PHOTOBIOREACTOR IN SPACE HABITAT: STATUS AND CHALLENGES

C. Paille, ESA
S. Hens, QinetiQ Space
S. Gass, RUAG Space

MELiSSA workshop
7-8 June 2016, Lausanne

Context

1. For future long term Manned missions, recycling of consumables is mandatory
    - a. Average 1 kg O2 per day per person
    - b. for mission to mars: ca 4 tons O2

2. Safety and reliability requirements for space habitat require accurate control of the air regeneration process

3. Consumer characteristics:
    - a. variable respiration rate (0,6 to 6 kg O2)
    - b. Dynamic
    - c. CO2 limit 4000 ppm

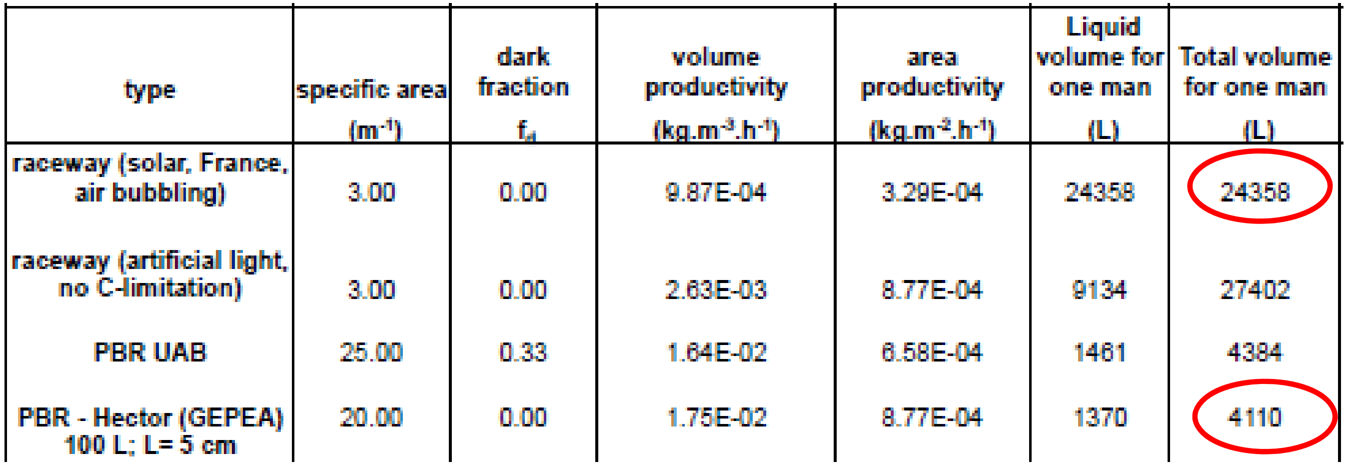
4. Need to regenerate the air with processes easy to control and with short time constant such as Photo-bioreactor

Today

1. Main limiting engineering factor is light distribution and availability in the reactor

2. Coupling light transfer and kinetic rate in a photo-bioreactor

$$\langle r_X \rangle = \gamma \frac{1}{V_\ell} \iiint_{V_\ell} r_{X,\ell}\, dV + (1-\gamma) \frac{1}{V_d} \iiint_{V_d} r_{X,d}\, dV$$



type	specific area (m^{-1})	dark fraction f_d	volume productivity (kg.m^{-3}.h^{-1})	area productivity (kg.m^{-2}.h^{-1})	Liquid volume for one man (L)	Total volume for one man (L)
raceway (solar, France, air bubbling)	3.00	0.00	9.87E-04	3.29E-04	24358	24358
raceway (artificial light, no C-limitation)	3.00	0.00	2.63E-03	8.77E-04	9134	27402
PBR UAB	25.00	0.33	1.64E-02	6.58E-04	1461	4384
PBR - Hector (GEPEA) 100 L; L= 5 cm	20.00	0.00	1.75E-02	8.77E-04	1370	4110

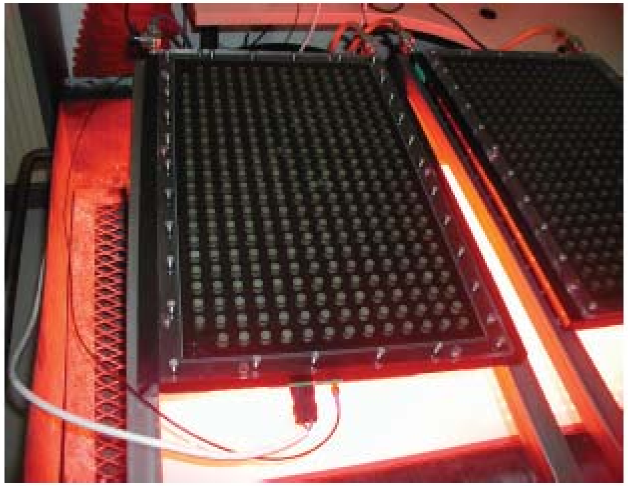
External lighting
Not up-scalable

For tomorrow

1. Intensification of photo-bioreactor **(Cornet & Dussap, 2009, Biotech. Prog.)**

$$\langle r_X \rangle_{\max} \propto a_{light} \ln\left[1+\frac{\bar{q}}{K}\right] = \alpha_1 \, a_{light} \ln\left[1+\frac{\bar{q}}{K}\right]$$

2. Increase specific illuminated area by decreasing the physical thickness
    a. Natural lighting: Flat panel ⇒ high surface
    b. Artificial lighting: Internal lighting ⇒ adequate for space application



Critical issues

1. Light source: geometry, materials, lightening sources, energy consumption, incident spectrum angular distribution

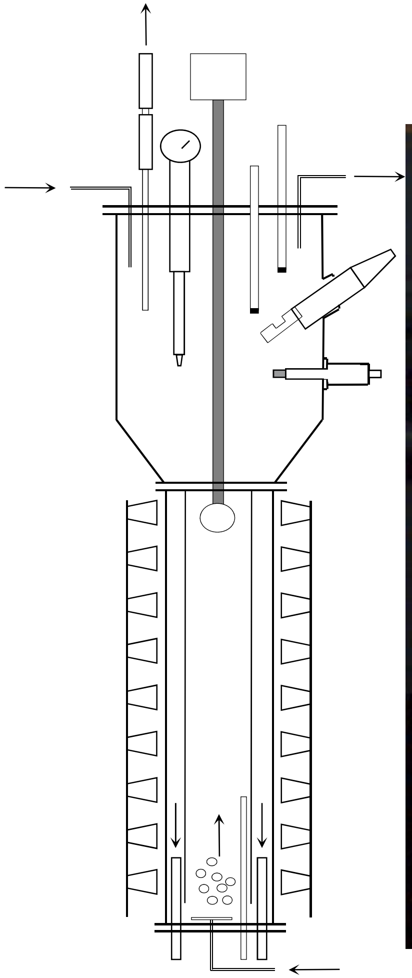
2. Mass transfer: nutrient in confined culture conditions

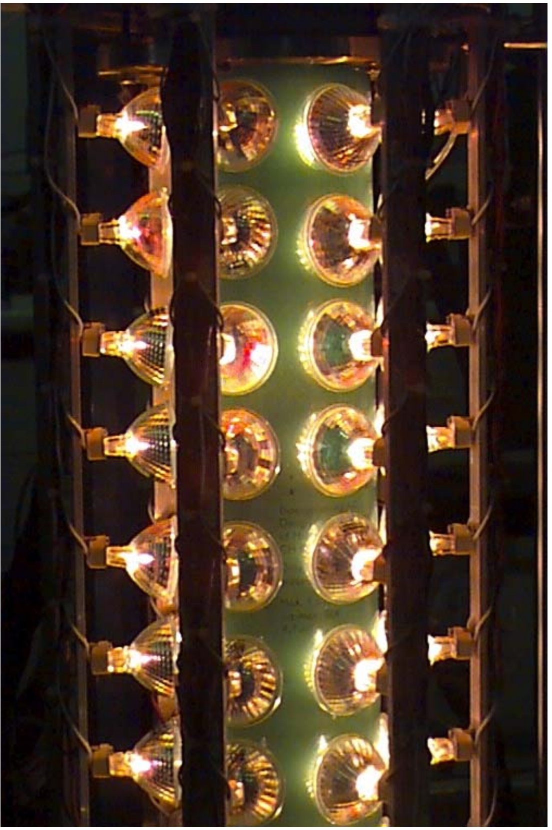
3. Heat transfer: heat dissipated from light source, temperature

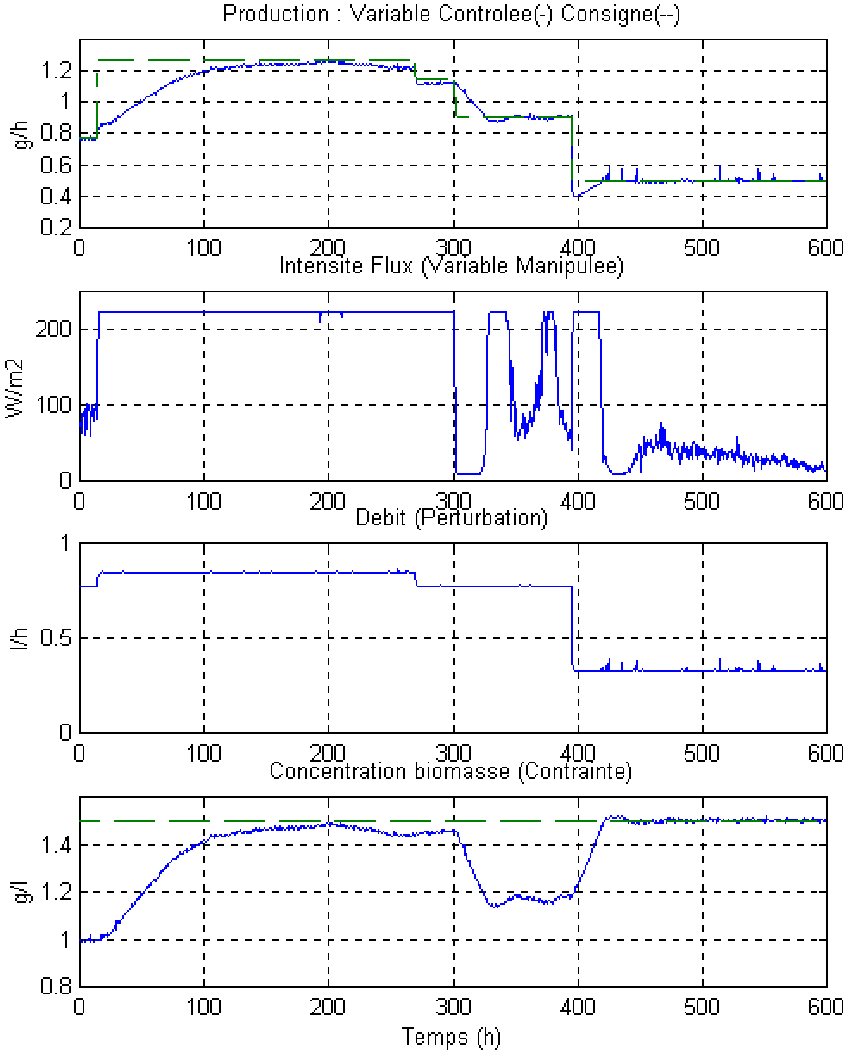
4. Macro and micro mixing: specific issues of adhesion, clogging with internal structures, hydrodynamics conditions with high biomass concentration in confined flows..

5. Metabolism adaptation: high cell density, increased O2 partial pressure,

For further application in space: control test

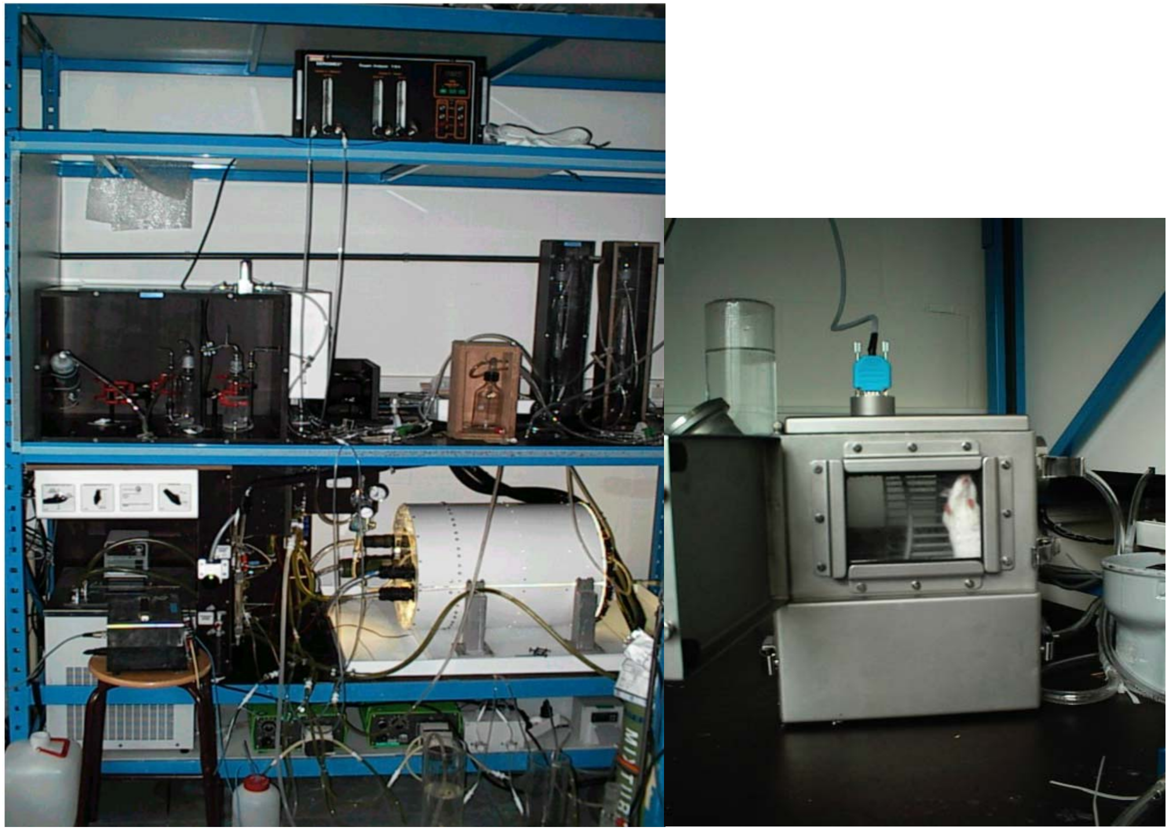




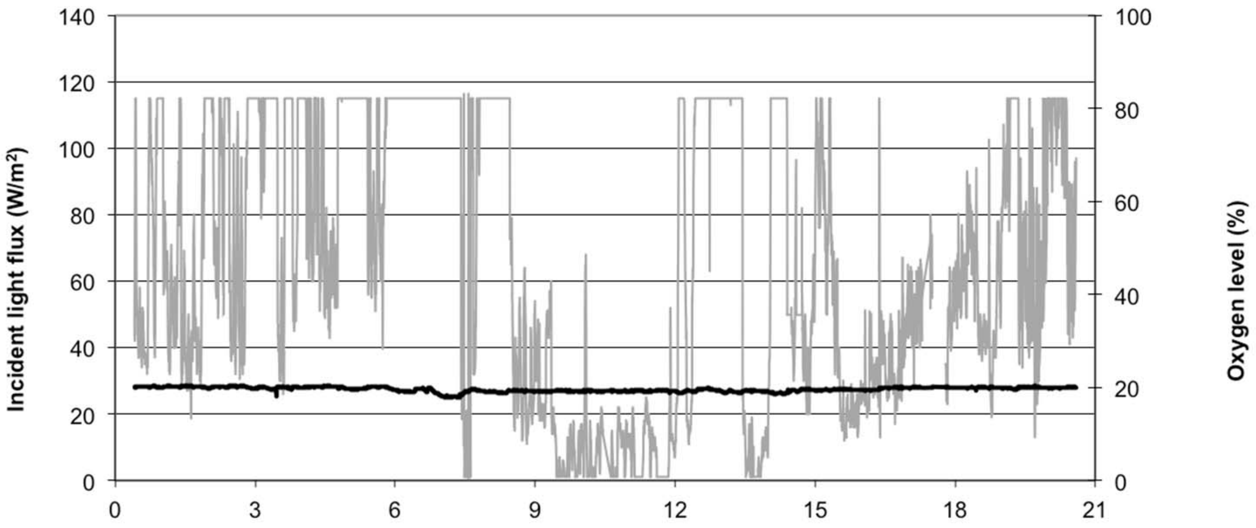


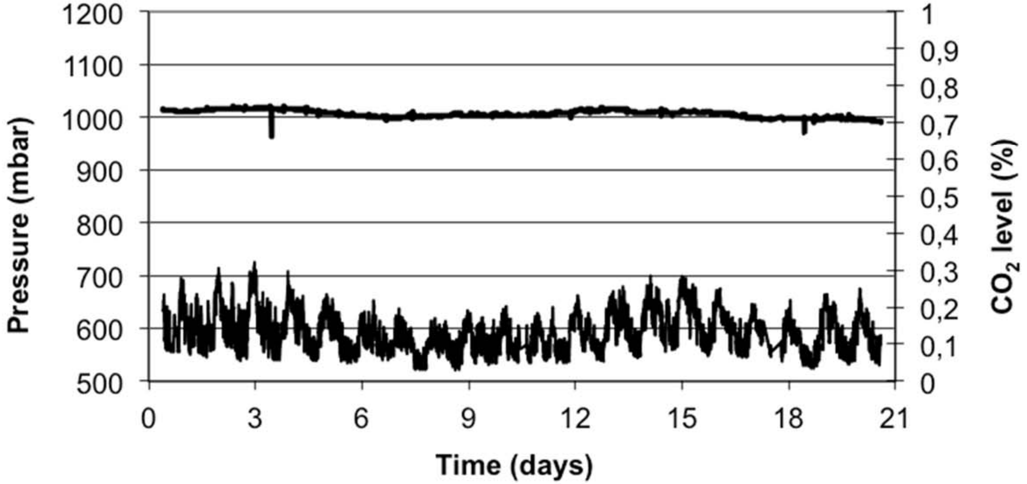
For further application in space: Demonstration with consumer

1. Control of the atmosphere of a crew with a photobioreactor



Result of 3 weeks experiment

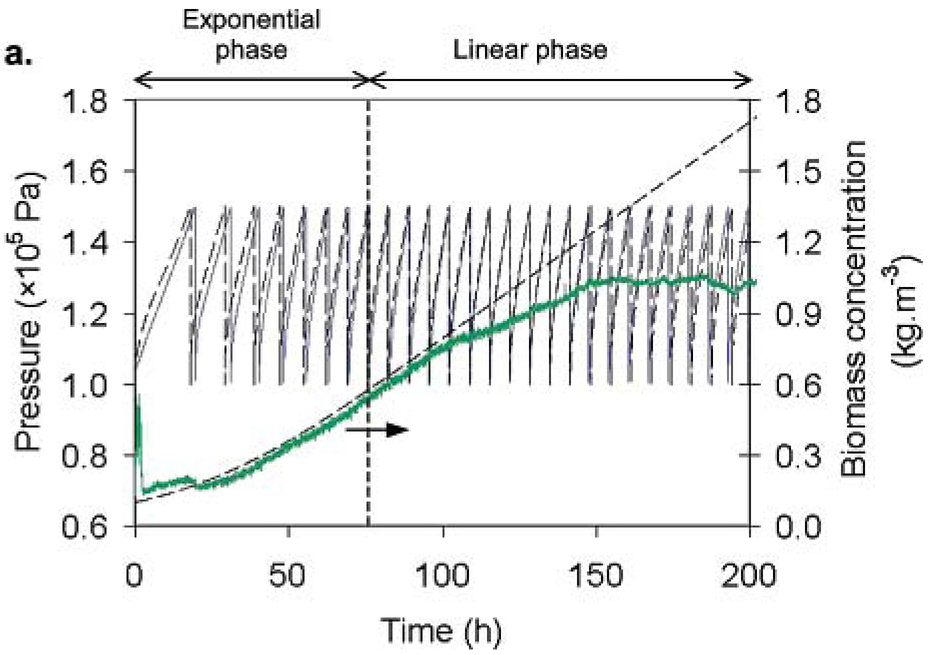


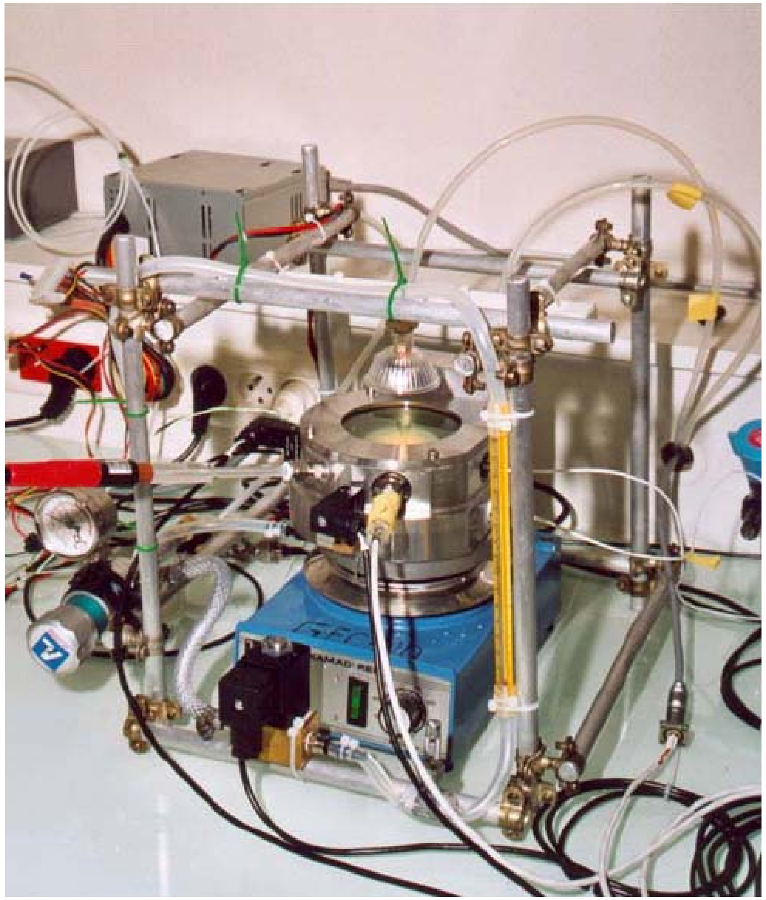


Model validation in space

1. MASK (1998-2002): Micro-gravity Analysis of Spirulina Kinetics

2. Objective: study the growth kinetics of Arthrospira platensis by following the oxygen production (pressure increase)





Steven Hens

Project Manager QinetiQ Space

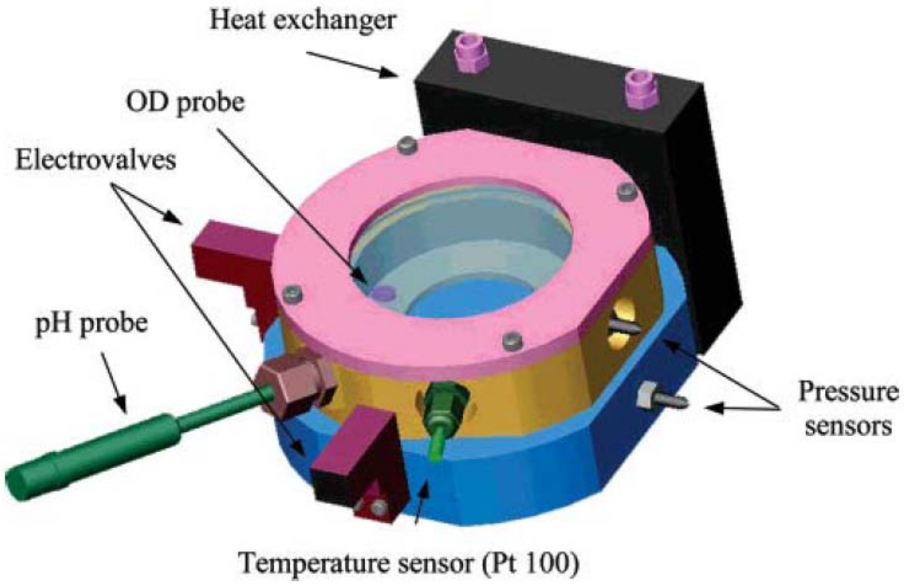
ARTEMISS

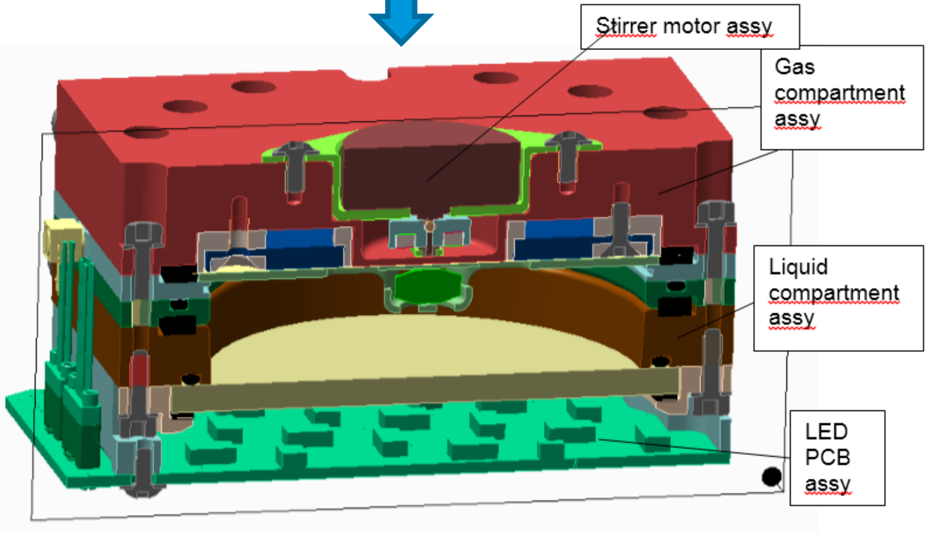
From science prototype to flight model

Source: Design, Operation, and Modeling of a Membrane Photobioreactor to Study the Growth of the Cyanobacterium *Arthrospira platensis* in Space Conditions

Guillaume Cogne,* Jean-Francois Cornet, and Jean-Bernard Gros

Target: Artemiss Flight Model





Scientific objectives

Behaviour of MELiSSA-C4 *Arthrospira* sp. PCCC8005 in space flight in BIOLAB

a. Investigating
  - Oxygen production
  - Biomass production
  - Biochemical composition (food value)

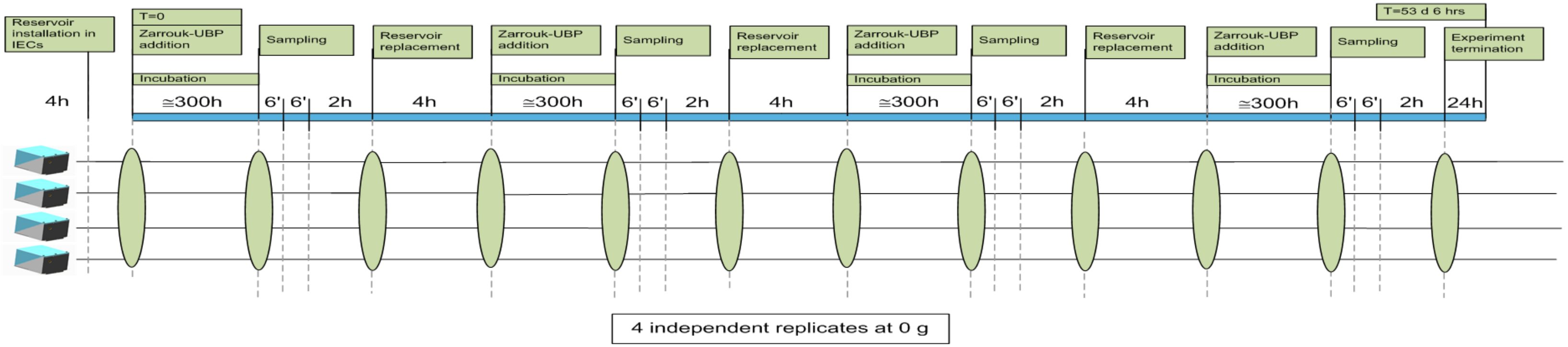
b. In a photo-bioreactor, axenic (1 strain), in batch & continuous mode with continuous illumination (no day/night cycle), and controlled temperature and nutrient dose

c. Under real “*spaceflight*” conditions (= relevant combination of altered gravity, radiation, magnetism, …)

Scientific objectives

Science objectives

- Biolab (ISS) – 4 rotor positions inside with thermal control
- 4 Flight models to facilitate 16 runs
- Experiment needs to fit Biolab: H/W/D dimensions: 125mm/147mm/174mm
- Maximum mass: 4,5 kg



Flight Design Process

Phases of Flight experiment Design

Phase A: Specification study phase

Phase B: Breadboarding phase → Preliminary design

Phase C: Critical design Phase, including building Engineering Unit and Qualification Model, including Science models

Phase D: Flight models MAIT (manufacturing, assembly, integration and testing)

Phases of Safety validation

Safety review 0/1: First presentation of design to Safety panel – overall safety approach agreed (Phase B)

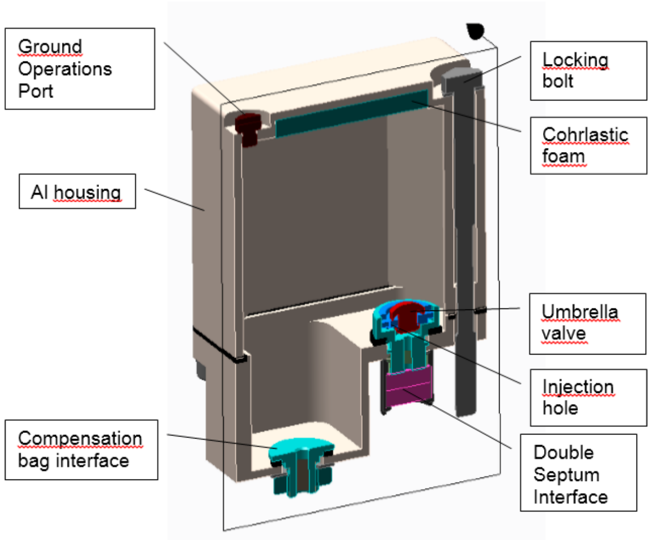
Safety review 2: updated presentation of final design to Safety panel – all safety verifications agreed (Phase C)

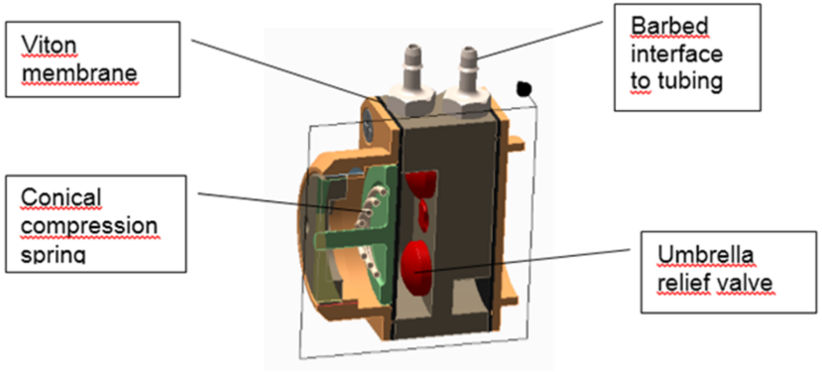
Safety review 3: Review of safety verifications → all verification to be closed prior to launch. (Phase D)

Flight Design Challenges

Challenges for flight design

- Safety precautions
    - Hazard level to be determined by NASA toxicologist
    - MDP (Maximum Design Pressure)
        - Design to be 2 Failure Tolerant in worst case conditions
            - Storage of samples after experiment run in freezer, to be tested at -130°C (materials to be compliant)
            - Reservoirs to withstand maximum temperature, including failure cases → units to be tested at 2,7 barg





Flight Design Challenges

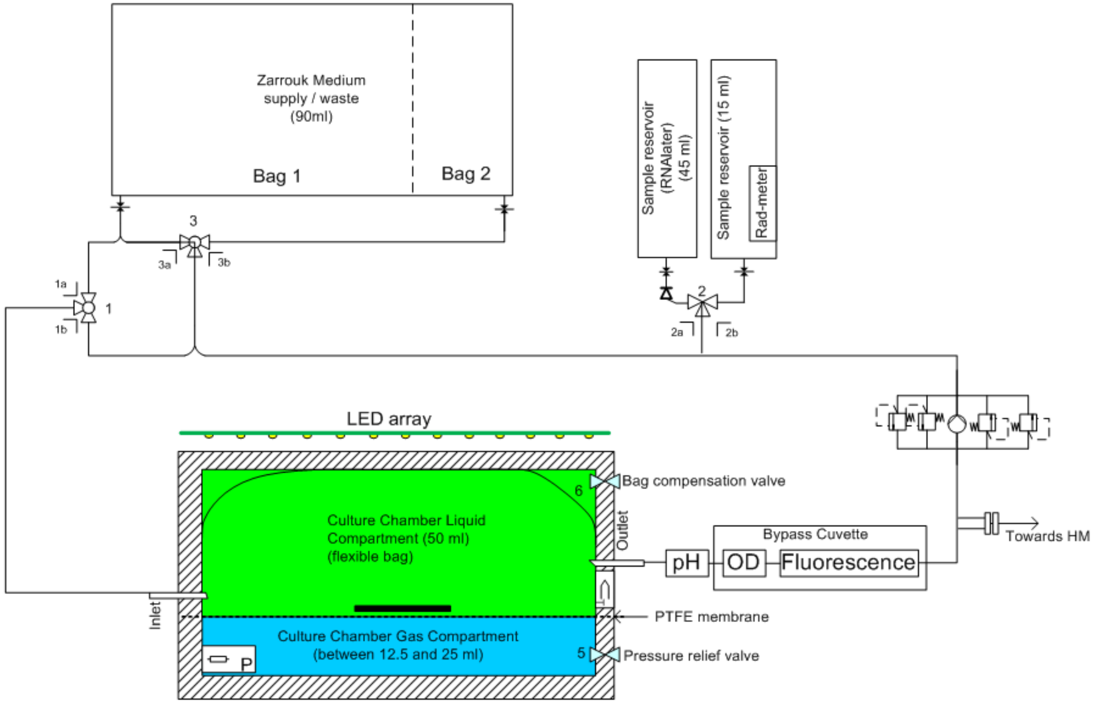
Challenges for flight design

- Safety precautions
    - Hazard level to be determined by NASA toxicologist
    - MDP (Maximum Design Pressure)
    - Chemical compatibilty
        - Materials to be compatible with experimental liquids
    - Biocompatibility
        - Experimental liquids to be compatible with used materials
    - Flammability
        - Artemiss creates enriched oxygen environment
    - Outgassing, Electrical hazard, ...

Flight Design Challenges

Challenges for flight design

- Limited Mass / Limited Volume / Limited Crew time
- Bubble free filling
    - 4 full runs on each unit implies a bubble free filling for each run
    - Closed volumes shall create pressure build up, thus venting needs to be implemented



Flight Design Challenges

Challenges for flight design

- Instrumentation to fulfill scientific objectives
  - Implemented
    - Gas pressure
    - Optical density (through by pass loop)
    - Fluorescence measurement (combined with OD)
  - Discarded
    - pH measurement (no sensor available above 9 pH which fits in small volume available
    - Microscopy sampling: foreseen in design, but available microscopy on-board in-sufficient for Artemiss experiment

Flight Design Challenges

Challenges for flight design

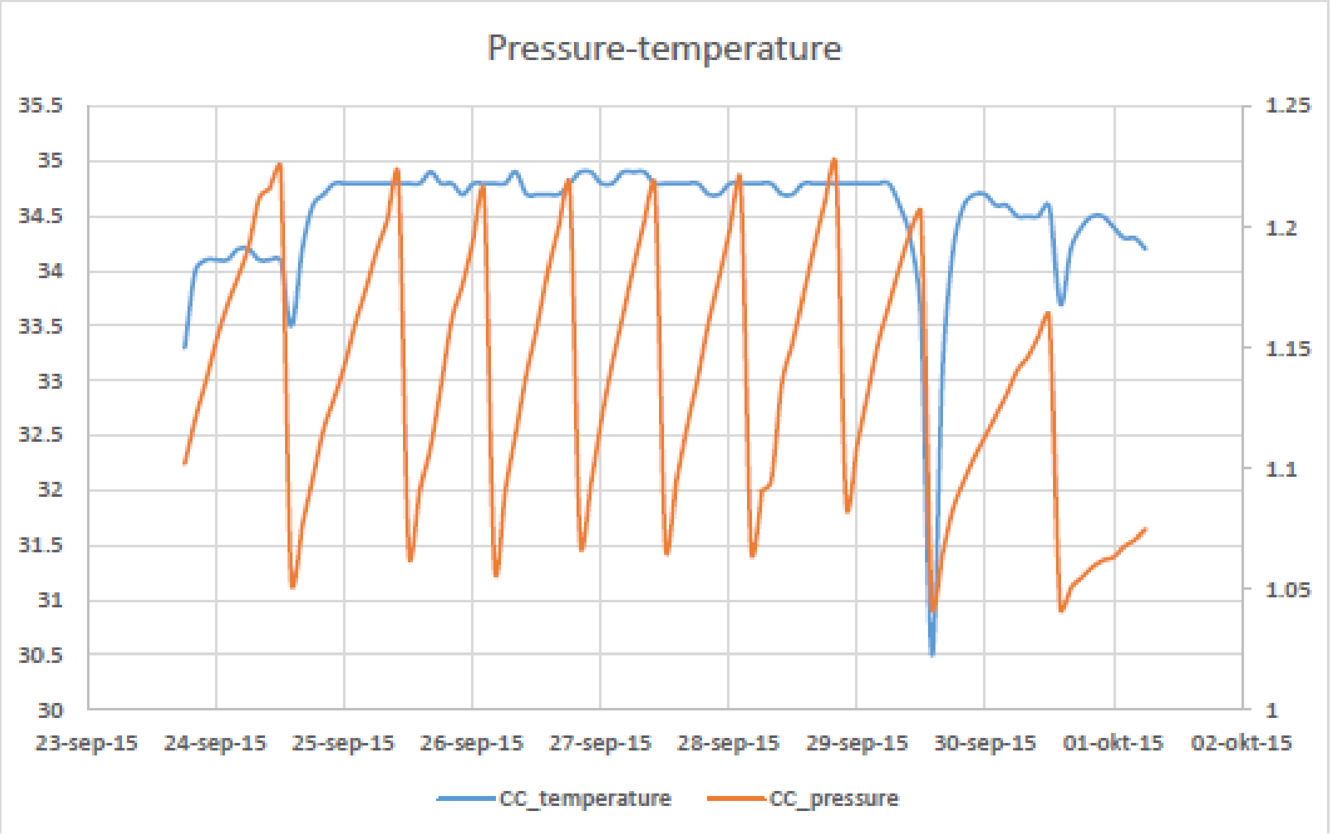
- Validation testing
    - Before the units are released to the science testing, all hardware is extensively tested (vibration, thermal, …).

- Science testing:
    - Although the science requirements and boundaries are taken into account during the design as formal science requirements:
        - Final flight parameters need to be optimized on ground units prior to the flight campaign. E.g: stirrer speed, stirrer direction, temperature, liquid pressure, light intensity, …

Flight Design Challenges

Challenges for flight design

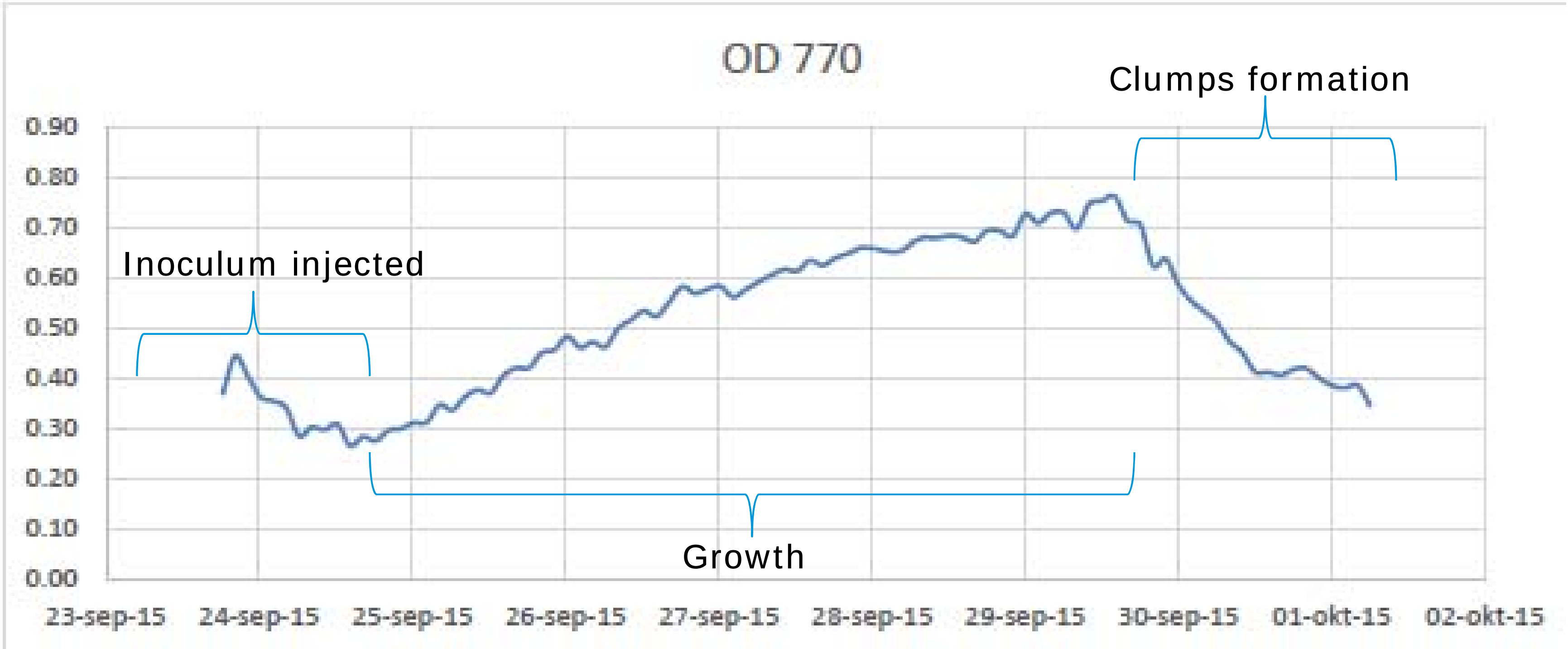
- Science testing: 8 day test campaign September 2015



Flight Design Challenges

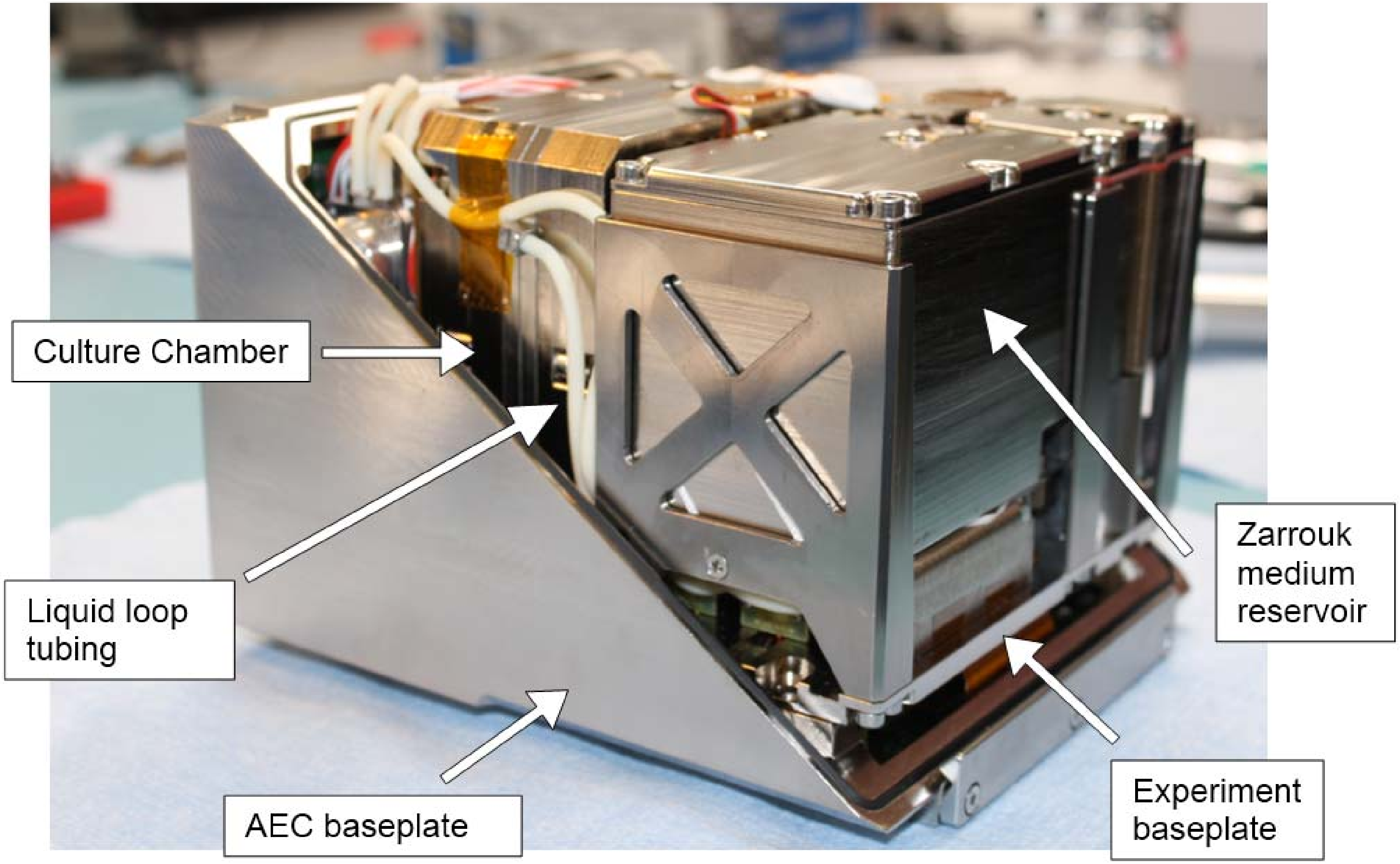
Challenges for flight design

- Science testing: 8 day test campaign September 2015



Flight Design Challenges

Final design !



Samuel Gass

Project Manager RUAG Space

BIORAT 1

European Space Agency

BIORAT1

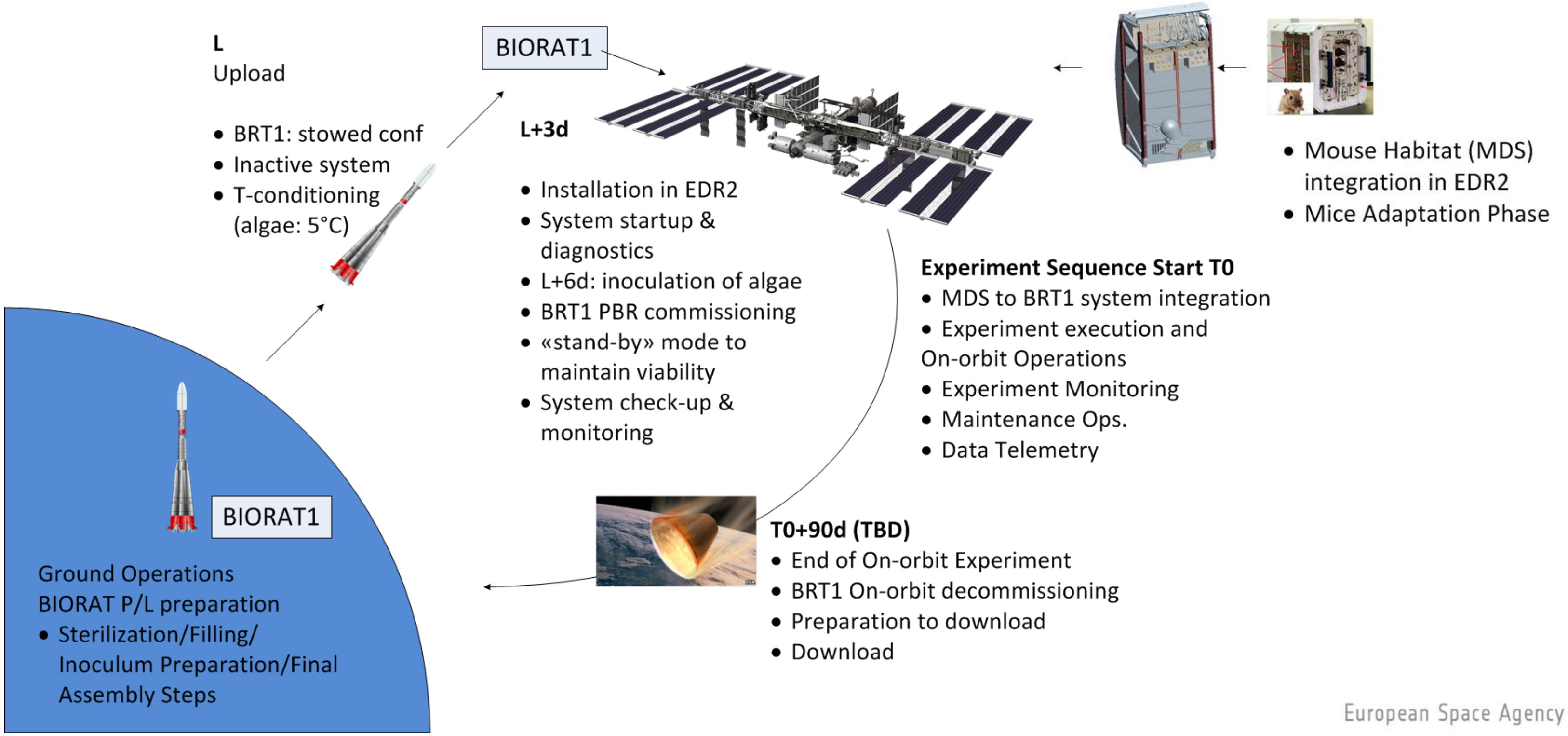
Outline:

- Flight Demonstrator Objectives and Mission Concept
- Principal Engineering Challenges for BIORAT1
- Development Status and Preliminary Design (link to Engineering Challenges)
- Photo-bioreactor and Liquid-loop Breadboard
- Next Steps
- Engineering Challenges beyond BIORAT1

BIORAT1 Flight Demonstrator Objectives

1. BRT1 shall support life of **3 mice** in **closed system** by recycling the air (converting CO_2 into O_2) of the habitat for **3 months** experiment on board **ISS**
2. BRT1 shall implement **predictive control** for closed-loop automated operations in micro-gravity, with limited maintenance activities

Concept of Operations



L
Upload

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

BIORAT1

L+3d

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

- Mouse Habitat (MDS) integration in EDR2
- Mice Adaptation Phase

Experiment Sequence Start T0

- MDS to BRT1 system integration
- Experiment execution and On-orbit Operations
- Experiment Monitoring
- Maintenance Ops.
- Data Telemetry

T0+90d (TBD)

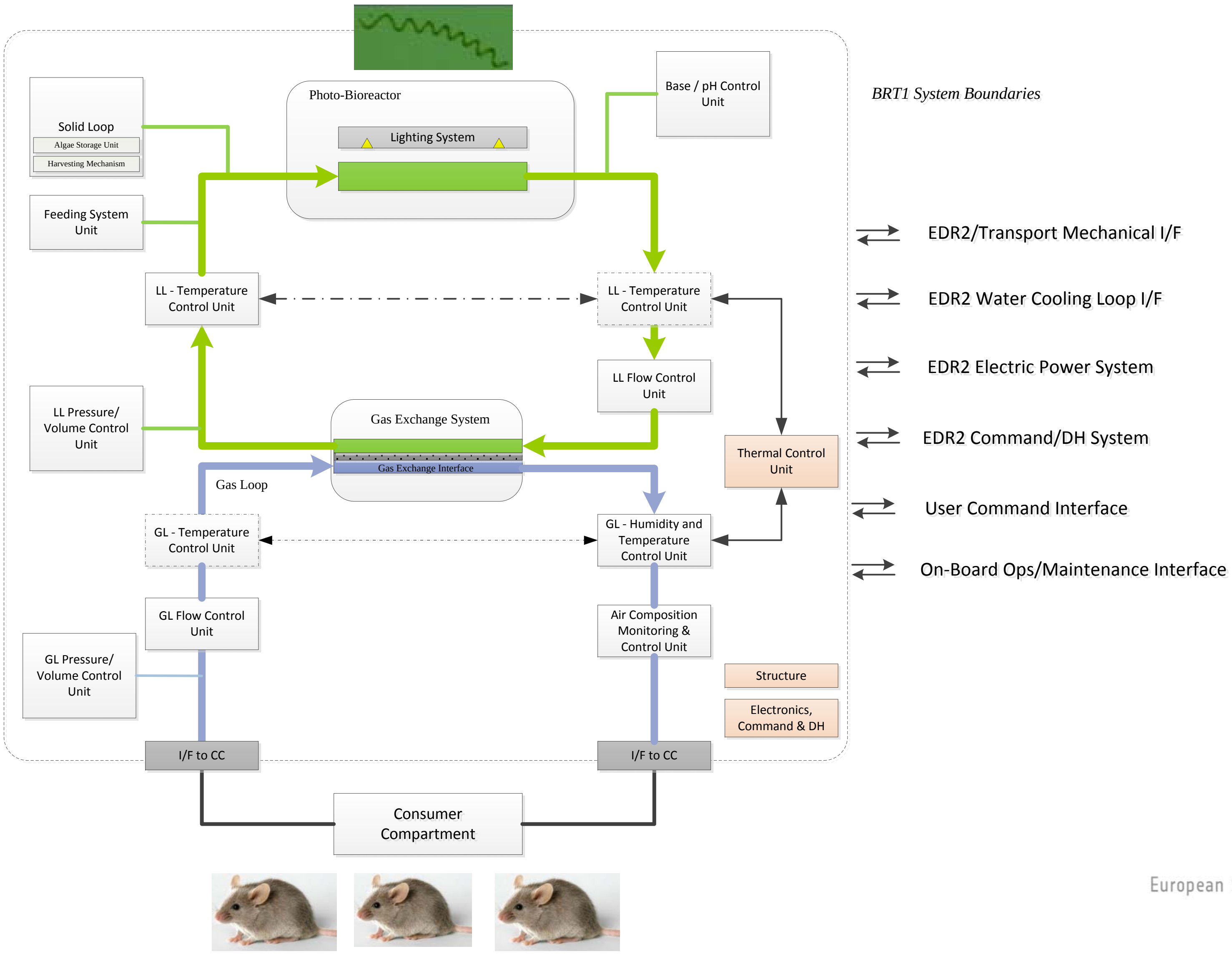
- End of On-orbit Experiment
- BRT1 On-orbit decommissioning
- Preparation to download
- Download

BIORAT1

Ground Operations
BIORAT P/L preparation

- Sterilization/Filling/ Inoculum Preparation/Final Assembly Steps

BIORAT1 System Overview



BRT1 System Boundaries

Photo-Bioreactor

Lighting System

Solid Loop

Algae Storage Unit

Harvesting Mechanism

Feeding System Unit

Base / pH Control Unit

LL - Temperature Control Unit

LL - Temperature Control Unit

LL Flow Control Unit

LL Pressure/ Volume Control Unit

Gas Exchange System

Gas Exchange Interface

Gas Loop

Thermal Control Unit

GL - Temperature Control Unit

GL - Humidity and Temperature Control Unit

GL Flow Control Unit

Air Composition Monitoring & Control Unit

GL Pressure/ Volume Control Unit

Structure

Electronics, Command & DH

I/F to CC

I/F to CC

Consumer Compartment

⇄ EDR2/Transport Mechanical I/F

⇄ EDR2 Water Cooling Loop I/F

⇄ EDR2 Electric Power System

⇄ EDR2 Command/DH System

⇄ User Command Interface

⇄ On-Board Ops/Maintenance Interface

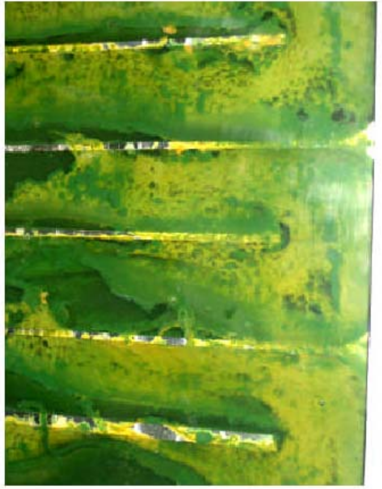
BIORAT1 Engineering Challenges

- Mass & heat transfer (chemical species, biomass) effectiveness in terrestrial and micro-gravity
- Gas formation and dynamics in buoyance-free environment (difficult to predict and / or test on ground during qualification)
- Avoid biomass adhesion to surfaces
- Handling water content in gas loop (condensate removal)
- Efficient separation of biomass
- Robust control system under wide range of operative scenarios

- Limited on-board maintenance crew operations
- Volume / Power budget limited by integration in EDR2
- Safety requirements (ISS)

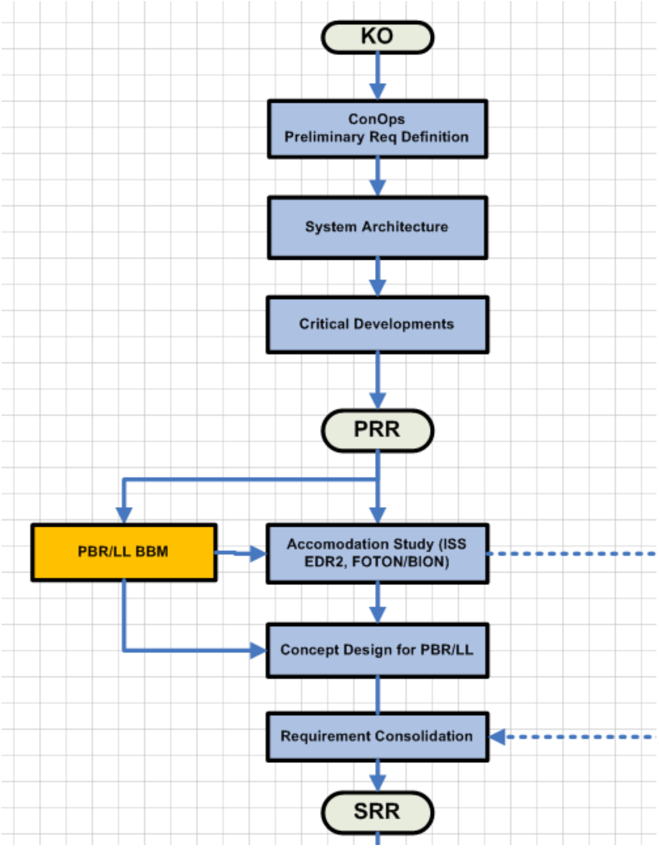
- Behaviour of algae in micro-gravity environment

Sedimentation/Adhesion of algae onto reactor walls



BIORAT1 Development Status

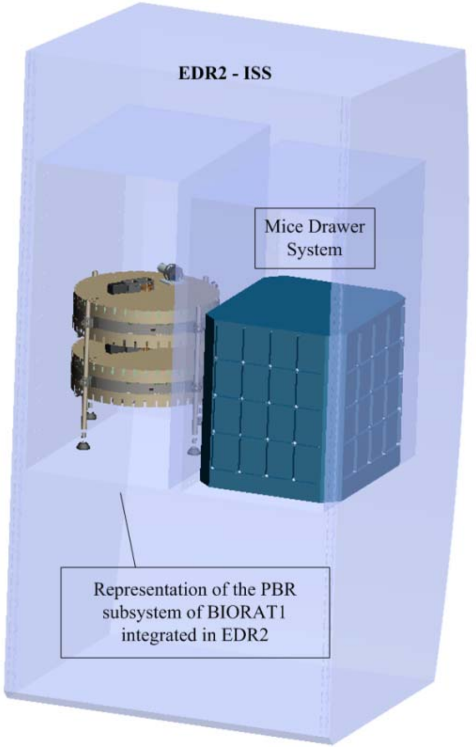
- Preliminary **Requirement Definition**
- System and Sub-System Level **Conceptual Design**:
    - Gas exchange systems concepts, parametric design and scaling laws
    - Photo-bioreactor concepts
    - Integrated solutions
- Preliminary **System Modeling**:
    - knowledge models (Spirulina photosynthesis process)
    - Engineering models of physical processes (heat transfer, mass transfer)
- Critical Developments identification and early **bread boarding**



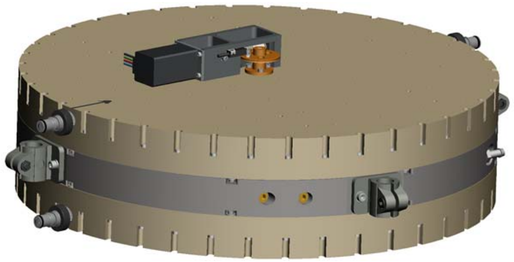
BIORAT1 Preliminary Design

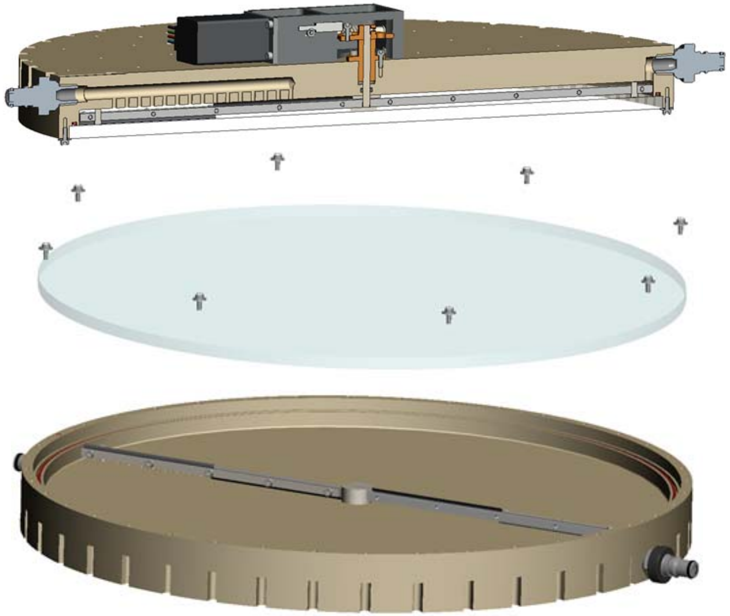
Photo-Bioreactor:

- Active mechanism in PBR to support mass transfer, heat transfer and anti-adhesion functionalities
- Recirculation loop for mass transfer enhancement and flushing/cleaning functionalities
- (selection of) ISS/EDR2 integration requirements flown down to this subsystem



6.75 mmol/h of O2 production (nominal individual module capability)



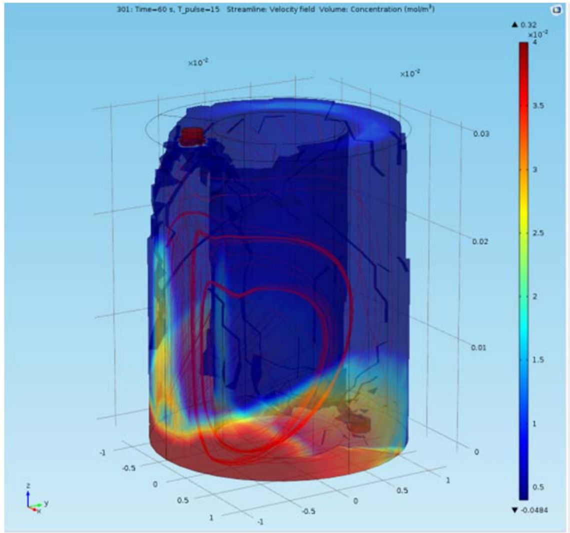


BIORAT1 PBR/LL Preliminary Design

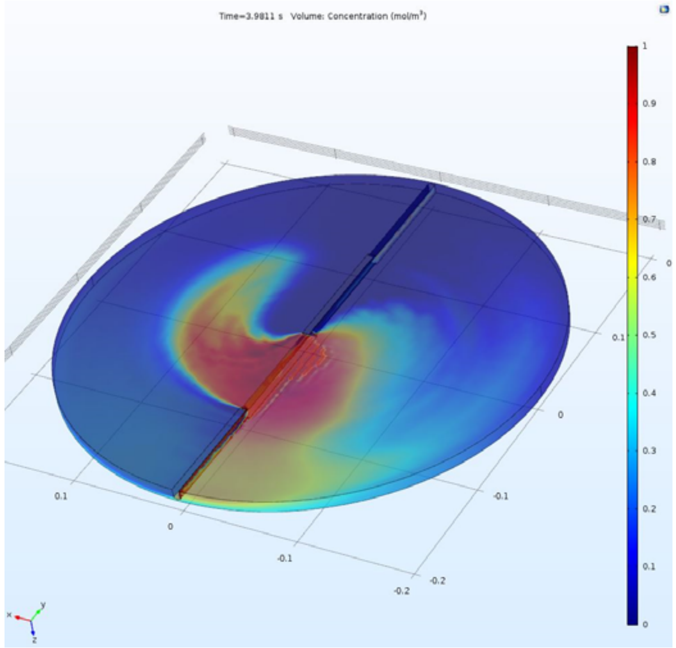
Analytical Studies - CFD

- Analysis of the relative importance of terms in energy, momentum and chemical species balance equations
- Development of numerical models to support design concepts

Time Evolution of O2 concentration



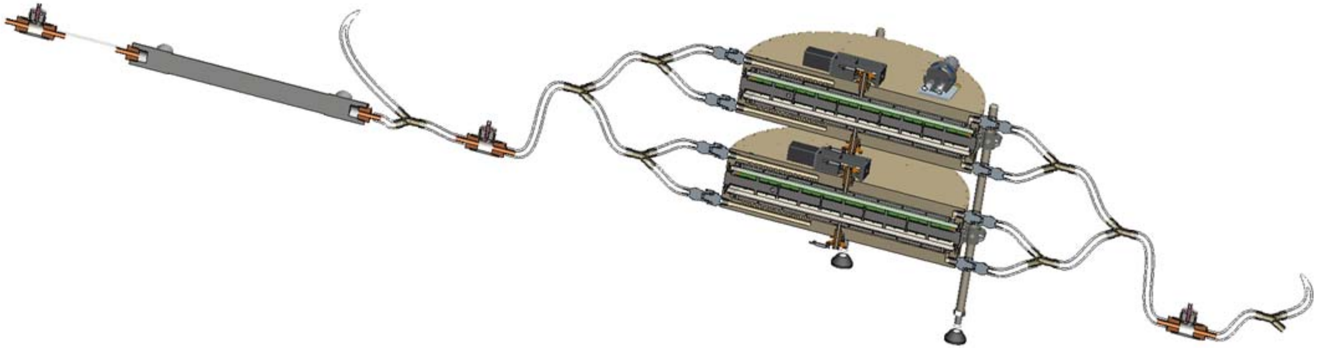
CO2 consumption step responses analysis



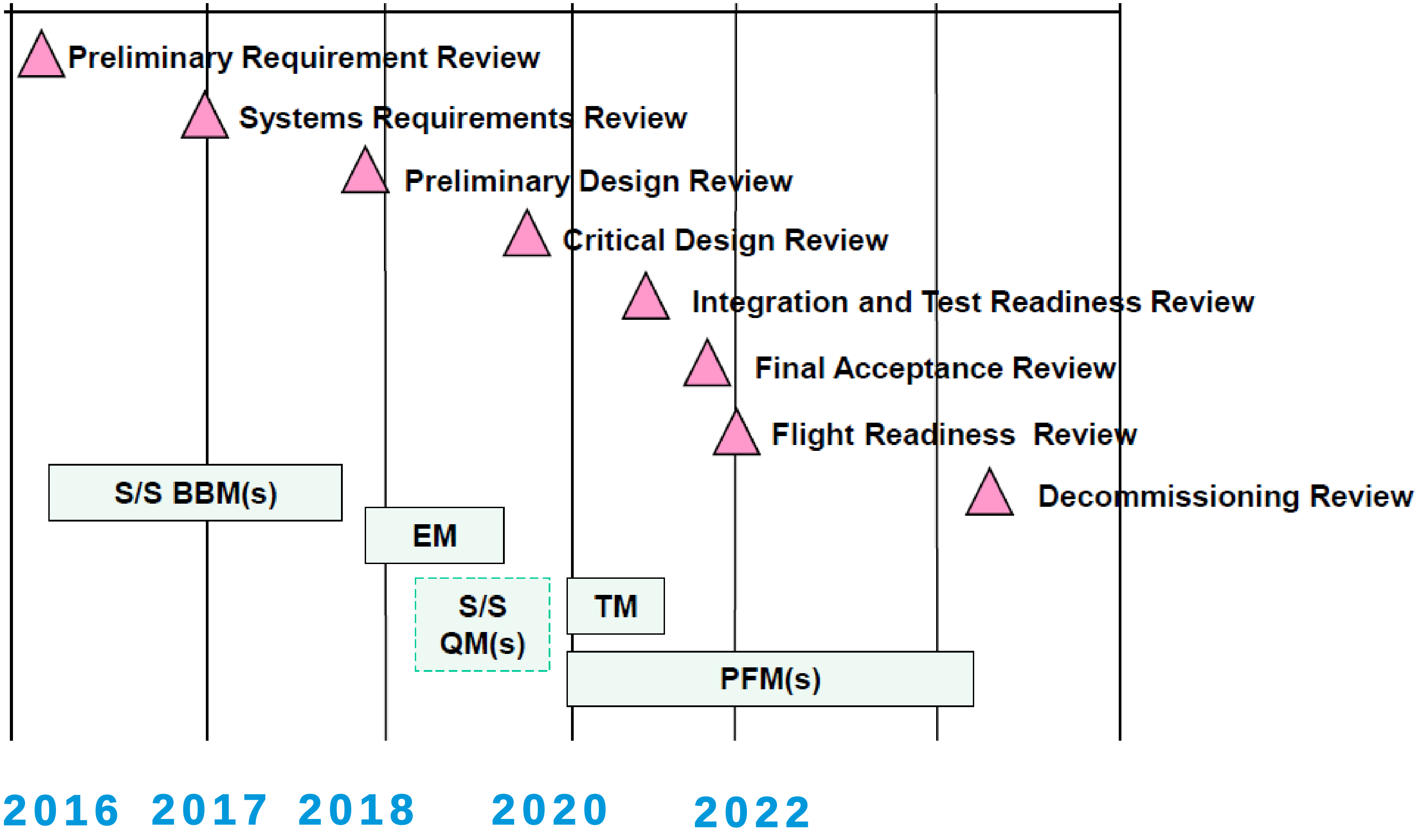
Early-stage bread-boarding
(membrane gas exchanger)

BIORAT1 PBR / LL Breadboard

- Proof of concept and validation of design and models (focus on PBR and LL)
- Implementation of design concepts (GES recirculation loop, PBR recirculation loop, temperature regulation) aimed at supporting future Flight Demonstrator design selections
- Preliminary steps towards process intensification:
    - PBR working volume
    - System pressure
    - CO2 partial pressure
- Control System specifications approach:
    - Identification of time-scale separation of physical phenomena
    - Coupling of system dynamics
    - MIMO vs. SISO



BIORAT1 Timeline



Preliminary Requirement Review

Systems Requirements Review

Preliminary Design Review

Critical Design Review

Integration and Test Readiness Review

Final Acceptance Review

Flight Readiness Review

Decommissioning Review

S/S BBM(s)

EM

S/S QM(s)

TM

PFM(s)

2016 2017 2018 2020 2022

CONCLUSIONS

Conclusions 1 / 2

1. Knowledge models and engineering approach are required to reach challenging objectives of the atmosphere control of CELSS.

2. Predictive control of a photo-bioreactor in stand-alone and closed gas loop are successfully demonstrated

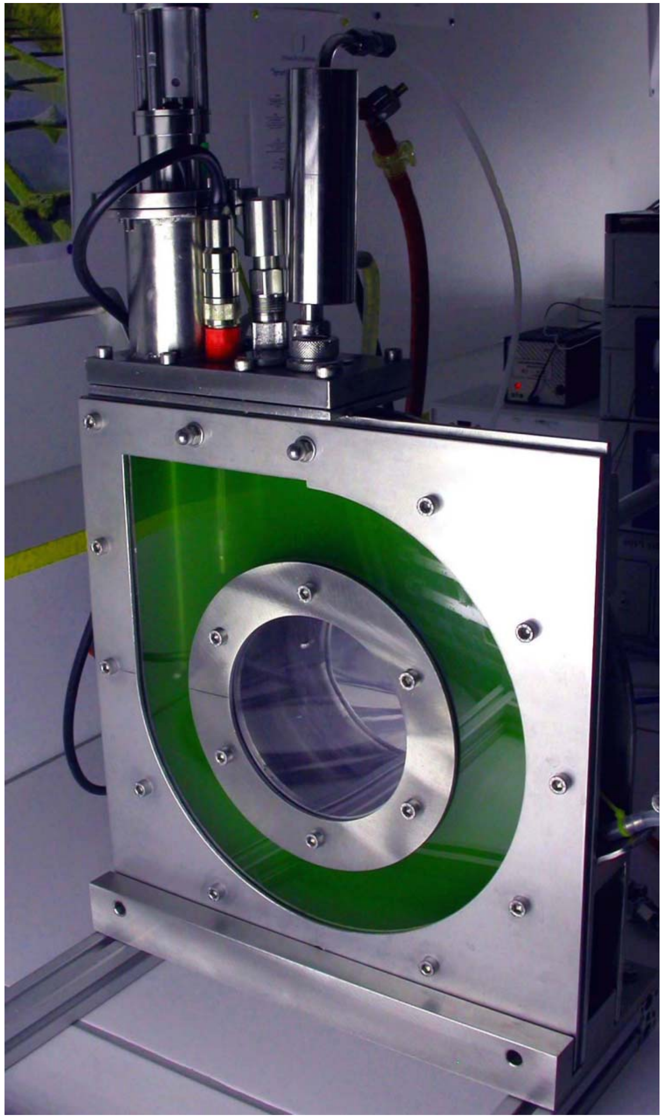
3. Space application development for the Validation of both technology and predictive control is on-going. However, today no direct transfer from terrestrial technology design possible:
    a. Safety
    b. Reliability
    c. Materials
    d. Operability
    e. ……

Conclusions 2 / 2

1. Increased efficiency for mass transfer across phases
    - Specific surface of exchange
    - Reduced mass transfer resistance in liquid phase (tailored hydrodynamics)
    - High-transfer membrane materials
    - Increased working pressures

2. Efficient Phase Separation
    - Gas from liquid
    - Solid from liquid
    - Liquid from gas

3. System Optimization (mass, volume, power) and scale-up for crew



Thank you for your attention