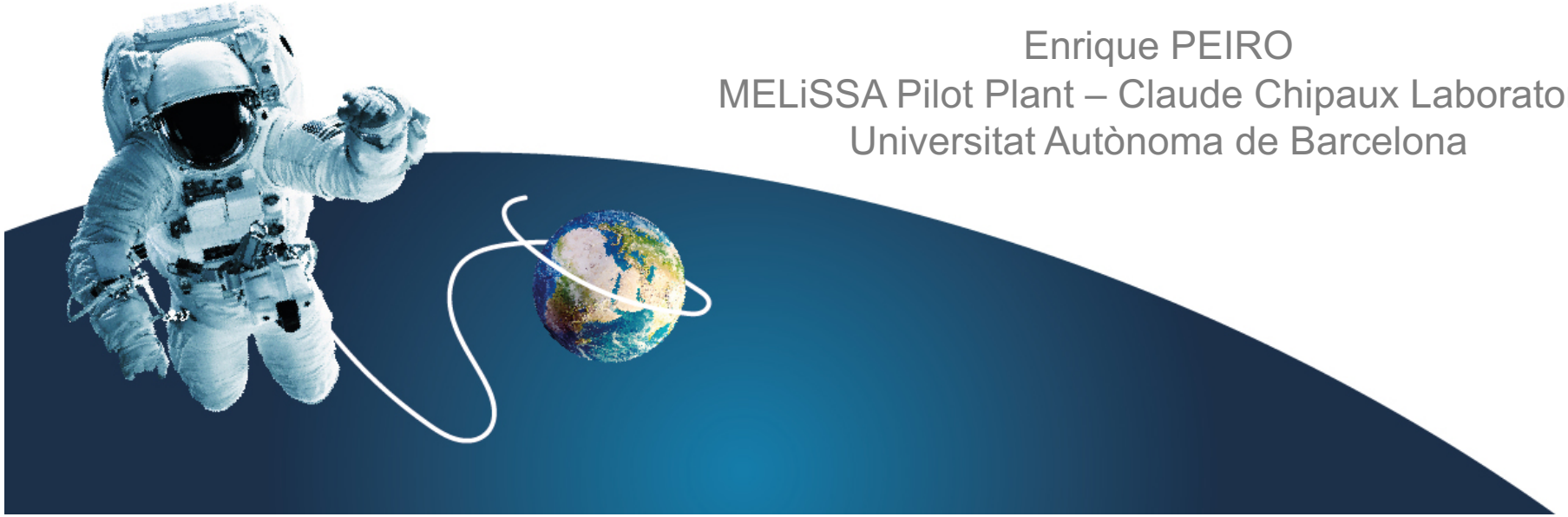
MELiSSA
MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

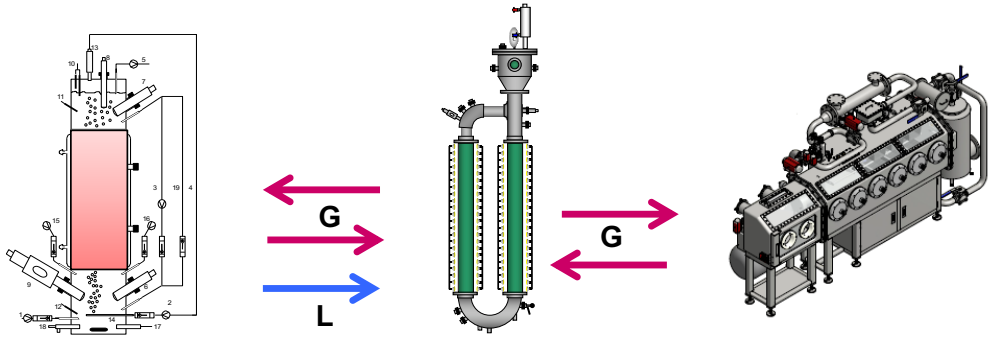
CREATING A CIRCULAR FUTURE

Continuous operation of C3, C4a and C5 Compartments in the MELiSSA Pilot Plant interconnected in gas and liquid phases



Enrique PEIRO
MELiSSA Pilot Plant – Claude Chipaux Laboratory
Universitat Autònoma de Barcelona

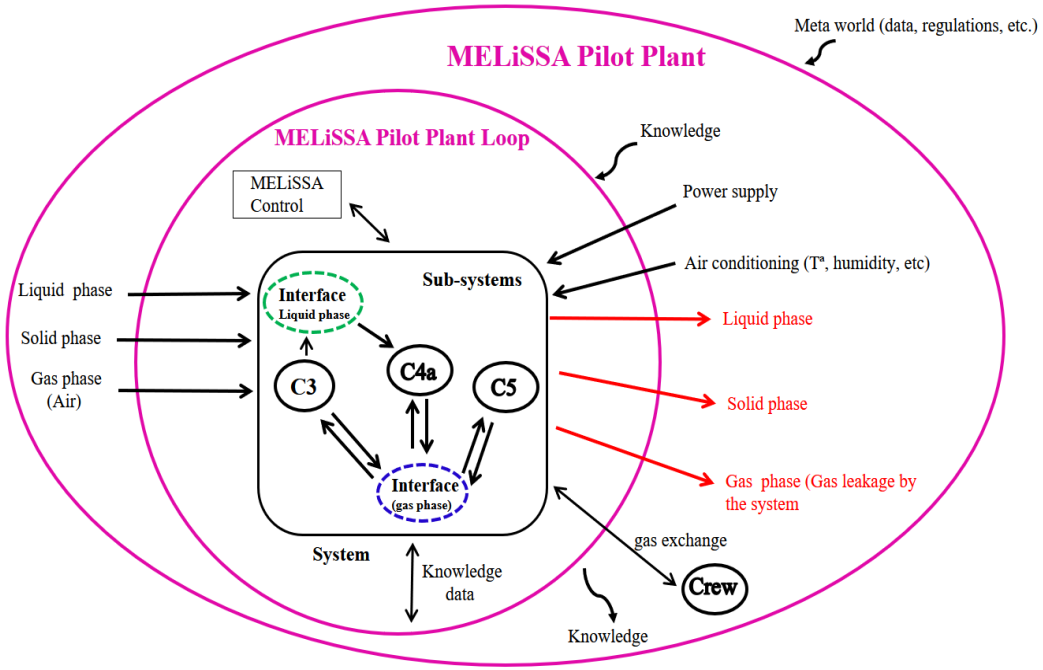
INTEGRATION WP6: C3 + C4a connection in liquid phase and C3 + C4a + C5 in gas phase



Integration WP1	Integration WP3	Integration WP4	Integration WP6
C4a + C5 gas		C4a + C5 gas	C3 + C4a + C5 gas
	C3 + C4a liquid	C3 + C4a liquid	C3 + C4a liquid

Objective: integration of the liquid and gas phase of nitrifying packed-bed bioreactor (C3), air-lift photobioreactor (C4a) and rats isolator as a mock crew (C5)

WP6: WP6 Context Diagram



Entering into the system:

- Solid phase: Food, bedding, rats, C3 and C4a inocula.
- Liquid phase: Drinking water and medium components (C3 and C4a nutrients).
- Gas phase: Air interaction (Air entering for leak compensation to the system).

Exiting the System:

- Solid phase: C3&C4a biomass, rats faeces, bedding and food residues.
- Liquid phase: Urine, medium, condensates.
- Gas phase: Gas leaked from the system.

WP6: Main requirements

- The system shall address the dynamic **oxygen demand for 3 rats** while addressing the oxygen demand of C3 and achieving highest gas loop closure.
- The system shall **prevent chemical/microbial contamination** in the liquid/gas phase which could be toxic for C3, C4a process and the crew.
- The system shall **not leak more than 20%** of the initial gas volume in 4 weeks.
- Gain knowledge on **closure regenerative life support system**: C3, C4a, C5.
- Demonstration/validation of control **model robustness**.
- Validate **long term continuous operation** of processes, technology items.

WP6 Scope

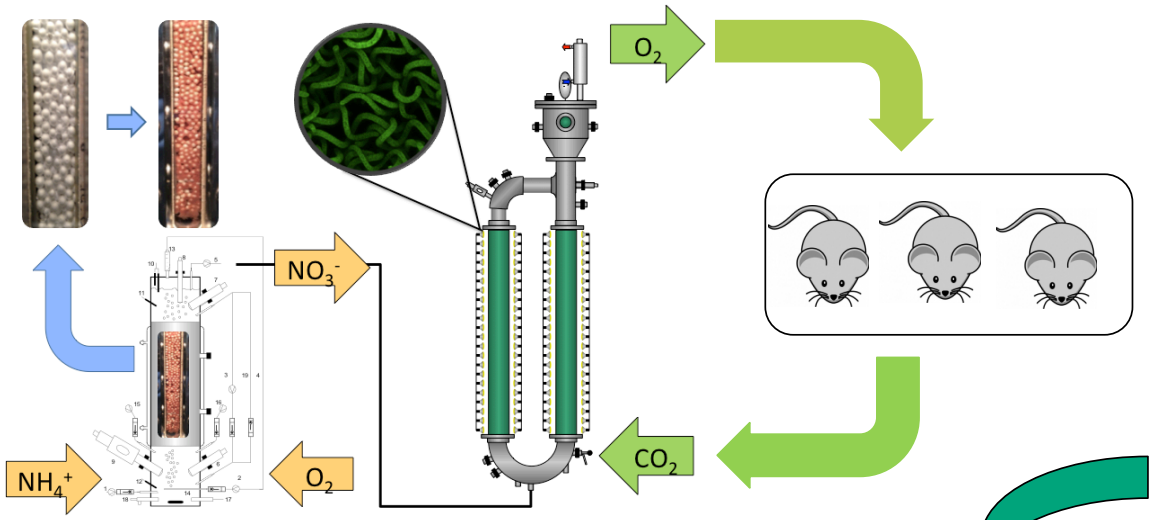
- C4a should produce the **oxygen needed in** C5 and C3 compartments (rats+nitrification), with different demand dynamics:
  - O2 demand in C5 depending on **day/ night cycles** of the rats
  - Several **O2 concentration set-points** in C5 will be tested (19-21%)
  - O2 demand in C3 depending on N load (range 710-1500 ppm/day to be tested)

- C3 should produce the **nitrate needed in C4a** to produce oxygen for C3 and C5 (3 rats)
  - Min. load approx. of **710 mg N/L·d** ($Y_{N/O}$ =0.06 g N/g O_2 in C4a, experimental data from MPP)

- Prepare **future integration steps** in the MPP:
  - Test N loads corresponding to the **potential urine introduction** into C3 compartment (higher oxygen demand in C3 and potential C limitation in C4a (C input required)
  - Consider potential inputs/outputs to future connection of the **higher plants chamber** gas loop.

WP6 integration; C3&C4a connection by liquid phase and C3&C4a&C5 by gas phase

Oxygen demand in C3 and C5 (previous tests):



PREVIOUS TEST RESULTS						
WP3 test results C3 compartment Oxygen needs			WP1 test results C5 comp. oxygen needs (g O_2/h) (average)		WP3 test results C4 Compartment Oxygen production (high light intensity)	
N- Load (mg N/L d)	L O_2/d	g O_2/h	1 rat	3 rats	Inlet flow (L/d)	Oxygen production (g O_2/h)
438	10.2	0.56	0.59	1.77	20	2.44
876	20.9	1.14			30	2.76

Average O2 needs: around 2,8 g/h (C3+C4a)

C4a Characterization (New illumination system)

Max. Oxygen demand in C3 and C5 (WP6):

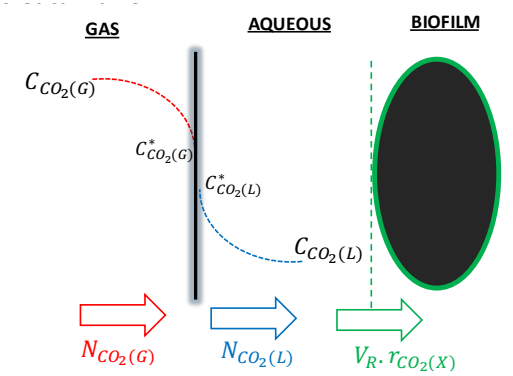
O2 Max. needs for Integration WP6 Test				
N-NH_4+ Load (ppm/d)	C3 O_2 needs (g/h)	Max C5 O_2 needs (g/rat/h)	Max C5 O_2 needs for 3 rats (g/h)	Total O_2 WP6 req (g/h)
710	0.91	0.73	2.19	**3.10**

Condition	Q_L (L/d)	W/m2	CDW (g/l)	O2 prod (g/h)
1	20	364	2.25	3.26
2	30	364	1.74	3.80
3	40	364	1.27	3.94
4b	50	250	0.96	3.53
4c		300	0.98	3.61

- **C4a production 3.30-4 gO2/h**
- **All conditions can be tested in WP6 mode 1**

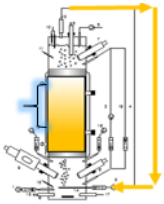
WP6 Oxygen needs for C3 Compartment

- Depending on N load according to stoichiometry $NH4^+ \longrightarrow NO3^-$
- Keeping **constant K_La** as far as hydrodynamic conditions are maintained in the bioreactor
- Depending on gas-liquid transfer rate $\longrightarrow$ **O_2 partial pressure** in gas phase



INPUTS

C3 Volume (L)	7
C3 Temperature (°C)	30
C3 Pressure (mbarg)	80
C^*_{DOL} (AIR, 30°C) (g/L)	0.00757
Weight kLa TOP Section (%)	85



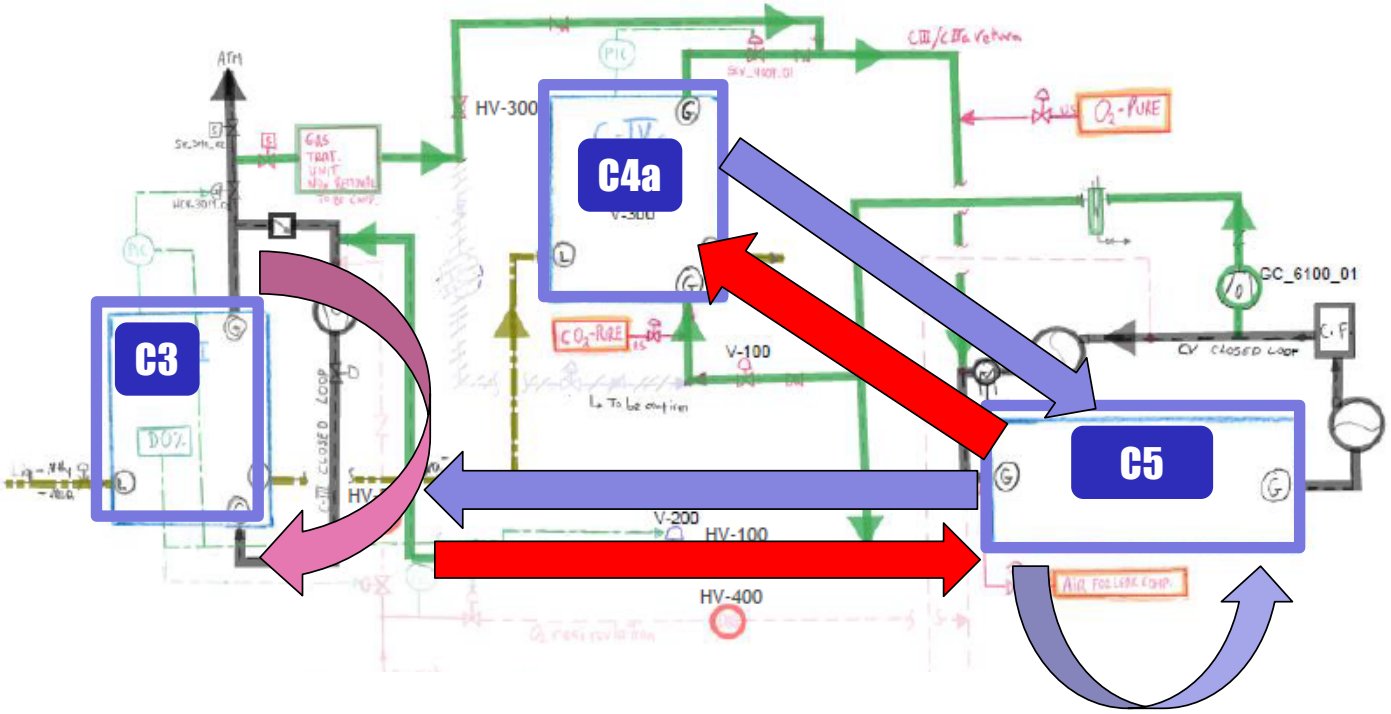
			Total Air flowrate		k_La TOP		k_La LOWER			TOTAL N_{O2}	MATERIAL BALANCE
MODE *	C3 Feed Load (ppm/d)	C3 Actual Load (ppm/d) Conv.:93.3%	(L/min)	(L/h)	(1/h)	(1/s)	(1/h)	(1/s)	(% mol/mol) O_2 C3 Gas Phase	TOTAL O_2 trans. flow gas to liquid (gO_2/h)	O_2 consumption by Bacteria (gO_2/h)
MODE 1	251	235	3.0	180	31.995	0.0089	52.785	0.0147	19.0	0.3359	0.3140
MODE 1	486	453	3.0	180	31.995	0.0089	52.785	0.0147	22.0	0.6140	0.6062
MODE 2	1286	1199	3.0	180	31.995	0.0089	52.785	0.0147	33.4	1.7250	1.6046
MODE 2	1714	1599	3.0	180	31.995	0.0089	52.785	0.0147	40.4	2.3954	2.1380

(*) MODE 1: LOW N LOAD MODE ; MODE 2: OXYGEN CONCENTRATION

WP6: PFD FOR NOMINAL OPERATION MODE 1

LOW AMMONIUM LOAD in the system

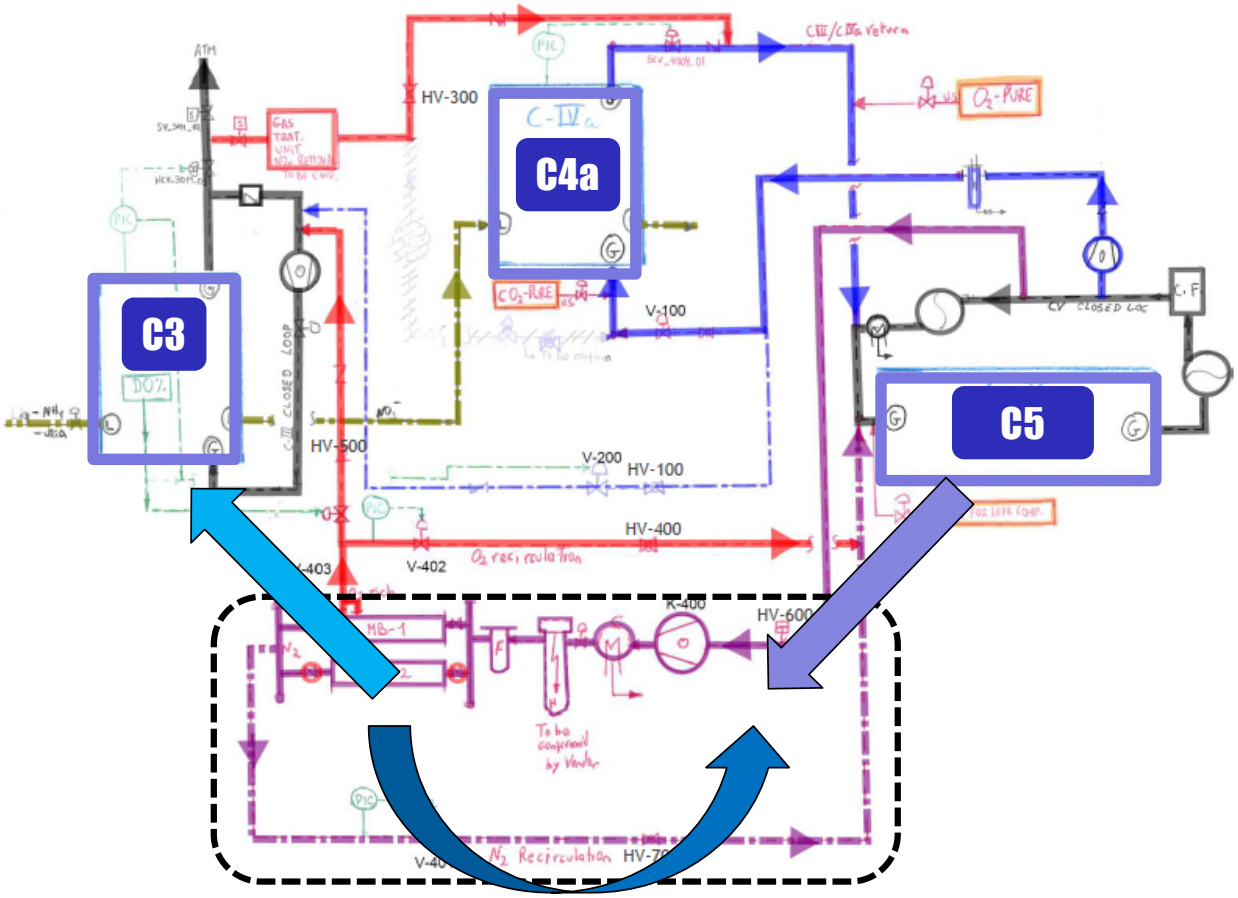
- C4a outlet is sent to C5 compartment.
- C5 outlet is divided to C4a and C3 compartments.
- C3 outlet is sent to C5 compartment.
- C3 closed gas loop is maintained (pulses addition when required).



WP6: PFD FOR NOMINAL OPERATION MODE 2

HIGH AMMONIUM LOAD in the system

- ❑ Part of C5 outlet is sent to C4a compartment
- ❑ Part of C5 outlet is sent to an oxygen enrichment membrane module to fulfil C3 oxygen requirements.



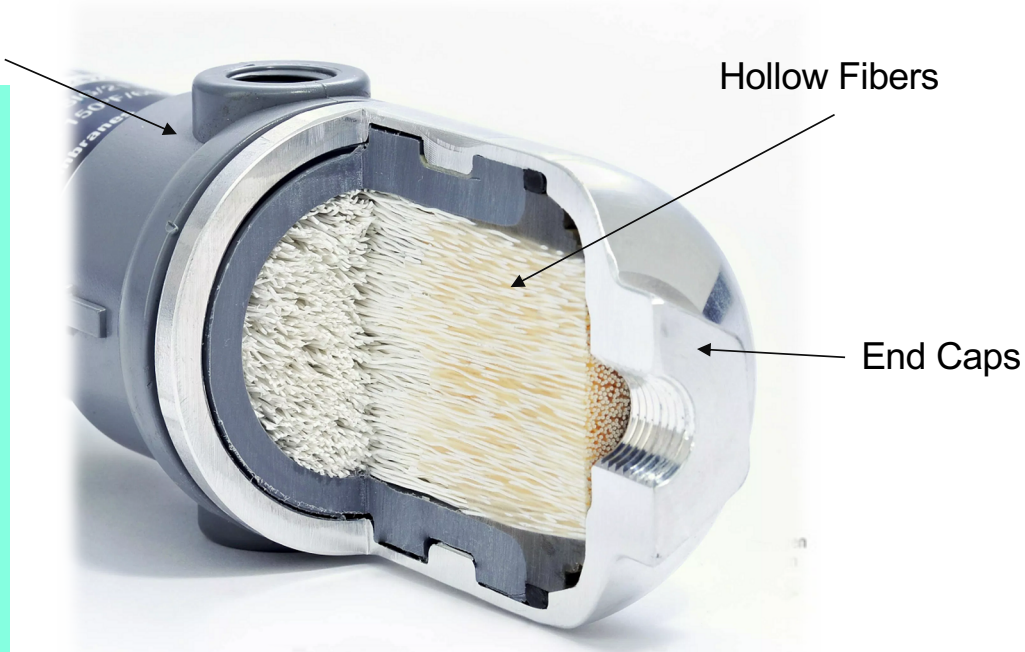
Oxygen enrichment unit (OEU) design

Evaluated technologies for Oxygen concentration:

- Cryogenic air separation units (ASUs)
- Pressure swing adsorption (PSA)
- Membranes separators

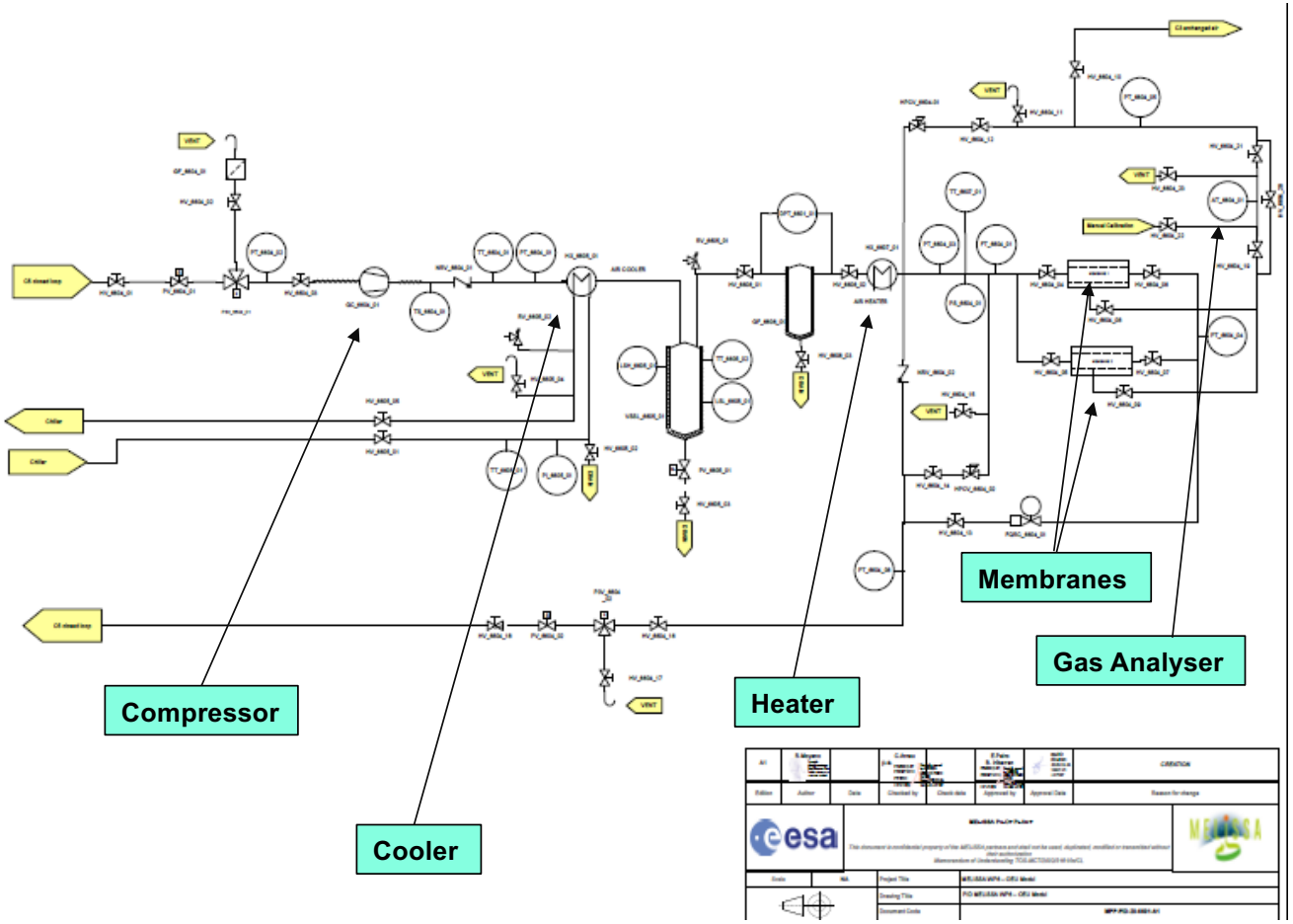
Critical points in the OEU design:

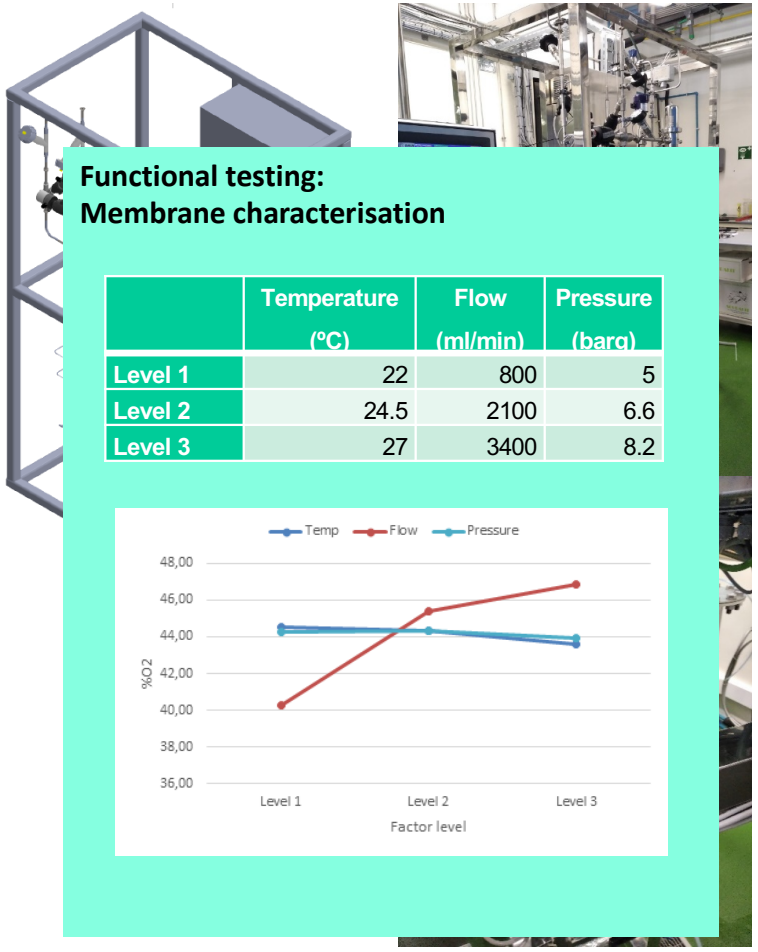
- High operating pressure **(6-8 bar)** compatible with very low P in C5 **(2 mbar)**
- Regulation of **retentate Flow, temperature and Pressure**
- Avoiding presence of **condensates and NH_3** → cooler+automatic drainage; coalescing filter; C filter in C5
- Dedicated **O_2 analyser** at the permeate side



PA1010-P3 membrane (AIR PRODUCTS)

Oxygen Enrichment Unit (OEU) design and installation





Functional testing:
Membrane characterisation

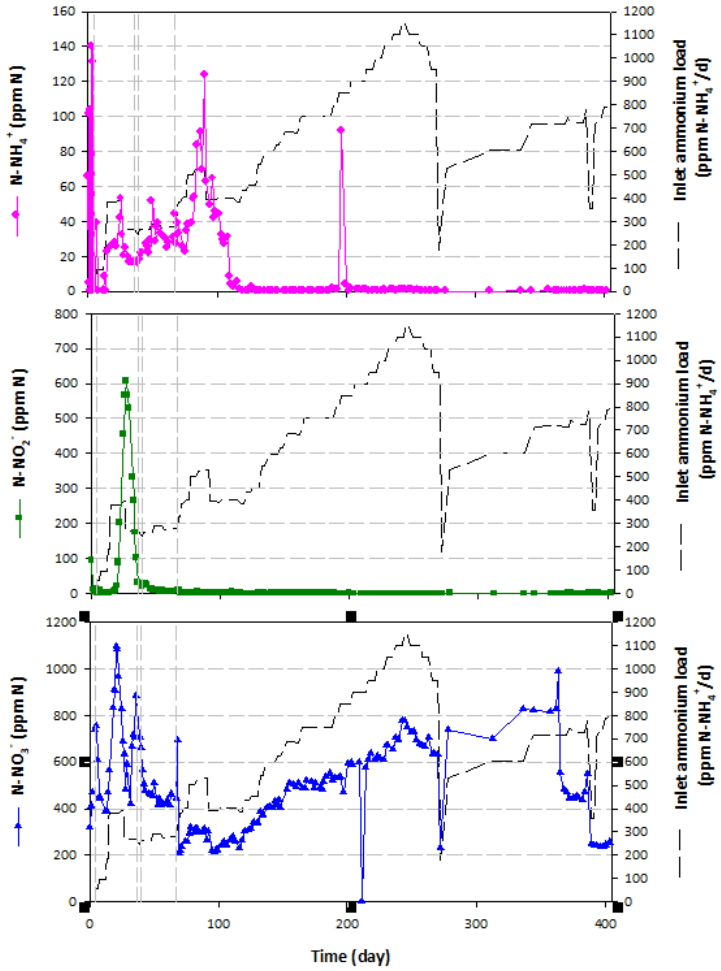
	Temperature (ºC)	Flow (ml/min)	Pressure (barg)
Level 1	22	800	5
Level 2	24.5	2100	6.6
Level 3	27	3400	8.2

WP6 MODE 1 CONDITIONS

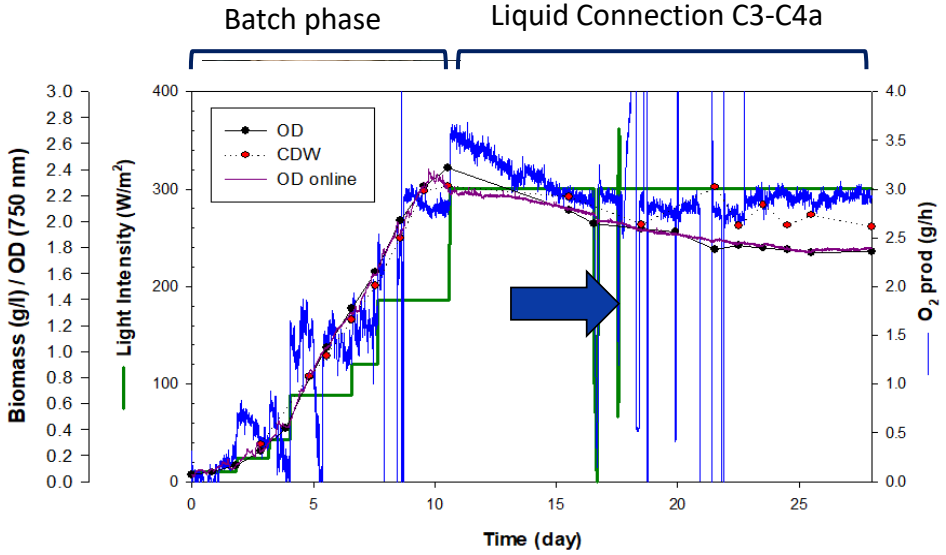
C3 compartment					WP6 OXYGEN NEEDS	
Inlet ammonium load in C3 (mg N-NH4/L/d)	N elimination in C3 (%)	O_2 consumption. (gO_2/h)	DO set-point	Inlet gas concentration (%)	Max. O_2 consumption per rat (C5; night period)	Total O_2 consumption (C3+C5) 3 rats
710	99%	0.90	50	21.29	0.73	3.10
			45	19.18		
			30	17.10		

- **INLET FLOW FIXED at 20-30-40-50 L/day (3 HRT at steady state)**
- **AMMONIUM LOAD fixed at 710 mg N/L/d**
- **OXYGEN SET-POINT in C3 CONTROLLED at 45%**
- **SEQUENTIAL CHANGES of OXYGEN SET-POINT in C5 (21-19-20-21%)**
- **NUMBER OF RATS 3.**

C3 and C4a start-up, stand-alone and liquid connection phases)



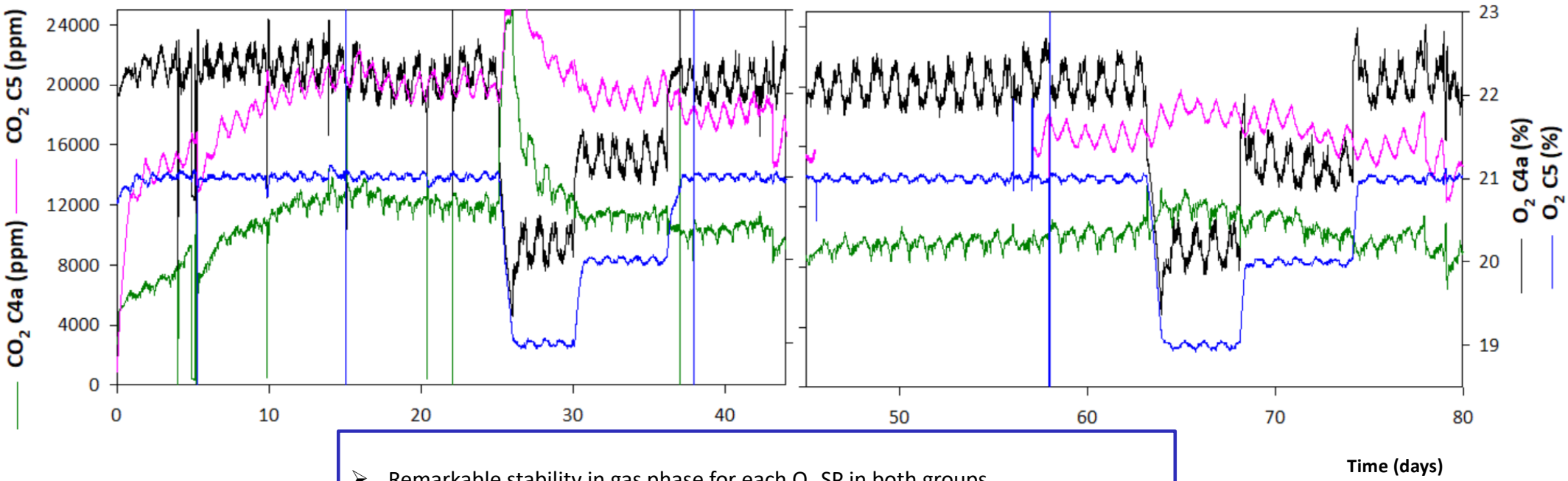
- C4a Initial batch phase with target OD of **2.5**
- **Liquid Connection to C3** at **20 L/d**
- **Stable O2** production level
- **Nitrate conc.** kept above 30-50 ppm (no N limitation)
- **TIC** kept above 200 ppm (no C limitation)



C4a-C5 O_2 and CO_2 evolution

1st group; 20 L/d

2nd group; 30 L/d

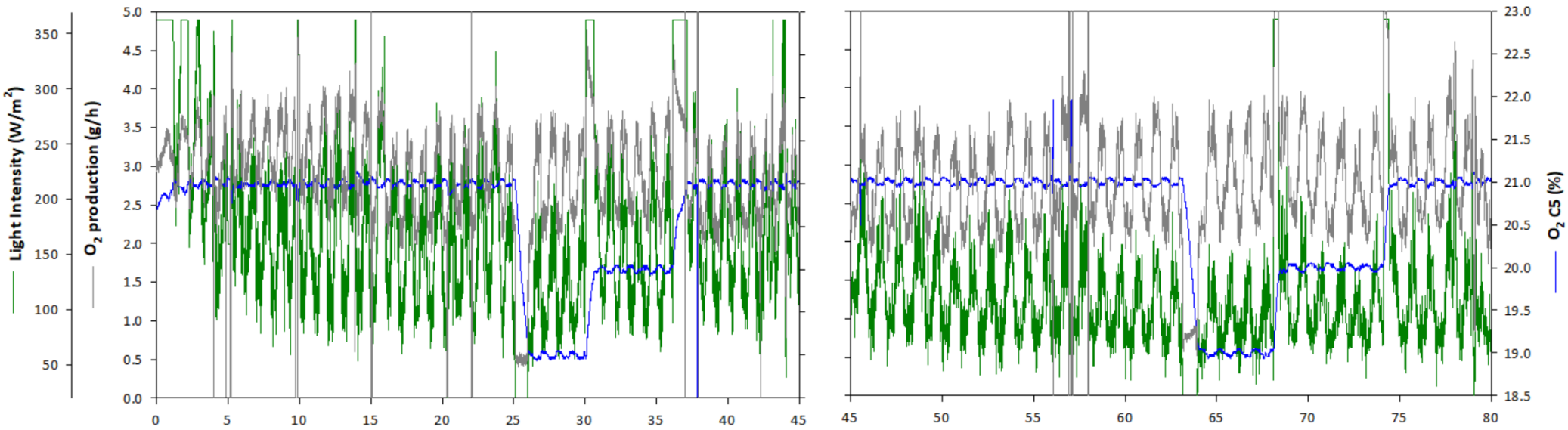


- Remarkable stability in gas phase for each O_2 SP in both groups
- CO_2 maintained ≤2% most of condition, except during a few transient phases

C4a-C5 O2 production and Light evolution

1st group; 20 L/d

2nd group; 30 L/d

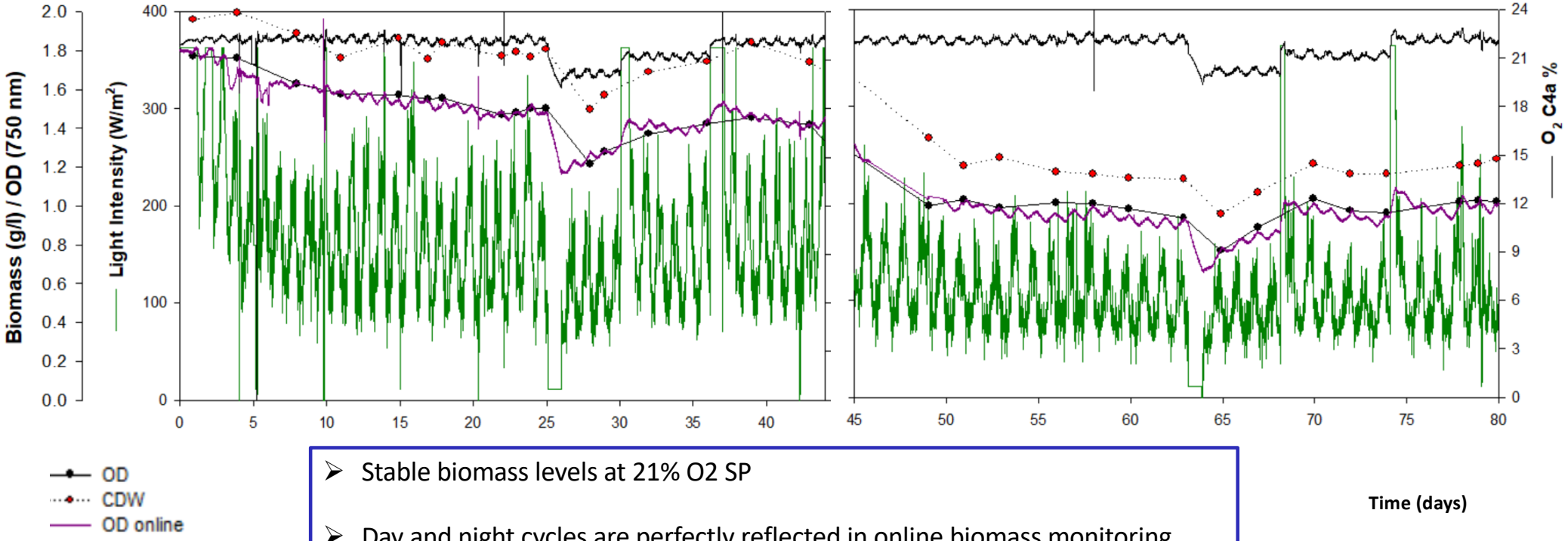


- Initial light intensity at full power → Light decreases when C4a culture cells adapt to new conditions
- Lower light intensity is needed in 2nd group (higher dilution rate) for the same O_2 production

C4a Biomass evolution

1st group; 20 L/d

2nd group; 30 L/d

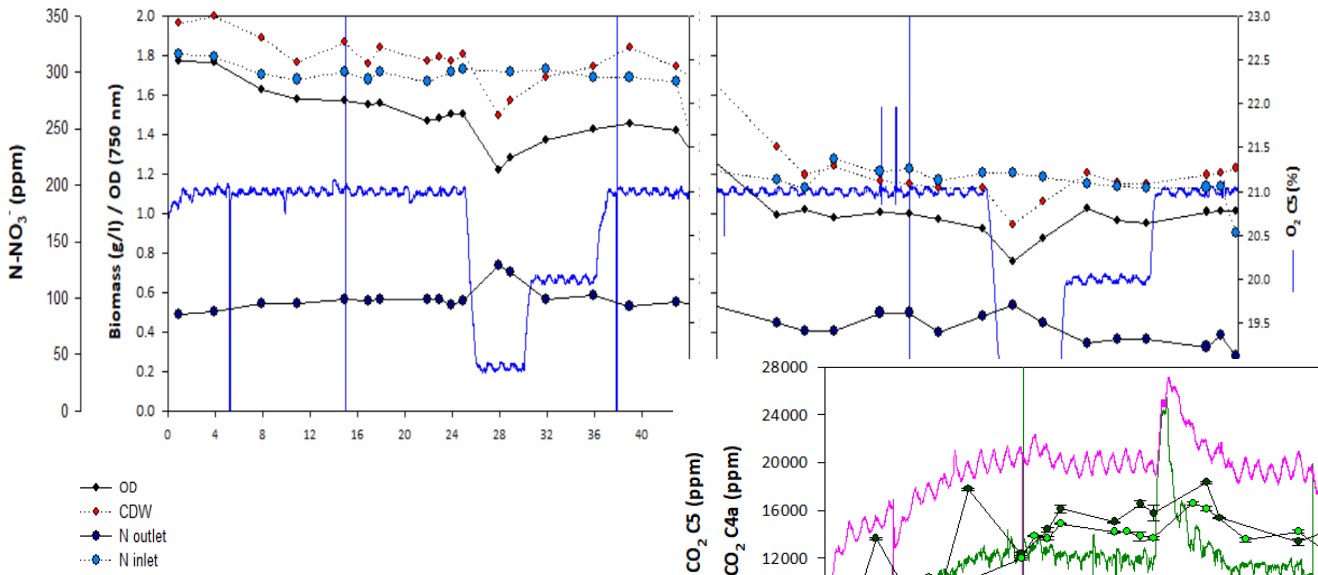


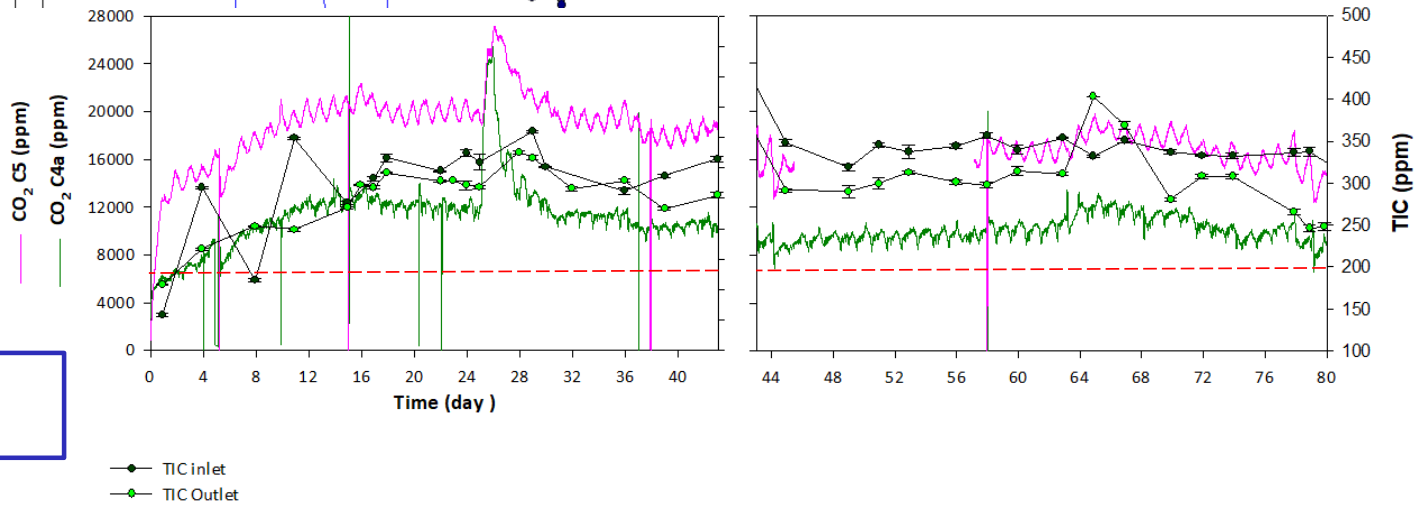
- Stable biomass levels at 21% O2 SP
- Day and night cycles are perfectly reflected in online biomass monitoring
- Same behaviour of second group, at a lower biomass level

C4a Nitrogen and Carbon content

1st group; 20 L/d

2nd group; 30 L/d

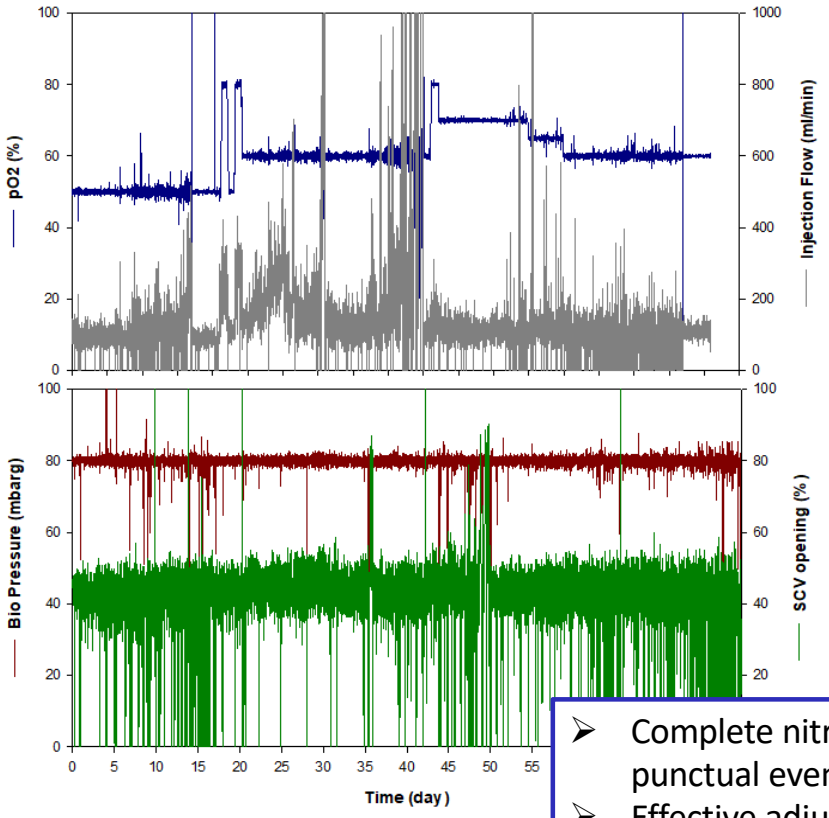




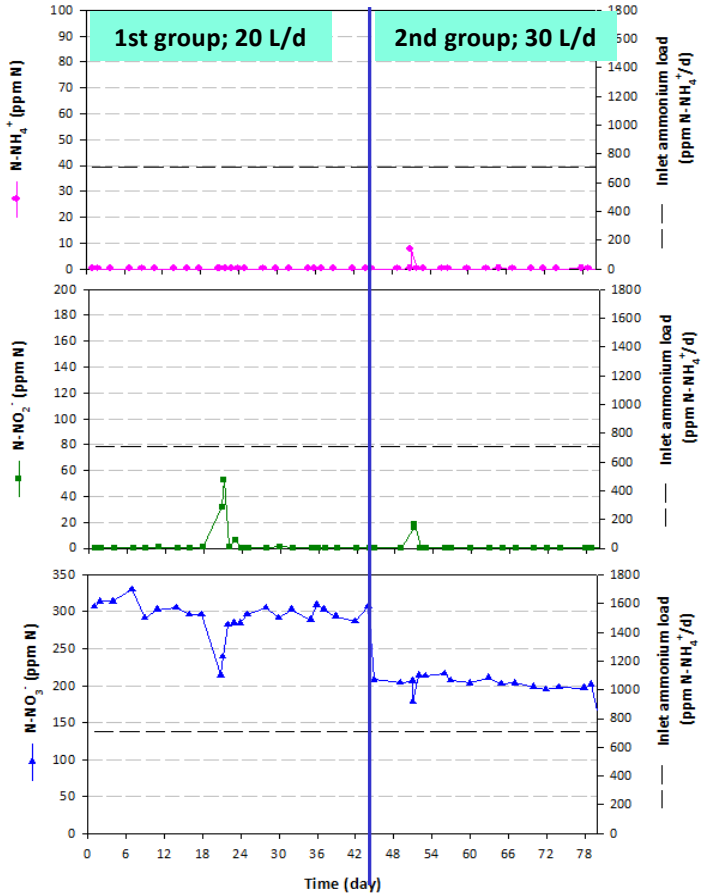
➢ Residual N in liquid phase >50 ppm avoiding potential N limitation

➢ Residual C in liquid phase >200 ppm avoiding potential C limitation

C3 gas and liquid phases



- Complete nitrification during the test except punctual events
- Effective adjustment of D.O. level (50-70%)
- Correct regulation of C3 head pressure



Production calculations

Flow	O_2 SP	Biomass (g/l)	O_2 prod (g/h)	LI (W/m^2)	C3 need stoich. (g/h)	O_2 rats (g/h)	CO_2 prod (g/h)	RQ (rCO2/rO2)	N-NO3 in (ppm)	N-NO3- out (ppm)	$Y_{N/X}$ (g/g)
20 L/d	21%	1.79	2.9	156.8	0.93	2.0	2.64	0.95	298	97	0.11
	21 - 19%	-	-	11		2.0	-	-	-	-	-
	19%	1.51	2.8	118		1.9	2.76	1	300	126	0.12
	19 - 20%	-	4.1	364		1.9	-	-	-	-	-
	20%	1.72	2.9	146		2.0	2.65	0.95	299	100	0.12
	20 - 21%	-	3.8	364		2.2	-	-	-	-	-
	21%	1.79	2.7	155		1.8	2.53	1	294	94	0.11
30 L/d	21%	1.14	2.8	97		1.9	2.11	0.82	210	80	0.11
	21 - 19%	-	-	11		1.9	-	-	-	-	-
	19%	1.00	2.8	88		1.9	2.12	0.81	209	79	0.13
	19 - 20%	-	5.1	364		1.8	-	-	-	-	-
	20%	1.17	2.8	102		2.0	2.12	0.78	199	64	0.12
	20 - 21%	-	4.9	364		1.9	-	-	-	-	-
	21%	1.20	2.9	96		1.9	2.05	0.79	198	68	0.11

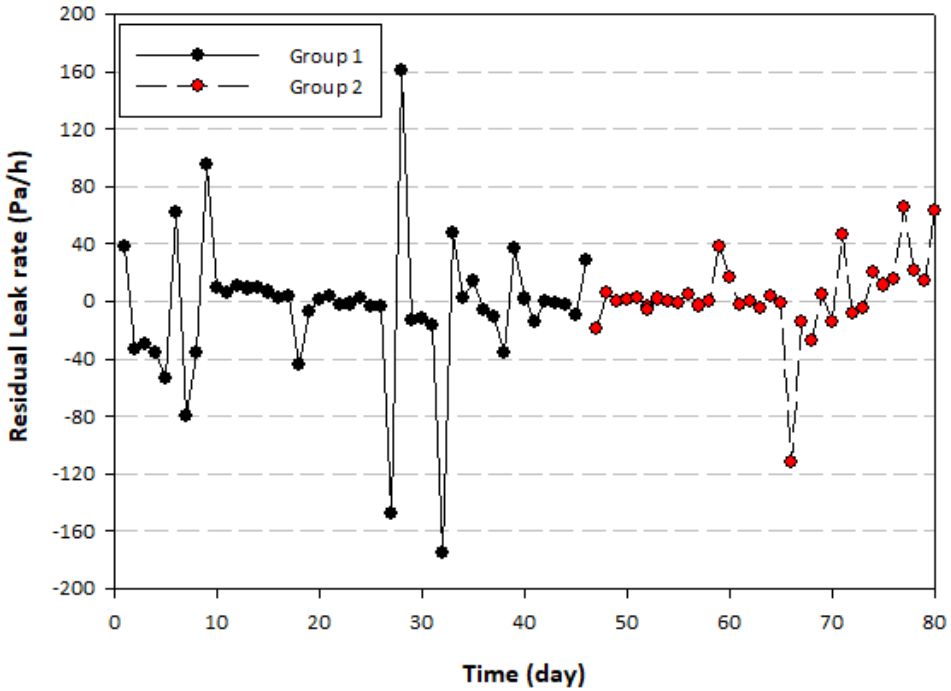
Theorical need (710 N-ppm/d)

Expected: 0.08-0.10

Mode 1 – next phases schedule

Condition #	HRT C3/C4a (h)	Inlet N-NH4+ conc. (ppm)	Inlet N-NH4+ load	Flow (L/d)	TIC inlet (ppm)	C5 O_2 SP	pO_2 C3	Estimated duration (days)	Flexibility (days)	Rats	Status
1	8.3/99.6	245	710	20	445	21%	45%	25	4	New group	Completed
2						19%		1+4			Completed
3						20%		2+4			Completed
4						21%		2+2			Completed
5	6.55 / 66	165		30	355	21%		17+2	2	New group	Completed
6						19%		1+4			Completed
7						20%		1+4			Completed
8						21%		1+3			Completed
9	4.14 / 49.8	122		40	327	21%		12+4	5	New group	Ongoing
10						19%		1+4			
11						20%		1+4			
12						21%		1+3			
13	3.13 / 39.8	98		50	300	21%		10+4	0	New group	18/11/2020
14						19%		1+4			
15						20%		1+4			
16						21%		1+3			16/12/2020

System tightness



Group	Injected air (L)	Air flow (L/h)	Residual leak (Pa/h)	Total leak (Pa/h)
1	362	0.34	-0.7	-22.3
2	181	0.22	+3.5	-11.3

Leak specification: <30 Pa/h

WP6 MODE 2 CONDITIONS

Oxygen Enrichemnt Unit (OEU): O_2 enrichment available 40-50%

C3 compartment					OXYGEN CONSUMERS		
Inlet flow (L/d)	Inlet ammonium load in C3 (mg N-NH_4/L d)	O_2 consump. (gO_2/h)	DO set-point	Inlet gas concentration (%)	Max .O_2 consumption per rat (C5; *night period*)	Total O_2 consumption (C3+C5)	Total O_2 consumption (C3+C5) considering 3 rats
40	900	1.2	80	29.57	0.73	1.93	3.35
	1200	1.6	80	34.14		2.33	3.74
	1500	1.9	80	37.2		2.63	4.12

- ❑ **INLET FLOW FIXED at 40 L/day (3 RT at steady state)**
- ❑ **AMMONIUM LOAD from 710 mg N/L d to 1500 mg N/L d**
- ❑ **OXYGEN SET-POINT in C3 CONTROLLED at 80%**
- ❑ **SEQUENTIAL CHANGES of OXYGEN SET-POINT in C5 (21-19-20-21 %)**
- ❑ **NUMBER OF RATS 3.**

Preparing urine introduction in C3: expected N load of 2174 mg N/L day)

Preparing HPC future integration: potentially pure O_2 injection

Conclusions

Integration WP6 (in progress) main conclusions

- WP6 hardware design and validation completed
- Test conditions defined
- Testing phase (Mode1) progressing successfully, achieving continuous operation during 3,5 months of three compartments in gas and liquid phases, demonstrating the robustness of the system
- Mode 2 conditions defined; still to be modulated based on knowledge gained during Mode1
- Paving the integration of relevant future integration steps: introduction of urine and connection with next compartments (HPC) in the MELiSSA loop

MELiSSA

MICRO-ECOLOGICAL
LIFE SUPPORT SYSTEM
ALTERNATIVE

THANK YOU.

Enrique Peiro
MELiSSA Pilot Plant – Claude Chipaux Laboratory
Enrique.peiro@uab.cat

www.**melissafoundation**.org

Follow us

PARTNERS

IN COOPERATION WITH

esa
European Space Agency

MELiSSA
FOUNDATION

ENGIN SOFT

GHENT UNIVERSITY

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

SEMiLLA
IPSTAR Circular Systems™

SHERPA ENGINEERING

University of Antwerp

UAB
Universitat Autònoma de Barcelona

UNIVERSITÉ Clermont Auvergne

UNIVERSITY of GUELPH

UMONS
Université de Mons

UNIL | Université de Lausanne

vito