarily meant to be enjoyed on Earth. But Space is the ultimate stress test of a circular economy: It represents both an opportunity to advance the history of science and a chance to grow and diversify our business."

\- ARTTU LUUKANEN,
VP OF SPACE & DEFENCE

Results From ESA OSIP Activity:

Deep-space food production based on single-cell protein production by means of gas fermentation

Project Objectives

The main objectives of the project were:

Work package 1: Establish preliminary system requirements for an operational-scale Solein bioprocess system integrated with the onboard Environmental Control and Life Support System (ECLSS).

Work package 2: Carry out the preliminary design for an operational-scale (4 crew members) Solein bioprocess system based on the preliminary system requirements.

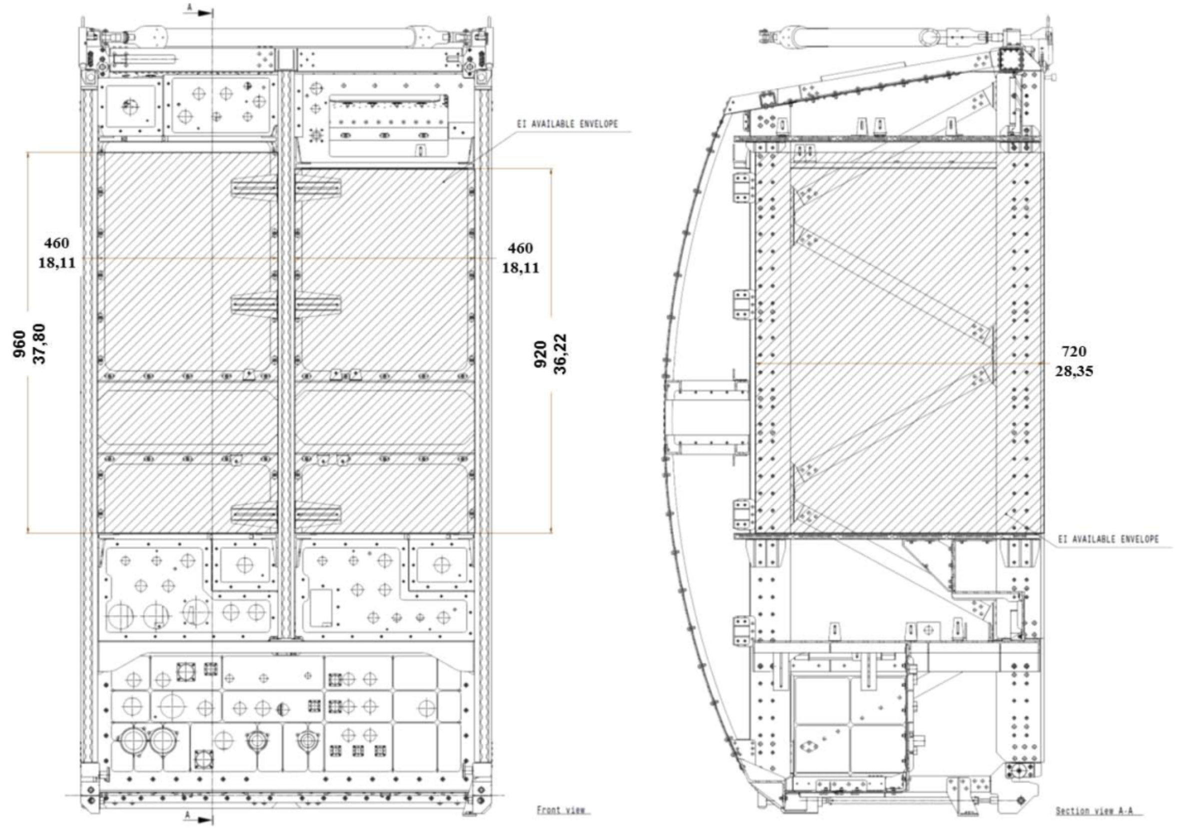
Work package 3: Breadboard and demonstrate a cross-flow filtration system to increase microbial biomass concentration in the end product.

Work package 4: Carry out a risk assessment with respect to the potential hazards associated with the technology.

Work package 5: Assess potential waste treatment methods for a) nitrogen recovery from crew urine and b) mineral recovery from crew feces via a literary study.

System specifications were captured in WP1 through dialogue with ESA

Specification	Value	Note
Dry mass	≲ 150 kg	
Dimensions	To fit within an EDR2 rack	Footprint requirement for a future operational system at this stage unknown
Power consumption (average)	≲ 900W	Steady state.
Power consumption (peak)	~3 kW	Cleaning, 2-3 hours 2-4 times/year, dominated by steam generator heater power consumption
Protein produced/day	370 g	140% of recommended daily intake (0.8 $g/kg_{body\ mass}$/day, corresponding to 240 g/day for a crew of 4 with an average body mass of 75 kg
Gravity environment	microgravity	
Inputs (from other systems)	H_2 (0.3 kg/d), CO_2 (1.1 kg/d), O_2 (1.6 kg/d), potable water (2.7 kg/d)	
Outputs	Protein (370 g/d), water (5.2 kg/d), brine water (140 g/d), heat (370W)	



The European drawer Rack-2 (EDR2) is a modified International Standard Payload Rack (ISPR)

DESIGN OF MEDIA MIXING, BIOREACTOR, DSP, AUTOMATION

Preliminary System Design

Detailed System Hierarchy and bill of materials were used to record all the different parts needed in the design

Philosophy:

- Reliability
- Maintainability
- Safety
- Autonomy

COTS

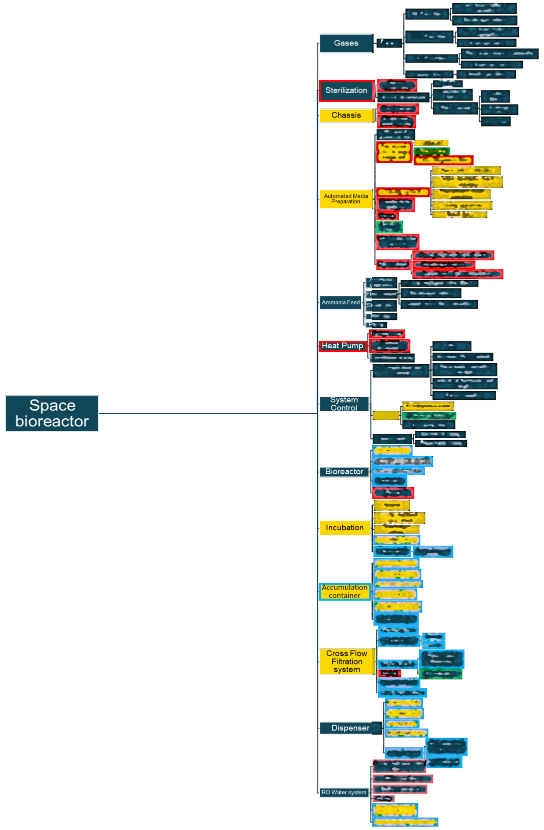
Custom

TBD

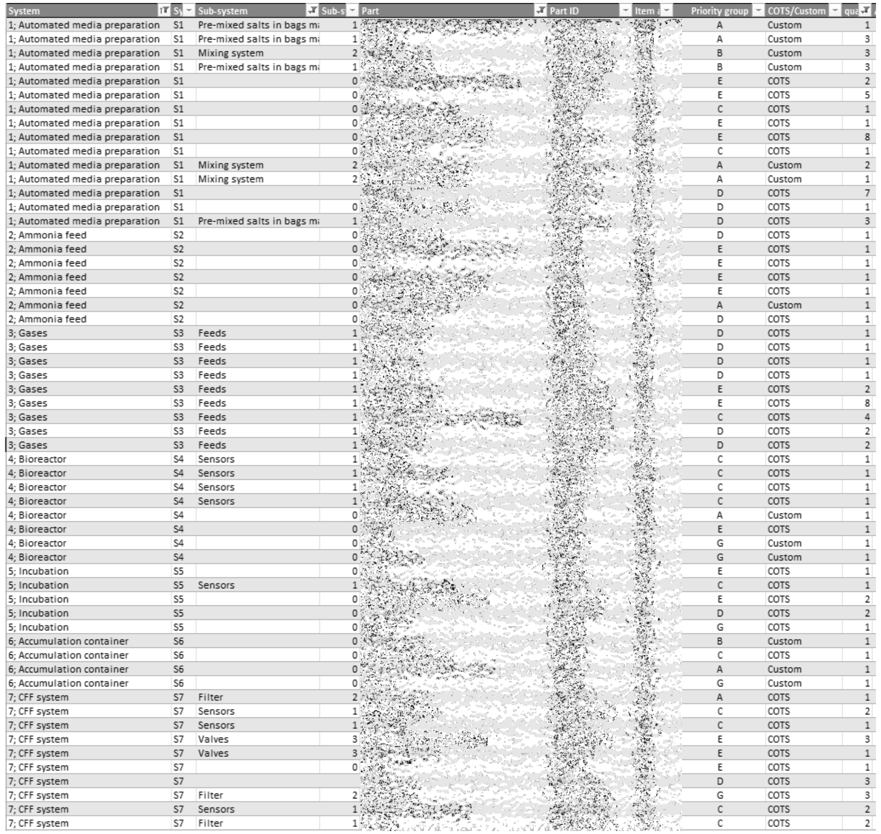
Steam clean compatible

Serviceable

Replaceable



System Hierarchy



System	Sy	Sub-system	Sub-s	Part	Part ID	Item a	Priority group	COTS/Custom	qua
1; Automated media preparation	S1	Pre-mixed salts in bags m	1	[redacted]	[redacted]	[redacted]	A	Custom	1
1; Automated media preparation	S1	Pre-mixed salts in bags m	1	[redacted]	[redacted]	[redacted]	A	Custom	3
1; Automated media preparation	S1	Mixing system	2	[redacted]	[redacted]	[redacted]	B	Custom	3
1; Automated media preparation	S1	Pre-mixed salts in bags m	1	[redacted]	[redacted]	[redacted]	B	Custom	3
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	E	COTS	2
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	E	COTS	5
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	C	COTS	1
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	E	COTS	1
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	E	COTS	8
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	C	COTS	1
1; Automated media preparation	S1	Mixing system	2	[redacted]	[redacted]	[redacted]	A	Custom	2
1; Automated media preparation	S1	Mixing system	2	[redacted]	[redacted]	[redacted]	A	Custom	1
1; Automated media preparation	S1			[redacted]	[redacted]	[redacted]	D	COTS	7
1; Automated media preparation	S1		0	[redacted]	[redacted]	[redacted]	D	COTS	1
1; Automated media preparation	S1	Pre-mixed salts in bags m	1	[redacted]	[redacted]	[redacted]	D	COTS	3
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	D	COTS	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	E	COTS	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	E	COTS	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	E	COTS	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	E	COTS	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	A	Custom	1
2; Ammonia feed	S2		0	[redacted]	[redacted]	[redacted]	D	COTS	1
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	1
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	1
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	1
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	1
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	E	COTS	2
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	E	COTS	8
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	C	COTS	4
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	2
3; Gases	S3	Feeds	1	[redacted]	[redacted]	[redacted]	D	COTS	2
4; Bioreactor	S4	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
4; Bioreactor	S4	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
4; Bioreactor	S4	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
4; Bioreactor	S4	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
4; Bioreactor	S4		0	[redacted]	[redacted]	[redacted]	A	Custom	1
4; Bioreactor	S4		0	[redacted]	[redacted]	[redacted]	E	COTS	1
4; Bioreactor	S4		0	[redacted]	[redacted]	[redacted]	G	Custom	1
4; Bioreactor	S4		0	[redacted]	[redacted]	[redacted]	G	Custom	1
5; Incubation	S5		0	[redacted]	[redacted]	[redacted]	E	COTS	1
5; Incubation	S5	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
5; Incubation	S5		0	[redacted]	[redacted]	[redacted]	E	COTS	2
5; Incubation	S5		0	[redacted]	[redacted]	[redacted]	D	COTS	2
5; Incubation	S5		0	[redacted]	[redacted]	[redacted]	G	COTS	1
6; Accumulation container	S6		0	[redacted]	[redacted]	[redacted]	B	Custom	1
6; Accumulation container	S6		0	[redacted]	[redacted]	[redacted]	C	COTS	1
6; Accumulation container	S6		0	[redacted]	[redacted]	[redacted]	A	Custom	1
6; Accumulation container	S6		0	[redacted]	[redacted]	[redacted]	G	Custom	1
7; CFF system	S7	Filter	2	[redacted]	[redacted]	[redacted]	A	COTS	1
7; CFF system	S7	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	2
7; CFF system	S7	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	1
7; CFF system	S7	Valves	3	[redacted]	[redacted]	[redacted]	E	COTS	3
7; CFF system	S7	Valves	3	[redacted]	[redacted]	[redacted]	E	COTS	1
7; CFF system	S7		0	[redacted]	[redacted]	[redacted]	E	COTS	1
7; CFF system	S7			[redacted]	[redacted]	[redacted]	D	COTS	3
7; CFF system	S7	Filter	2	[redacted]	[redacted]	[redacted]	G	COTS	3
7; CFF system	S7	Sensors	1	[redacted]	[redacted]	[redacted]	C	COTS	2
7; CFF system	S7	Filter	1	[redacted]	[redacted]	[redacted]	C	COTS	2

Bill of materials

A total of 15 subsystems were defined, designed and modelled

- Main system components were laid out in a detailed P&ID diagram.
- Shows how different components are connected to one another and where external interface are needed.
- Shows the level of accessibility needed.
- Used to assemble a 3D model of the system

Sub-systems:

1. Automated media preparation system (AMPS)
2. Ammonia/urea feed
3. Gases
4. Bioreactor
5. Incubation (Heat Treatment)
6. Accumulation Container
7. Crossflow filtration system
8. Dispenser
9. Chassis
10. Heat pump
11. Sterilization System
12. System control
13. Ultrasound system
14. Purified Water System
15. Other feeds system

Integrated within an International Standard Payload Rack. Interfaces with ECLSS include:

- Carbon dioxide
- Electrolyser outputs
- Potable water
- Nitrogen recycling system
- Data & power

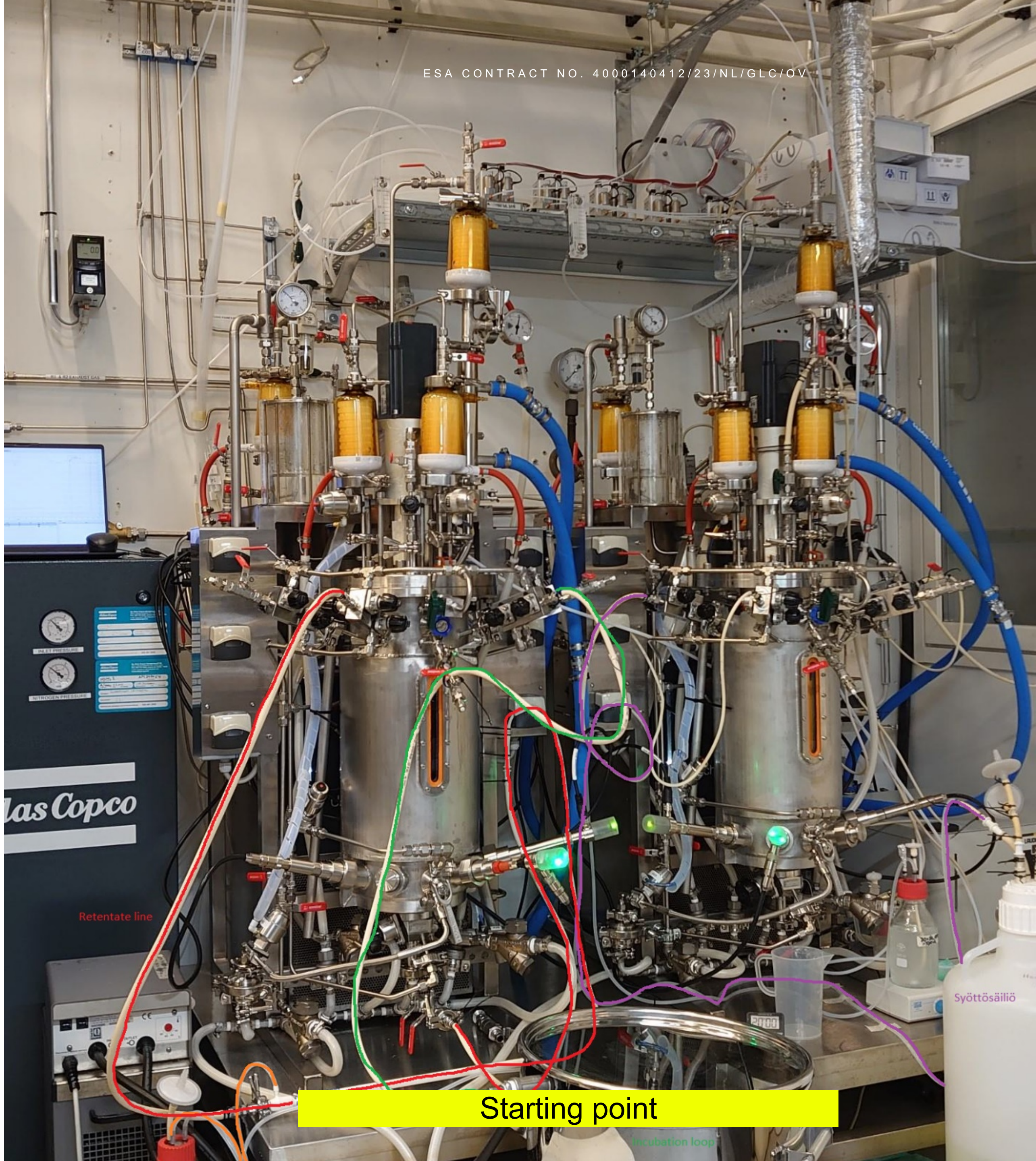
PRELIMINARY SYSTEM DESIGN

BREADBOARD MANUFACTURE, TESTING AND DEMONSTRATION

WP3: Breadboard of DSP

Hardware starting point

- Breadboarding done around our existing 10L bioreactor system
- Existing hardware: Allows for efficient utilization of resources
- **Aim:** To build a functioning downstream processing system (DSP) system capable of concentrating the product while remaining free from contamination.
- Caveat: 1 G

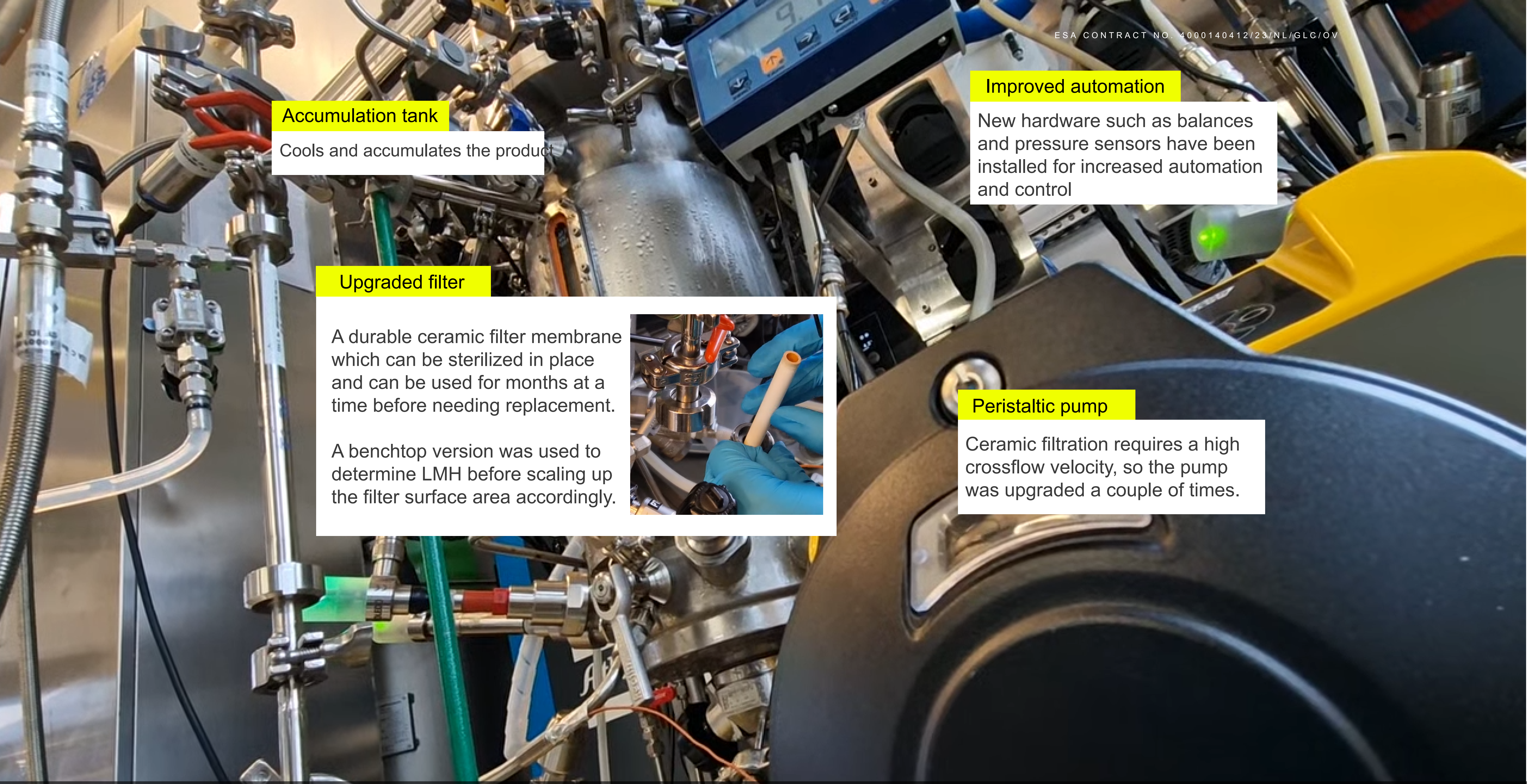


Starting point

Step 1 of DSP: Heat treatment vessel

Heat treatment (pasteurization)

The heat treatment operated for 101 days without viable cells passing thtough



Accumulation tank

Cools and accumulates the product

Improved automation

New hardware such as balances and pressure sensors have been installed for increased automation and control

Upgraded filter

A durable ceramic filter membrane which can be sterilized in place and can be used for months at a time before needing replacement.

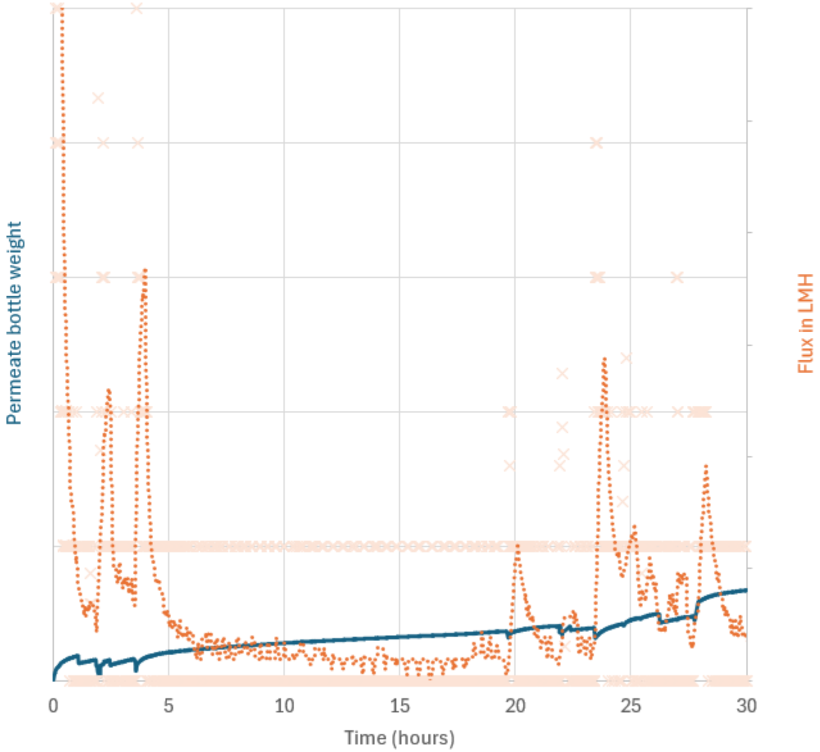
A benchtop version was used to determine LMH before scaling up the filter surface area accordingly.

Peristaltic pump

Ceramic filtration requires a high crossflow velocity, so the pump was upgraded a couple of times.

Step 2 of DSP: Crossflow filtration system

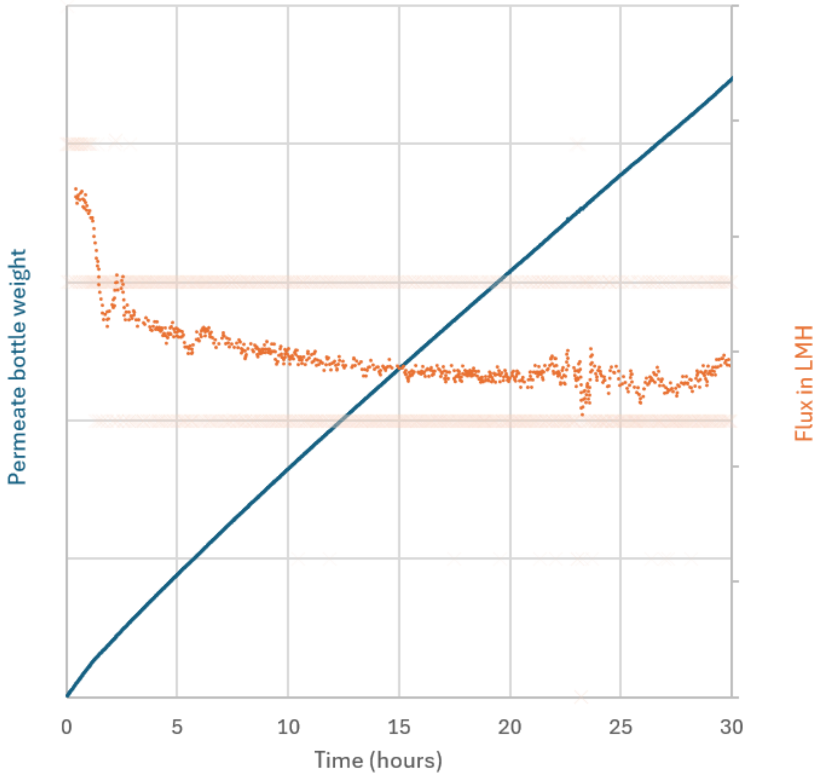
Crossflow optimization: the importance of crossflow velocity



Slower pump

- crossflow velocity: 4 cm/s
- Pump flow rate: 83 ml/min
- Backflushing performed

Both y-axes are to scale and start at 0

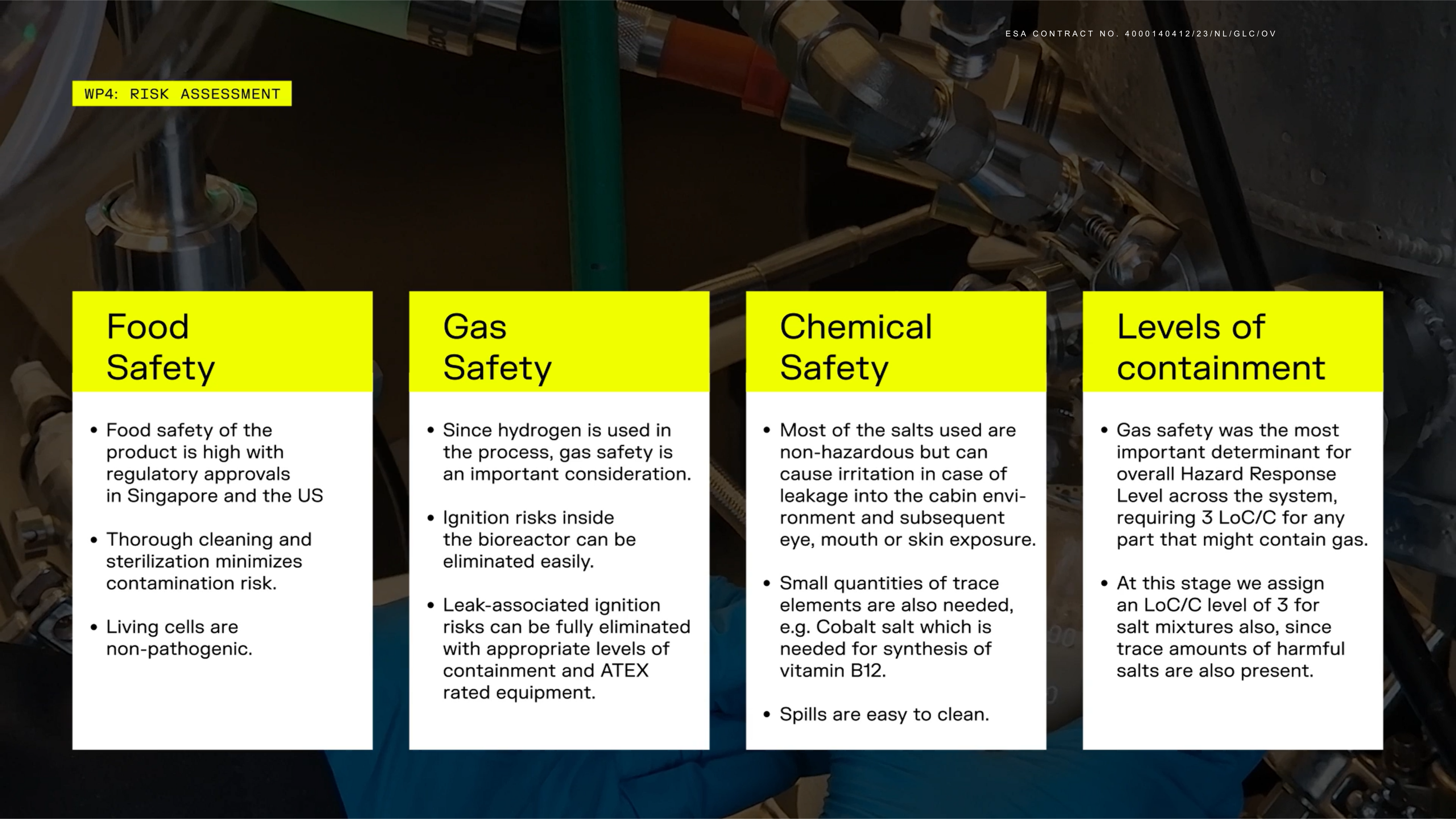


Upgraded pump

- crossflow velocity: 2 m/s
- Pump flow rate: 5 L/min
- Backflushing not needed

RISK ASSESSMENT AND MITIGATION

Risk assessment



WP4: RISK ASSESSMENT

Food Safety

- Food safety of the product is high with regulatory approvals in Singapore and the US
- Thorough cleaning and sterilization minimizes contamination risk.
- Living cells are non-pathogenic.

Gas Safety

- Since hydrogen is used in the process, gas safety is an important consideration.
- Ignition risks inside the bioreactor can be eliminated easily.
- Leak-associated ignition risks can be fully eliminated with appropriate levels of containment and ATEX rated equipment.

Chemical Safety

- Most of the salts used are non-hazardous but can cause irritation in case of leakage into the cabin environment and subsequent eye, mouth or skin exposure.
- Small quantities of trace elements are also needed, e.g. Cobalt salt which is needed for synthesis of vitamin B12.
- Spills are easy to clean.

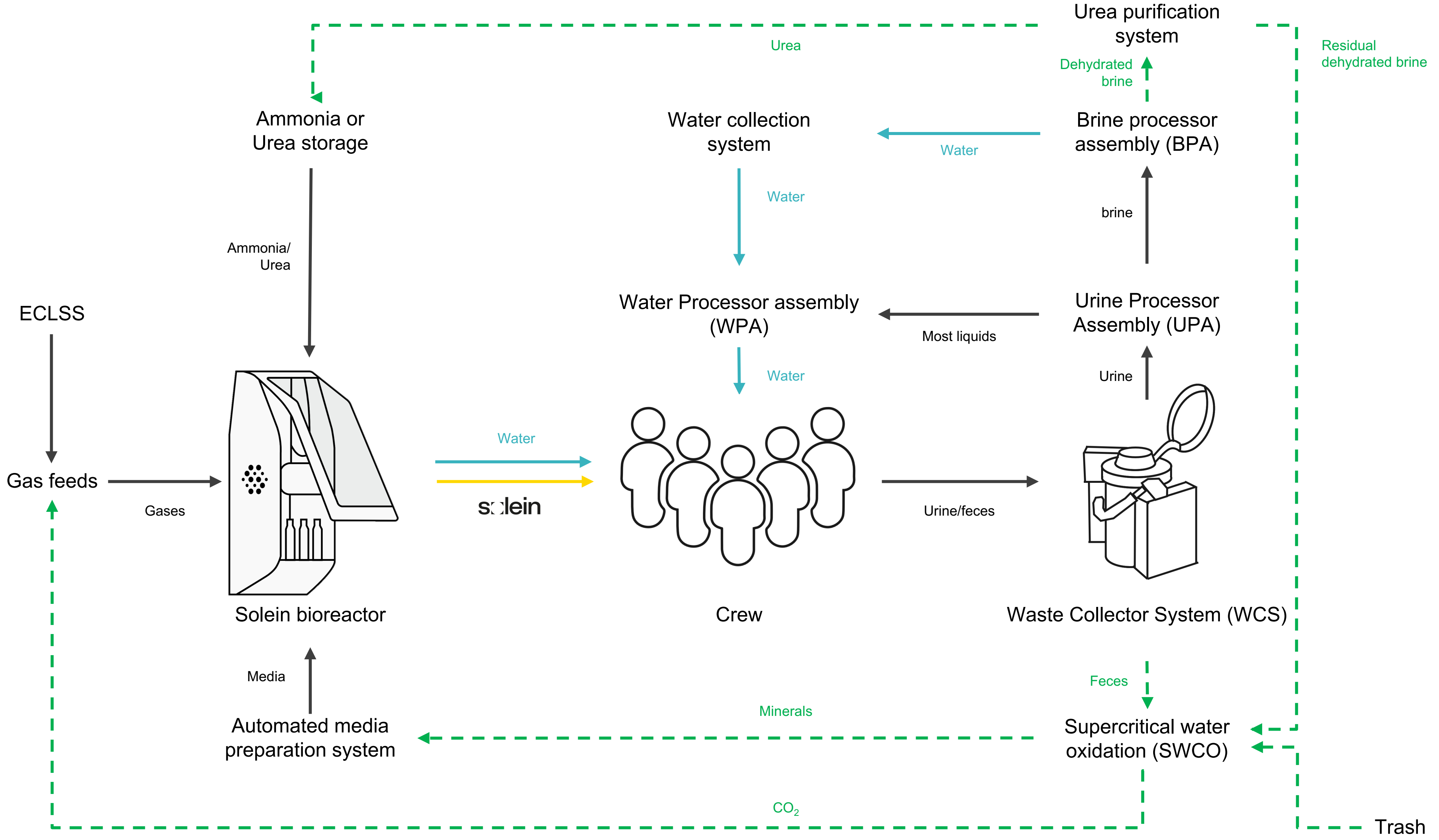
Levels of containment

- Gas safety was the most important determinant for overall Hazard Response Level across the system, requiring 3 LoC/C for any part that might contain gas.
- At this stage we assign an LoC/C level of 3 for salt mixtures also, since trace amounts of harmful salts are also present.

LITERATURE STUDY, WASTE UTILIZATION

Waste treatment assessment

A method to purify urea from brine and a method to recover minerals from solid waste would in theory create a fully circular system



Urea purification system

Residual dehydrated brine

Urea

Dehydrated brine

Ammonia or Urea storage

Water collection system

Water

Brine processor assembly (BPA)

Water

brine

Ammonia/ Urea

ECLSS

Water Processor assembly (WPA)

Most liquids

Urine Processor Assembly (UPA)

Water

Urine

Gas feeds

Gases

Water

solein

Urine/feces

Solein bioreactor

Crew

Waste Collector System (WCS)

Media

Feces

Minerals

Automated media preparation system

Supercritical water oxidation (SWCO)

CO_2

Trash

THIS WORK HAS BEEN CARRIED OUT UNDER A PROJECT FUNDED BY THE EUROPEAN SPACE AGENCY ESA UNDER THE CONTRACT NO. 4000140412/23/NL/GLC/OV. THE VIEWS EXPRESSED IN THIS PUBLICATION DOES NOT REFLECT THE OFFICIAL OPINION OF THE EUROPEAN SPACE AGENCY.

Thank you!

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