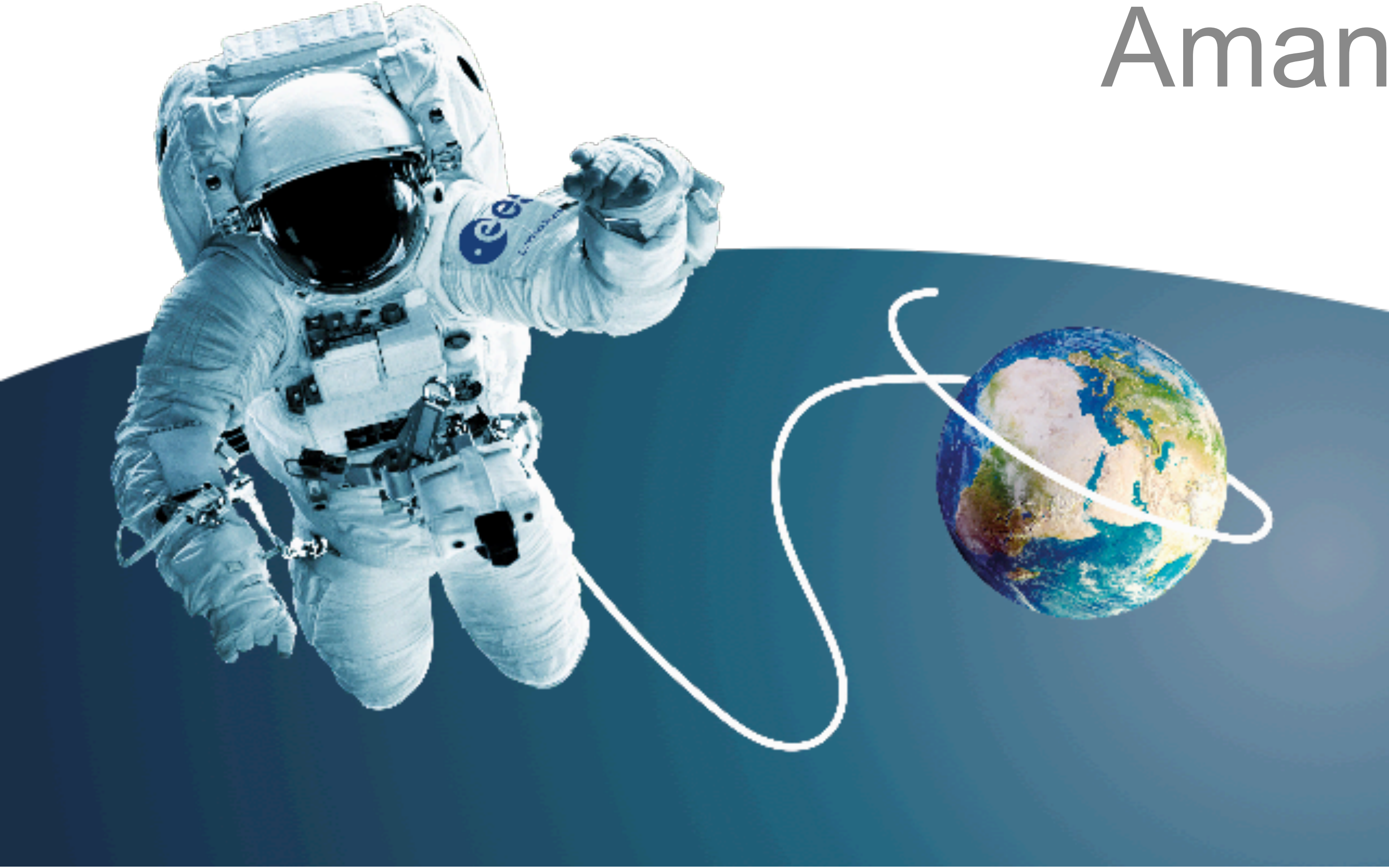
MELiSSA
MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

CREATING A CIRCULAR FUTURE

DESIGN AND CONTROL OF A BIOANODE FOR CO_2 RECOVERY IN REGENERATIVE LIFE SUPPORT SYSTEMS

Amanda Luther and Korneel Rabaey



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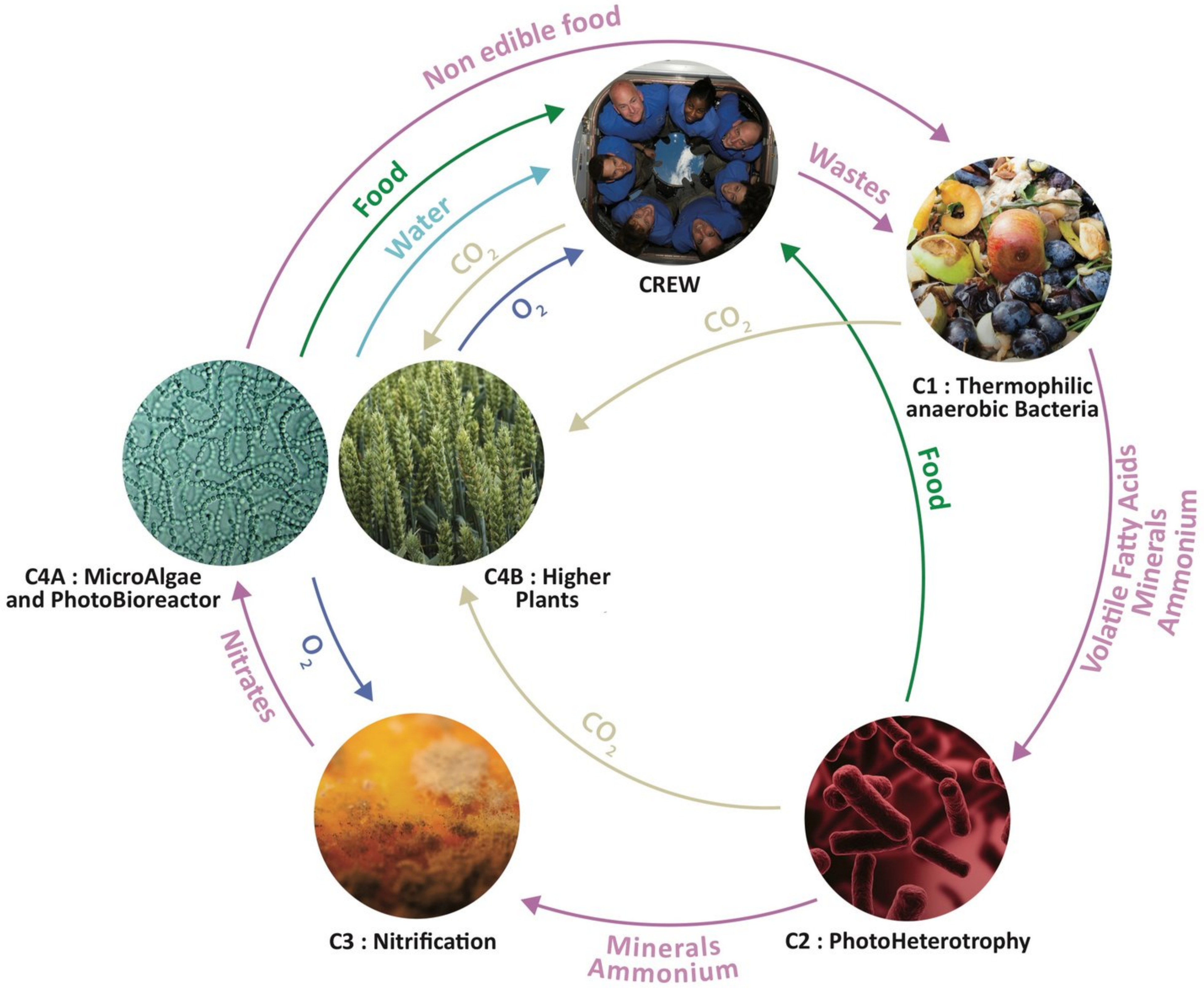
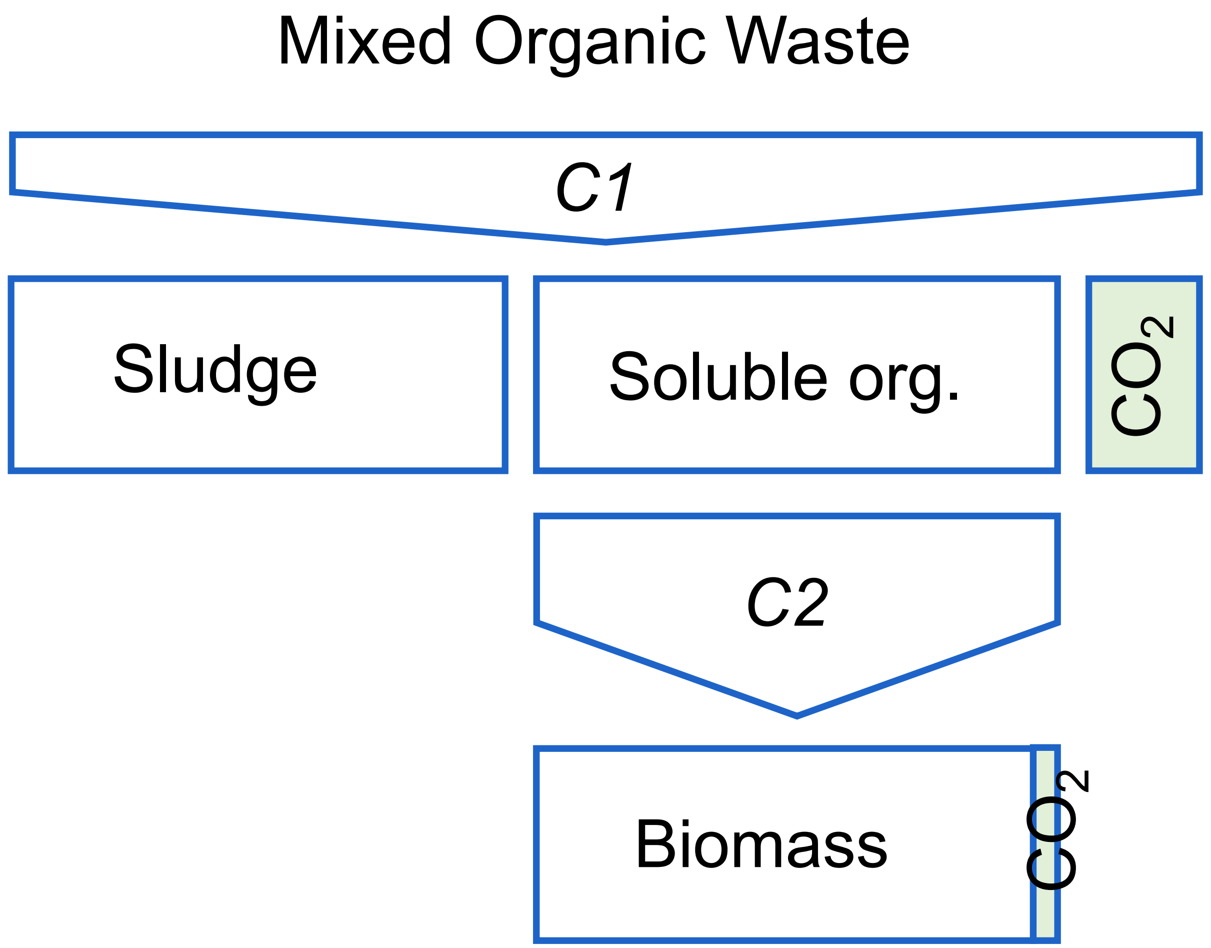
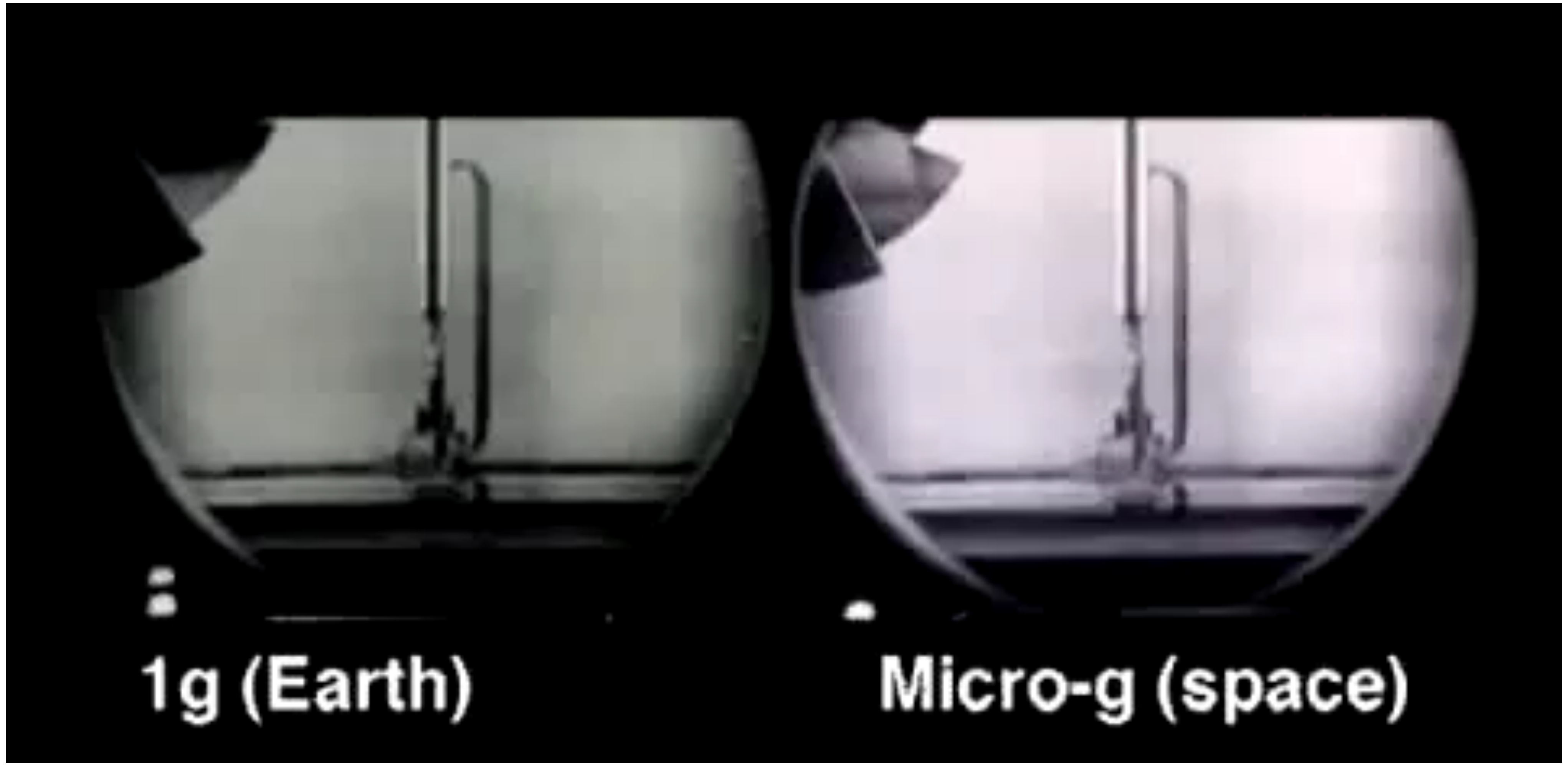
MELISSA: REGENERATIVE LIFE SUPPORT





CO_2 recovery through C1/C2 currently only ~ 15 %



Source: nasa.gov

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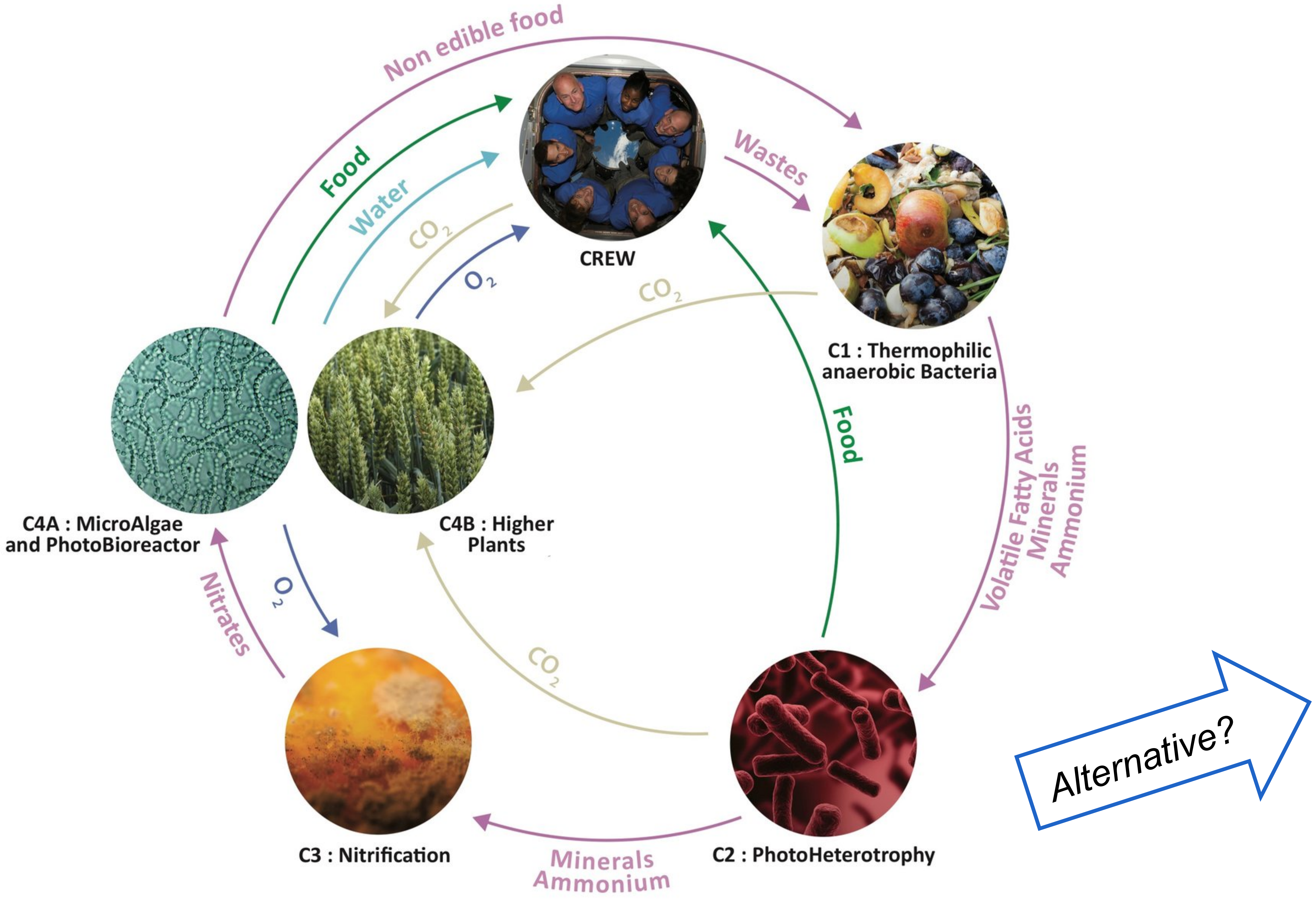
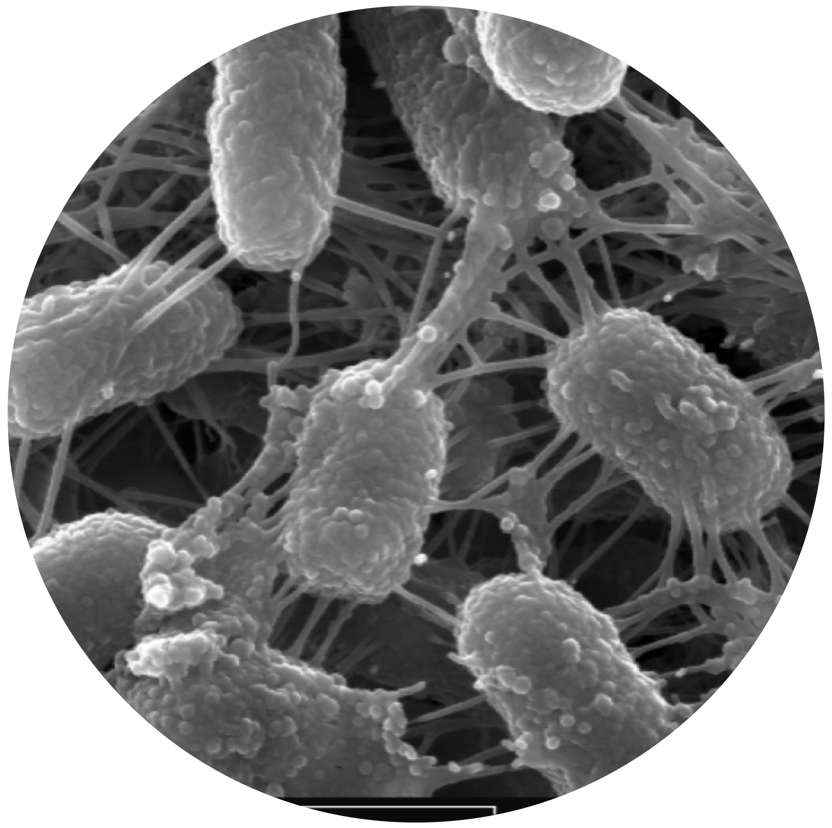
MELISSA: REGENERATIVE LIFE SUPPORT



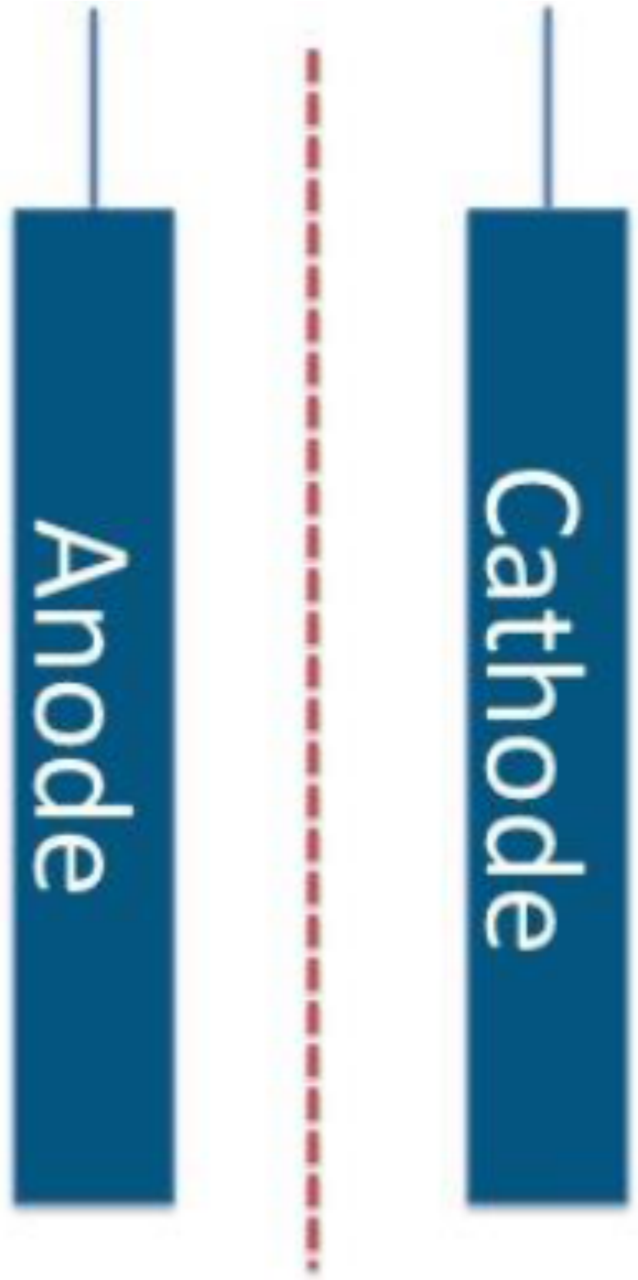
Alternative C2

- Current design has low potential for CO_2 recovery
- Bioelectrochemical systems have high potential for CO_2 recovery



C2: bioanodic respiration

AN ELECTROCHEMICAL CELL



Anode

Oxidation occurs

Cathode

Reduction occurs

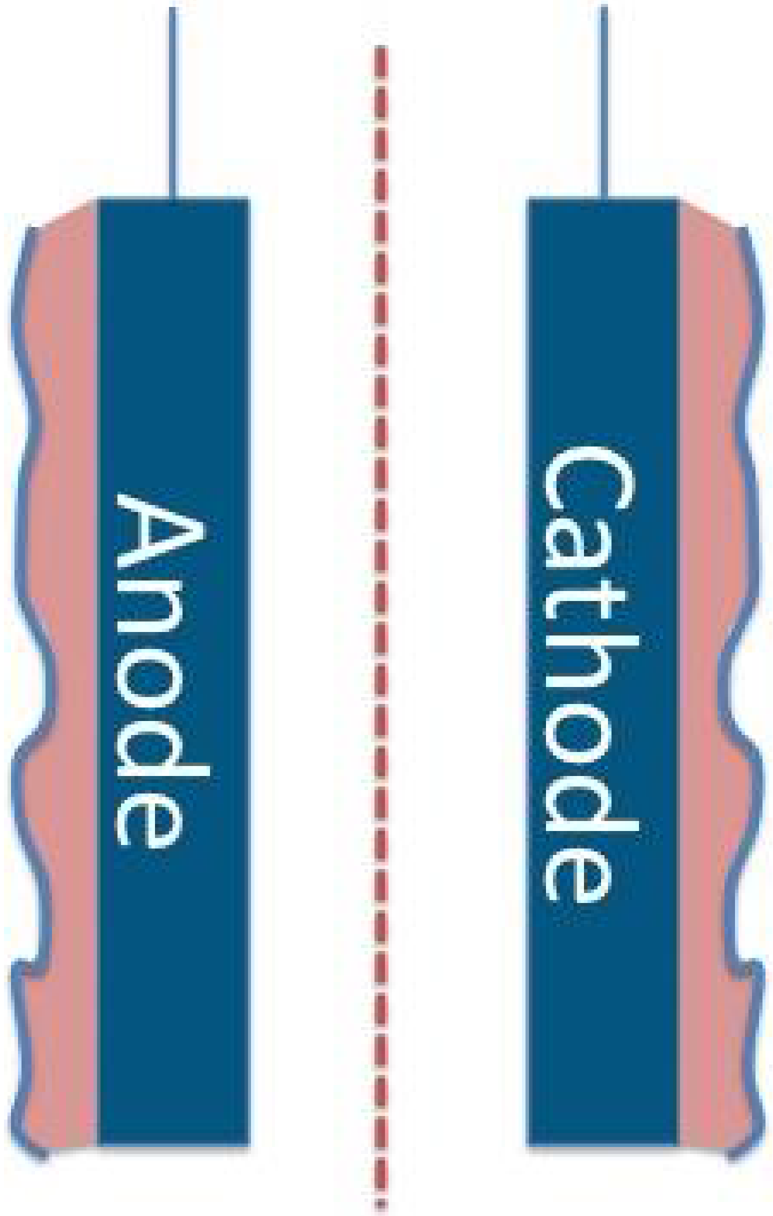
Separator

Ion exchange membrane

Cations

Anions

BIOELECTROCHEMICAL SYSTEMS (BES)



Microorganisms can be good catalysts:

(1) lower the reaction energy
(2) produce a wide variety of products
(3) take up a wide variety of substrates
(4) be highly specific
(5) renew themselves

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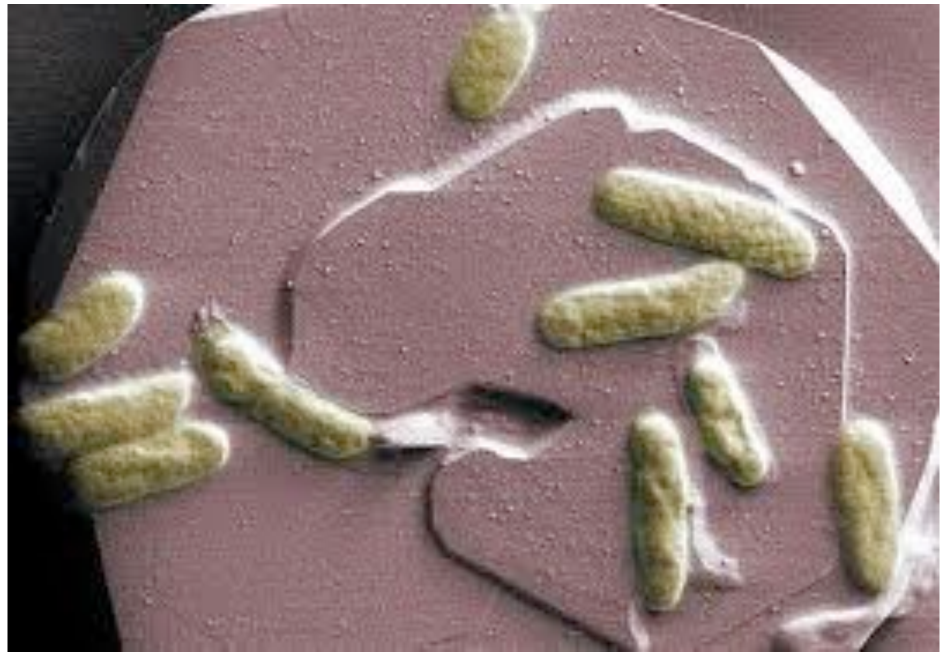
www.geobacter.org



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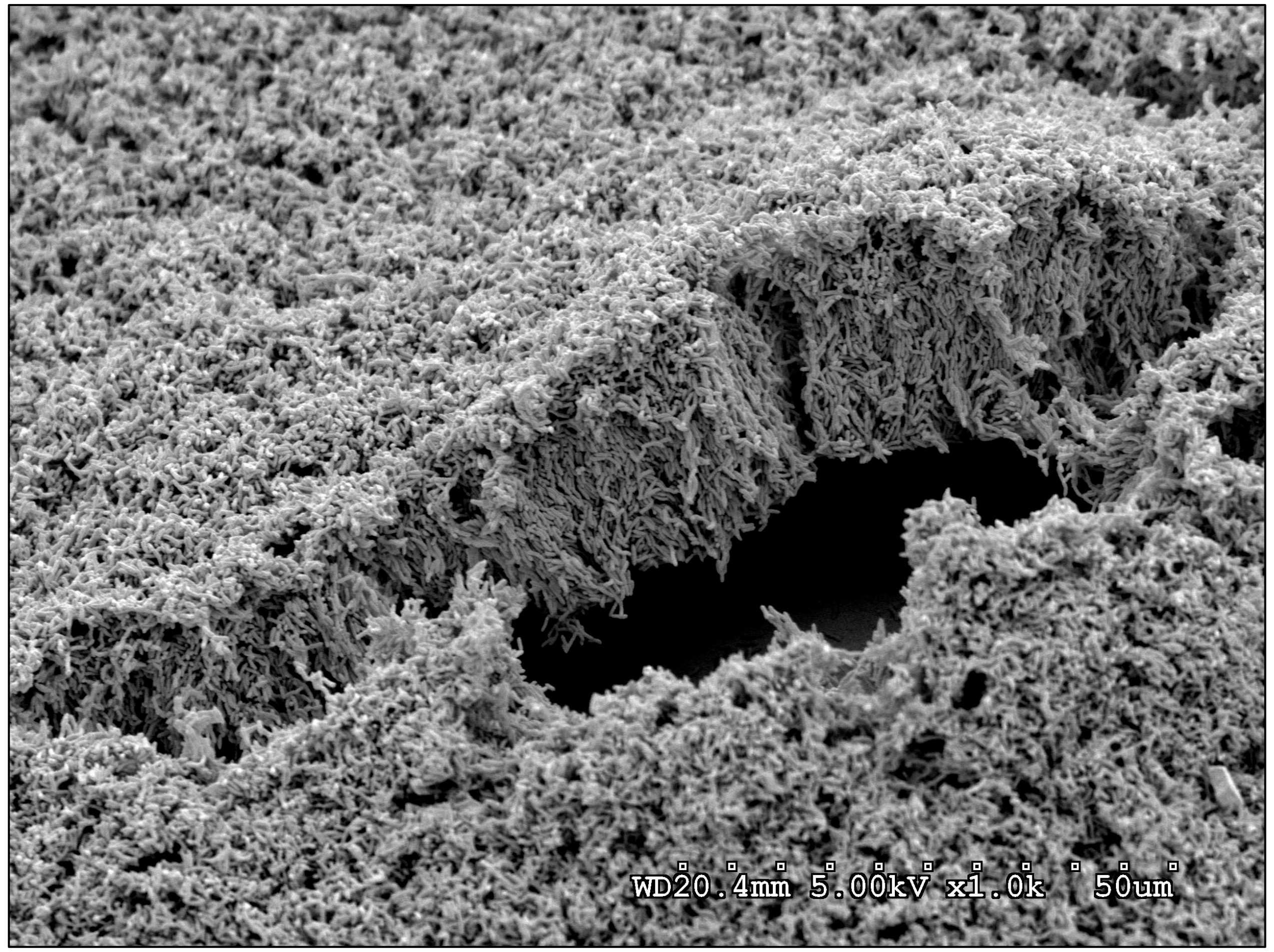


Image: Daniel Bond

Bioremediation (see www.electra.site)

Microbial electrosynthesis (BioRECO2VER, ELECTROTALK…)

Wastewater treatment (e.g. www.metfilter.com)

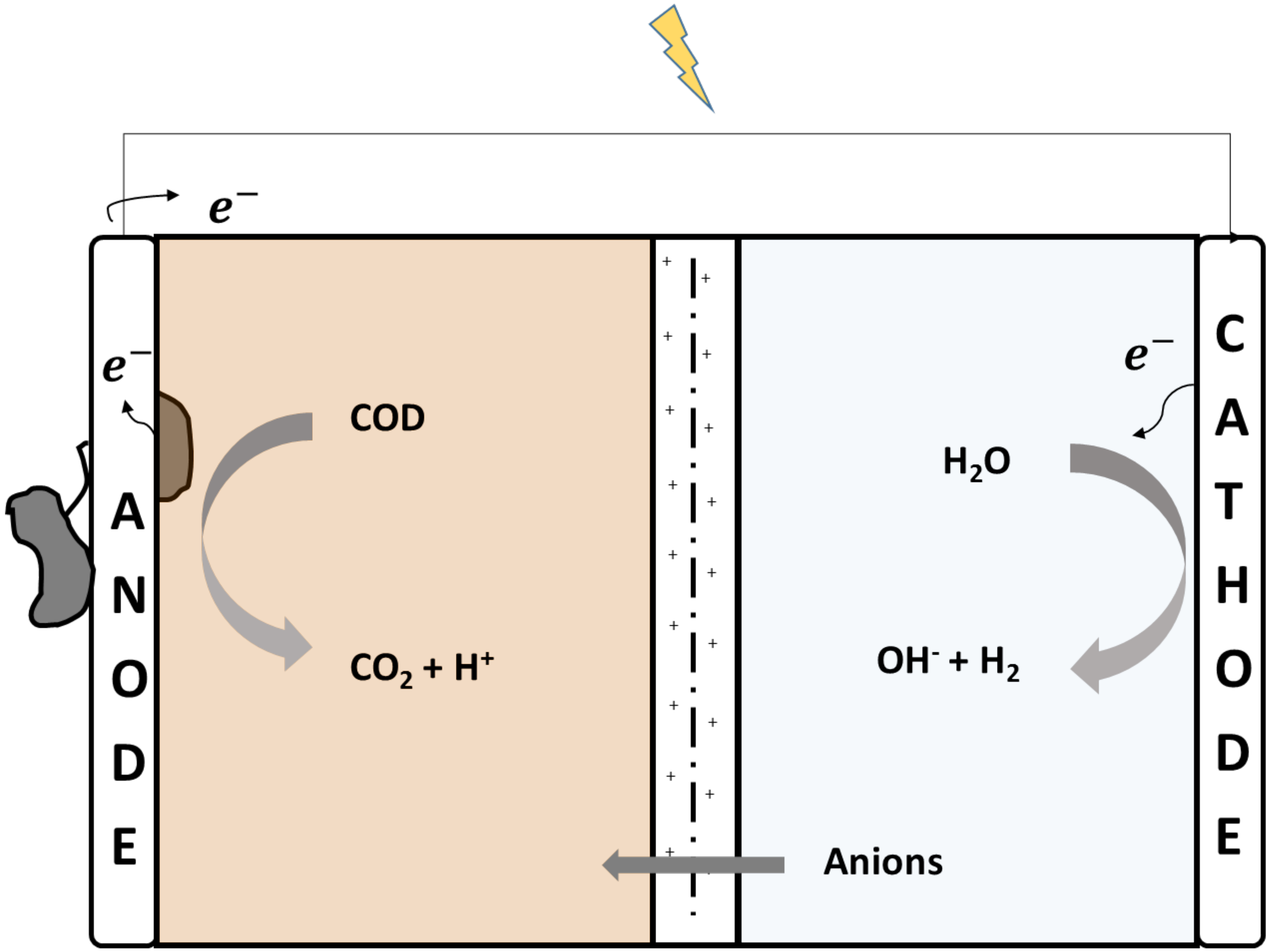
Biosensing (e.g. EA Biofilms)

Health

…

BIOANODIC OXIDATION – UNIQUE FEATURES

- Attached biomass at low yield
- Caustic production by cathode
- Anodic oxidation without gas sparging needs
- Ammonia stays ammonia
- Driven by electricity, highly controllable



COD = chemical oxygen demand = proxy for substrate

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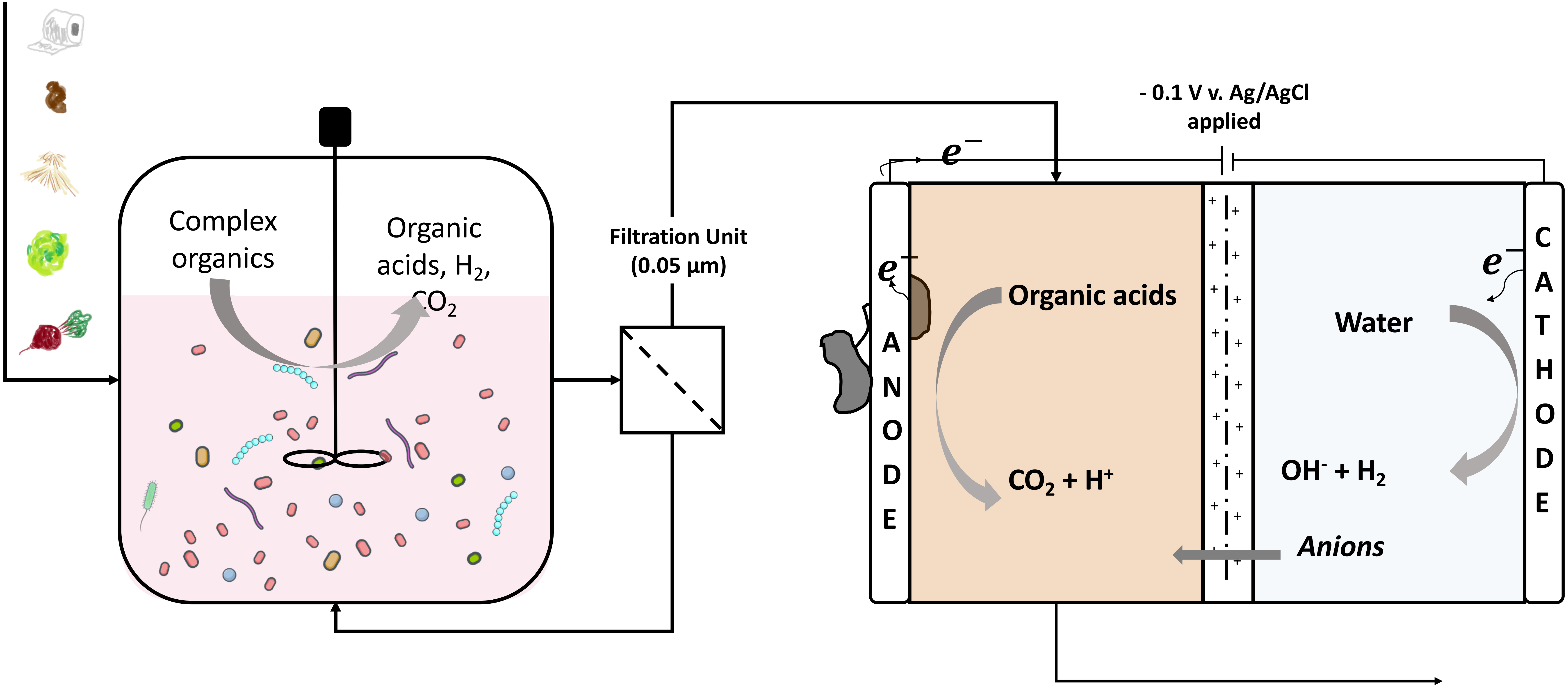
FERMENTATION + BIOANODE



Thermophilic Membrane Fermentation

Anodic Respiration

PERFORMANCE: FOLLOW THE ELECTRONS

Not degraded

(remains as VFA?)

Substrate COD

(acetate, butyrate, ethanol, etc)

(4 mol e^- per mol O_2)

Current produced

(result of respiration using anode as electron acceptor with production of CO_2)

Alternative electron acceptors?

(e.g., methanogenesis, fermentation)

Cell growth

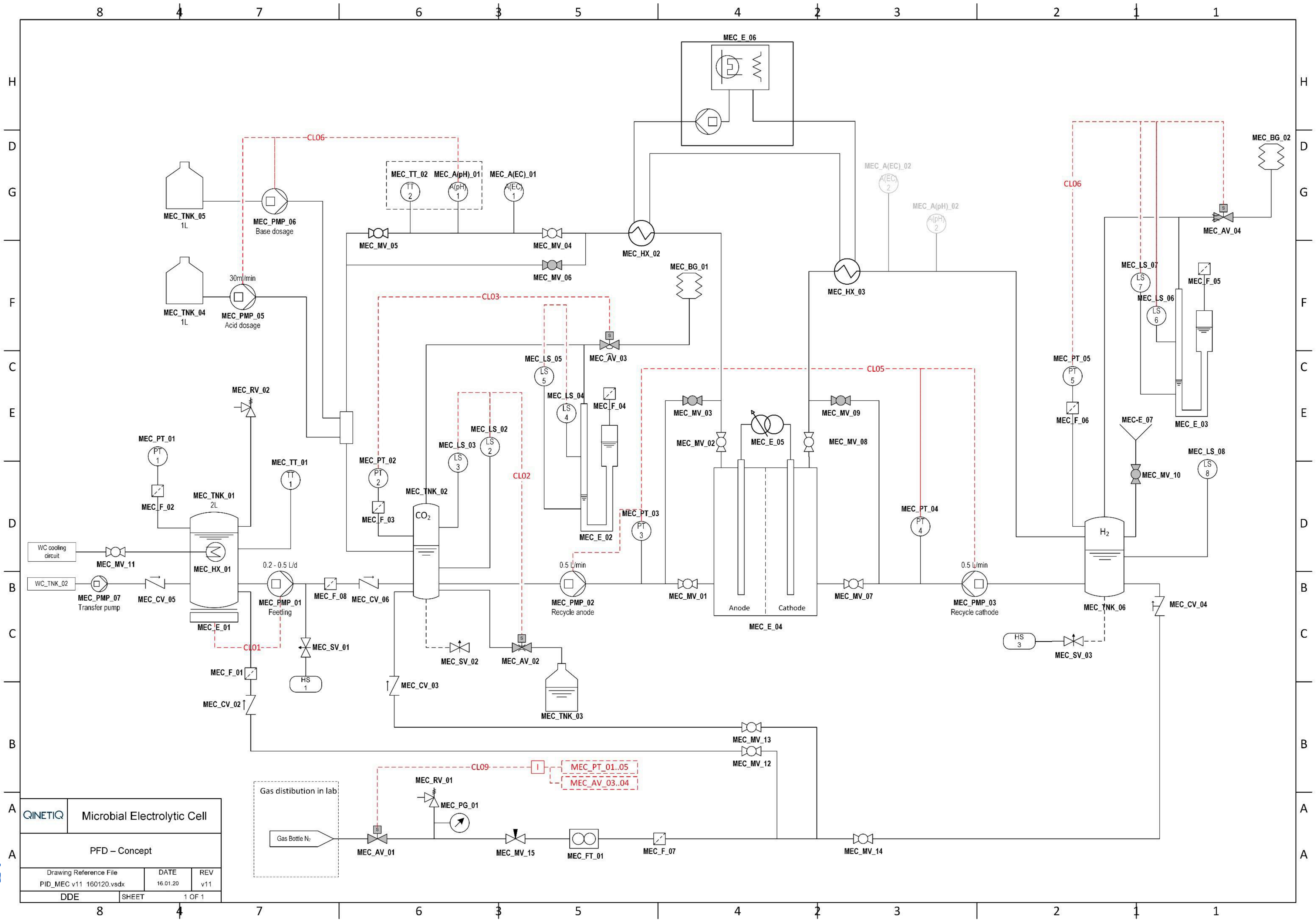
(biofilm, unavoidable)

PEFORMANCE TARGETS

- High efficiency of VFA conversion to CO_2
- Carbon and Nitrogen closure to 90 %
- System compatible with sterilization
- Low permeability for gas components
- Minimize bacterial growth on surfaces
- Long term stable performance

DESIGN FEATURES

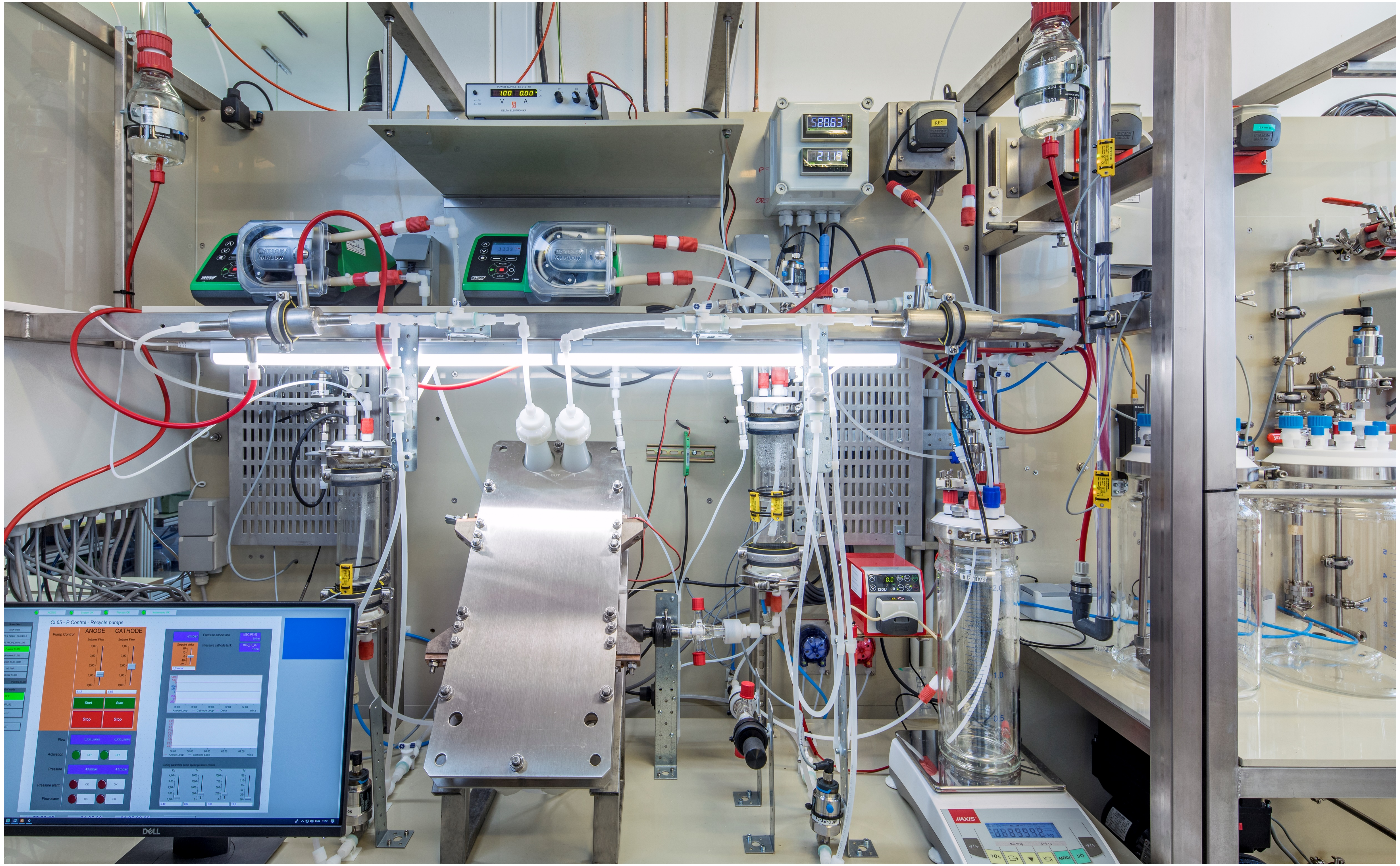
- ✓ Customized hardware and control system
  - ✓ Power supply
  - ✓ Pressure balance
- ✓ Careful material selection
- ✓ Gas tightness
- ✓ Sterile integration with upstream C1
- ✓ Multiple operation modes



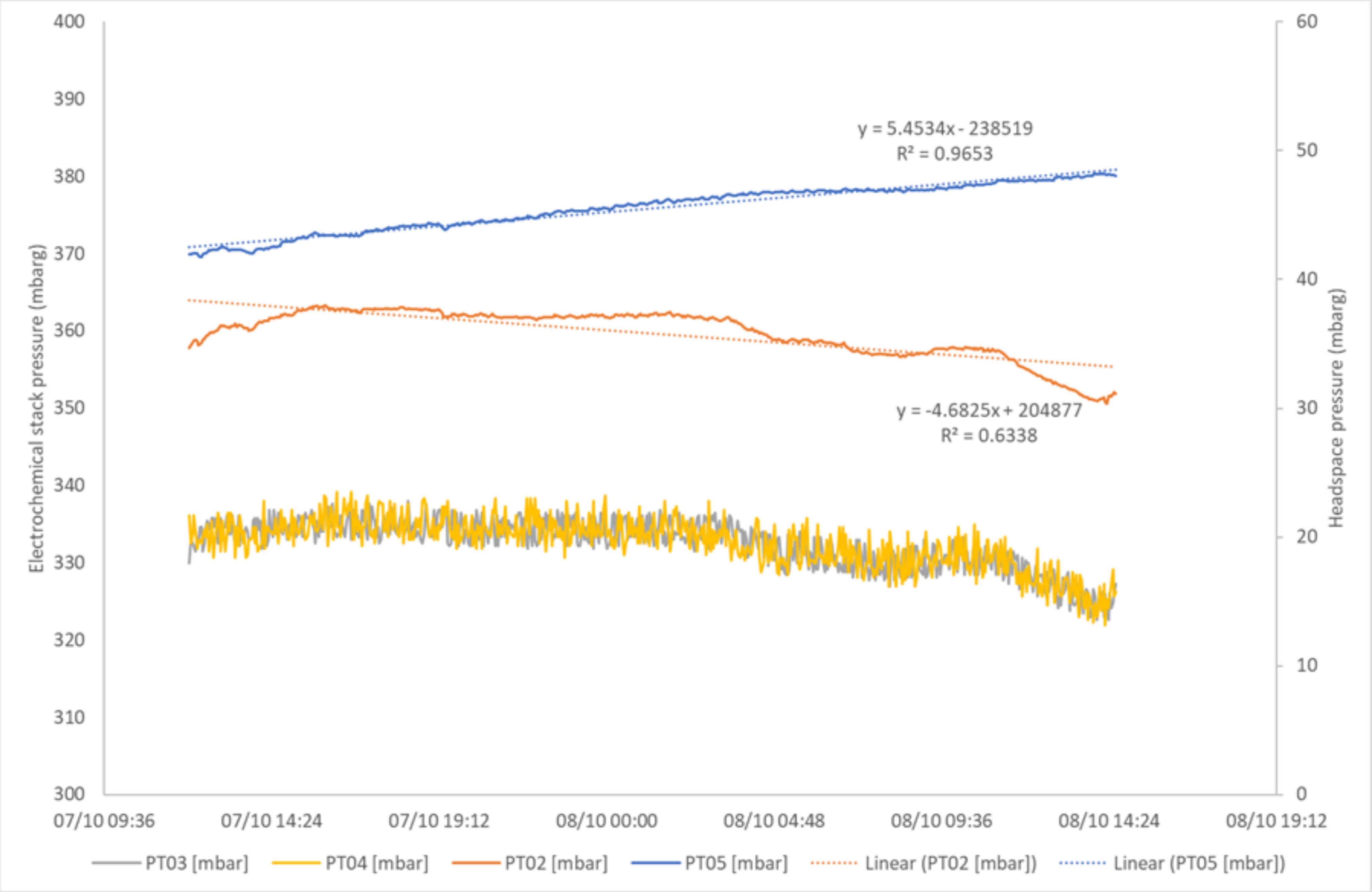
Microbial Electrolytic Cell
PFD – Concept
Drawing Reference File
PID_MEC v11 160120.vsdx
DATE
16.01.20
REV
v11
DDE
SHEET
1 OF 1
QINETIQ
Gas distibution in lab
Gas Bottle N2
MEC_E_06
MEC_TNK_05
1L
MEC_PMP_06
Base dosage
MEC_TNK_04
1L
MEC_PMP_05
Acid dosage
30ml/min
CL06
MEC_TT_02
MEC_A(pH)_01
MEC_A(EC)_01
MEC_MV_05
MEC_MV_04
MEC_MV_06
MEC_HX_02
MEC_HX_03
MEC_BG_01
MEC_BG_02
MEC_A(EC)_02
MEC_A(pH)_02
CL03
MEC_AV_03
MEC_AV_04
MEC_LS_05
MEC_LS_04
MEC_F_04
MEC_E_02
MEC_LS_07
MEC_LS_06
MEC_F_05
MEC_E_03
CL05
MEC_MV_03
MEC_MV_09
MEC_MV_02
MEC_E_05
MEC_MV_08
MEC_PT_05
MEC_F_06
MEC-E_07
MEC_MV_10
MEC_LS_08
MEC_RV_02
MEC_PT_01
MEC_F_02
MEC_TT_01
MEC_TNK_01
2L
MEC_PT_02
MEC_F_03
MEC_LS_03
MEC_LS_02
CL02
MEC_TNK_02
CO2
MEC_PT_03
MEC_PT_04
H2
WC cooling circuit
MEC_MV_11
MEC_HX_01
0.2 - 0.5 L/d
0.5 L/min
WC_TNK_02
MEC_PMP_07
Transfer pump
MEC_CV_05
MEC_PMP_01
Feeding
MEC_F_08
MEC_CV_06
MEC_PMP_02
Recycle anode
MEC_MV_01
Anode
Cathode
MEC_E_04
MEC_MV_07
MEC_PMP_03
Recycle cathode
MEC_TNK_06
MEC_CV_04
MEC_E_01
CL01
MEC_SV_01
MEC_SV_02
MEC_AV_02
HS 3
MEC_SV_03
MEC_F_01
HS 1
MEC_CV_03
MEC_TNK_03
MEC_CV_02
MEC_MV_13
MEC_MV_12
CL09
MEC_PT_01..05
MEC_AV_03..04
MEC_RV_01
MEC_PG_01
MEC_AV_01
MEC_MV_15
MEC_FT_01
MEC_F_07
MEC_MV_14


28.53
28.97
DI water
6.1

MEC SYSTEM HARDWARE



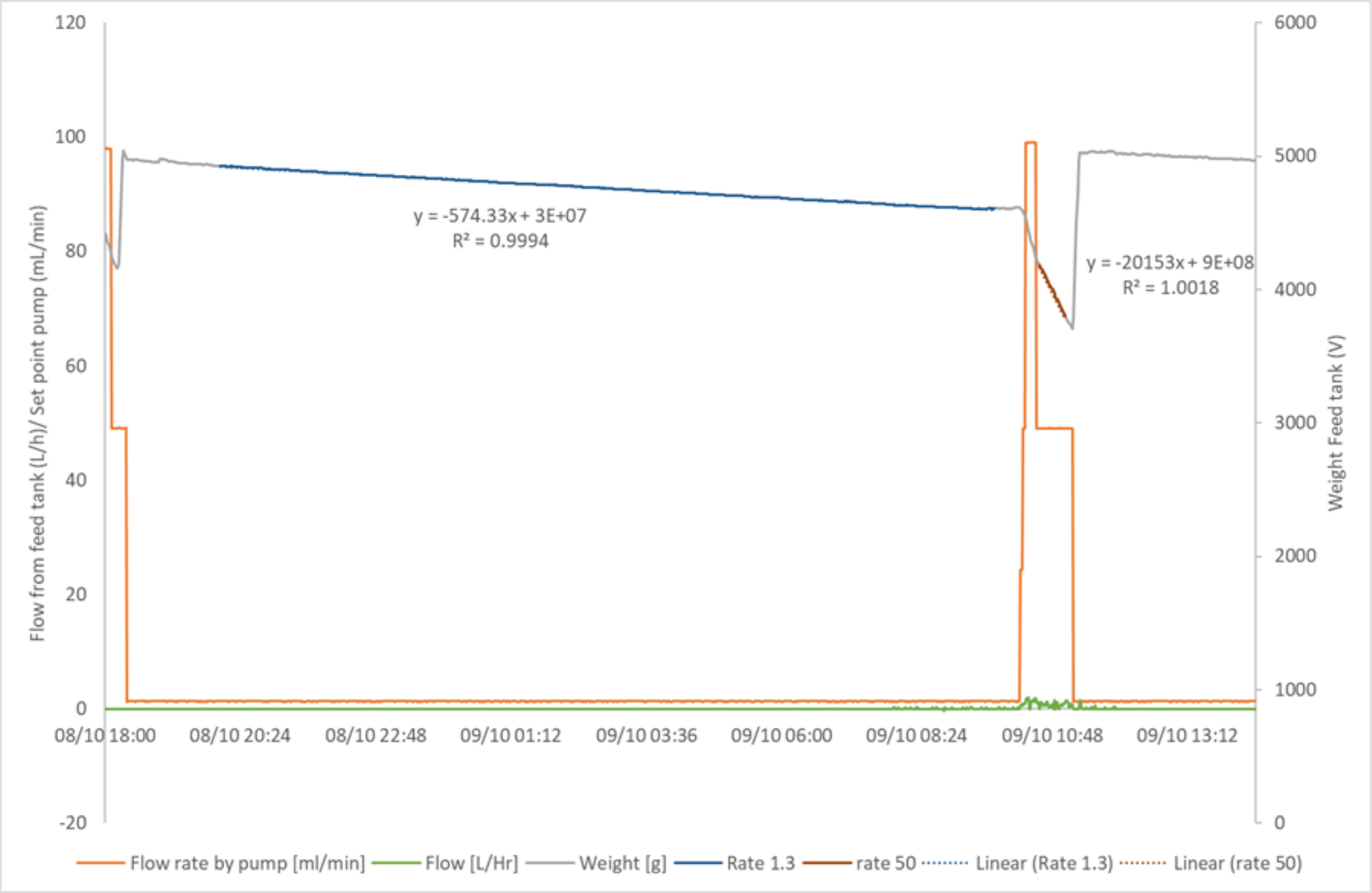
GAS TIGHTNESS ACHIEVED



- 24 h pressure test
- Slight gain cathode, slight drop anode due mainly to water migration
- Possible loss of ~5-10 mL gas per day

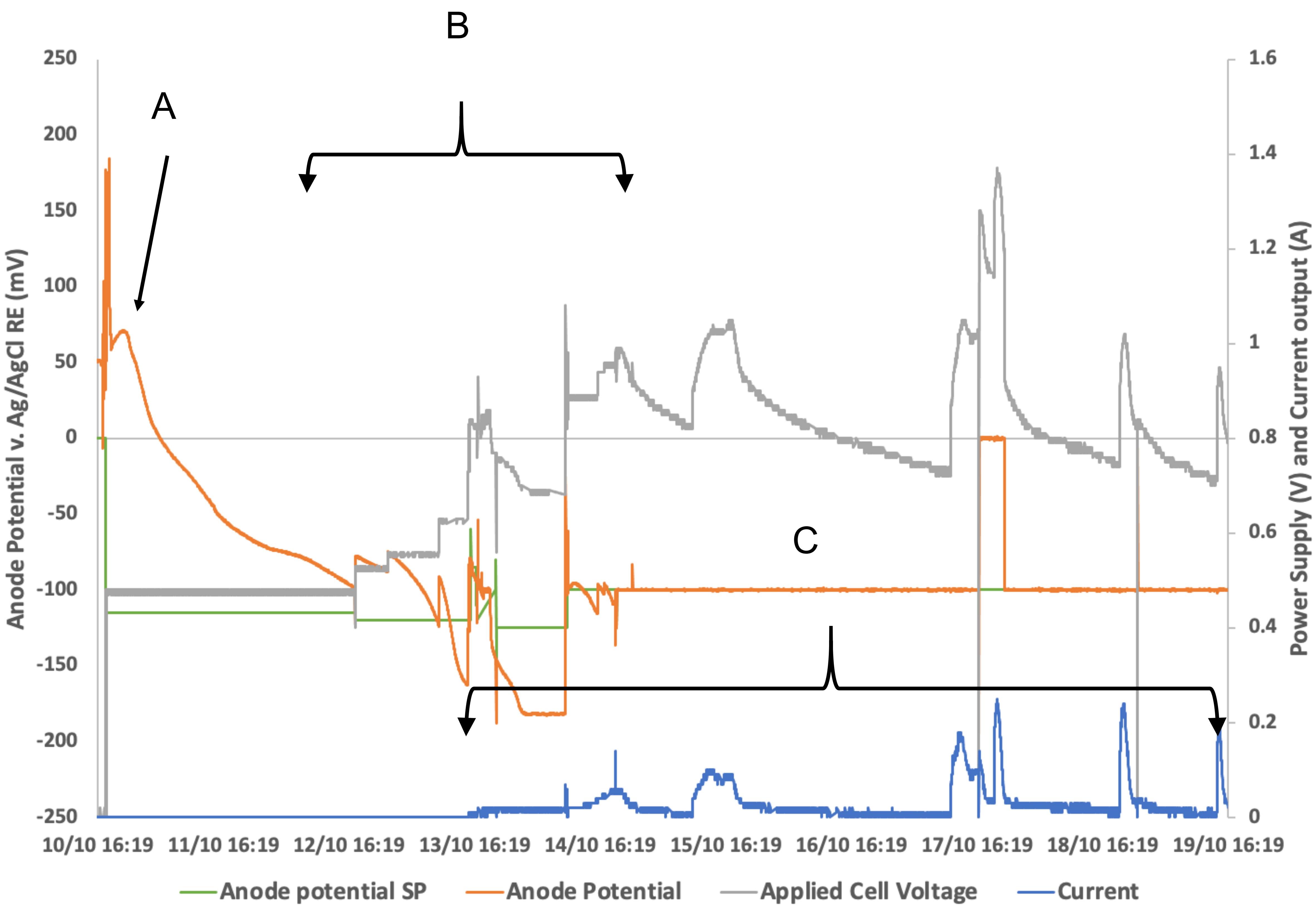
Anode headspace: red, cathode headspace: blue, anode stack inlet: grey, cathode stack inlet: yellow.

SYSTEM MASS FLOW BALANCE CONFIRMED



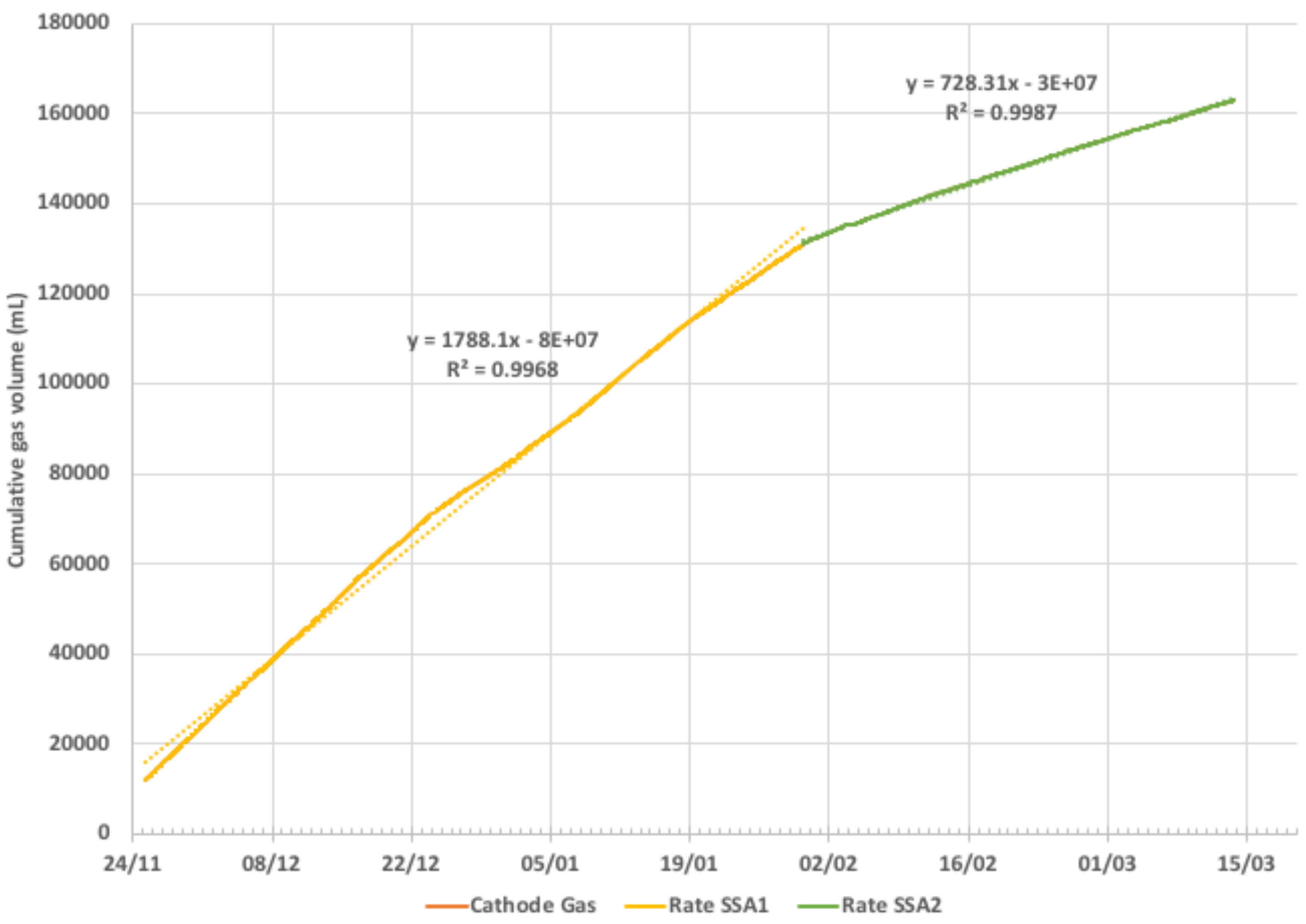
- Low salt solution + nitrogen gas, working pressure, near working flows
- 18 h test
- 99.6 % mass balance closure (effluent out over feed in)

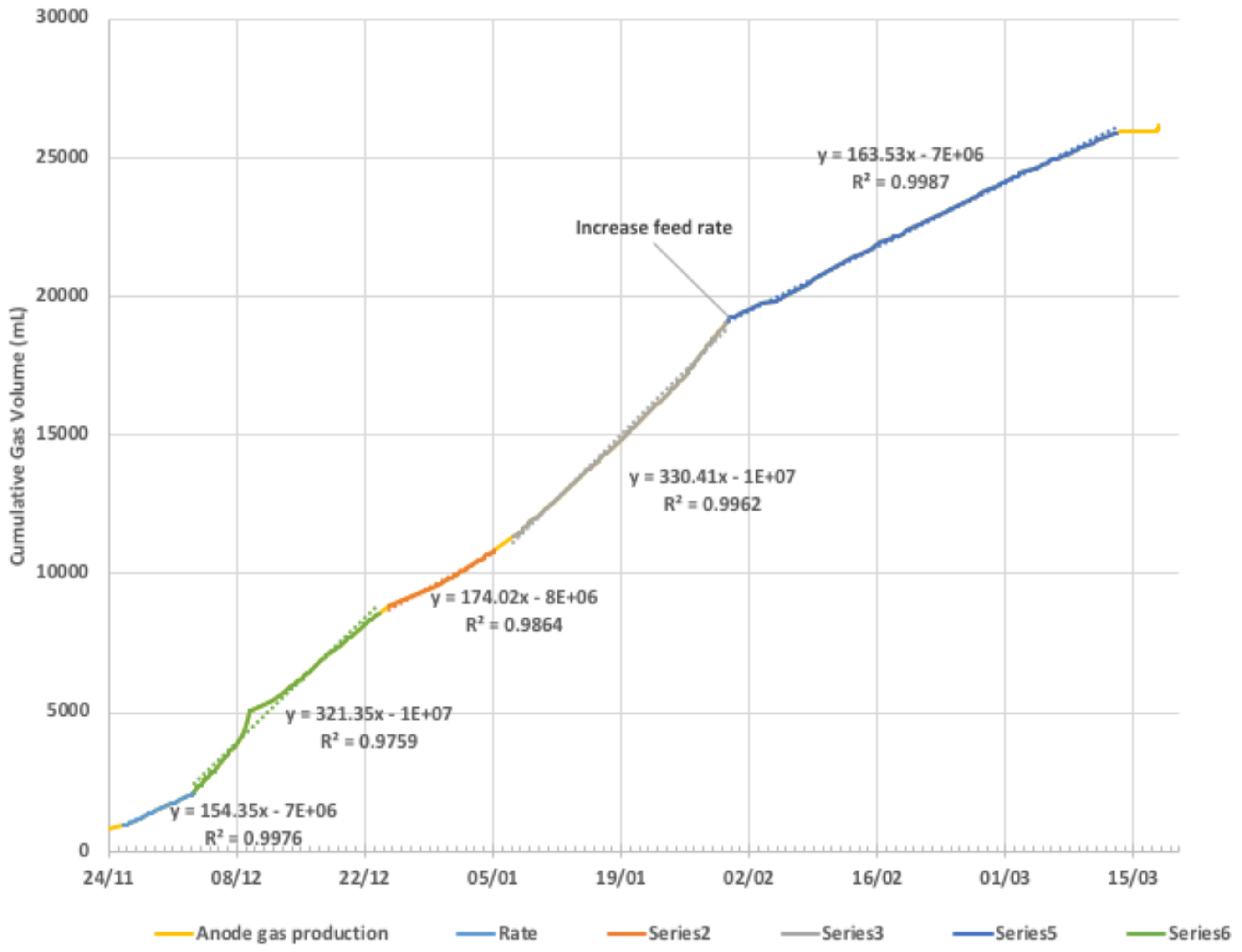
INOCULATION AND BATCH STARTUP



A. Inoculation
B. tuning anode potential control
C. batch feeding and potential control

STABLE GAS PRODUCTION





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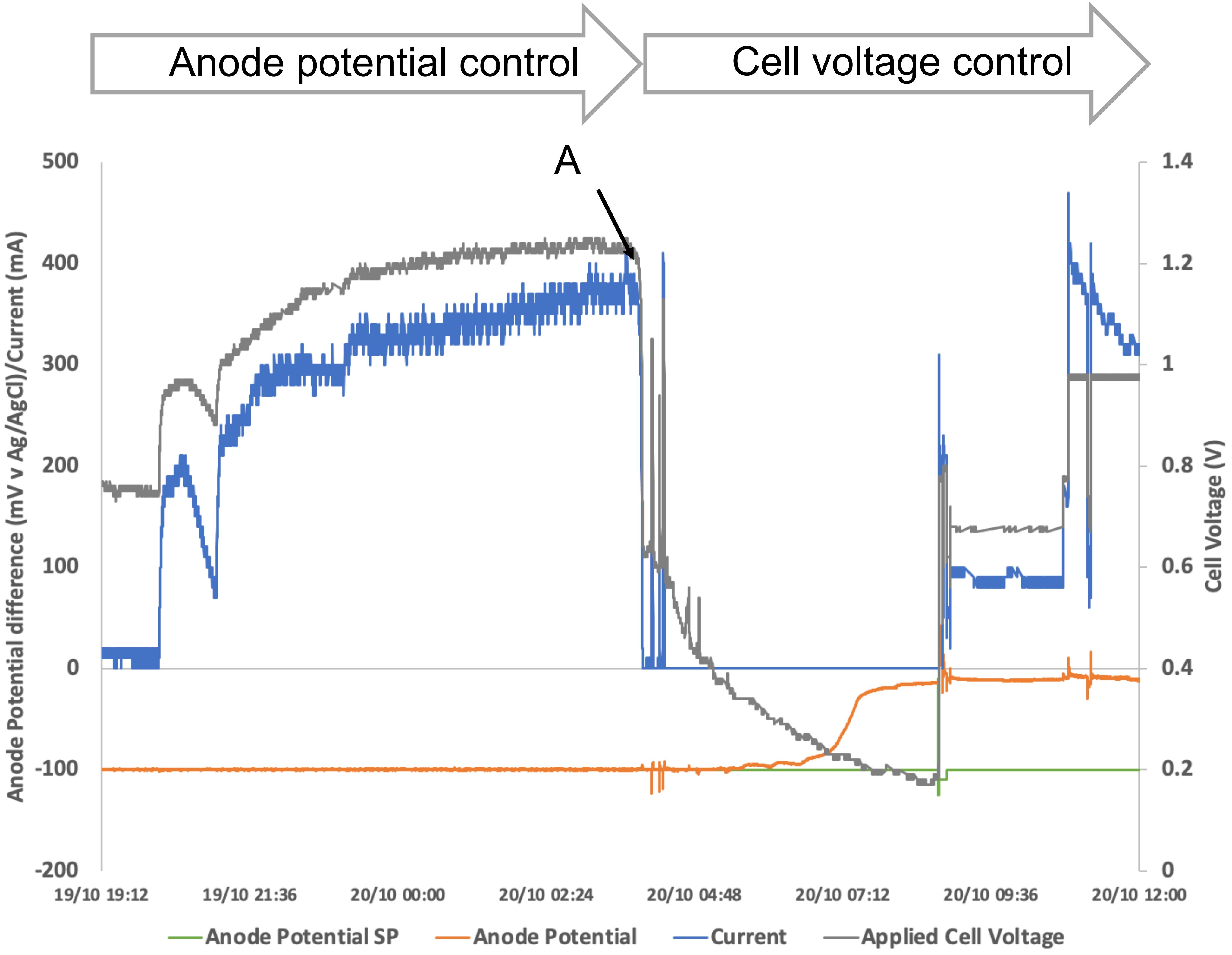
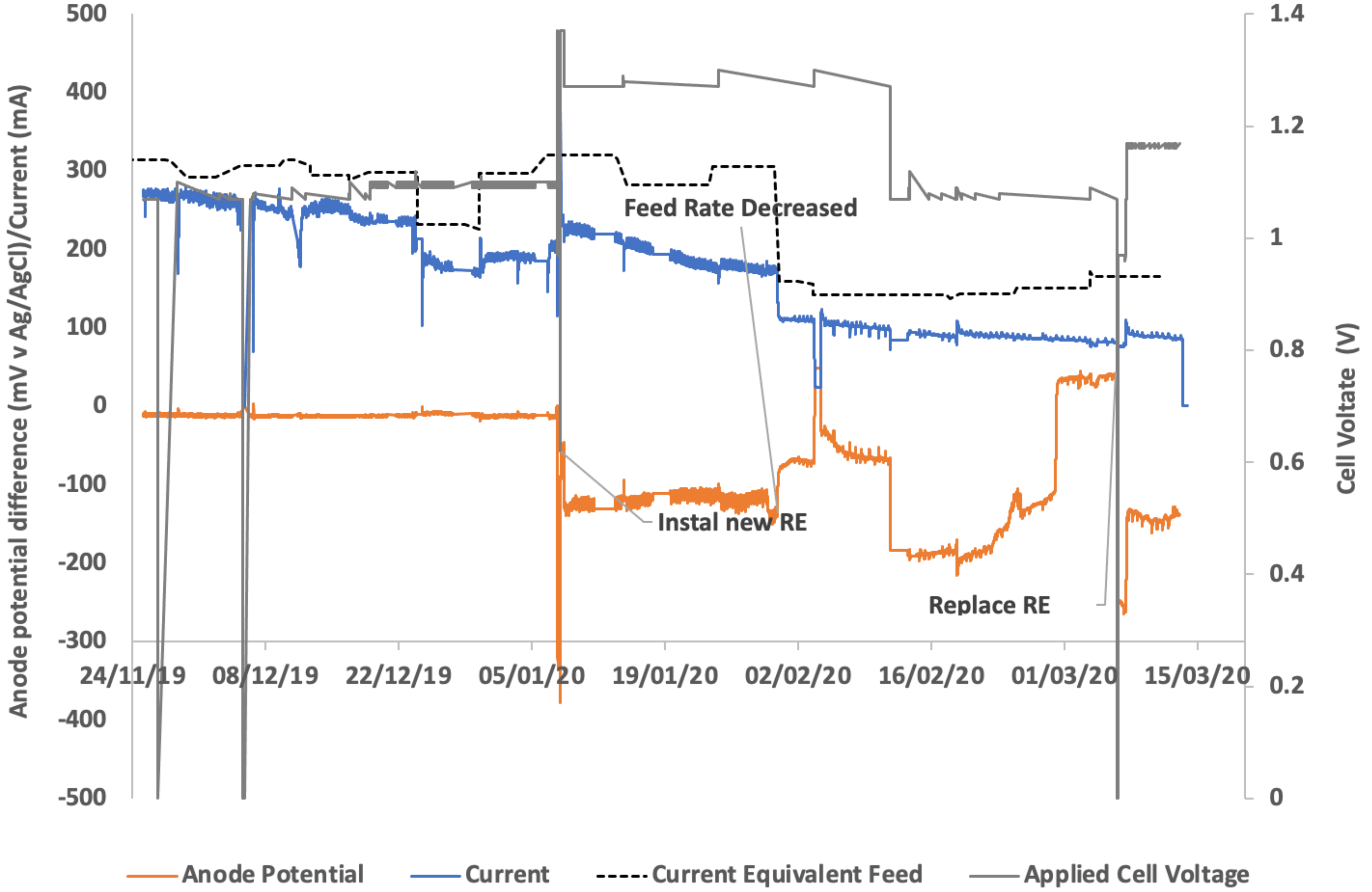
RE FAILURE AND POTENTIAL CONTROL



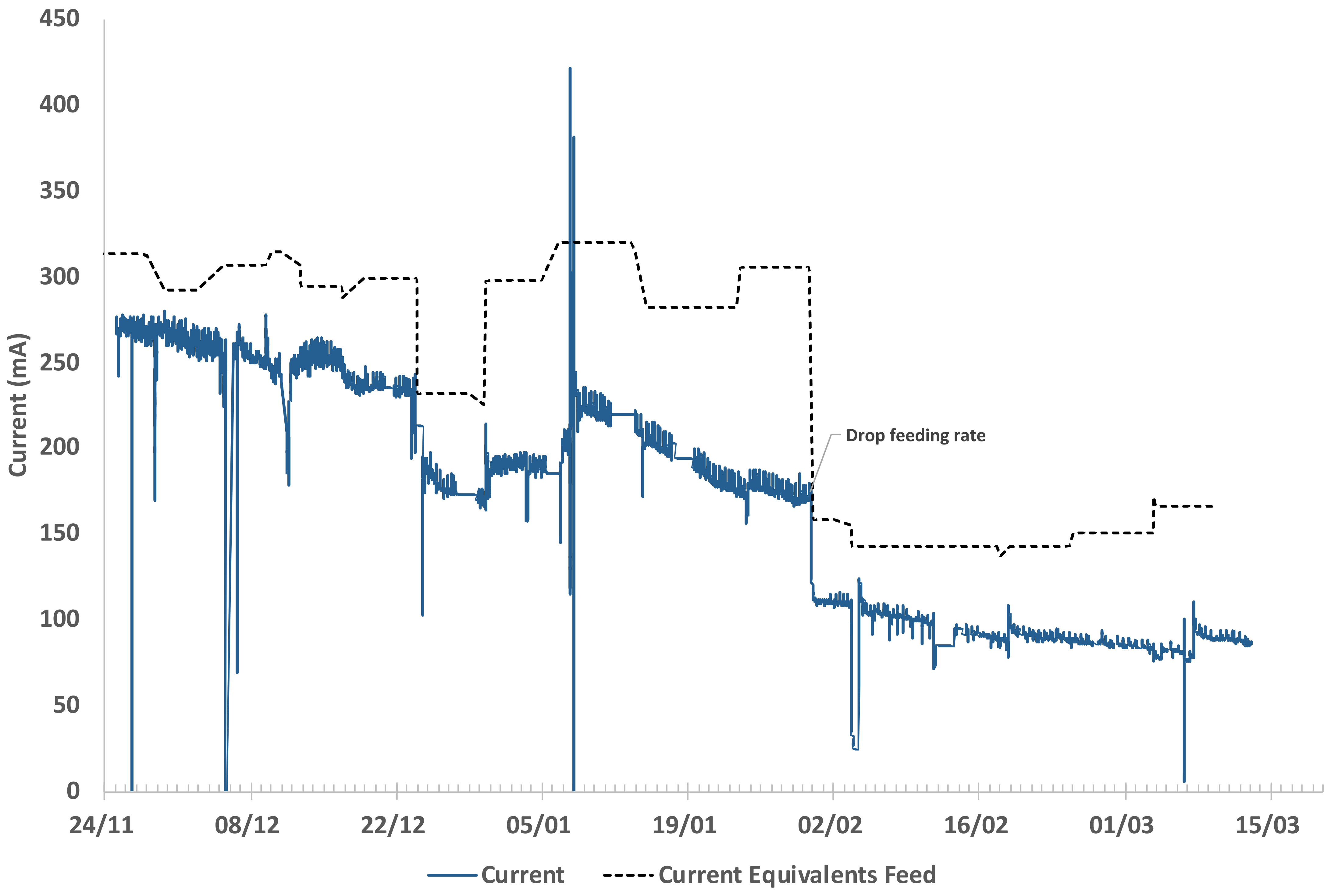
- RE failure (A)
- Switch control modes
- RE compatibility to be resolved in this system (humic acids/phenolics)

CURRENT PRODUCTION LONG TERM



- 4 month operation
- RE failure required fixed cell voltage control
- RE signal recovery

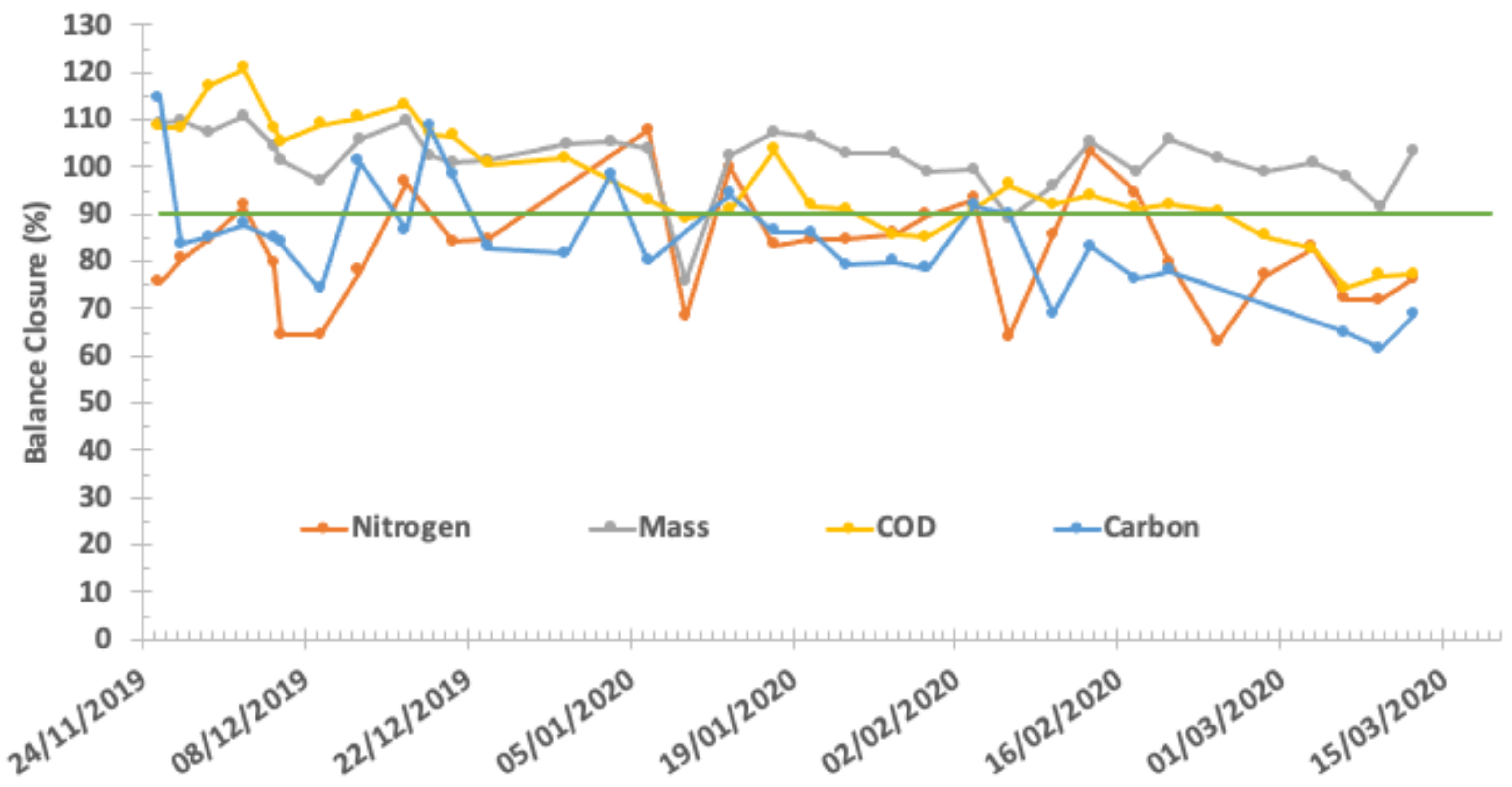
CURRENT PRODUCTION LONG TERM



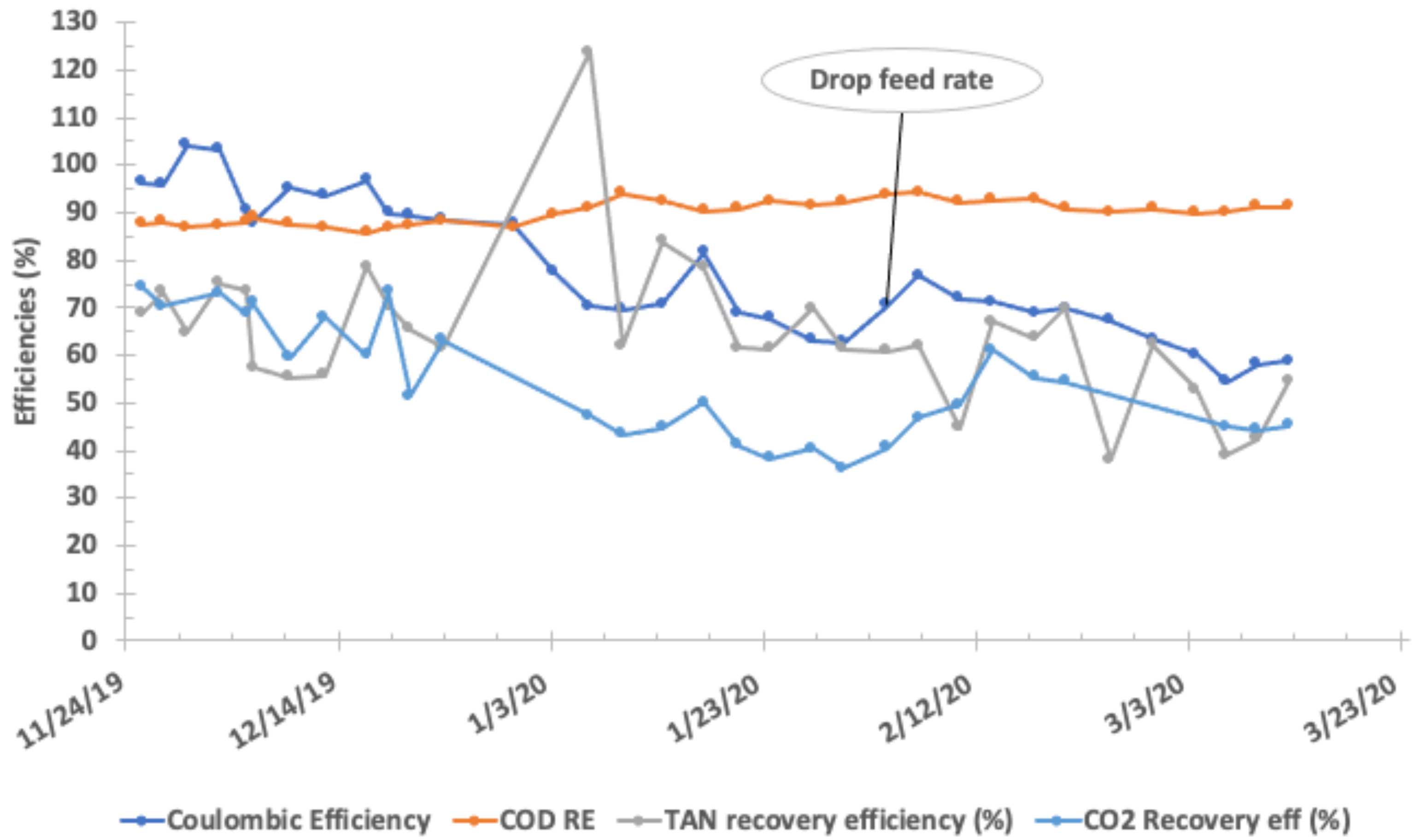
- 4 month operation
- RE failure required fixed cell voltage control
- RE signal recovery

STEADY STATE PERFORMANCE

Mass Balance

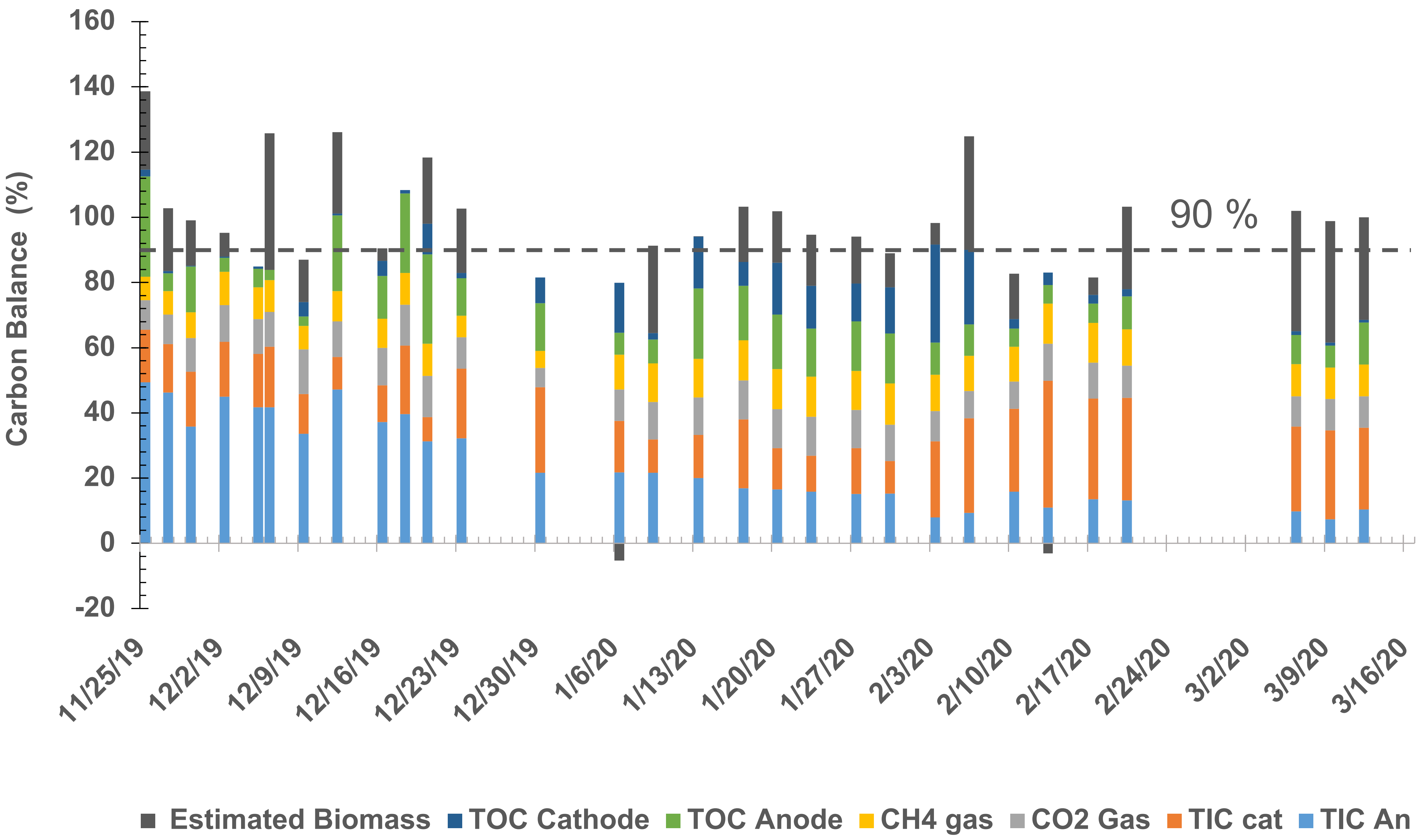


Efficiencies



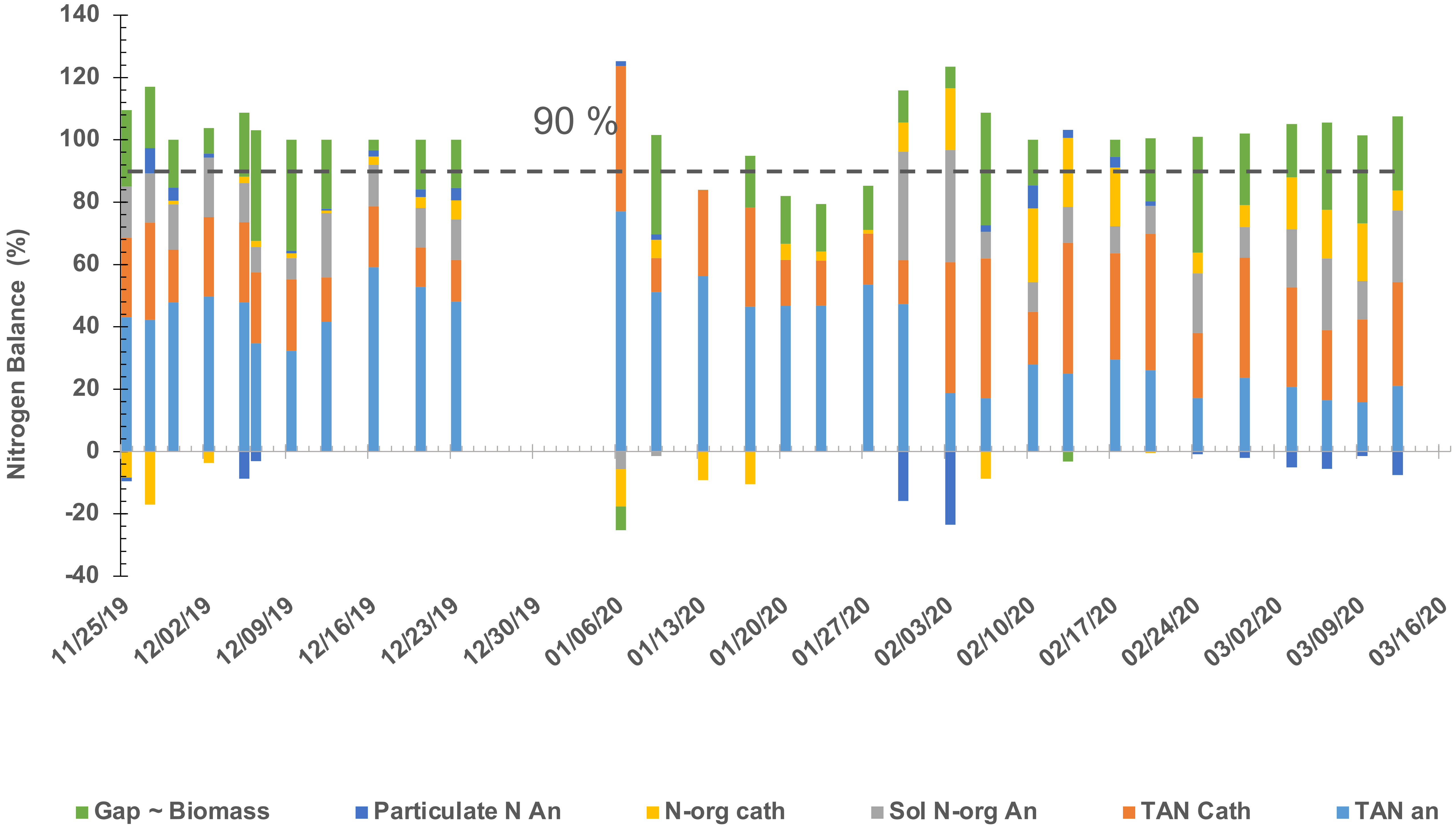
Efficiency of pH control by cathode was 83 % ± 2 %

CARBON DISTRIBUTION STEADY STATE



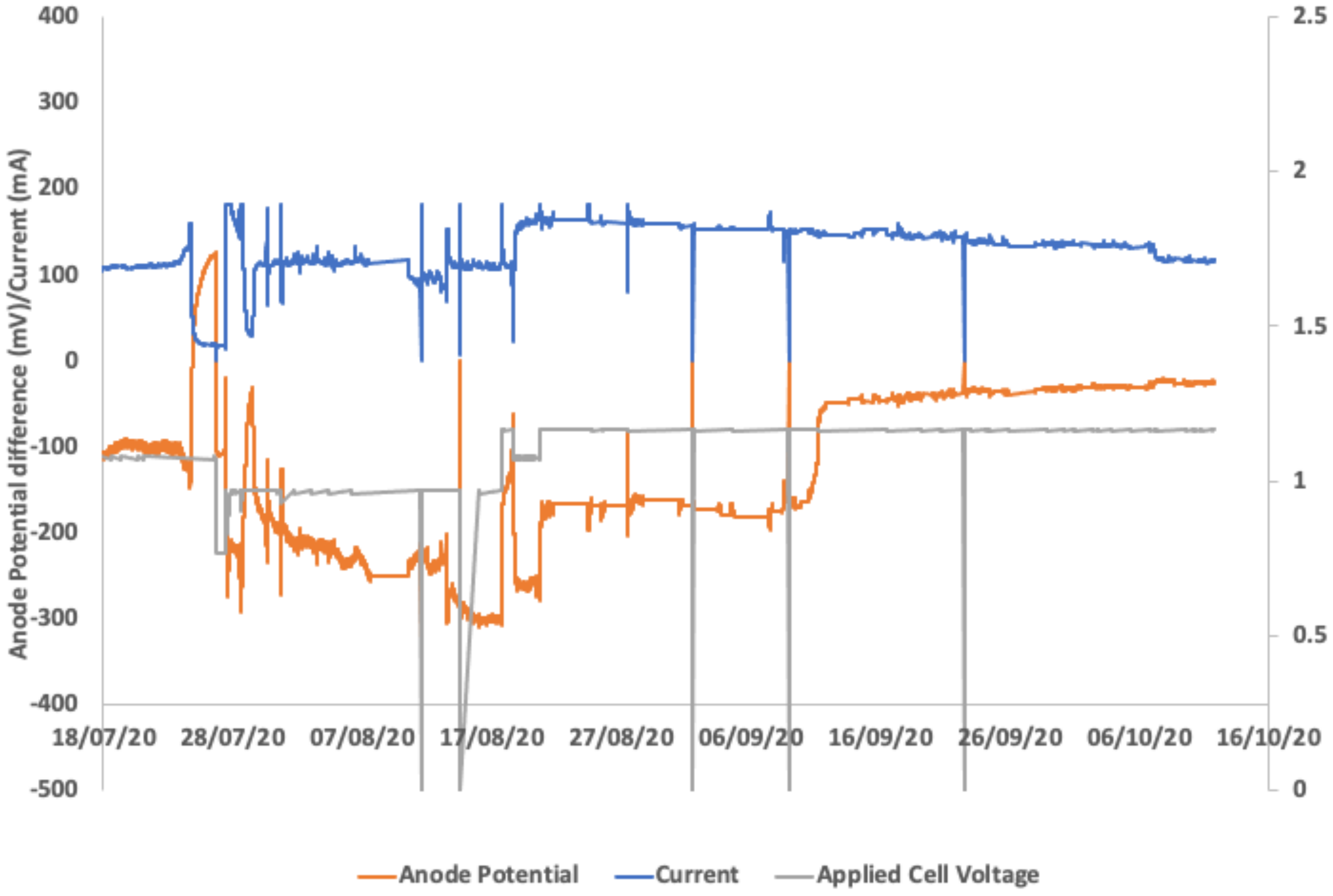
CO_2	57 ± 13 %
Organics	20 ± 11 %
Methane	10 ± 2 %
Biomass	16 ± 11 %

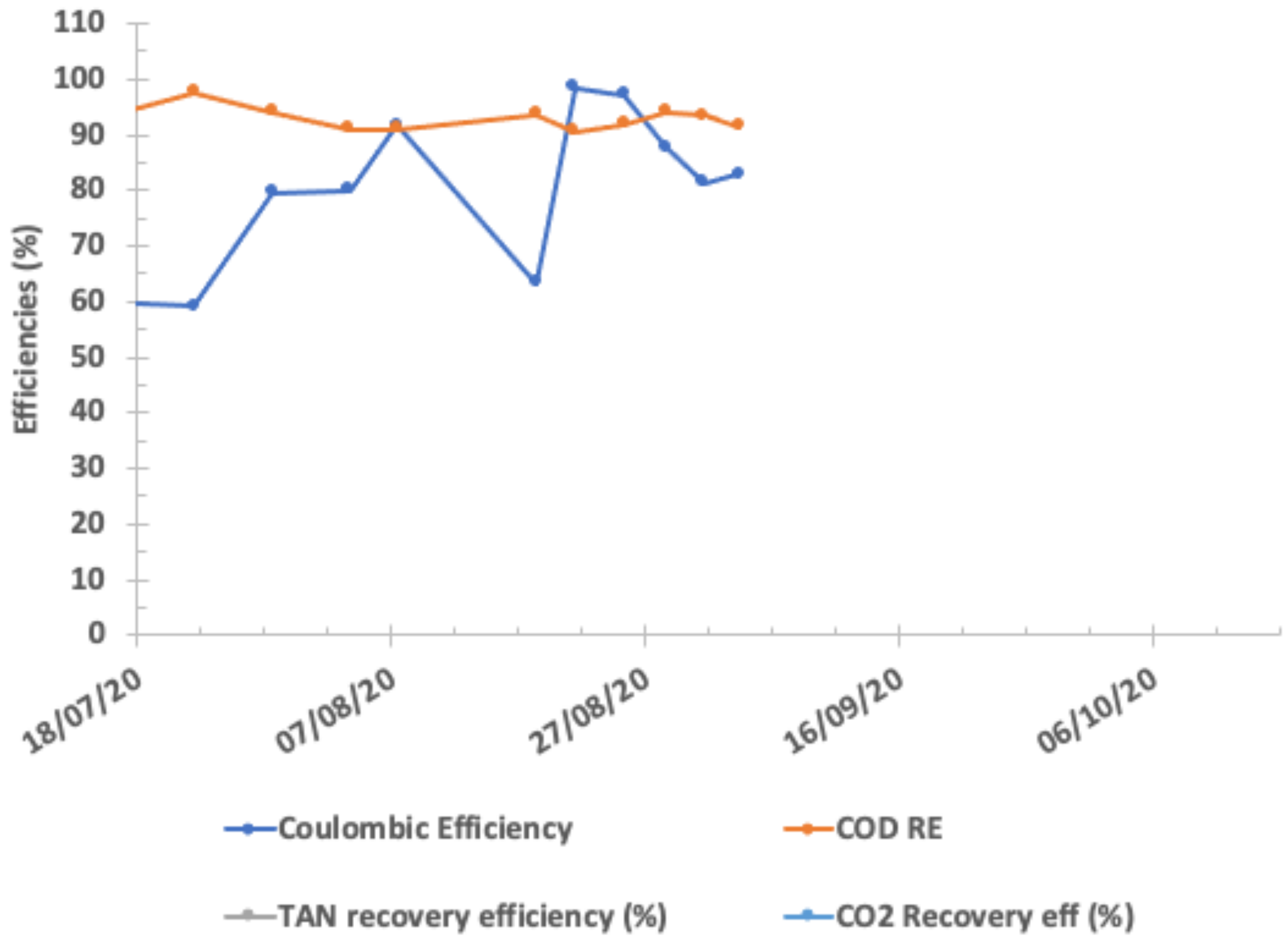
NITROGEN DISTRIBUTION



TAN	70 ± 15 %
Organic	~ 15-20 %
Biomass	16 ± 11 %

O


400
300
200
100
0
-100
-200
-300
-400
-500
Anode Potential difference (mV)/Current (mA)
2.5
2
1.5
1
0.5
0
Power Supply (V)
18/07/20
28/07/20
07/08/20
17/08/20
27/08/20
06/09/20
16/09/20
26/09/20
06/10/20
16/10/20
Anode Potential
Current
Applied Cell Voltage


110
100
90
80
70
60
50
40
30
20
10
0
Efficiencies (%)
18/07/20
07/08/20
27/08/20
16/09/20
06/10/20
Coulombic Efficiency
COD RE
TAN recovery efficiency (%)
CO2 Recovery eff (%)

PERSPECTIVE

- High efficiencies achieved
- Good balance demonstrated but needs to be improved
- Fluid flow through membrane complicates balances
- CO_2 recovery of 40 – 88 %
- Anode potential and loading control critical to avoid methanogenic competition

INTEGRATED CO_2 RECOVERY

MELiSSA Waste

Sludge fraction

10 % mass flow

~50 % Carbon

Slurry of sludge, VFAs, and nondigested solids

TBD (SCWO)

(48 % Carbon to CO_2)

C1 Fermentation

Gas

(CO_2, H_2, VOCs)

15 % Carbon to CO_2

Permeate fraction

90 % mass flow

~35 % Carbon

Mixed organic acids, minerals, NH_4^+

MEC

Gas, Liquid

CO_2, minerals, NH_4^+, H_2

25 % Carbon to CO_2

40 % CO_2 recovery with MEC, 80 % with MEC + SCWO

PERSPECTIVE

- High conversion efficiencies achieved, alkalinity maintained
- Energy investments 25-28 Wh $L^{-1}_{permeate}$
- Good balance demonstrated but needs to be improved
- Fluid flow through membrane complicates balances
- CO_2 recovery of 40 – 88 %
- Anode potential and loading control critical to avoid methanogenic competition

PROJECT TEAM

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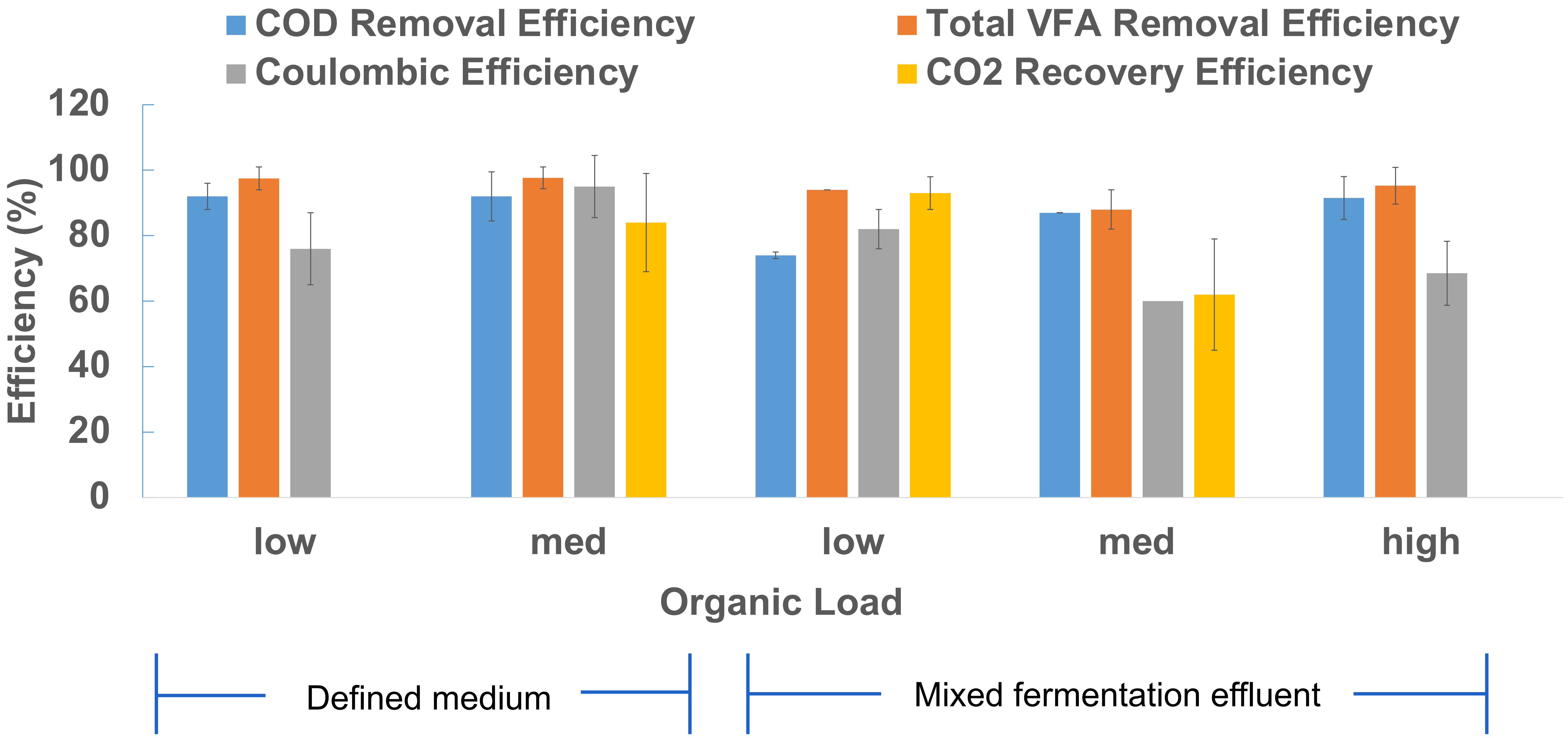
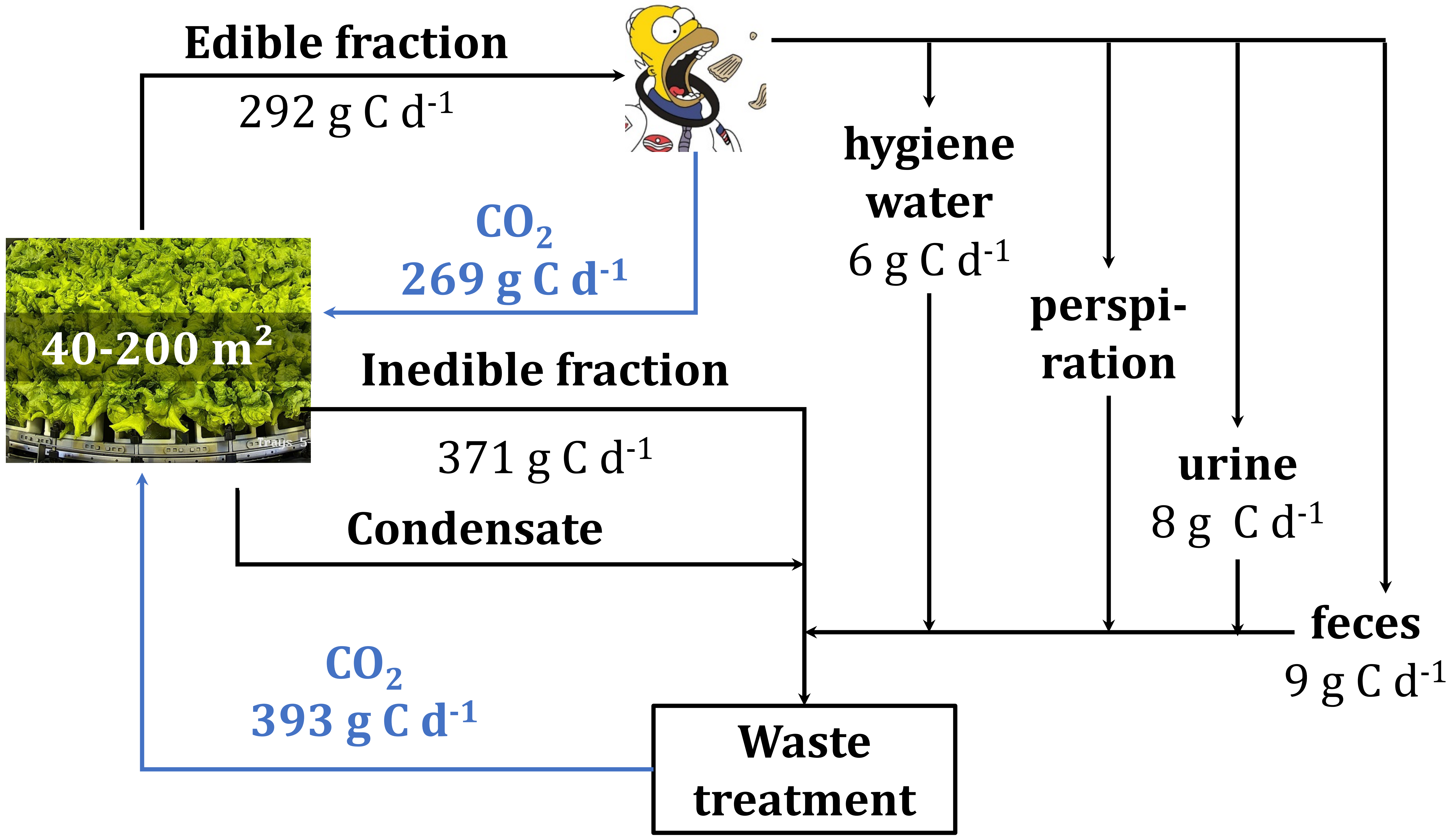
BENCH TESTS PERFORMANCE



CARBON BALANCING IN RLS



(After Hu et al. 2010)