MELiSSA
MICRO-ECOLOGICAL
LIFE SUPPORT SYSTEM
ALTERNATIVE

CREATING
A CIRCULAR
FUTURE

Characterization of oxygen production from photo-bioreactor for ISS cabin technology demonstrator

Dominique Chapuis

Outline

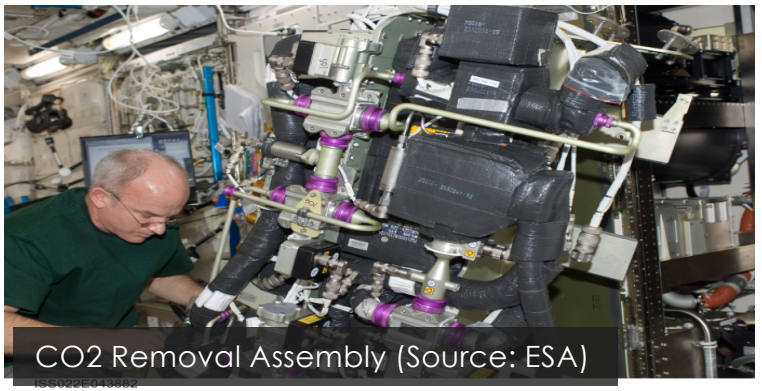
1. O2 Regeneration for Long-Term Human Space Missions
2. Algal Photo-bioreactors
3. BIORAT1 Flight Demonstrator Objectives, Mission & Design Overview
4. Photobioreactor-Liquid Loop Breadboard Model Test
    - Background & objectives
    - Hardware configuration
    - Biological results
    - O2 light intensity production model correlation
    - O2/Biomass stoichiometric ratio
5. Conclusions & Way Forward

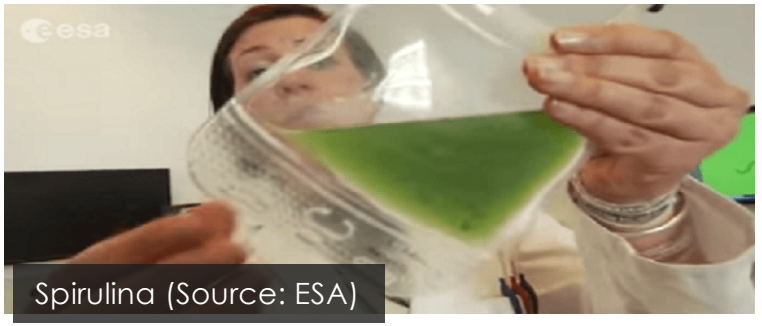
1 - O_2 Regeneration for Long-Term Space Missions

- **Efficient regeneration** of **O_2** is key for long-term human missions > **Bio-regenerative** (or hybrid) systems key

- Current O_2 generation and CO_2 capture on **ISS**:
  - **Electrolysis** of H_2O
  - Scrubbing of CO_2 (**CDRA**) and reduction to CH_4 (**Sabatier**)

- **Algal photo-bioreactors,** an efficient alternative (or complement) for O_2 regeneration
  - CO_2 capture and O_2 generation through photosynthesis
  - Generation of edible Biomass
  - Process controllable with short time constants


CO2 Removal Assembly (Source: ESA)

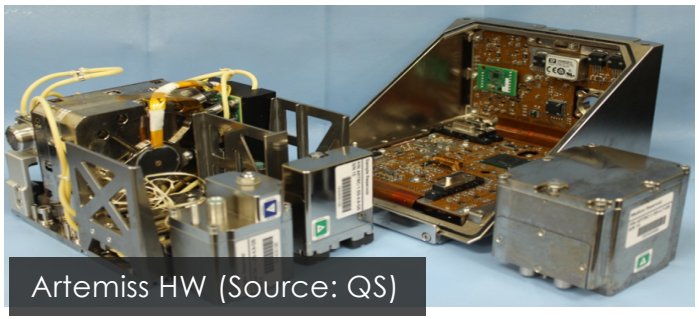


Spirulina (Source: ESA)

2 - Algal Photo-bioreactors - State-of-the-art

- **Ground-based** demonstrators
  - MELiSSA Pilot Plant
- **Small-scale Flight Experiments**
  - Artemiss (ISS BIOLAB)
    - First Photo-bioreactor on ISS
  - PBR@LSR
    - Flight on ISS in 2019
- Remaining **challenges** toward implementation in Life Support:
  - Production rate (**continuous cultivation**)
  - Optimal process **control**
  - Process **efficiency**: mass transfer, heat transfer, culture density
  - Long-term **reliability**

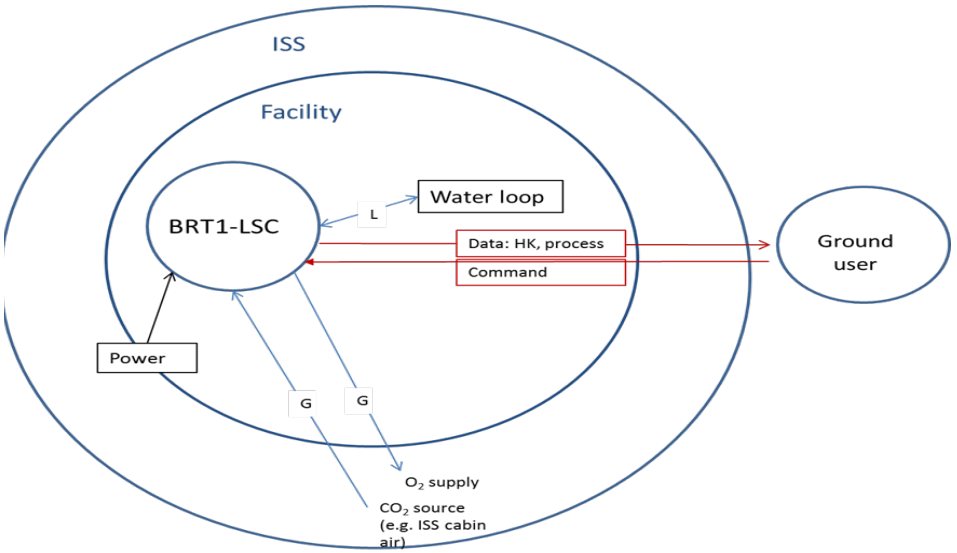

MELiSSA Pilot Plan (Source: ESA)


Artemiss HW (Source: QS)

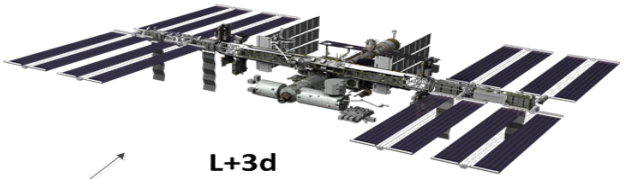
BIORAT 1
Flight Demonstrator

3 - BIORAT 1 Flight Demonstrator - Mission Objectives

- **Objectives:**
  - Demonstrate recycling of CO_2 **directly from ISS cabin** into O_2 for crew
  - Demonstrate **optimal process control**:
    - Precise regulation O_2 production on demand
    - Validation of model predictive strategy
  - Generate **edible biomass** (work in axenic conditions, avoiding contamination)
  - Demonstrate **long term operation and controllability**
- **Mission:**
  - Columbus Module (ISS), integrated in EDR2
  - 3 months continuous operations with limited maintenance



3 - BIORAT 1 Flight Demonstrator - Mission Overview



L
Upload

- BRT1: stowed conf
- Inactive system
- T-conditioning (algae: 5°C)

L+3d
BIORAT1

- Installation in EDR2
- System startup & diagnostics
- L+6d: inoculation of algae
- BRT1 PBR commissioning
- «stand-by» mode to maintain viability
- System check-up & monitoring

T0 (L+6d)

- BRT1-LSC activation
- Experiment execution and On-orbit Operations
- Experiment Monitoring
- Maintenance Ops. (T0+30d, T0+60d)
- Housekeeping Data Telemetry (ground)

T0+90d (TBD)

- End of On-orbit Experiment
- BRT1 On-orbit decommissioning
- Preparation to download
- Download

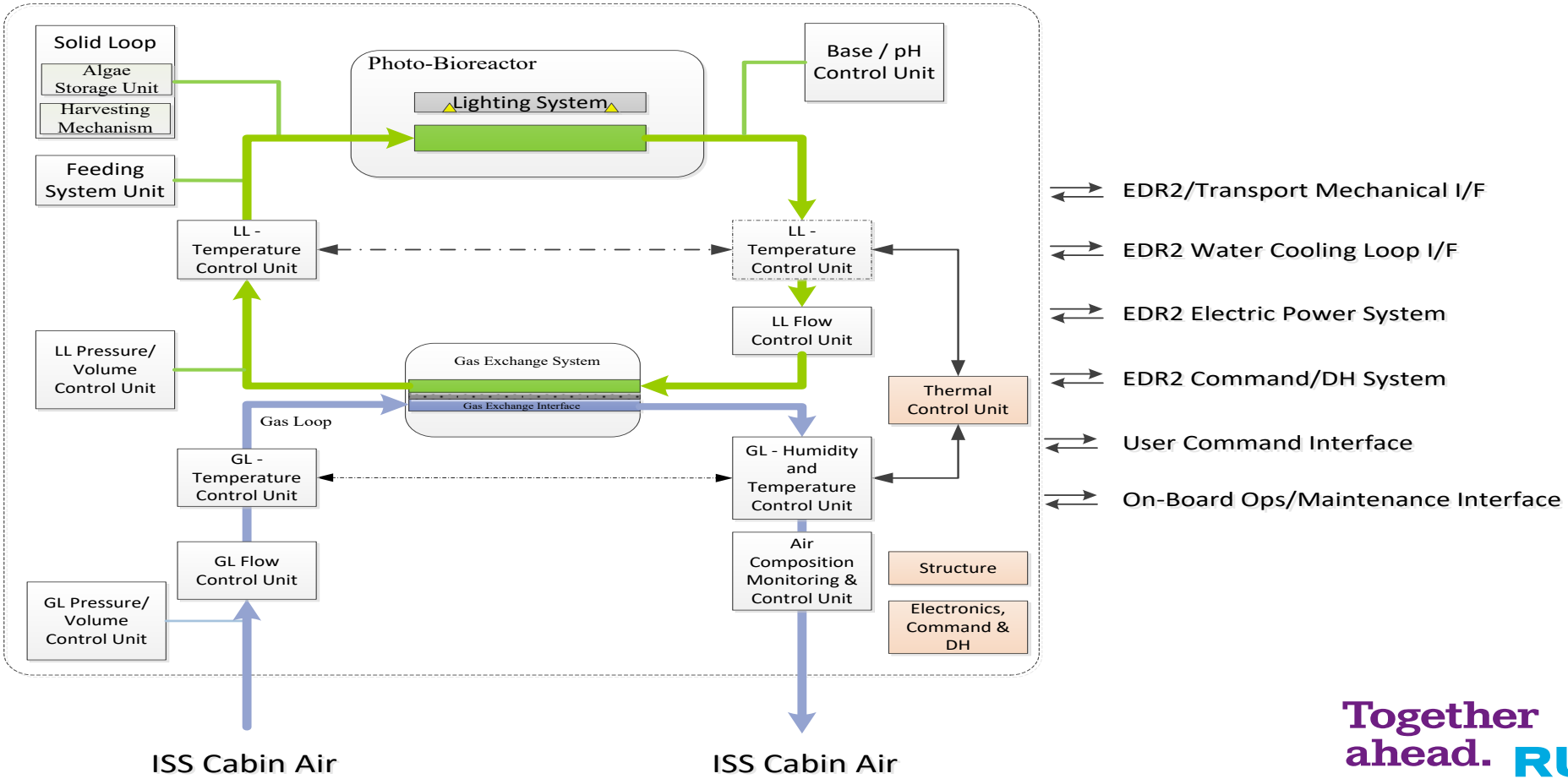
BRT1-LSC

L-4d
Ground Operations:
BRT1-LSC preparation

- Sterilization Steps
- Filling and final assembly of hardware
- Final checks (functional, leak tightness)
- Preparation of algae upload containers (5°C)

Together ahead. RUAG

3 - BIORAT 1 Flight Demonstrator - Design Overview



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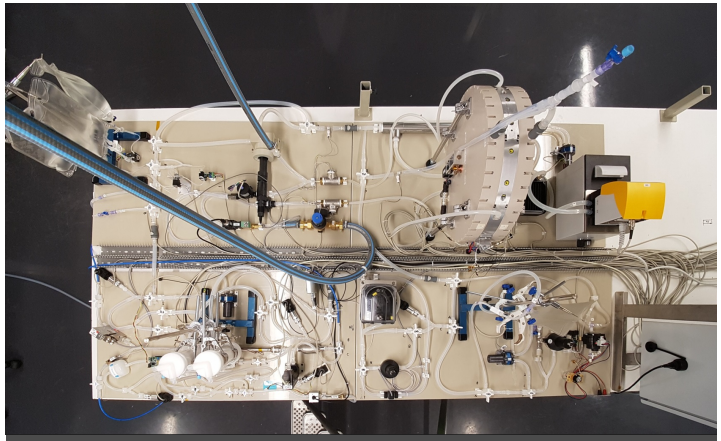
4 - PBR-LL Breadboard Model (BBM) - Background

- **2017 Test campaign achievements [Chapuis2018]**
  - Cultivation time 1 weeks
  - Biomass concentration up to 0.62g/L
  - Peak O2 production rate 8 mmol/hr

- **Current (2019) Test Campaign objectives:**
  - Cultivation time extension over 15 days
  - Biomass concentration extension up to 2g/L
  - Continuous O2 production rate 6.75 mmol/hr
  - O2, Biomass models verification



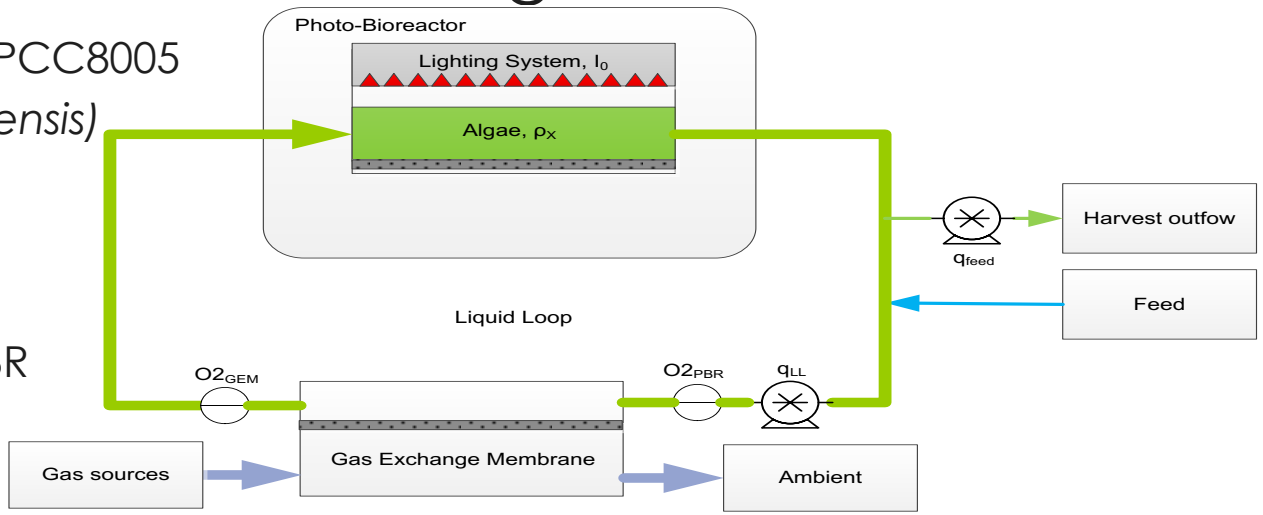
PBR-LL Breadboard model 2017
(Source: RUAG)

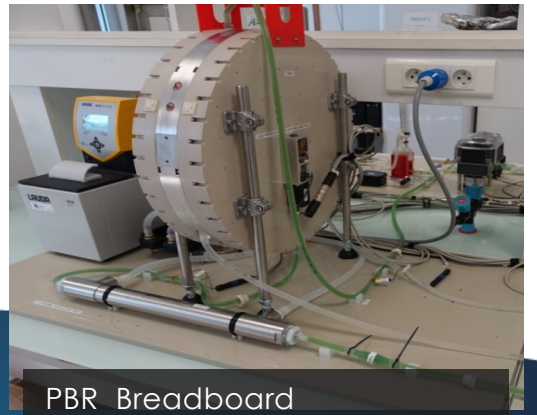
[Chapuis2018]: D. Chapuis, S. Nebuloni, P. Dainesi, S. Gass, C. Laroche, D. Duchez, C-G. Dussap, D. Demey, A. Delahaye, O. Gerbi, C. Paille. BIORAT 1: Oxygen Recycling between an Algae Photo-bioreactor and a Consumer. Presentation in Melissa Day 2018

4 - PBR-LL Breadboard Model (BBM) - Hardware configuration

- Spirulina strain: Limnospira indica PCC8005
  (Formerly known as Arthrospira platensis)

- BBM Key Functionalities
  - Continuous cultivation
    - PBR Photo-bioreactor PBR
    - Feeding
    - Harvesting
  - O2 mass transfer
    - LL Liquid loop
      - Gas Exchange Membrane
      - O2 Measurement
    - Gas conditioning

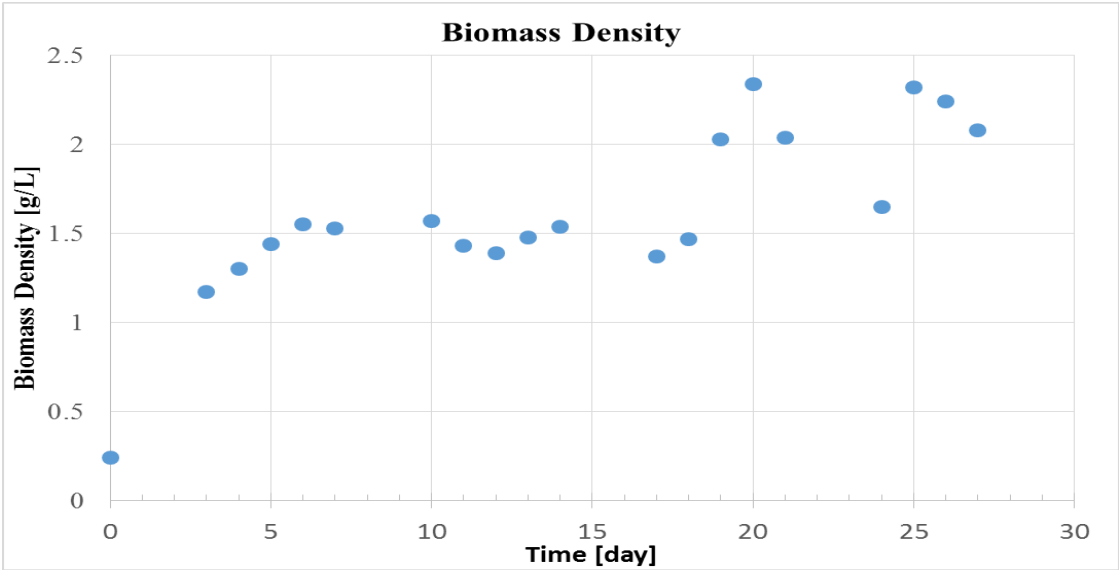




PBR Breadboard model(Source: RUAG)

4 - PBR-LL Breadboard Model (BBM) - Biological results

- Dry Biomass over time

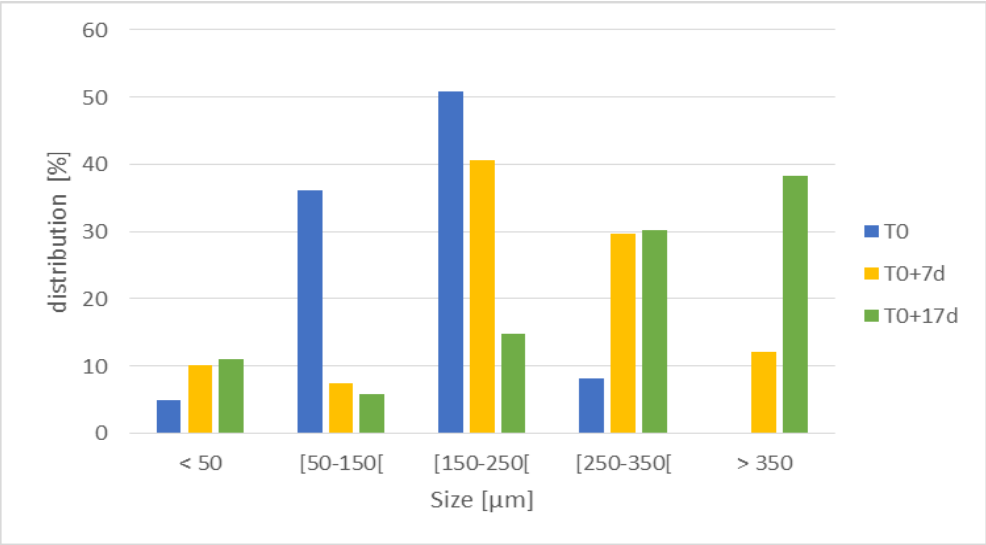


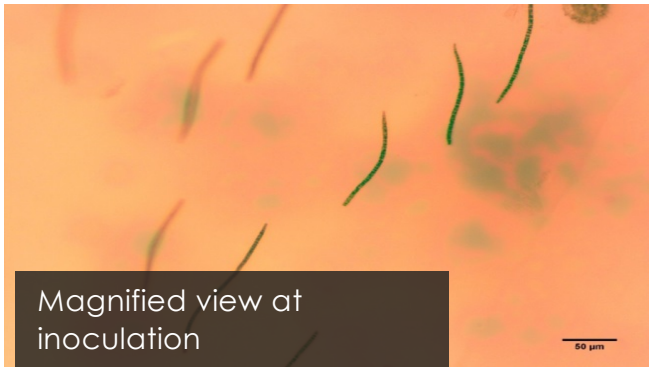
	Objective	Achieved
Cultivation time	>15 days	27 days
Biomass concentration	2 g/L	2.3g/L

4 - PBR-LL Breadboard Model (BBM) - Biological results

- Spirulina length over time
  - Increase of spears lengths
  - Absences of cell particles

➔PBR-LL Fluidic condition suitable

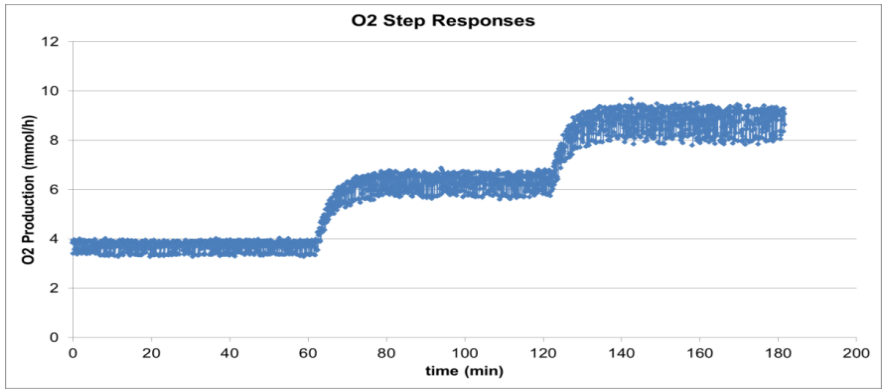




4 - PBR-LL Breadboard Model (BBM)
- O2 light intensity production model correlation

- O2 production rate model $\dot{n}^{a}_{O2,PBR}$: $\dot{n}^{a}_{O2,PBR} = \varepsilon_{PBR} \cdot \dot{n}_{O2,PBR}(I_0, \rho_x)$

  Where ε_{PBR} correlation factor, $\dot{n}_{O2,PBR}$ is O2 production rate function from [Cornet2013], I0 is light intensity, ρ_x is the biomass density.



Light Intensity (W/m2)	Measured $\dot{n}^{a}_{O2,PBR}$ (mmol/hr)	Correl. $\varepsilon_{PBR} \cdot \dot{n}_{O2,PBR}$ (mmol/hr)	Model Error (%)
20	3.7	4.69	26.7
35	6.3	6.61	4.90
50	8.8	7.98	-9.31

- Light step response (Range I_0 = [20;50W/m2], Biomass ρ_x =1.17g/L)
- Up to 8.8 mmol/hr produced
- Identified ε_{PBR} =0.953
- Maximum correlated error<1mmol/hr

Nominal cultivation intensity 40W/m2➔~7.1mmol/hr ✔

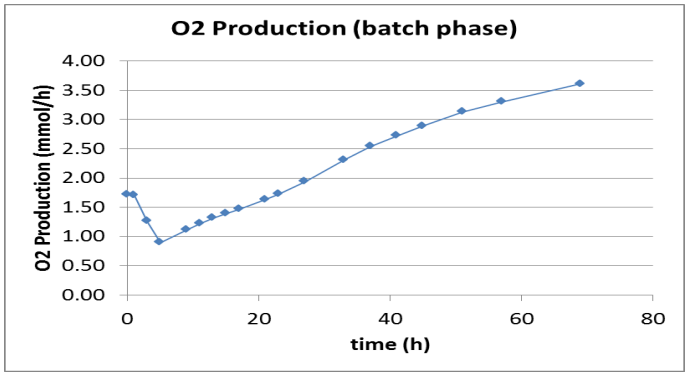
4 - PBR-LL Breadboard Model (BBM) - O2/Biomass stoichiometric ratio

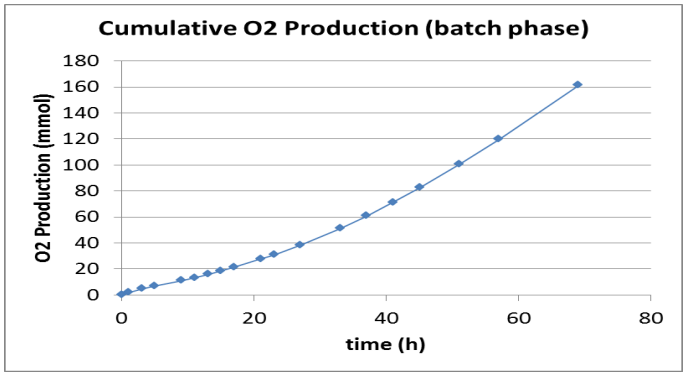
- Stoichiometric relationship from [Cornet2017]:

$$CO_2 + 0{,}673\ H_2O + 0{,}192\ HNO_3 + 0{,}005\ H_2SO_4 + 0{,}006\ P_i \xrightarrow{\bar{J}_{XA}} \underbrace{CH_{1{,}566}O_{0{,}405}N_{0{,}192}S_{0{,}005}P_{0{,}006}}_{\text{Biomasse active}} + Q_P\ O_2$$

Where $\mathbf{Q_P}$ *is the photosynthetic quotient (ratio of O2 mole produced per mole of biomass produced)*

- O2 & Biomass Mass balance during initial batch cultivation
  - Measured Q_P : 1.2±0.1 (literature measured values typical range [1.29;1.40])





[Cornet2017]Cornet, J-F., "Procédés Limités par le Transfert de Rayonnement en Milieu Hétérogène," Université Blaise Pascal - Clermont-Ferrand II, 2007, pp.295-296

5 - Conclusions & Way Forward

Main Conclusions

- Month long system operation
- Algae compatible with PBR-LL hardware & cultivation condition
- Continuous O2 target production met
- Biomass concentration target met
- Correlation of O2 production rate model
- Measurement of produced Biomass and O2 production rate

Way Forward

- Upgrade from PBR-LL to Flight Demonstrator BBM
  - Process control (autonomous)
  - Addition of Solid Loop Sub-system
  - 90 days life test experiment to be performed

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THANK YOU.

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