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belspo

Water cycling for manned Space missions: State-of-the-art within the MELiSSA concept

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QinetiQ

vito vision on technology

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eawag aquatic research

SCK•CEN STUDIECENTRUM VOOR KERNENERGIE CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

Managing water supply
for **terrestrial** life support:

1. Surface water
2. Groundwater
3. Seawater
4. Wastewater reuse

Value of wastewater ('used water')

Potential recovery	Per m³ sewage	Market prices	Total per m³ sewage
Organic carbon	0.10 kg	0.200 €/kg	0.020 €
Methane	0.14 m^3	0.338 €/m^3CH_4	0.047 €
Nitrogen	0.05 kg	1.0 €/kg	0.050 €
Phosphorus	0.01 kg	0.7 €/kg	0.007 €
Water	**1 m^3**	**0.250 €/m^3**	**0.250 €**

Take home: A potential value ~ 0.4 €/m^3,

mainly as "water"

(Verstraete & Vlaeminck, 2011)

Managing water supply
for **extraterrestrial** life support:
1. Terrestrial re-supply
2. Wastewater reuse
3. In-situ resource mining (?)

(redrafted after Lamaze & Rebeyre)

Life support

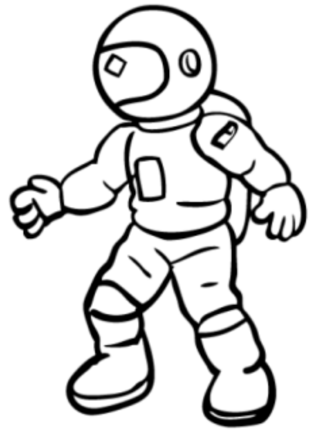
Inputs:

O_2 (0.84 kg, from 0.47 kg H_2O)

H_2O (**2-12** kg)

Food (1.3 kg)

(per crew member per day)



Outputs:

Faeces

Urine

CO_2

Perspiration

Microbial and chemical contaminants

Safe reuse

Disposal

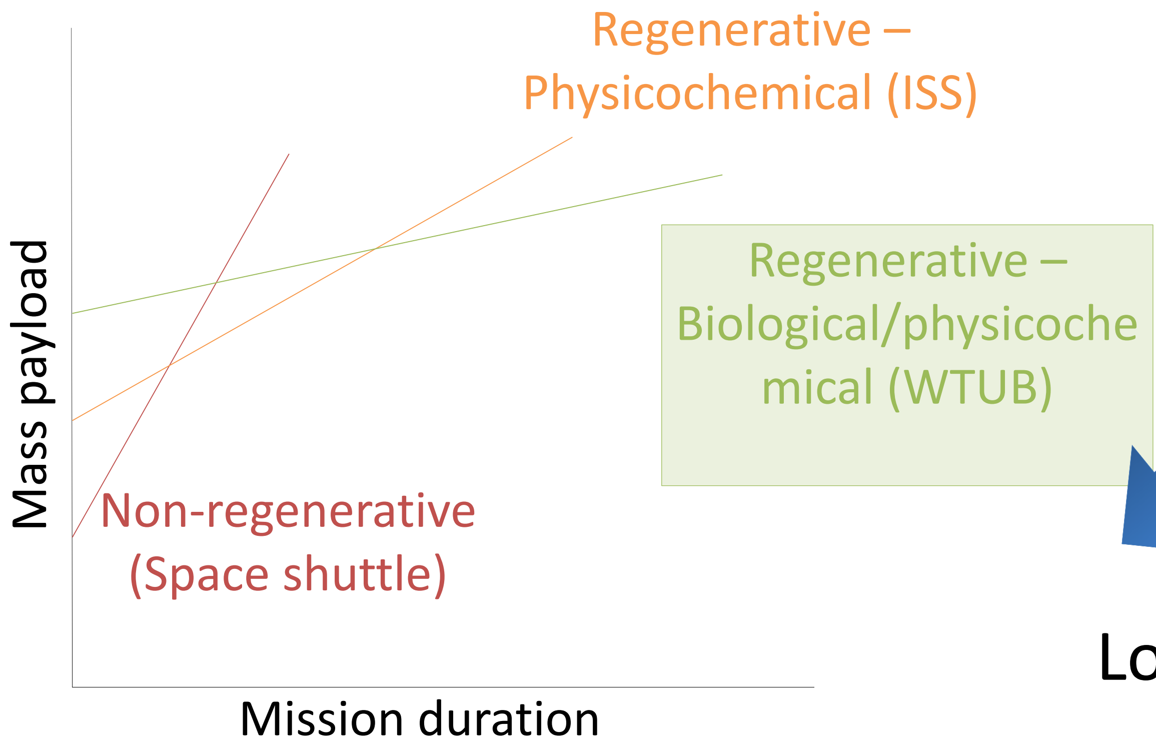
Energy (solar), H_2O and chemicals driving the conversions

Water in space missions

1 astronaut: 12 L d^{-1} water

Crew: 6 members
Flight duration: 3 year

79 tonnes water
vs.
ISS: 420 tonnes
Heaviest launcher: 9 tonnes



(Adapted from Lasseur *et al.* 2007)

Long missions need **reuse**

Life Support in Space:
Objectives depend on type of mission

Low Earth Orbit (LEO)

- **H_2O: treatment & recycling >90%**
- O_2 production: electrolytically from **H_2O**
- Faeces (organic carbon/nutrients): waste management (disposal)
- Respiration: CO_2 management (reduction to CH_4, then venting)

-> Necessary resources: energy, food, (H_2O)

Human Space Exploration

- **H_2O: treatment & recycling > 99%**
- O_2 production: phototrophically from **H_2O**
- Faeces and harvest/kitchen waste: processing (to CO_2 and nutrients) and recycling
- CO_2 and nutrients: re-convert to biomass (= food)
- (In-situ resources exploration)

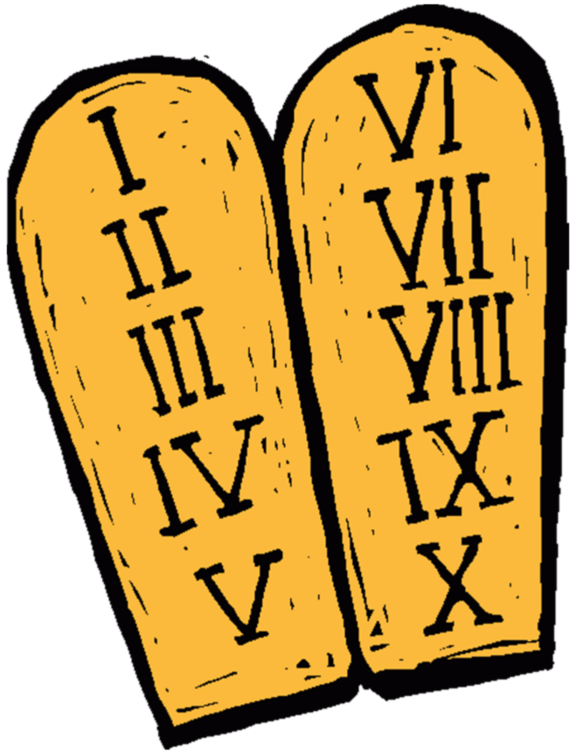
-> Necessary resources: energy

(adapted after Demey - Qinetiq)

The commandments of regenerative life support

Recycling shall be done…

1. At high efficiency
2. In a compact manner (low volume; fast processes)
3. In a light manner (low mass)
4. Consuming few energy
5. Consuming few chemicals
6. Imposing minimal risk to the crew (safety)
7. At high reliability/robustness
8. With limited buffer capacity
9. With limited crew time
10. Under Space compatible conditions (radiation/microgravity)



H_2O: biggest impact on mass flow

-> first priority for recycling

-> is already (partly) ongoing already at ISS

Water use in Space

Short mission:

- Drinking water
- Hygiene water (hand-washing, shower, etc.)
- Food water (to hydrate food or for cooking)
- Water for oxygen production (electrolysis)

Long mission, extra:

- Service water (laundry, dish-washer, etc.)
- Water for food production

Parameters		ESA Drinking water standard	ESA Hygiene water standard
pH		6.5 - 8.5	5.0 - 8.5
Conductivity (mS / cm)	$mS.cm^{-1}$	0.75	3
Turbidity (NTU)	NTU	2.5	10
TOC (mg/L)	mg/L	0.5	10
NH_4^+ (ppm)	ppm	0.5	0.5
Bacteria			
Total count at 37 ºC	CFU x ml^{-1} x 48 h	0	0
Total count at 22 ºC	CFU x ml^{-1} x 48 h	1	1
Enteric bacteria	CFU x 100 ml^{-1}	0	0
Human pathogens	CFU x 100 ml^{-1}	0	0

(Advanced Life Support Baseline Values and Assumptions Document - Architecture Study for Sustainable Lunar Exploration CDF Study Report)

Water use	Units	Nominal value	Quality required
Drink water	Kg/CM/d	2.0	Potable
Food water	Kg/CM/d	1.909	Potable
Hygiene [from R 16]	Kg/CM/d	10	Hygiene

Table 1 Water requirements per crew[1]

Wastewater generated in Space

Short mission:

- Respiration/transpiration crew: condensate
- Urine
- Grey water (from hygiene activities)

- Sabatier water ($CO_2 + 4H_2 \rightarrow 2\mathbf{H_2O} + CH_4$)

Extra for long mission:

- Black water (from toilet flush)
- Service wastewater (laundry, dish-washer, etc.)
- Transpiration water (food production with plant)

Water source	Units	Nominal value	Waste water type
Faecal Water	Kg/CM/d	0.091	Black water
Urine water (ISS value)	Kg/CM/d	1.2	Yellow water
Urine flush water	Kg/CM/d	0.3	Yellow water
Condensate water [from R 16]	Kg/CM/d	1.5	Grey water
Hygiene water [from Table 1]	Kg/CM/d	10	Grey water

Table 2 Waste water requirements per crew

(Advanced Life Support Baseline Values and Assumptions Document - Architecture Study for Sustainable Lunar Exploration CDF Study Report)

State of the art - Water in Space and MELiSSA

ISS

Reuse of

- Urine
- Condensate
- Sabatier water

(Quality monitoring)

MELiSSA

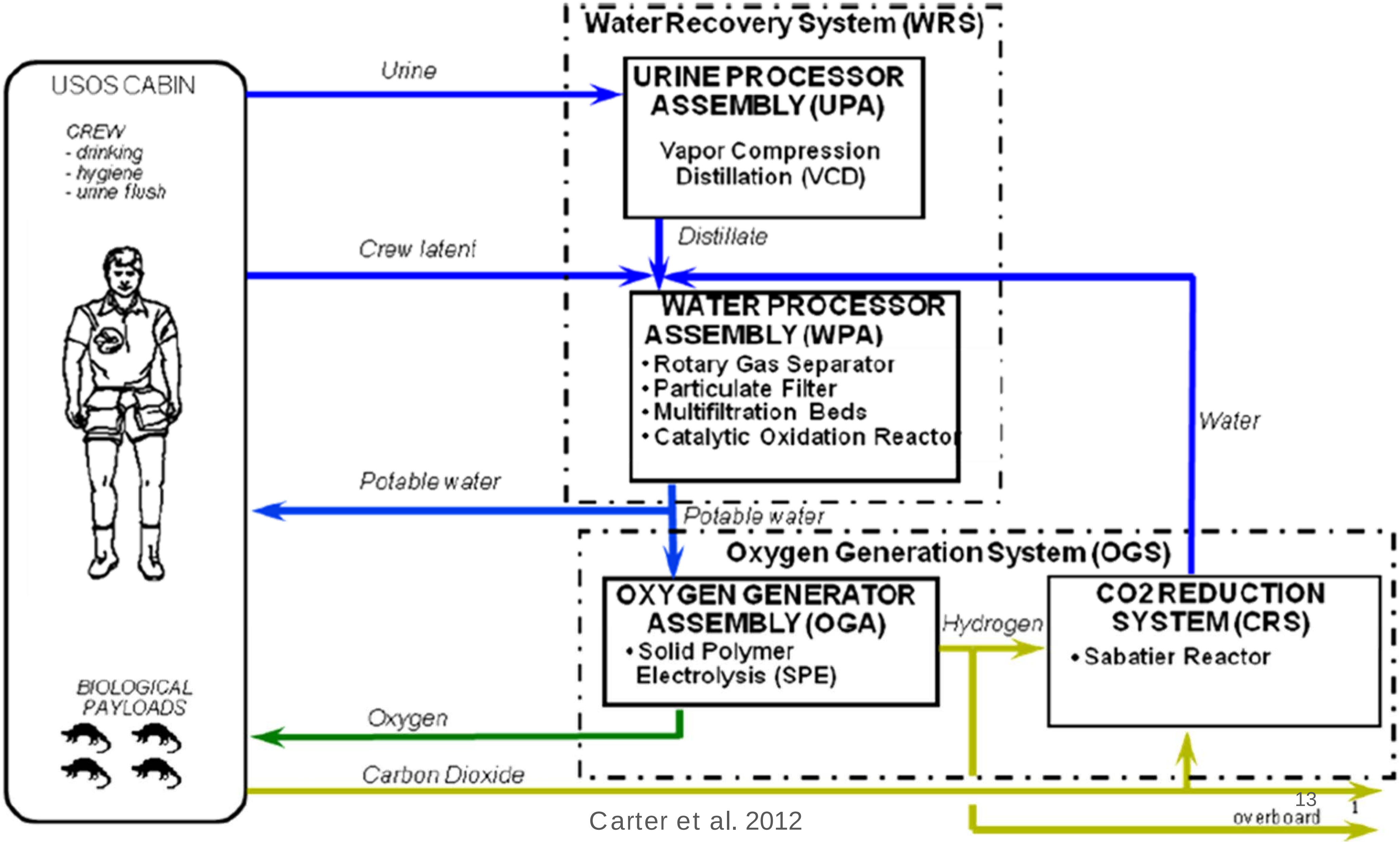
Reuse of:

- Urine (alternative technology)
- Condensate (alternative technology)
- Grey water (from hygiene activities)
- Black water (from toilet flush)

Solutions integrating treatment of several streams

(Quality monitoring and risk management)

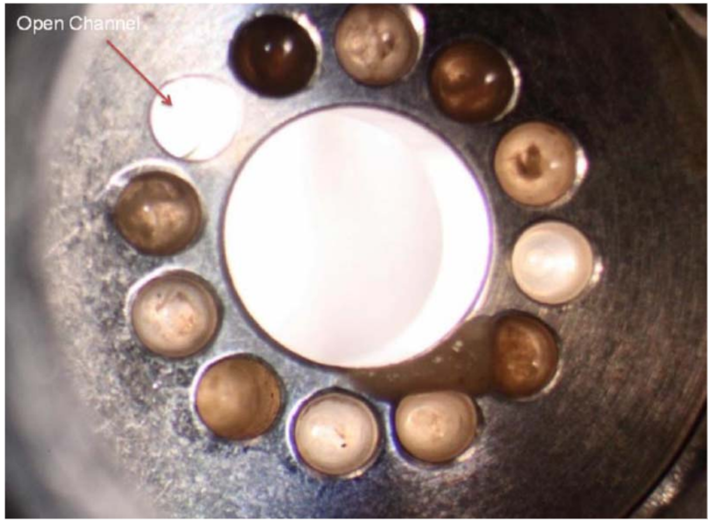
Water treatment in ISS (US segment)



Carter et al. 2012

Current ISS water treatment

- Urine:
  - Relatively high amounts of inorganic compounds (salts, ammonia) and biodegradable carbon -> scaling and fouling
  - Vapor compression distillation (VCD)
    - relatively high energy demand (7-12 kWh/m^3)
    - 70% water recovery (designed for 80%, but limited in Space due to scaling)
  - Pre-treatment (biological inactivation): ‘nasty’ chemicals (e.g. CrO_3)



Biomass growth in valve

Scaling in evaporator

- Condensate and Sabatier water (and urine distillate):
  - relatively low levels of chemicals contaminants -> technically less challenging to treat
  - filter (particles) – multifiltration beds (inorganics & organics) - catalytic reactor (organics) – ion exchange (mineralisation) – disinfection (biocide + pasteurization)

ISS – water quality monitoring and risk management

1. Basic water quality monitoring is in place

- Key analyses are off-line
- Frequency of monitoring is low
- Analysis is limited to a simple chemical characterization and bacterial counting

2. However, microbial contamination occurs

- To our knowledge, no pathogen has ever been detected in ISS water loop but microbial contamination can be found in recycled water.
- Recovered organisms from the ISS water system show resistance to:
  - heavy metals (i.e. nickel leaching from stainless steel tubing)
  - biocides currently used (such as iodine).

3. And risk management opportunities are lacking

- ISS water recycling systems are not designed taking into account microbial risk: there is no possibility to fully disinfect a water recycling system.

-> there is room for improvement to guarantee crew health, especially at increased levels of recycling

State of the art - Water in Space and MELiSSA

ISS

Reuse of

- Urine
- Condensate
- Sabatier water

(Quality monitoring)

MELiSSA

Reuse of:

- Urine (alternative technology)
- Condensate (alternative technology)
- Grey water (from hygiene activities)
- Black water (from toilet flush)

Solutions integrating treatment of several streams

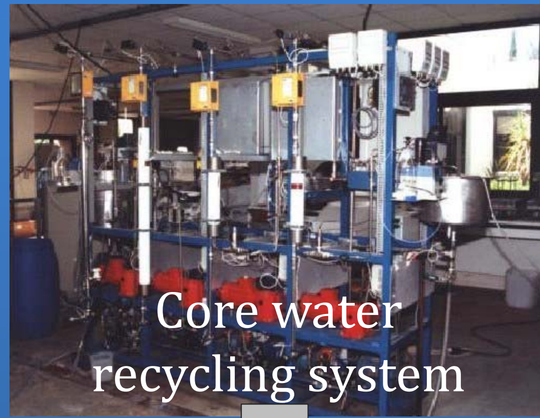
(Quality monitoring and risk management)

Urine -> nitrification

Grey water -> membranes **(UF/NF/RO)**

MELiSSA pilot plant

Microbial water treatment



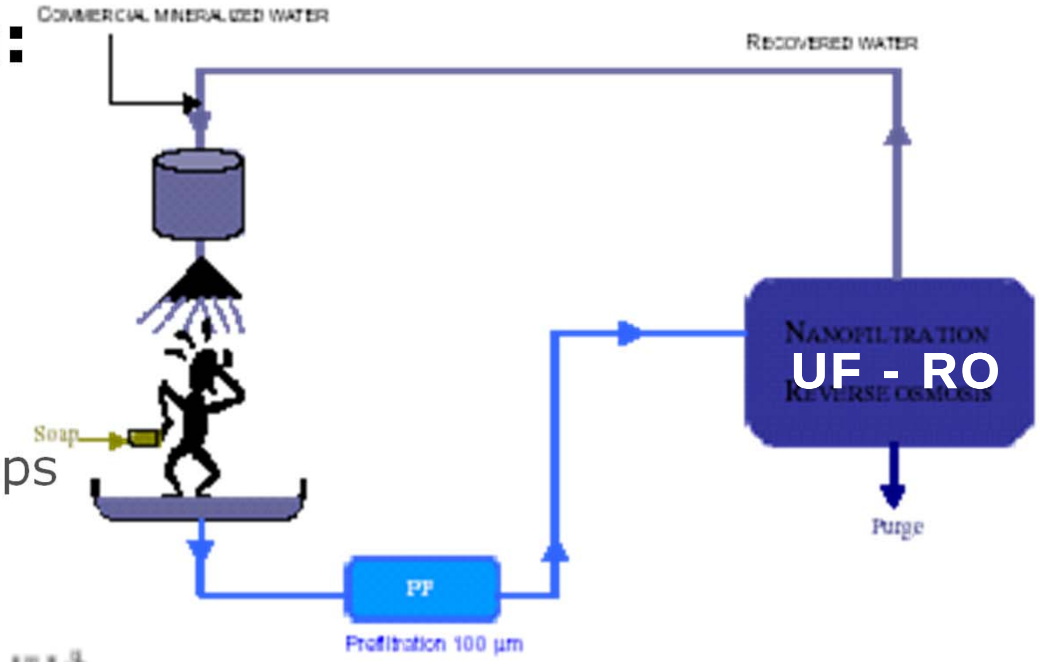
Water Treatment Unit Breadboard (WTUB):
Urine – condensate – grey water

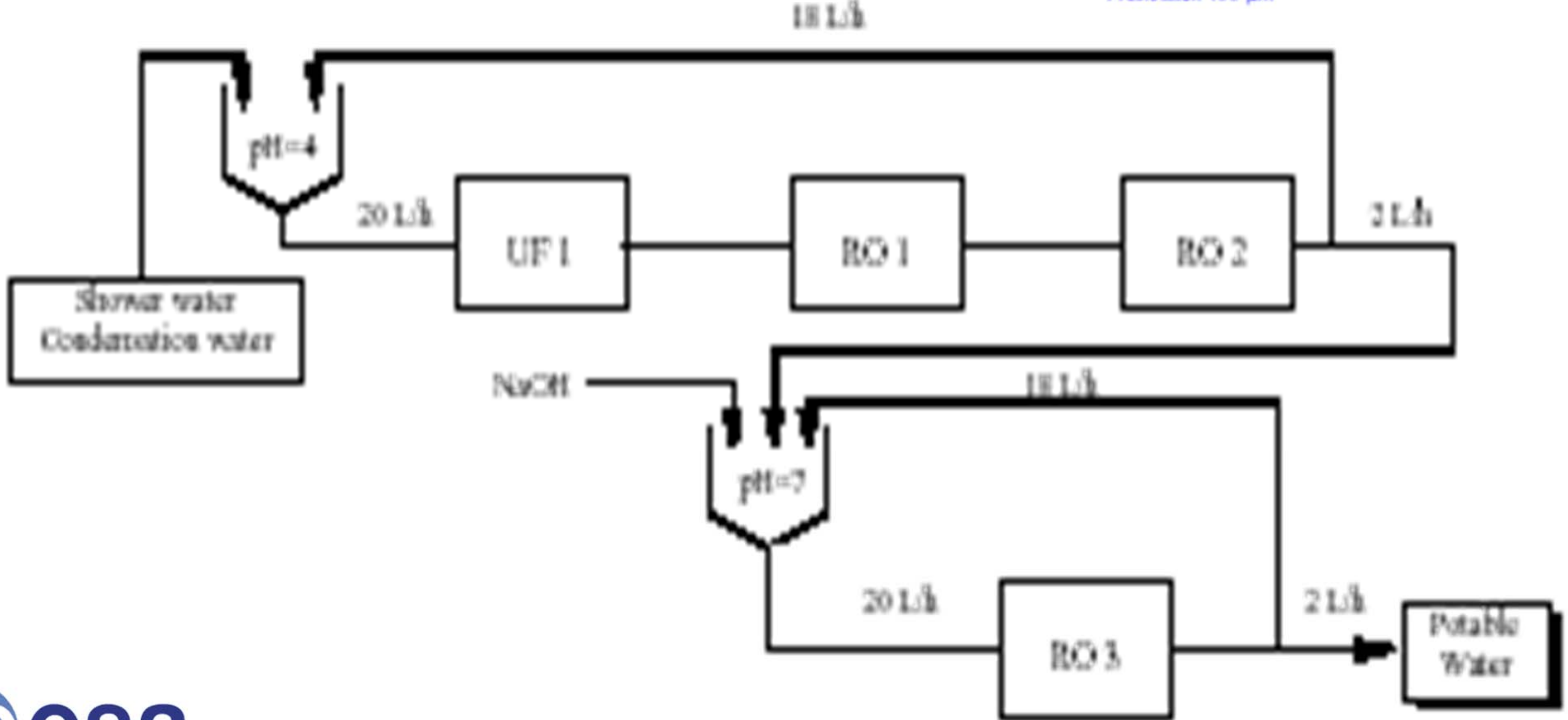
-> nitrification
-> membranes (UF/NF/RO)
+
-> crystallization
-> electrodialysis

Core water recycling system:
grey water + condensate

Combination of:

1. Ultra-filtration (UF)
2. Two/three reverse osmosis (RO) steps





- Fully automated breadboard (including drain)
- 6 months continuous operation on “real” shower water

→ Water recovery up to 95%

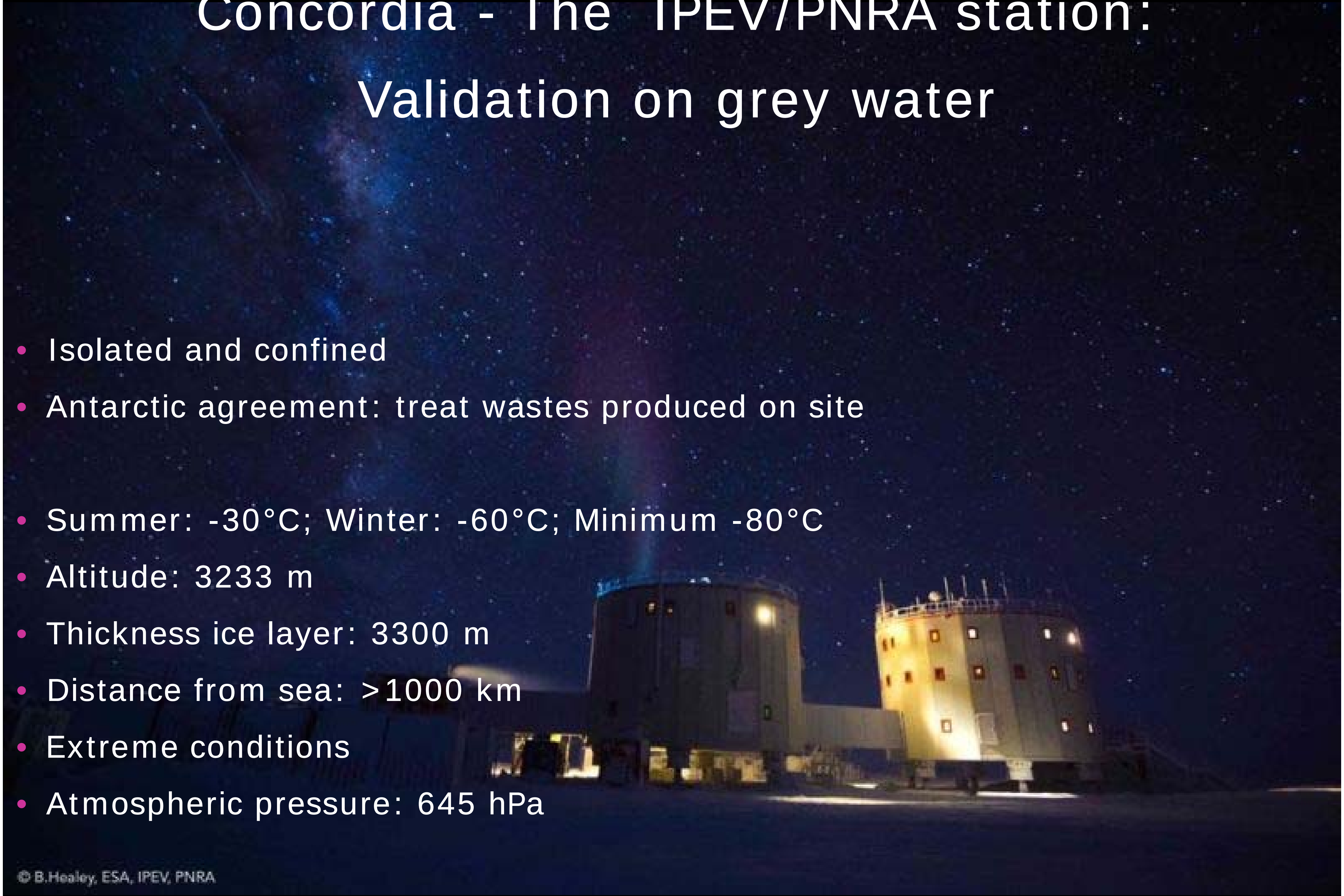
PARAMETERS	DRINKING WATER ESA STANDARD	HYGIENE WATER ESA STANDARD	RECOVERED WATER
pH	6.5 - 8.5	5 - 8.5	6.2 - 7.8
Conductivity ($mS.cm^{-1}$)	0.75	3	< 0.01
Turbidity (NTU)	2.5	10	< 0.25
TOC (ppm)	0.5	10	1.3 - 2.7
Oxidative power (ppm)	-	-	230
F^- (ppm)	1	10	< 0.8
Cl^- (ppm)	200	1000	< 1.1
NO_3^- (ppm)	25	50	< 0.4
PO_4^{2-} (ppm)	5	50	< 0.2
SO_4^{2-} (ppm)	250	TBD	< 1.1
Na^+ (ppm)	150	750	< 1.8
K^+ (ppm)	12	120	< 0.1
NH_4^+ (ppm)	0.5	0.5	< 0.1

Quality of recovered water matches ESA hygiene water standards

Concordia - The IPEV/PNRA station: Validation on grey water

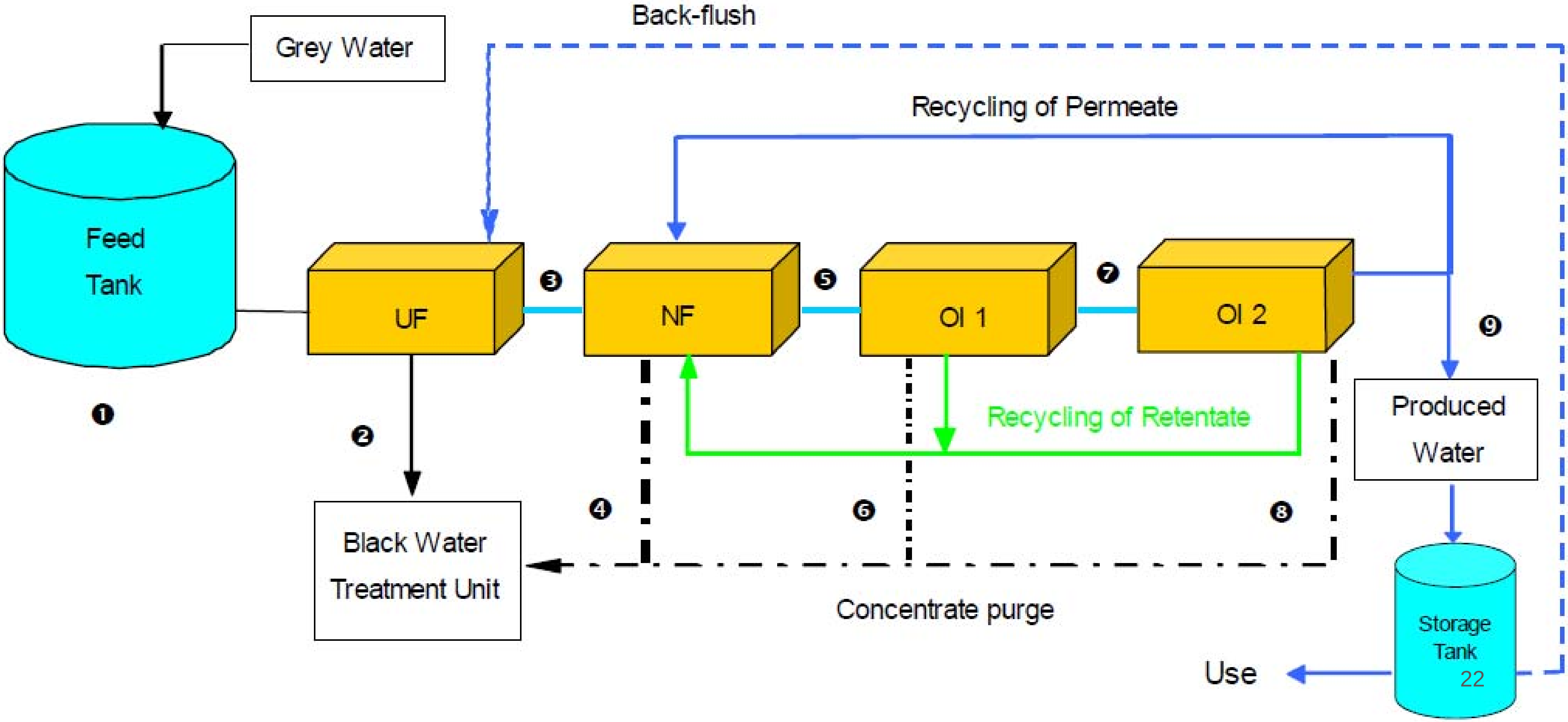
- Isolated and confined
- Antarctic agreement: treat wastes produced on site

- Summer: -30°C; Winter: -60°C; Minimum -80°C
- Altitude: 3233 m
- Thickness ice layer: 3300 m
- Distance from sea: >1000 km
- Extreme conditions
- Atmospheric pressure: 645 hPa



Grey water treatment unit (GWTU) @ Concordia

- Strategy based on membranes:
  - Ultrafiltration (UF) – nanofiltration (NF)
  - Reverse osmosis 1 (RO1) – Reverse osmosis 2 (RO2)
- System treating the grey water generated by 25 persons (2.5 m^3 d^{-1})
- Grey water streams are mixed and microbial growth is inhibited by addition of oxonia.



Concordia – Grey Water Treatment Unit

Ultrafiltration + Nanofiltration

Reverse Osmosis

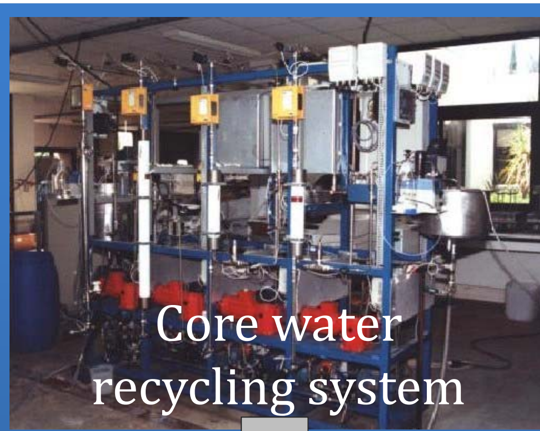
- On average: 75% water recovery
- ESA hygiene standard can be reached

Urine -> nitrification

Grey water -> membranes **(UF/NF/RO)**

MELiSSA pilot plant

Microbial water treatment



Water Treatment Unit Breadboard (WTUB):
Urine – condensate – grey water

-> nitrification
-> membranes (UF/NF/RO)
+
-> crystallization
-> electrodialysis

Urine - aerobic bioreactor: Objectives

1. Key nitrogen conversions in urine:

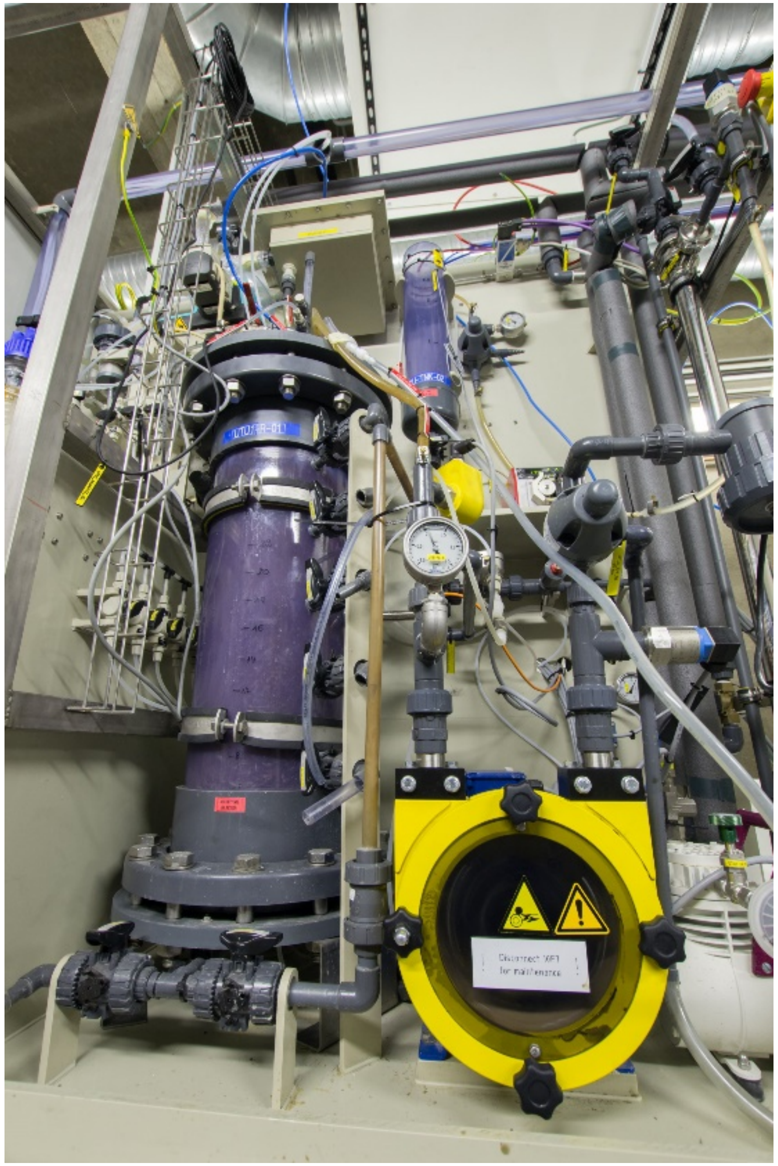
Hydrolysis: Urea → 2 NH_3 + CO_2

Nitrification (+ O_2): NH_3 → NO_2^- → NO_3^-

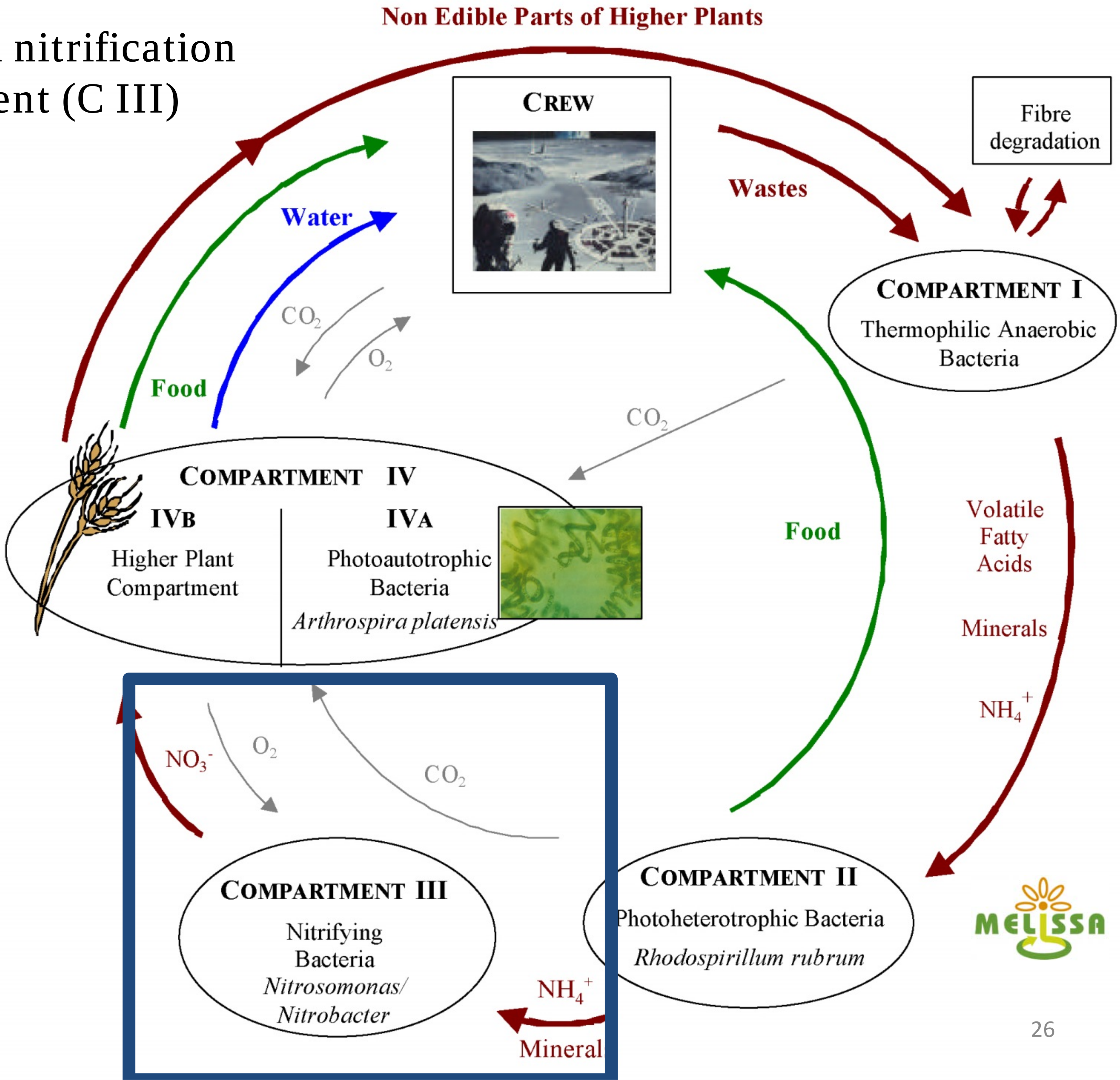
- Volatile
- More toxic
- Low RO retention

- Non volatile
- Less toxic
- High RO retention

2. Key organic carbon conversion (+ O_2): oxidation to CO_2



The MELiSSA nitrification compartment (C III)



Nitrification technology demonstration: MELiSSA pilot plant (MPP) – Barcelona (UAB)

- Packed-bed reactor
- Defined community: *Nitrosomonas europaea – Nitrobacter winogradskyi*
- Demonstrated continuous interconnected operation (Godia et al., 2002):

Anaerobic fermentation (CI)
-> Nitrification (CIII)
-> Photobioreactor (CIVa)

- A dynamic model for nitrifying biofilm reactors was developed and validated (Pérez et al., 2005)

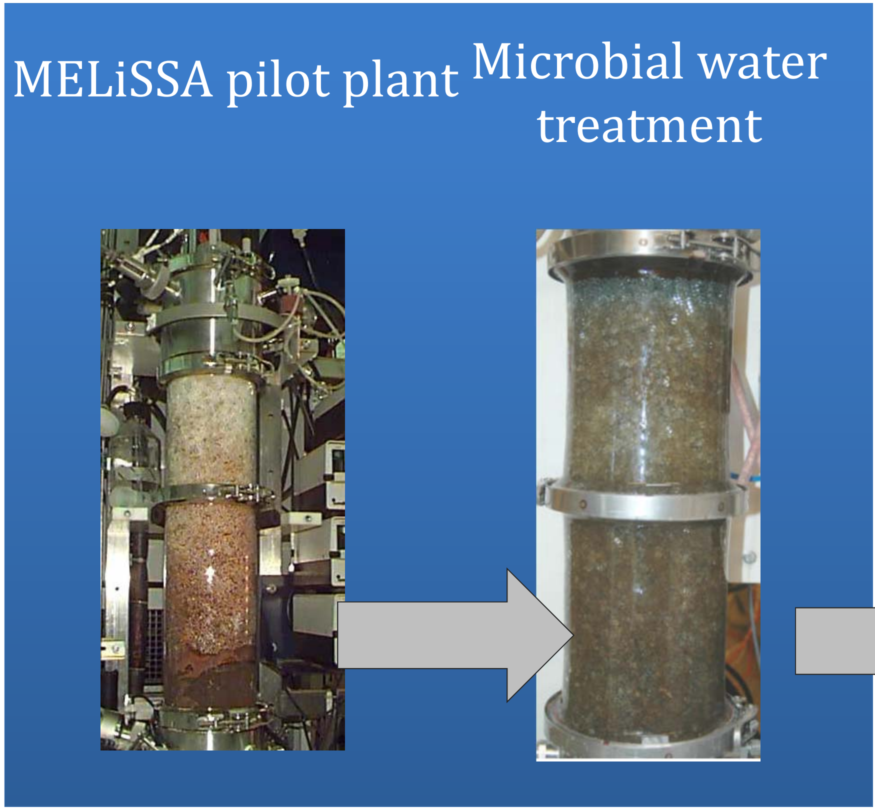
MELiSSA

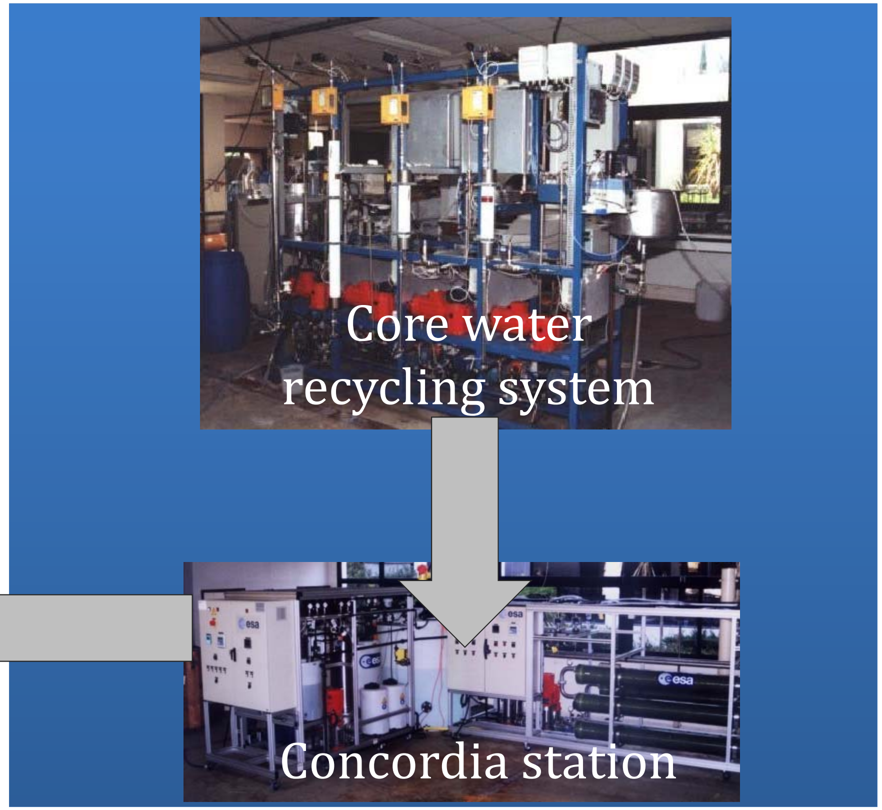
Urine nitrification: Microbial water treatment

- Packed-bed reactor
- Undefined community
- Treating pretreated urine (30% dilution), for ca. 60% of an astronaut
- Complete conversion of urine nitrogen to nitrate up to a volumetric loading rate of 1 g N/L/d

Urine -> nitrification

Grey water -> membranes **(UF/NF/RO)**

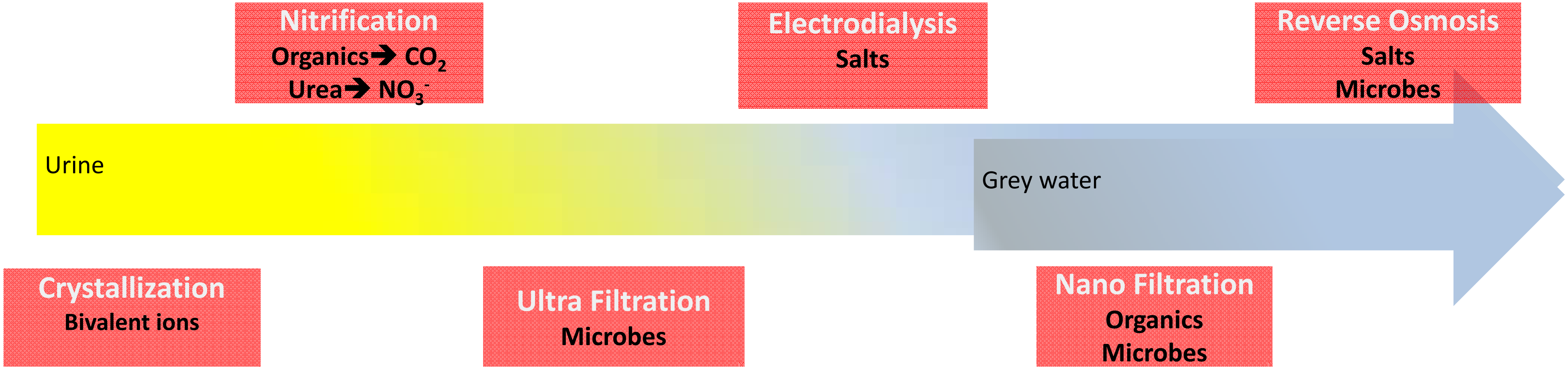




Water Treatment Unit Breadboard (WTUB):
Urine – condensate – grey water

-> nitrification
-> membranes (UF/NF/RO)
+
-> crystallization
-> electrodialysis

WTUB design philosophy



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Water Treatment Unit Breadboard (WTUB)

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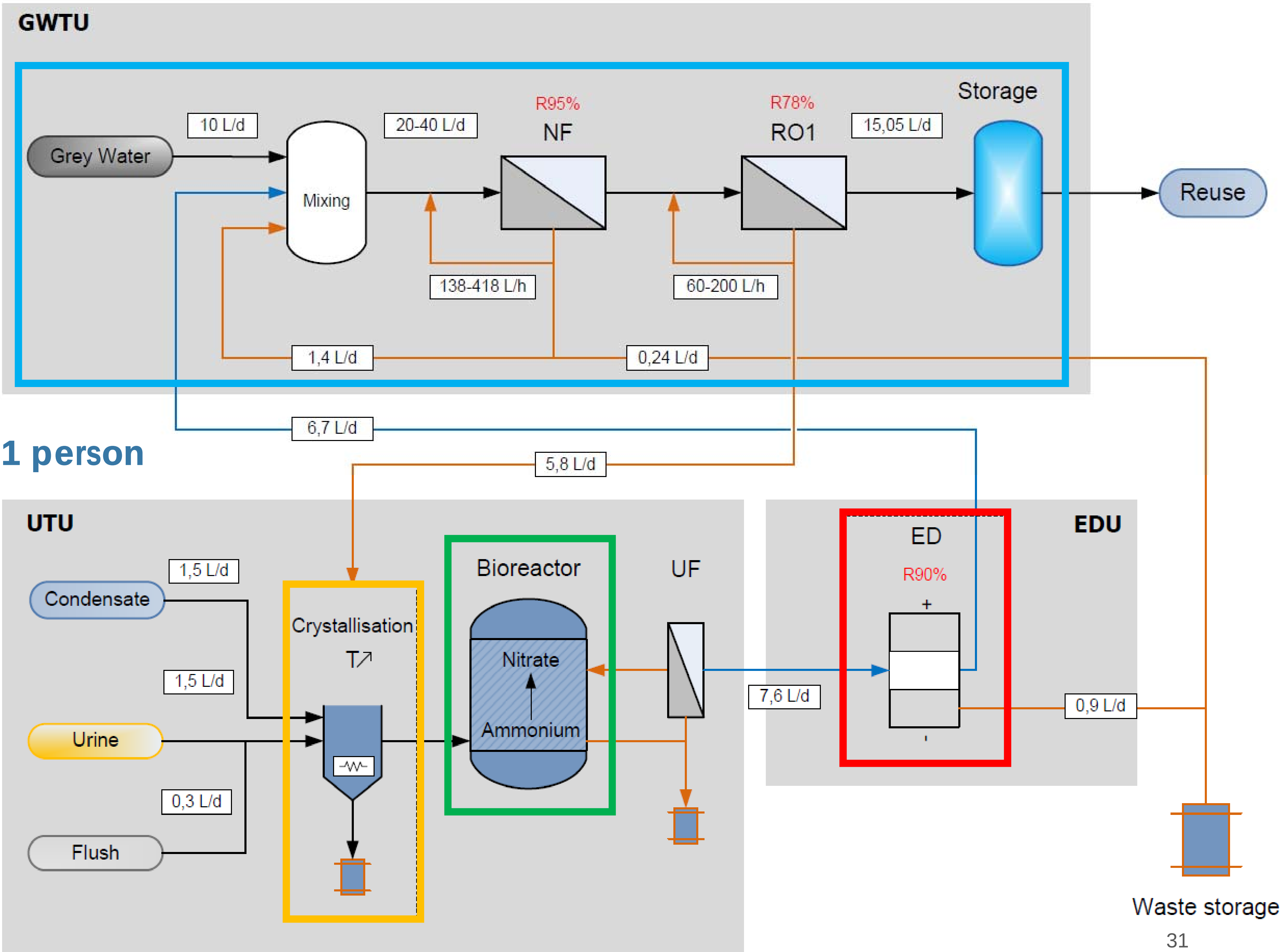
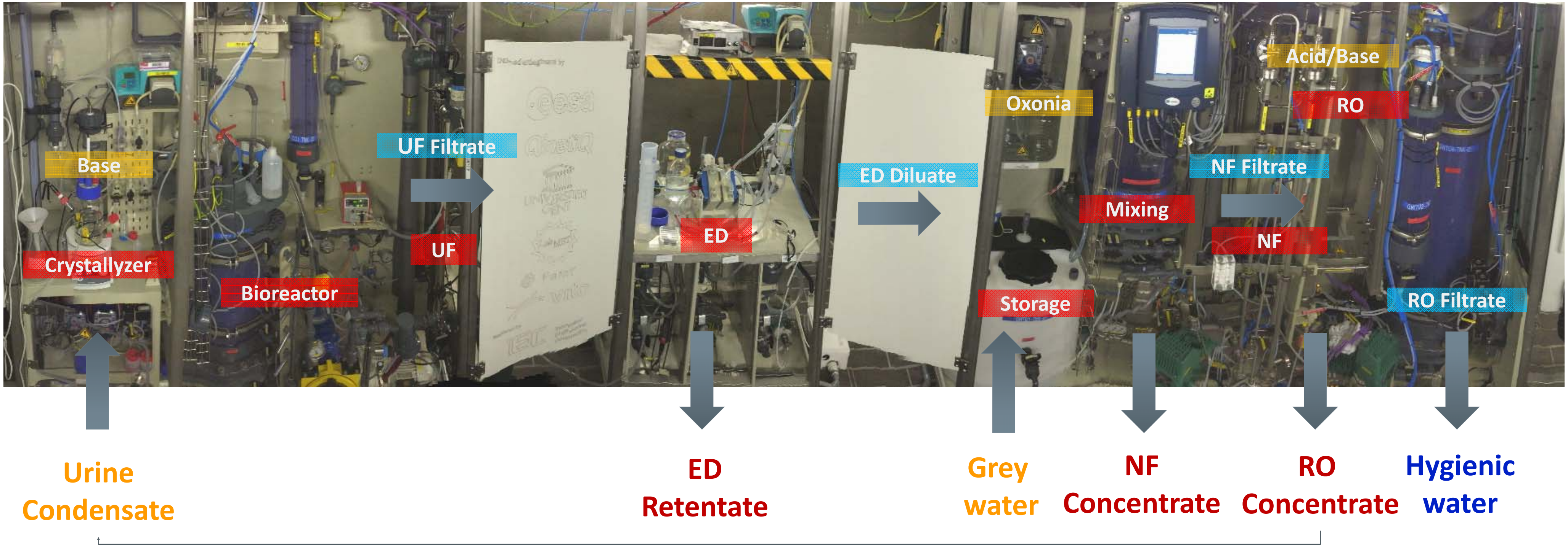


Sized for 1 person

Water Treatment Unit Breadboard

Rack 1 CCU + UTU	Rack 2 EDU	Rack 3 GWTU



- About 3 months continuous operation
- Up to 90% water recovery feasible
- RO filtrate complies with hygience water standards (except for nitrate: 13 > 11 mg N/L)
- Stable urine (around 30% diluted) nitrification (effluent down to <0.5 mg N/L)
- Crystallisation and electrodialysis are performant in mitigating scaling
- A bioreactor is performant in mitigating fouling

Water Treatment Unit Breadboard (WTUB): Urine – condensate – grey water

-> nitrification
-> membranes (UF/NF/RO)
+
-> crystallization
-> electrodialysis

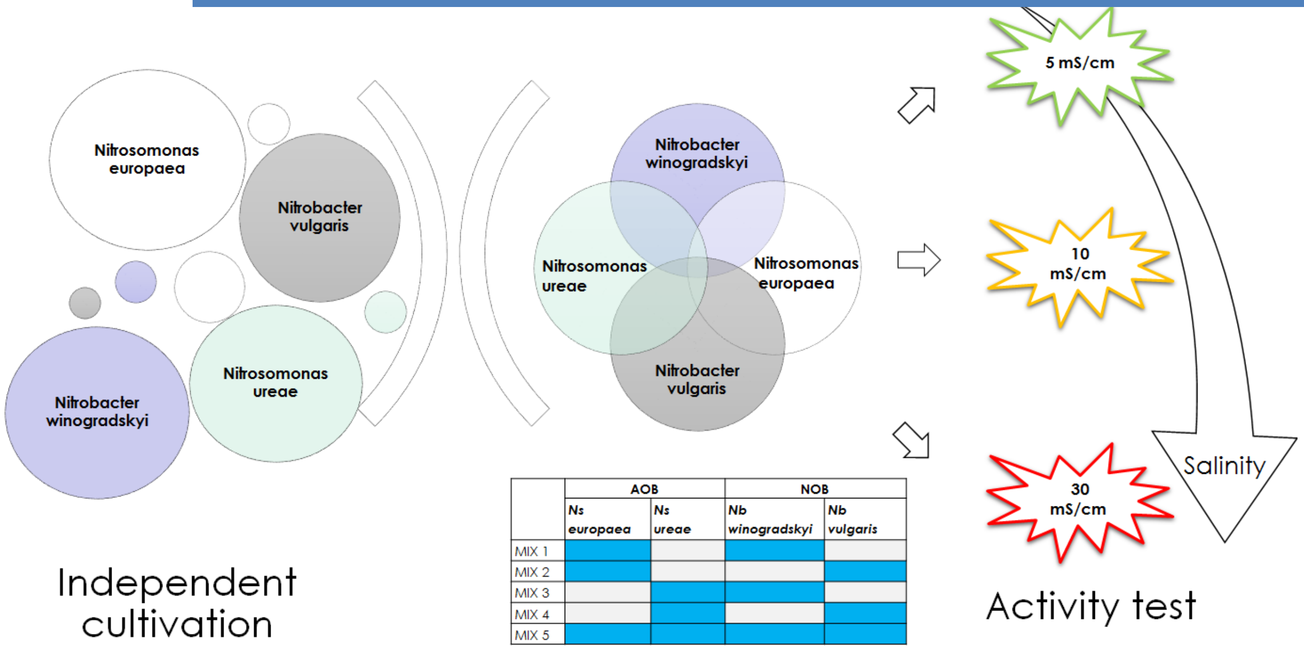
Ground demonstration:
from undefined to defined communities

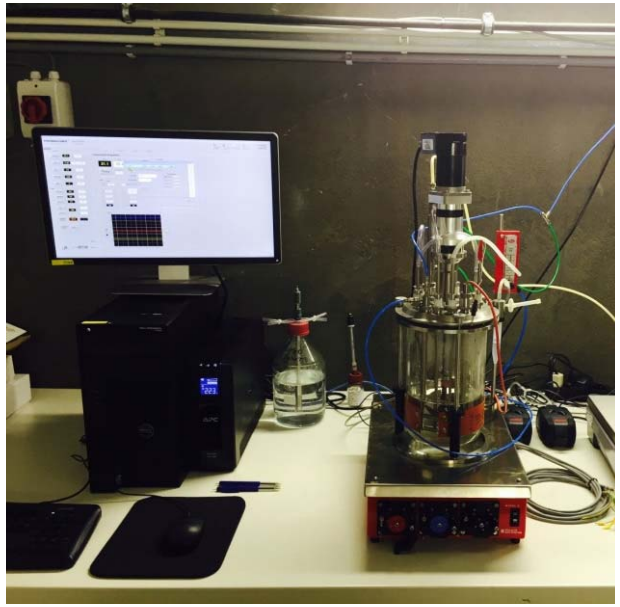
Space adaptation:
- **Gas/liquid transfer:** aeration for the bioreactor
- **Space environment:** effect of microgravity and radiation on microbial activity and biofilm formation

Urine nitrification: from undefined to defined communities

(Additional unit for increased water loop closure;
UNICUM: urine nitrification consortium)

- Pure strains → microbial collaborome
- Batch incubations → bioreactor





Chiara Ilgrande

Presence of a heterotroph enhances the nitrification rate

Marlies Christiaens

Good nitrification rates up to >45 mS/cm (less than 50% diluted)

Nitrification: understanding effect of the Space environment

Space

Reactions in Space

URINIS - ISS
(2016; UGent – SCK-CEN - UMons)

Pure strains + defined communities

Preservation under Space conditions (microgravity + 2x ISS radiation)

Bistro - ISS
(2015; UGent – SCK-CEN)

Pure strains + defined communities

Nitrimel – Photon M4
(2014; UGent – SCK-CEN)

Pure strains + 1 defined community + 3 undefined communities

MELISSA

Water recycling: Key MELiSSA achievements

- On a mass flow basis, H_2O recycling has the highest priority to limit resupply in Space
- There is no one-fits-all solution: Different water qualities/quantities…
  - …are required (hygiene/drinking/…)
  - …are available in wastestreams
- With all individual technologies available and schemes tested:
  - modular solutions (building blocks) can be offered
  - hygiene and/or drinking water can be recovered at high efficiency and reliability
  - demonstrated on the main water streams for human Space exploration (condensate – grey water – urine)
- Whenever urine is included in a scheme, a hybrid approach including biological, chemical and physical conversions is opted for

Water recycling: Future challenges

- For a specific solution: optimize processes and overall scheme according to the '10 commandments', more specifically wrt: sizing, energy consumption and crew time
- Space adaptation, most relevant for nitrification: initial key steps ongoing
- In Space, water is entangled with organic carbon and nutrients (N/P):
  - Water recovery goal: creating CO_2 and concentrated sidestreams (C/N/P)
  - 'Conventional' MELiSSA loop: element (C/N/P) recycling goal: N/P remain embedded in water until taken up by plants
  - Holistically closing the water and elements loop might require a hybrid solution
- Within the MELiSSA loop: salts will accumulate in the water in the food production compartment (higher plants) -> a treatment solution might be needed
- Adequate quality monitoring tools (fast/informative) are needed, within a solid risk management system:
  - Particularly for microbial contamination, but also for metals, pharmaceutical residues, hormonal substances,…
  - First steps have been set (BELISSIMA), and the development of a new development roadmap

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