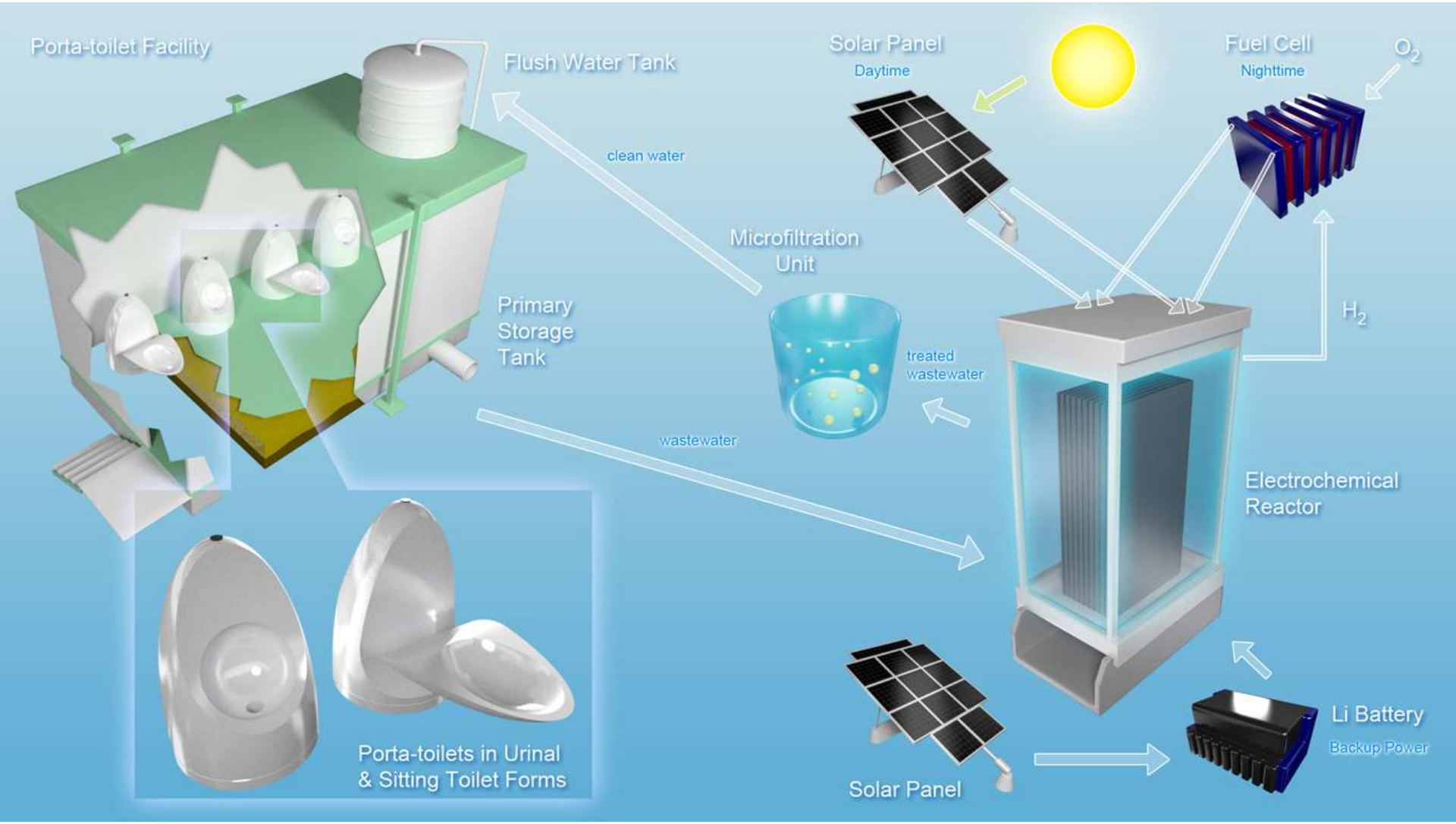
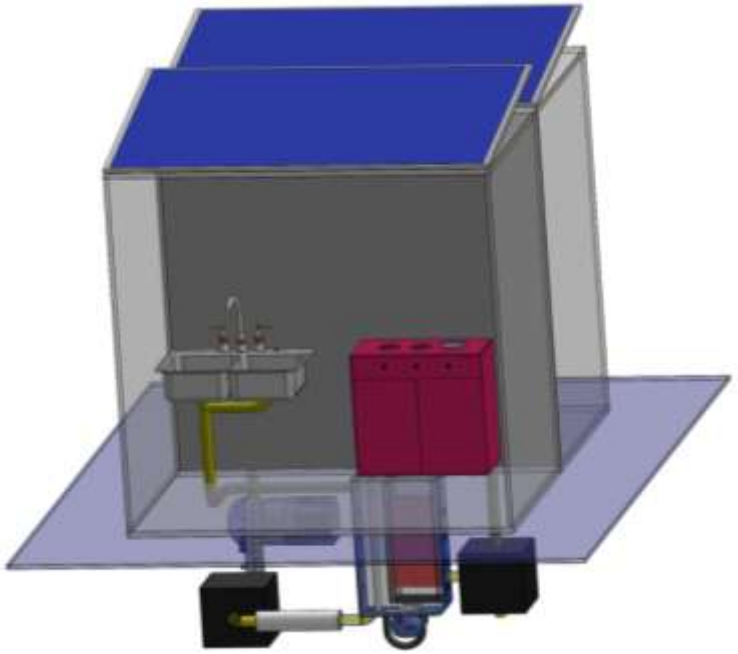
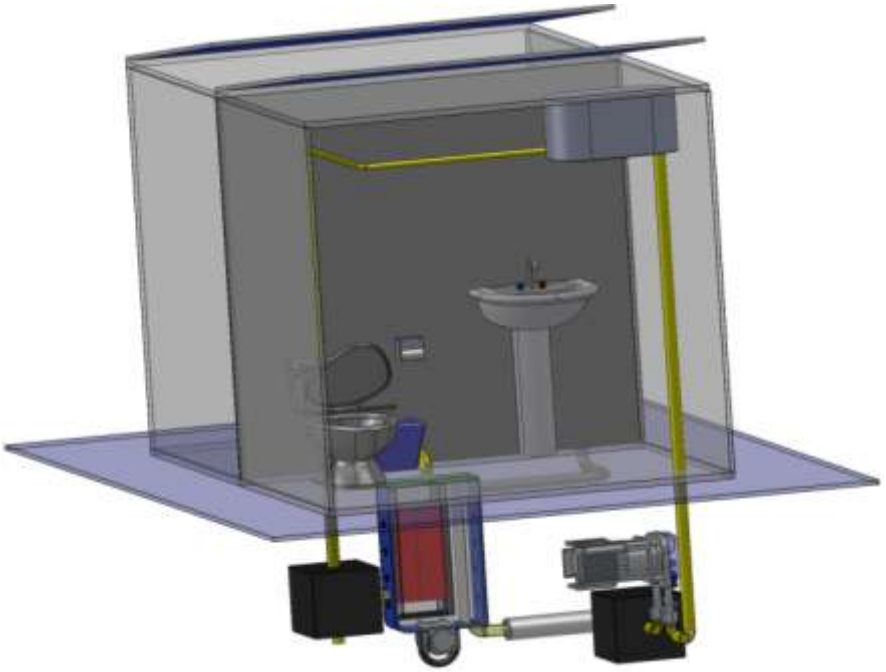
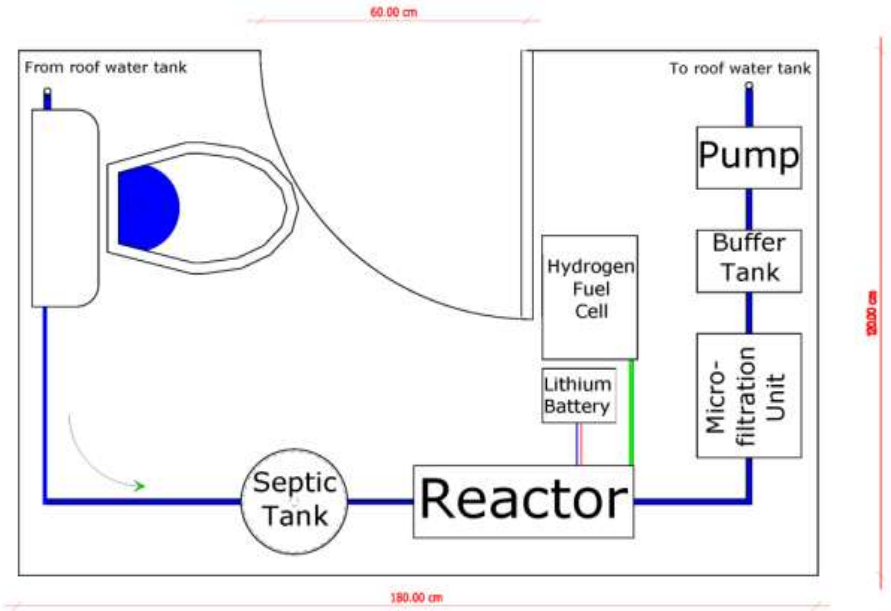
An Integrated Solar Fuels System

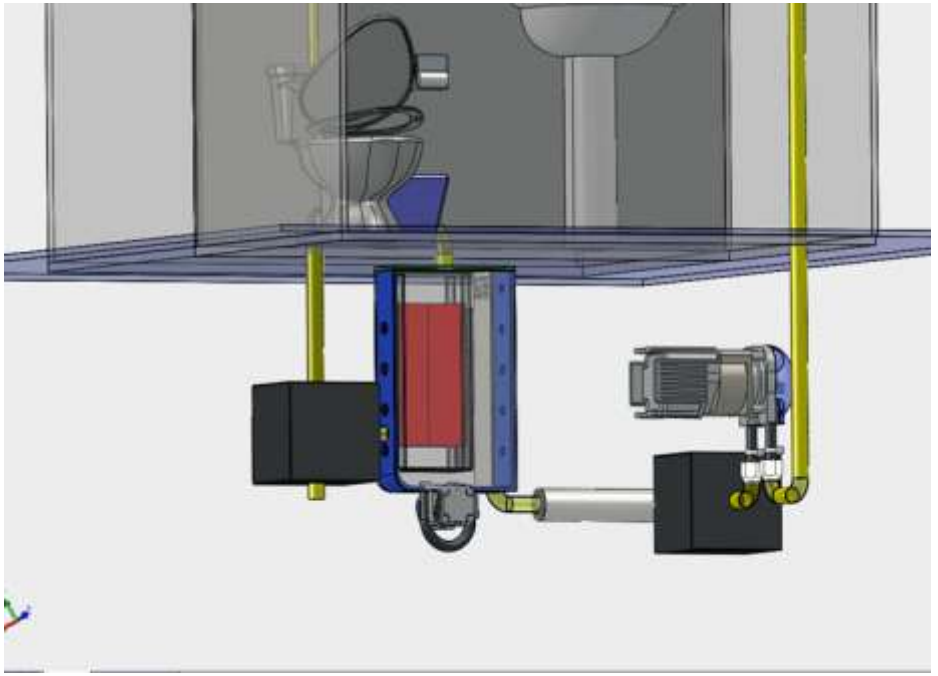


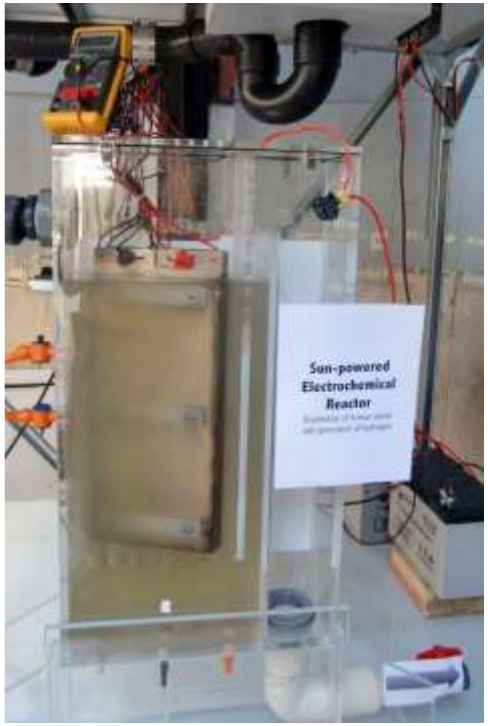
Caltech RTTC Project: Development of a Self-Contained, PV-Powered Domestic Toilet and Wastewater Treatment System

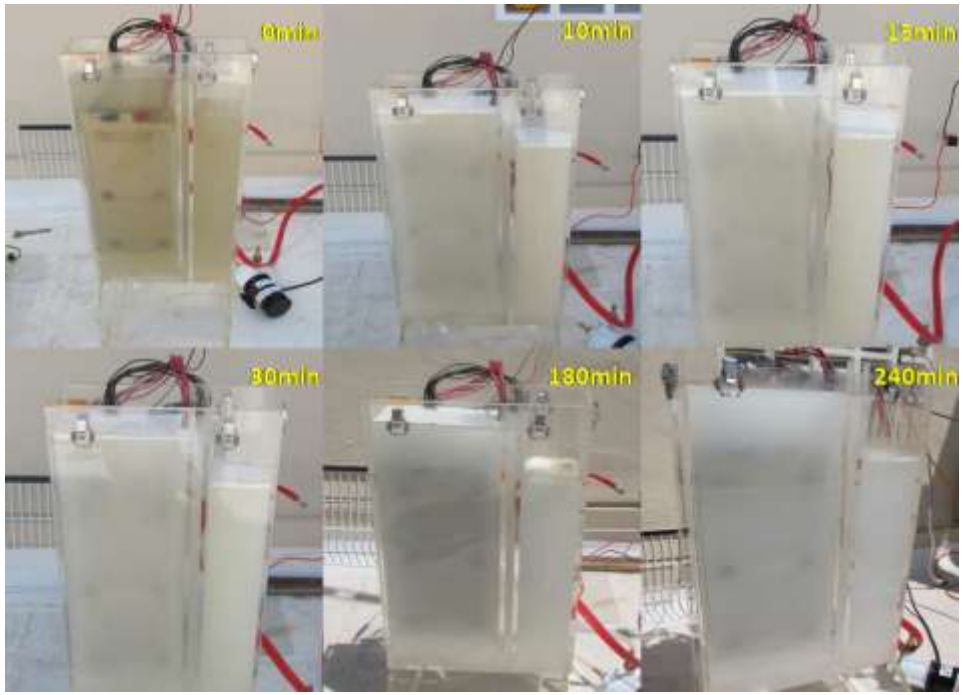




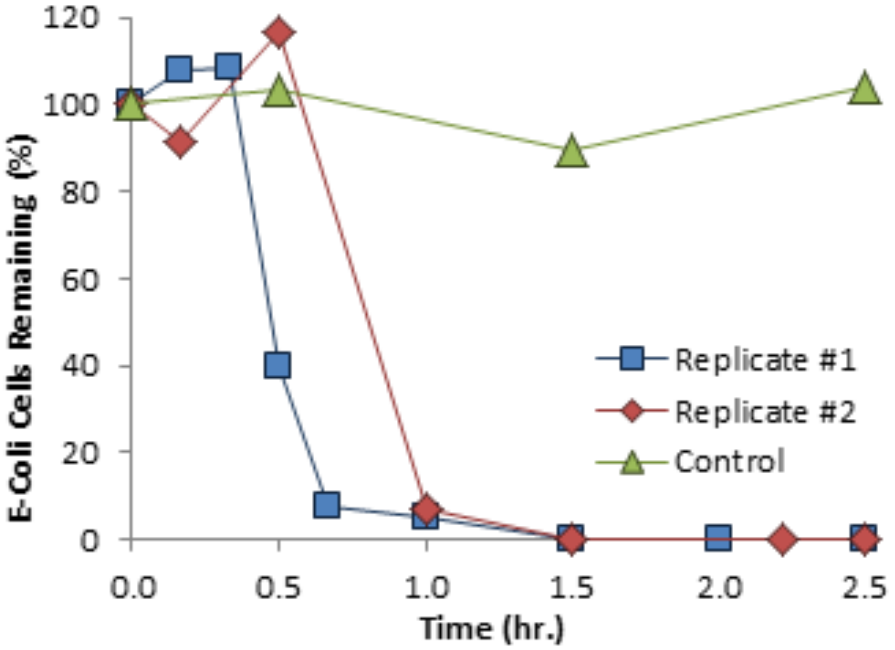

60.00 cm
From roof water tank
To roof water tank
Pump
Buffer Tank
Hydrogen Fuel Cell
Lithium Battery
Micro-filtration Unit
Septic Tank
Reactor
180.00 cm



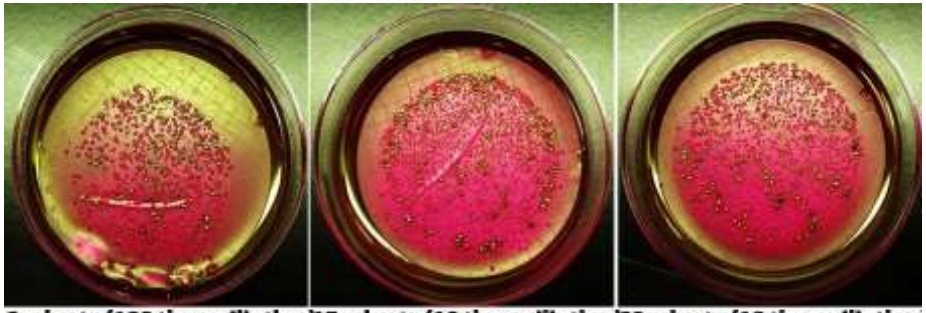

Sun-powered
Electrochemical
Reactor



Time-lapse Video of Reaction Progress



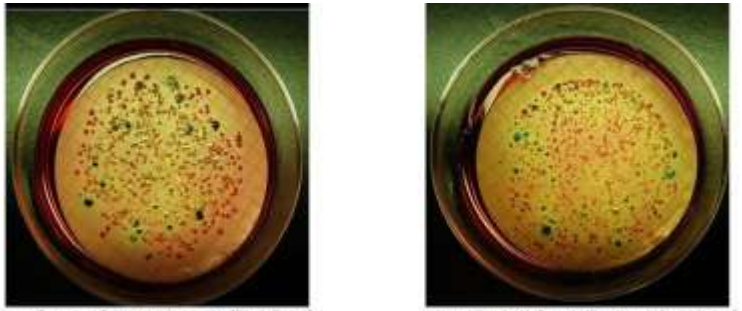
Total coliform



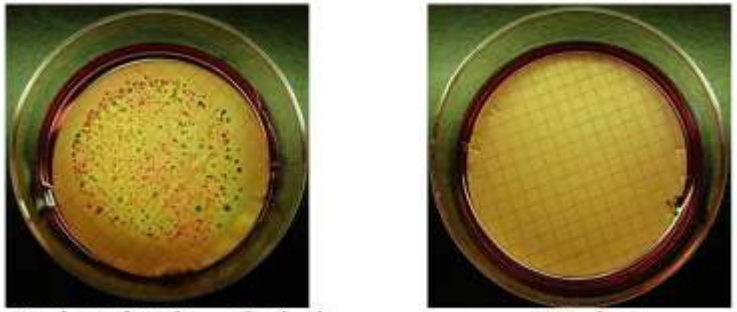
0 minute (100 times dilution) 15 minute (10 times dilution) 60 minute (10 times dilution

120 minute (10 times dilution) 180 minute

Fecal coliform

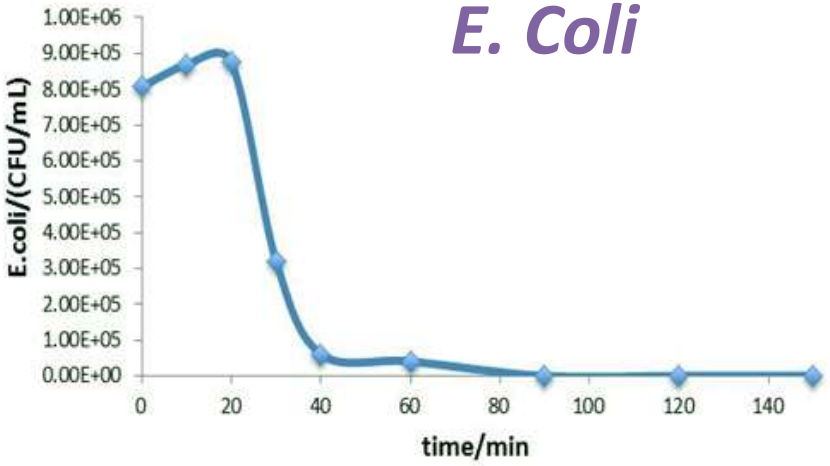


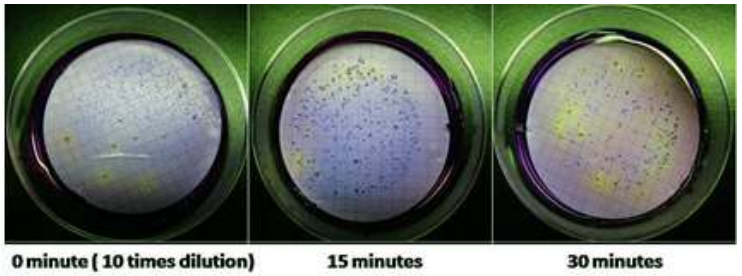
0 minute (100 times dilution) 30 minute (10 times dilution)



100 minute (10 times dilution) 180 minute

E. Coli

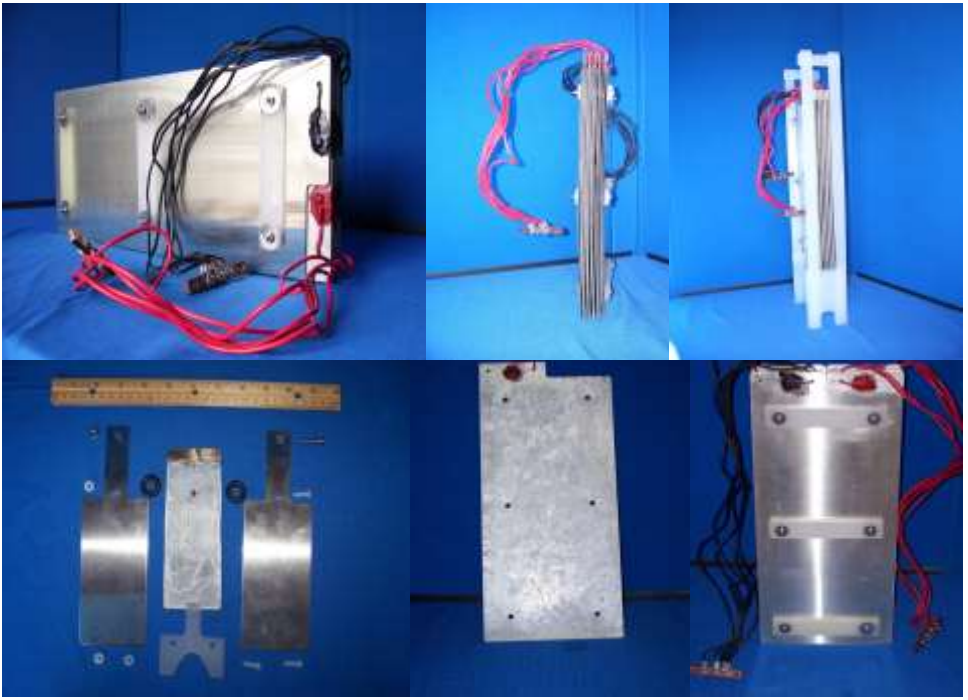


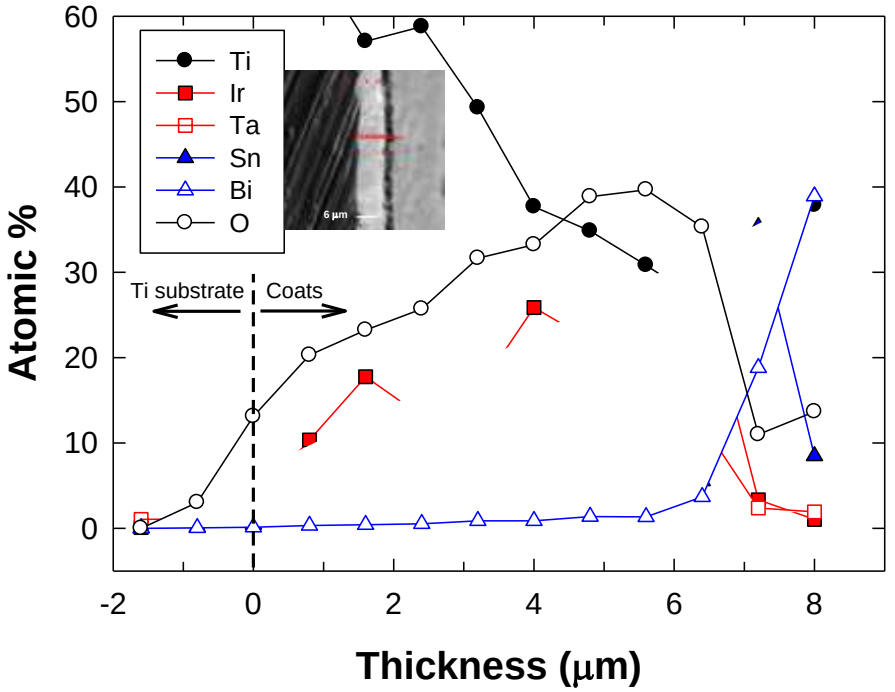


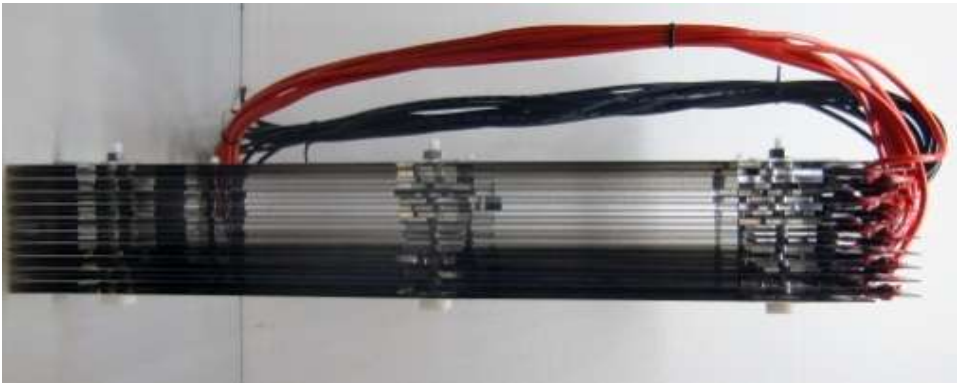
0 minute (10 times dilution) 15 minutes 30 minutes

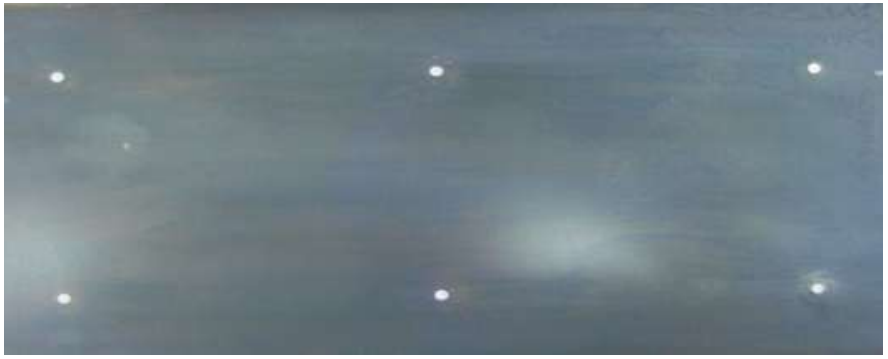
120 minutes 240 minutes

$IrO_2/Ta_2O_5/SnO_2/Bi_2O_3/TiO_2$ Composite Anodes

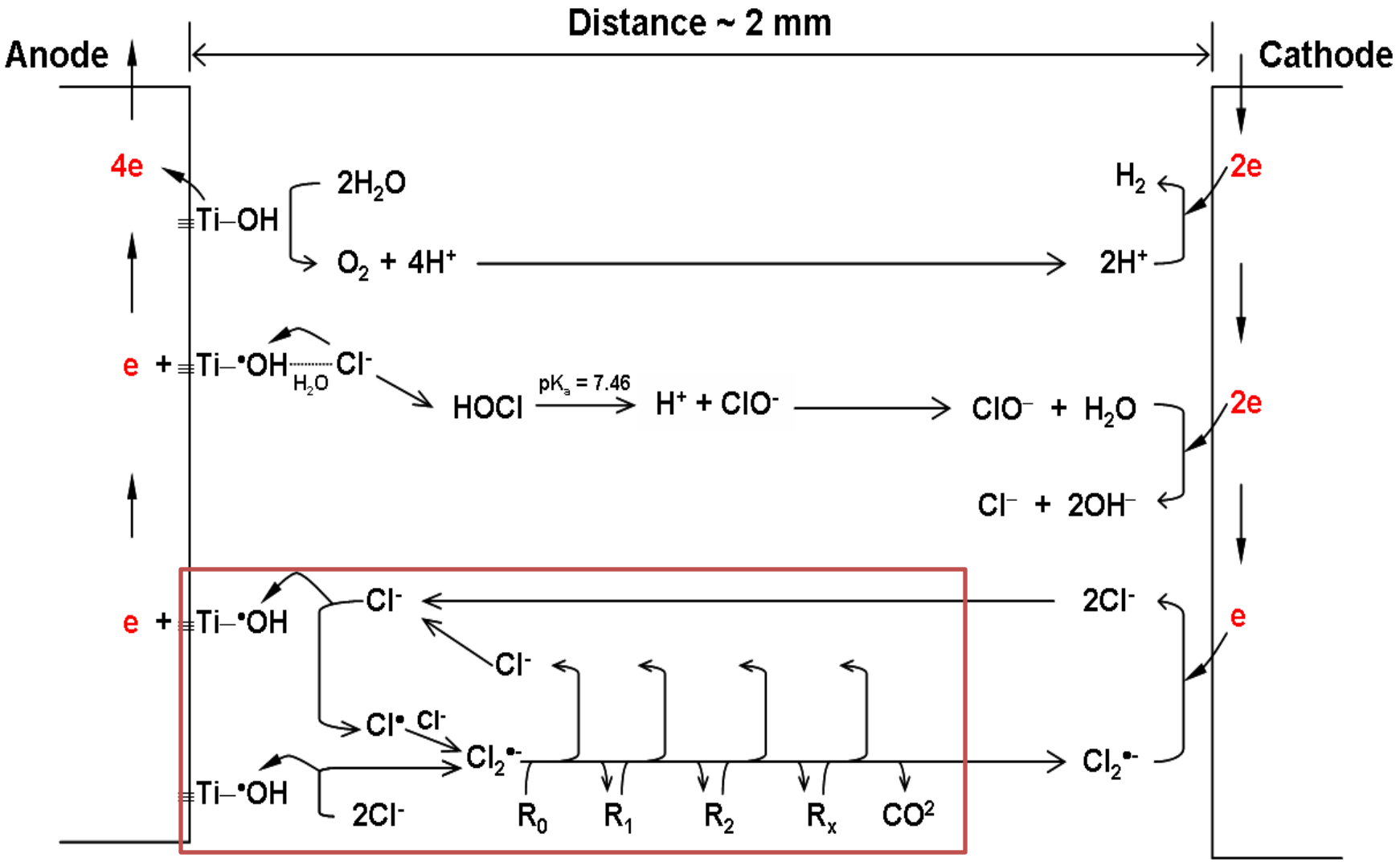






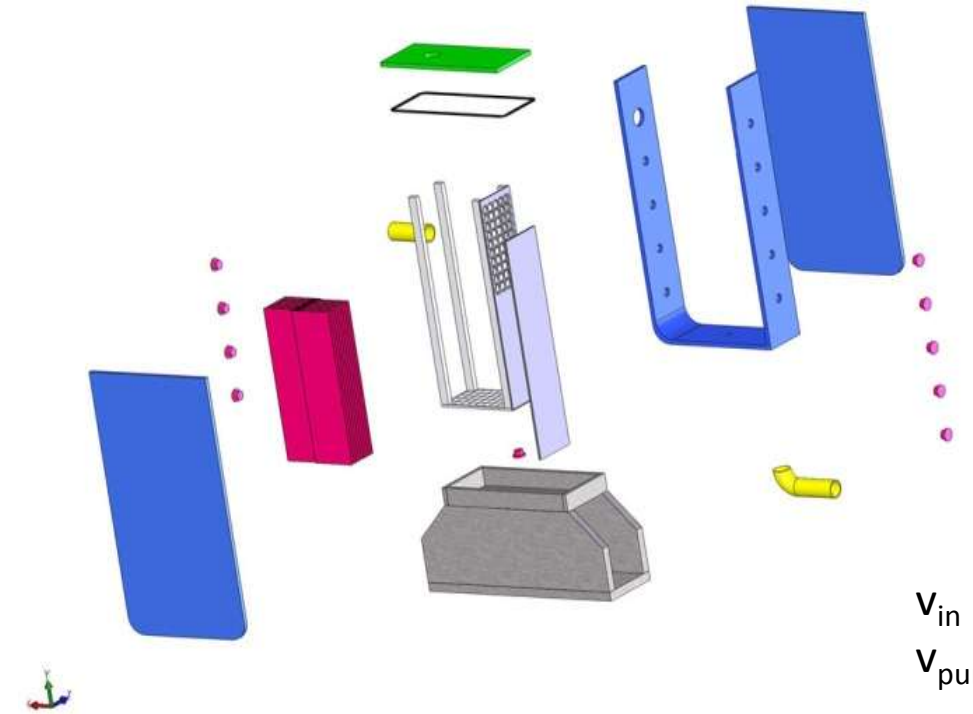


$IrO_2/Ta_2O_5/SnO_2/Bi_2O_3/TiO_2$ Composite Anodes



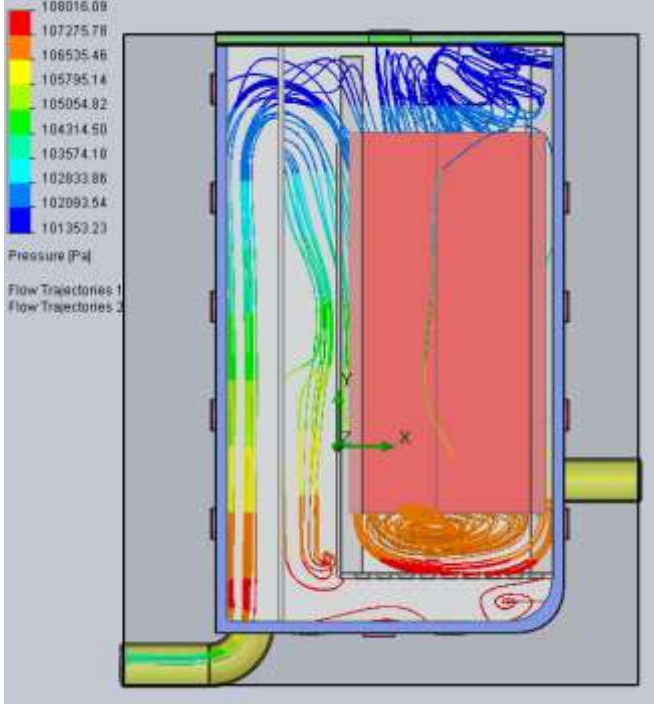
E (HClO,H^+/H_2O,Cl•) = -0.46 V; E (HOCl/Cl^-,•OH) = -0.04 V; E (ClOH•/Cl^-,HO^-) = 1.90 V

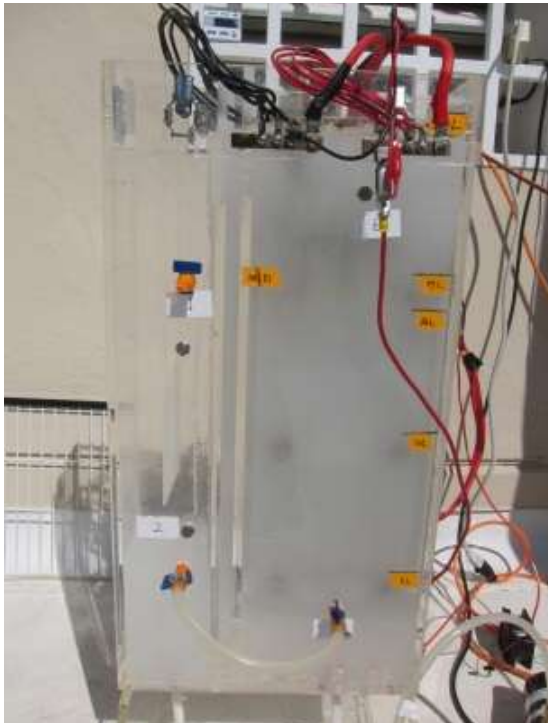
E (Cl•/Cl^-) = 2.55 V; E ($Cl_2^{\bullet-}$/2Cl^-) = 2.3 V; Cl• + Cl^- ↔ $Cl_2^{\bullet-}$ K = 1.4×10^5 M^{-1}

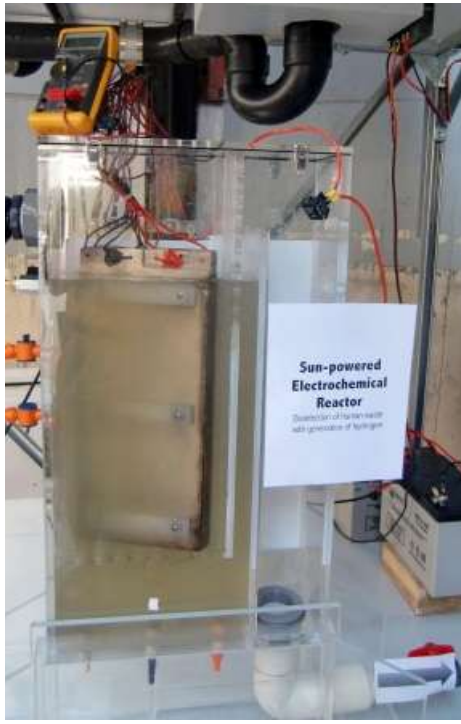


$v_{in} = 0.3\ m^3/s$

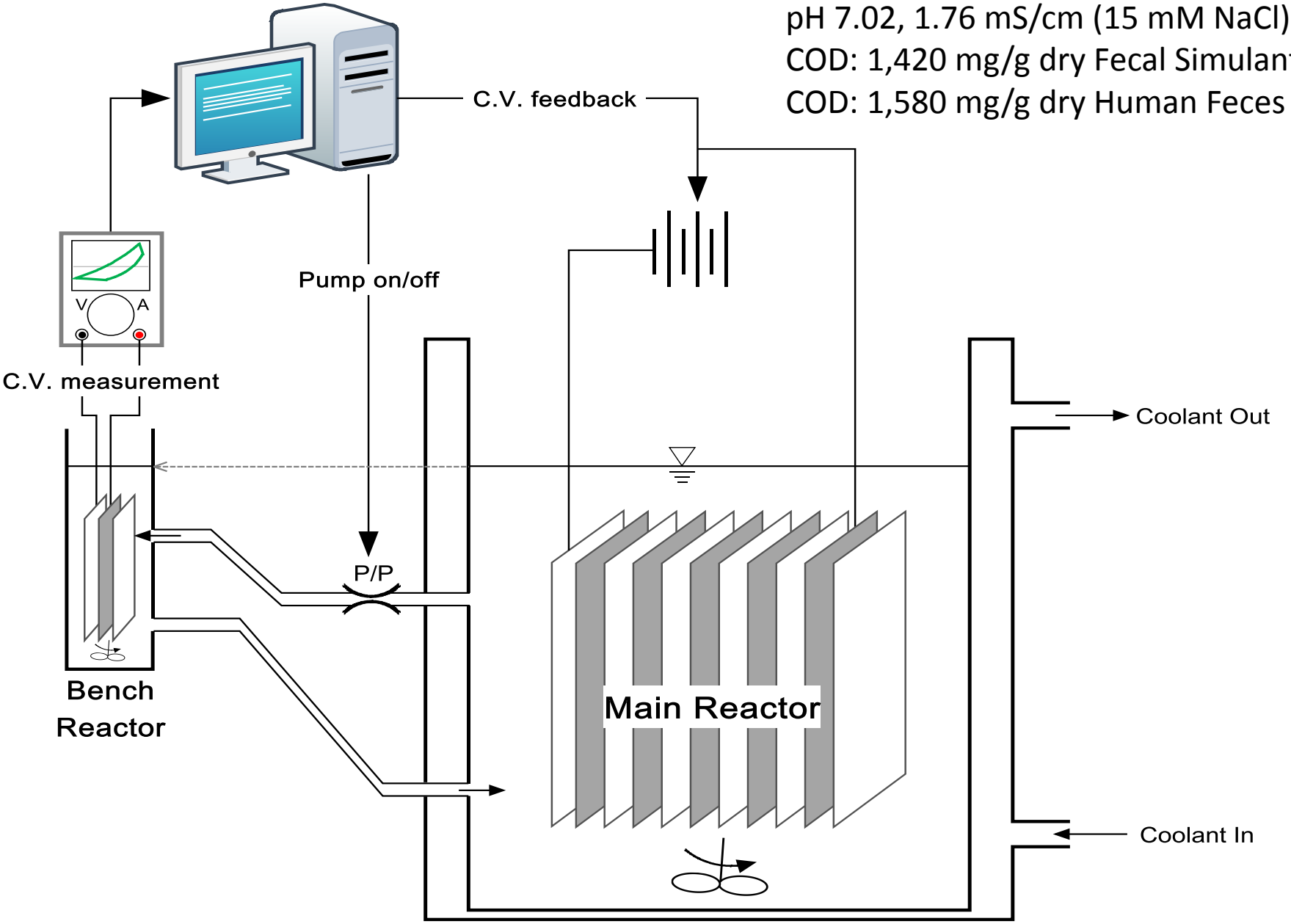
$v_{pump} = 0.12\ m^3/s$

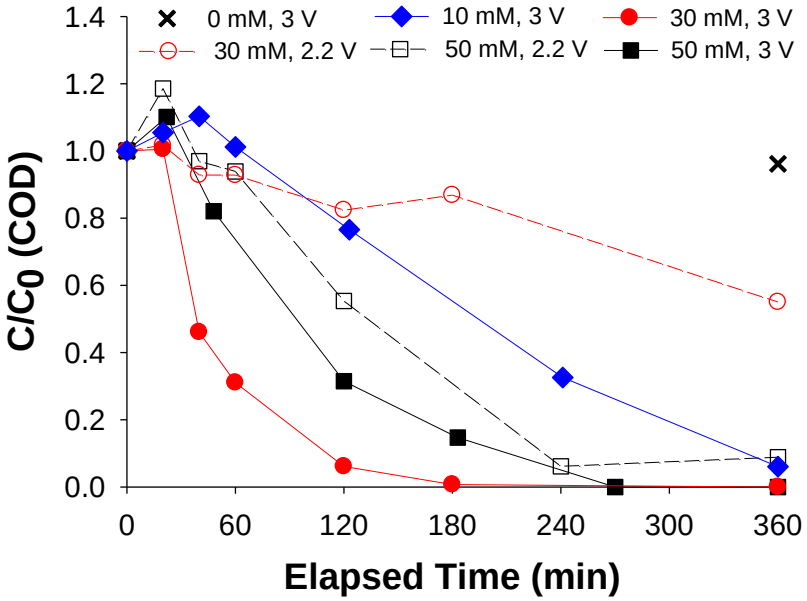


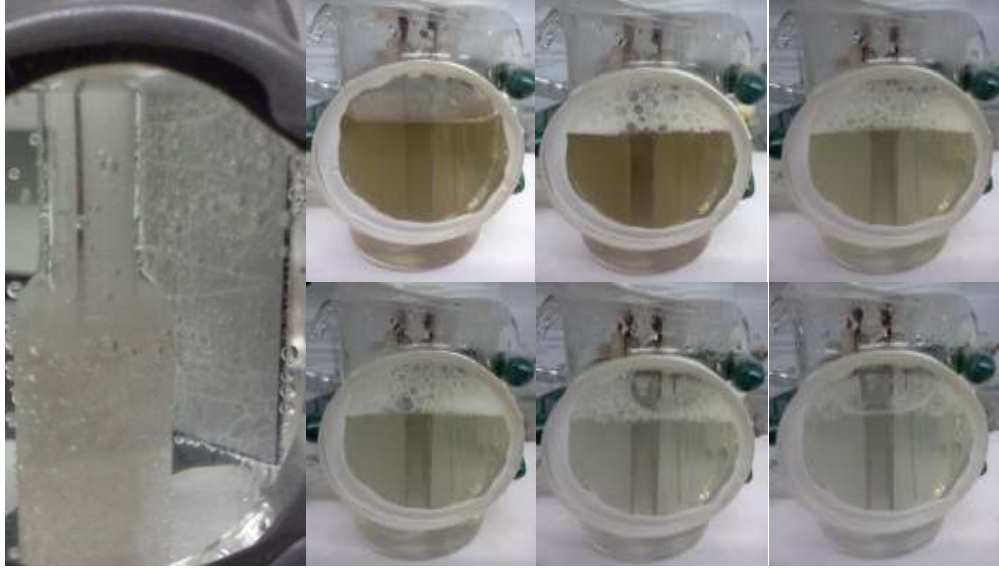




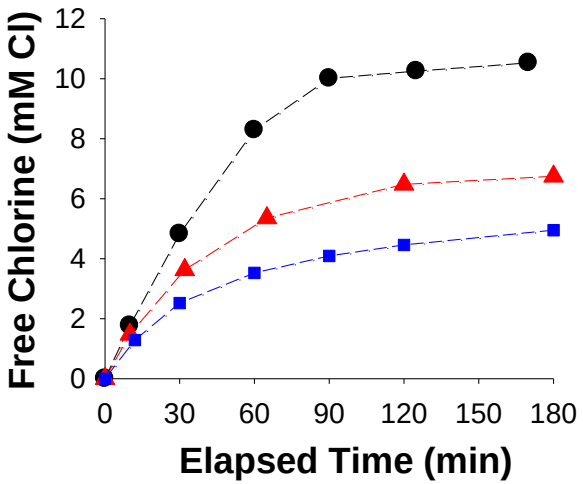
pH 5.41, 2.11 mS/cm
pH 7.02, 1.76 mS/cm (15 mM NaCl)
COD: 1,420 mg/g dry Fecal Simulant
COD: 1,580 mg/g dry Human Feces

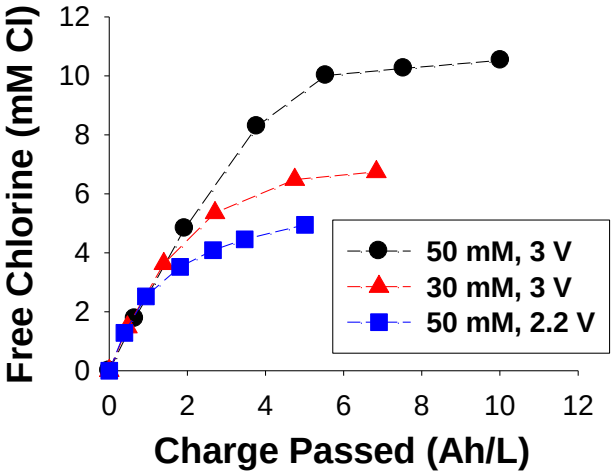






Bench-Top Tests of Fresh Urine & Actual Wastewater

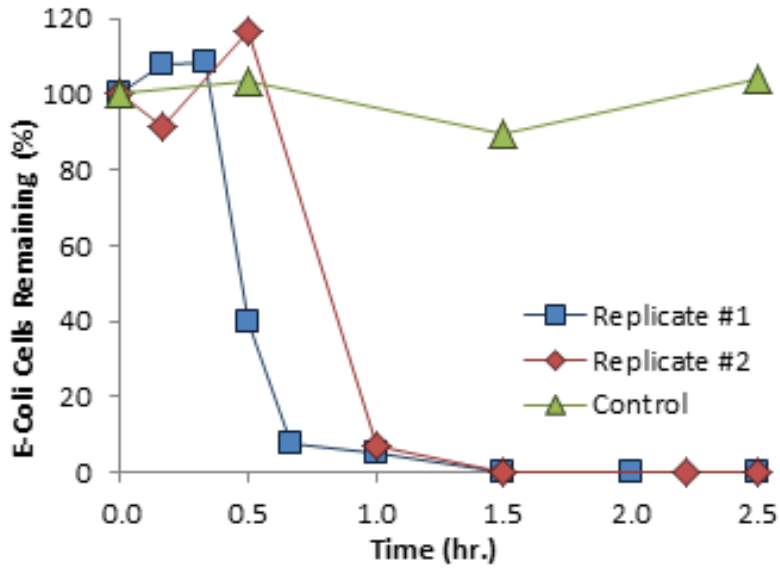


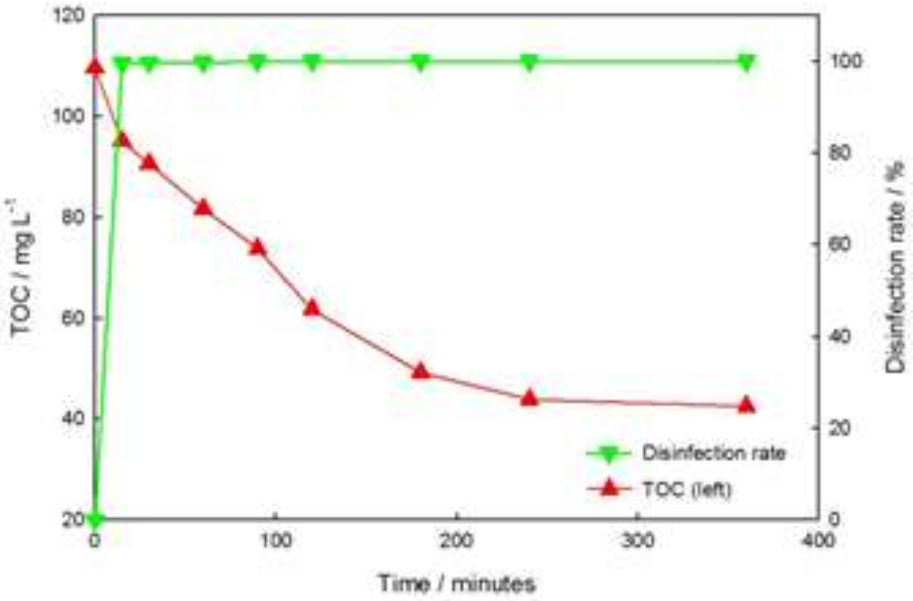


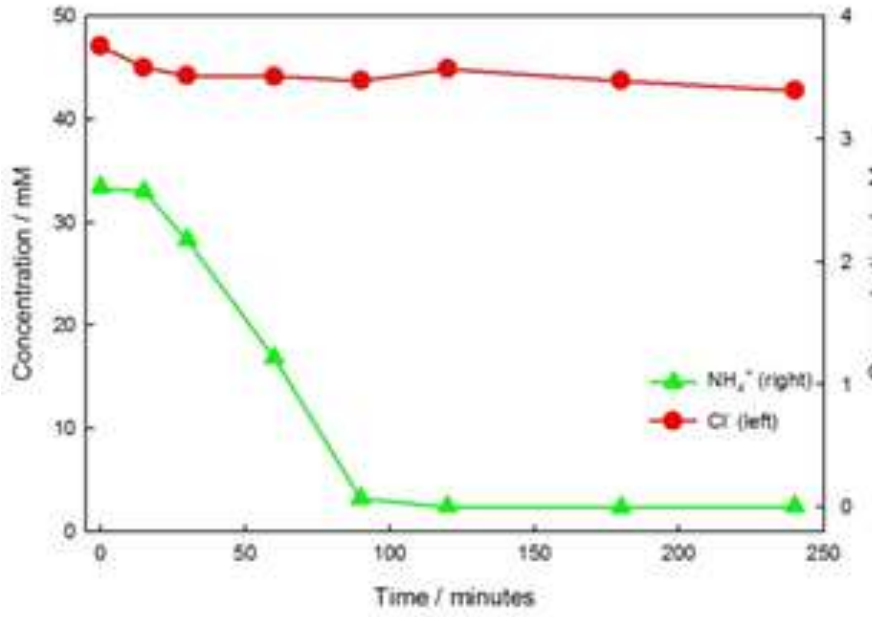
Composition of Domestic Wastewater

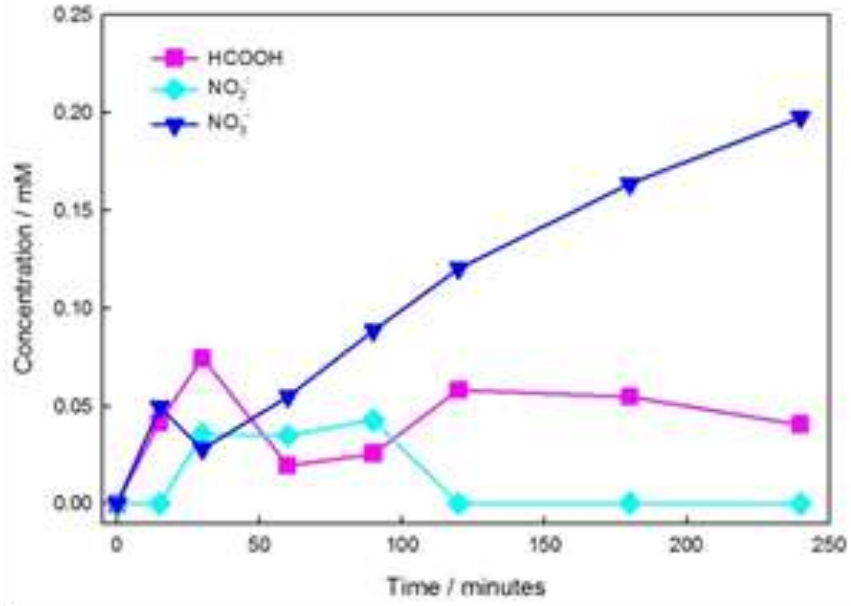
Constituent	Average
pH	6.6 ~ 7.3
COD (mg/L)	180.3
SCOD (mg/L)	99.4
TN (mM N)	2.594
NH_4^+ (mM)	1.910
NO_3^- (mM)	< 0.01
Cl^- (mM)	3.880
ClO_3^- (mM)	< 0.01
Organic Acids (mM)	< 0.01
Mg (mM)	0.6387
Ca (mM)	1.287
Protein (mg/L)	70.55
Carbohydrate (mg/L)	29.47

Domestic Wastewater Treatment







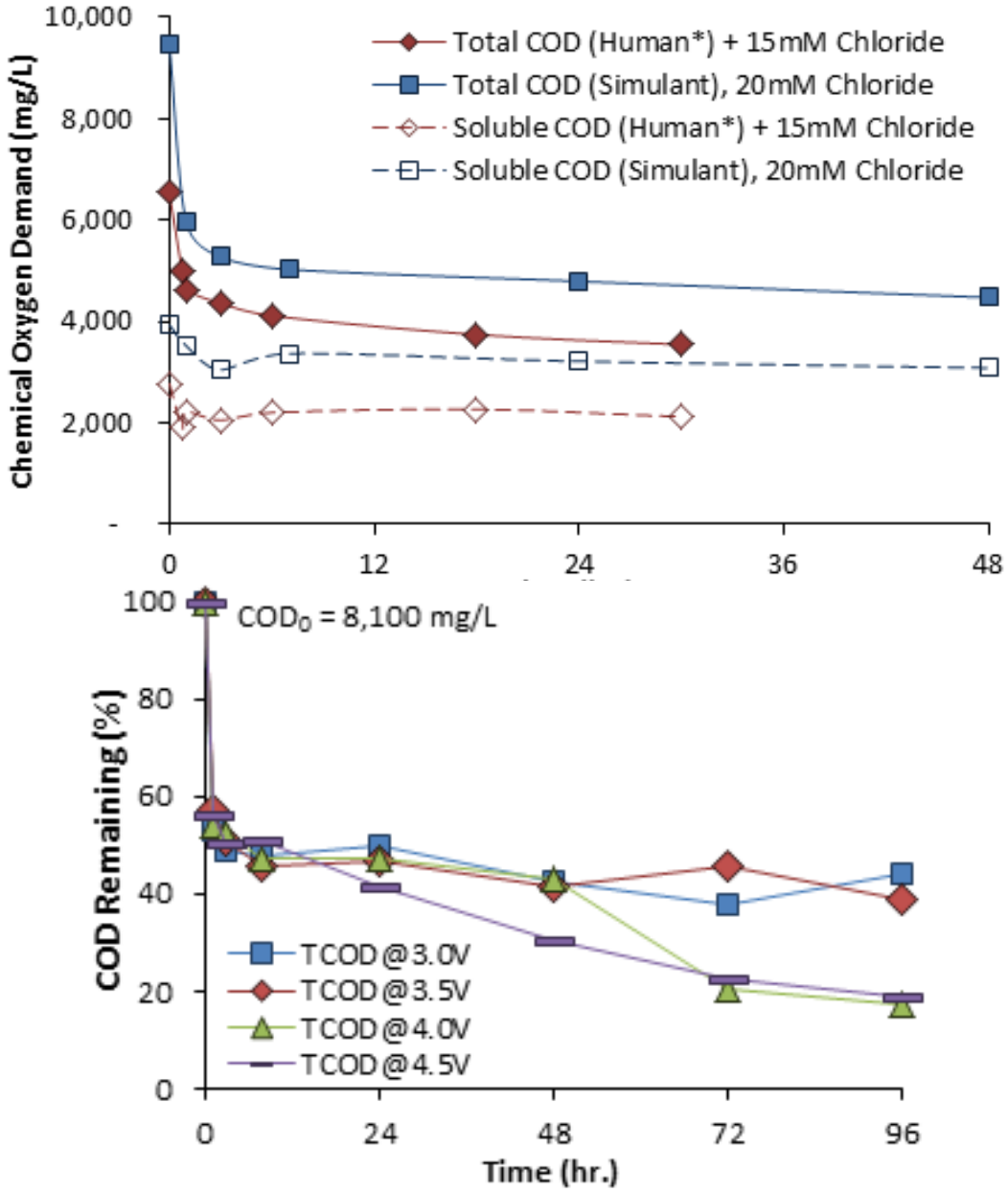


Caltech Synthetic Feces Chemical Composition

Organic Components	Amount (wt. %)	COD (mg L^{-1})	Molecular Wt. (g $mole^{-1}$)	Notes
Yeast (active)	30	2,960	-	*E. Coli* substitute
Cellulose	15	1,240	10^6 - 10^7	Insoluble fiber
PEG400	15	2,088	400 (avg.)	Soluble fiber
Oleic Acid	20	2,588	280	Fatty acid
Soy Protein	8	692	~ 10^6	Undigested protein
Inorganics	12	808		
SUM ($\sum$)	100	10,736		

Salt Added	MW (g $mole^{-1}$)	Added(mg g^{-1})
NaCl	58.4	40
KCl	74.6	40
$CaCl_2$	111	20
$MgCl_2$	95.2	20
$ZnCl_2$	136.3	0.8
$FeCl_2$	126.8	0.6
$MnCl_2$	125.8	0.3
$CuCl_2$	134.5	0.1

Electrochemical Treatment of Synthetic and Human Feces



* Treatment Flow with Resource Recovery for 40 persons per day Usage

Water-Free Urinal

Squat Toilet

40 L/d
- 1 L/d/person

120 L/d
- 1 excrement/d/person
- 3 L/flushing

Water Reuse (Flushing)

120 L/d (Disinfected, Colorless)

Gas Evolution
- Flow rate = 1.46 L/min
- H_2 Fraction = 73%
- **H_2 production = 68.8 mol/d**

COD	TN	TP
1200 mg/L	55 mM N (NH_4^+ 10%)	15 mM P

~ 400 L

Precipitate (MAP)

160 L/d

Septic Tank
- Retention Time: 2 d

Septic Tank Effluent

COD	460 mg/L
TN	66 mM N (NH_4^+ 70%)
TP	~ 0
Cl^-	33 mM

40 L

Electrochemical Reactor
- Retention Time = 6 hr
- V_{apply} = 5.7 V
- I = 135 A
- **Power = 0.77 kW (From Solar Cell)**

40 L/d

Sterilized Liquid Fertilizer (Nitrogen)

COD	~ 0 mg/L
TN	40 mM N (NH_4^+ 80%)
Cl^-	18 mM

P-Mineral Fertilizer

Nutrient Production
- **N production = 1.6 mol/d**
- **P production = 1.8 mol/d**

* All extensive values (current, molar production, power) by arithmetic scale up of 55 mL reactor to 40 L reactor
* Fecal supernatant is assumed to be analogous to the domestic wastewater
* COD: Chemical Oxygen Demand, TN: Total Nitrogen, TP: Total Phosphorus, MAP: $Mg_2NH_4PO_4$

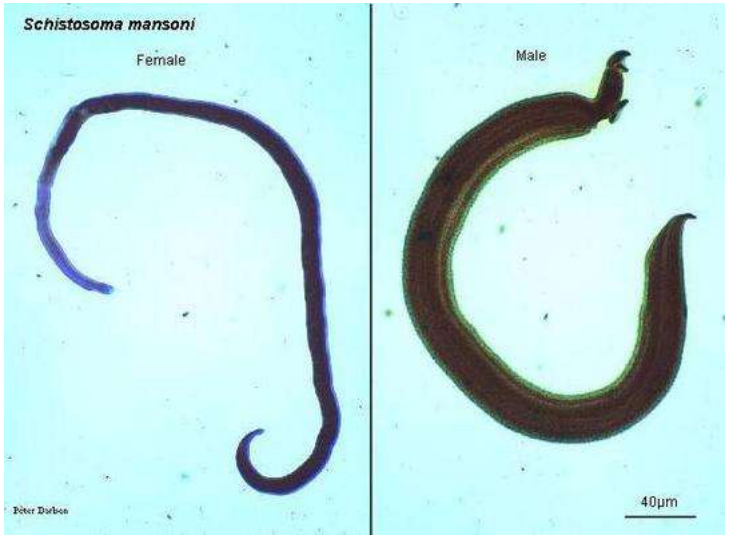
Future work - Helminth Egg Elimination

Helminth eggs:

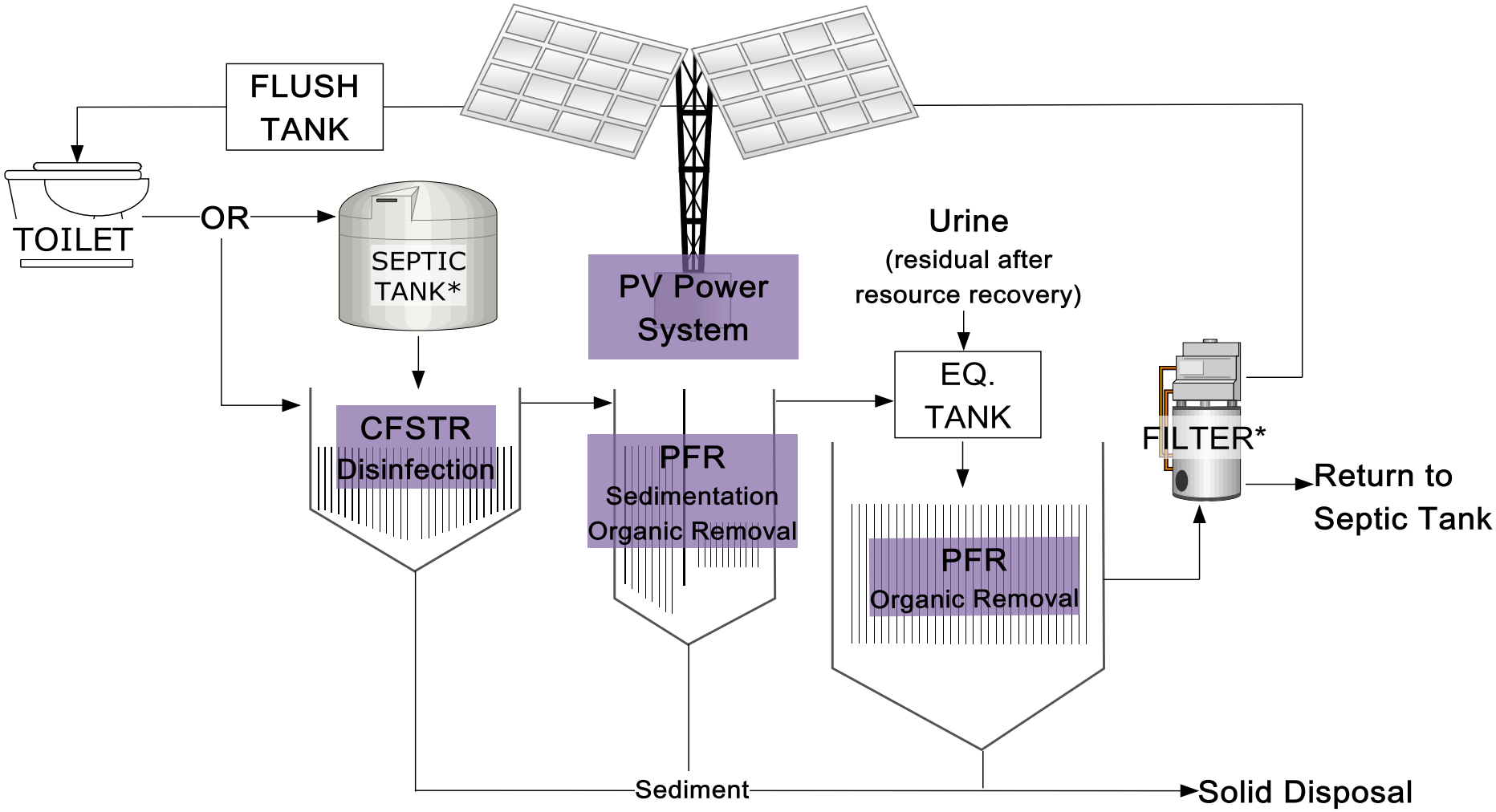
1. Cause helminthiases (e.g., Schistosoma);
2. Remain viable for 1-2 months in crop, wastewater and sludge; for several years in feces;
3. Difficult to inactivate using chlorine, UV-light or ozone.

Electrochemical disinfection:

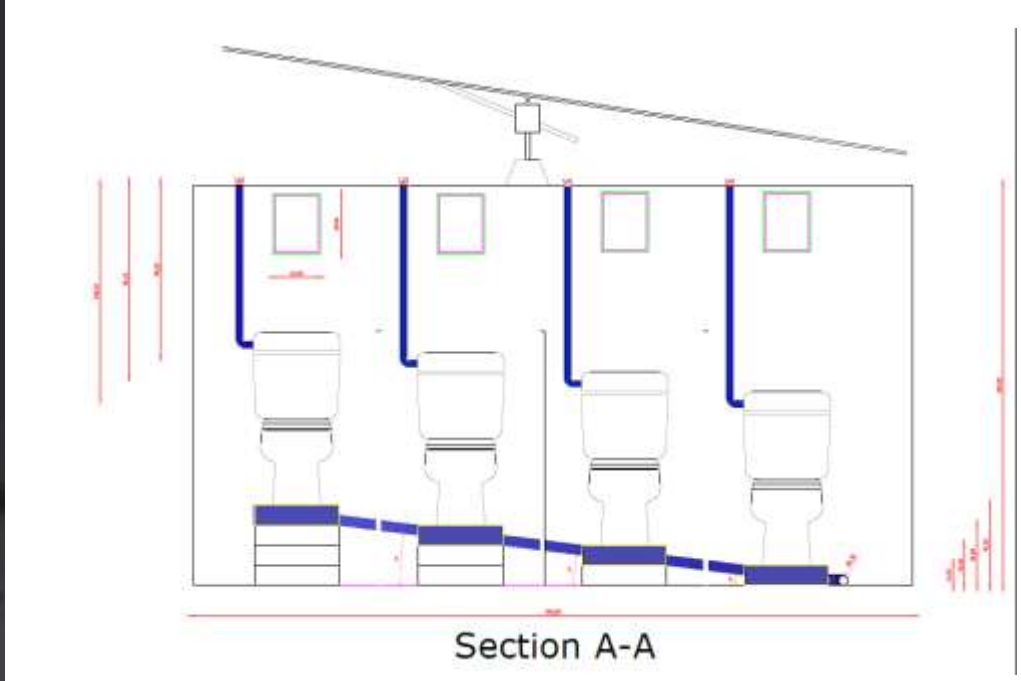
1. Initially with non-pathogenic nematodes (with Prof. Sternberg)
2. Quantify the numbers, survivability, and kinetics of Helminth egg disinfection.



The Caltech RTTC Process Flow Diagram



CFSTR = Continuous Flow Stirred Tank Reactor PV = Photovoltaic PFR = Plug Flow Reactor



Section A-A


BILL & MELINDA
GATES foundation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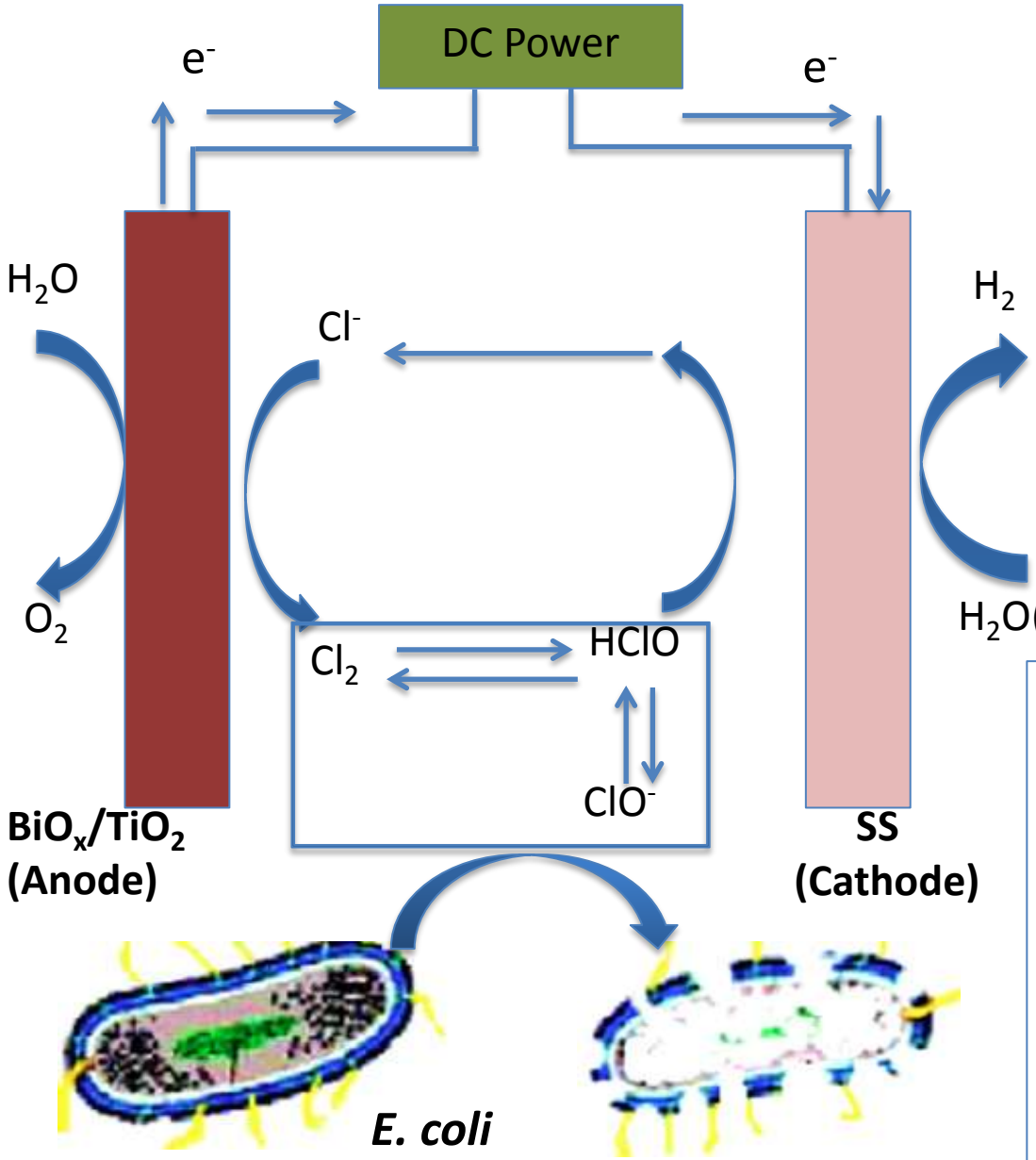
Michael R. Hoffmann, Principal Investigator
Clément Cid, PhD Student
Daejung Kwon, PhD Student
Kangwoo Cho, PhD Student
Asghar Aryanfar, PhD Student
Hao Zhang, PhD Student
Qu Yan, Post-doctoral Scholar
http://tinyurl.com/caltechtoilets

Big Bang Theory: Howard's Space Toilet Prototype Test

Electrochemical Disinfection



Cathode: $2H^+ + 2e^- \rightarrow H_2$

Anode: $2H_2O - 4e^- \rightarrow O_2 + 4H^+$

$2Cl^- \rightarrow Cl_2 + 2e^-$

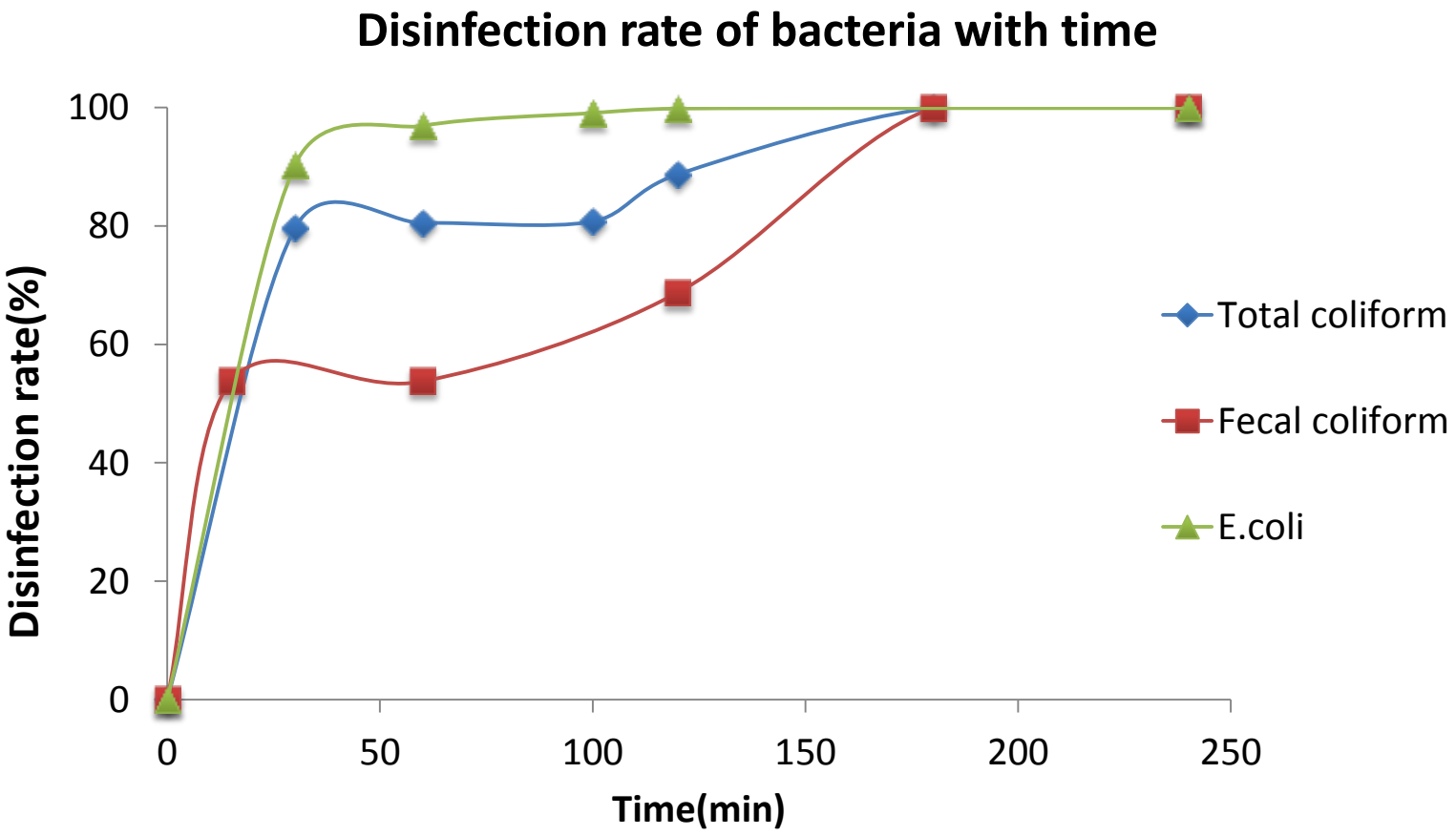
Bulk Aqueous Phase:

$Cl_2(aq) + H_2O \leftrightarrow HOCl + H^+ + Cl^-$

$HOCl \leftrightarrow H^+ + OCl^-$

Disinfection of domestic wastewater in 20 L Reactor

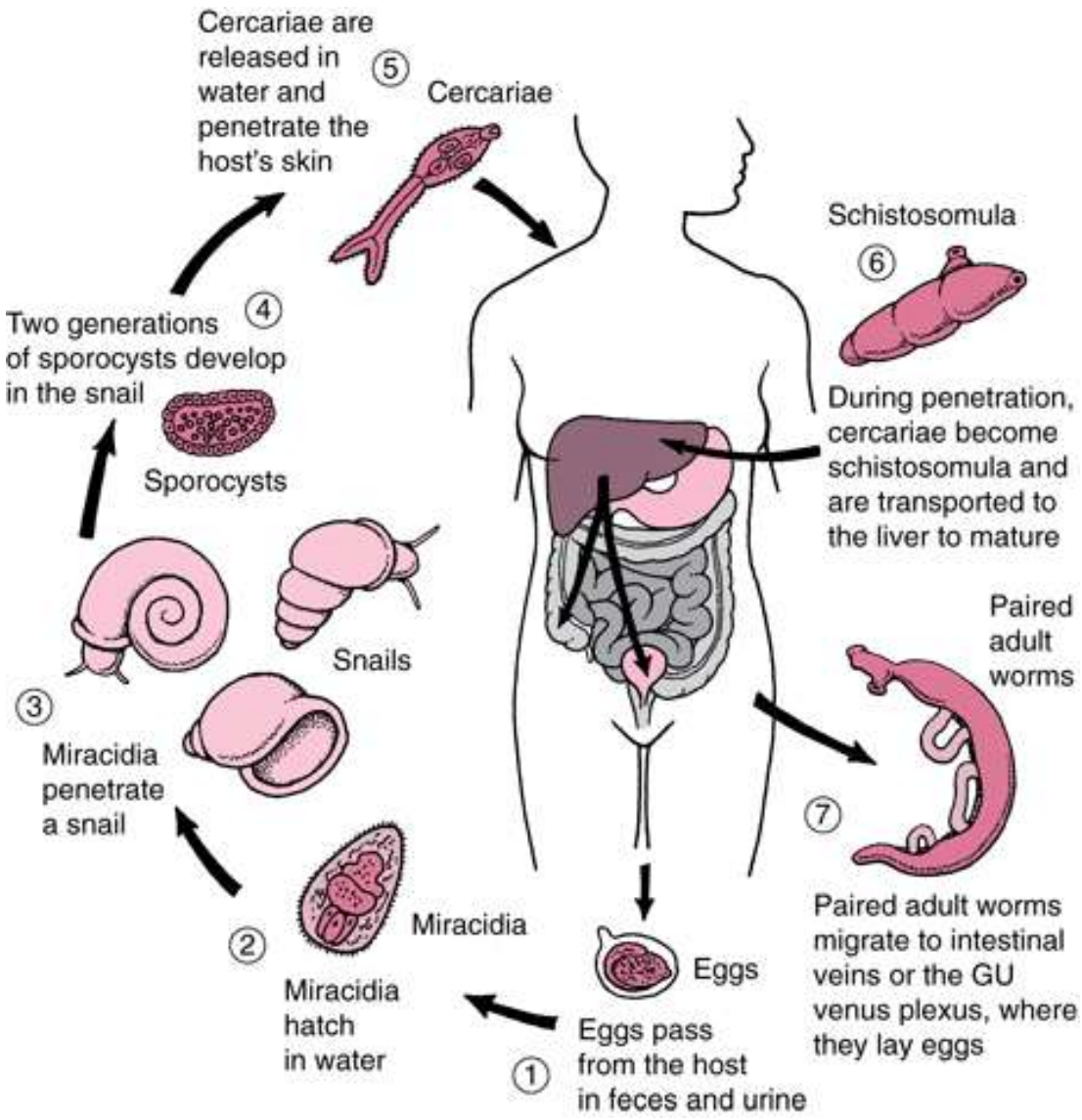
Initial Voltage = 3.89 V, Initial Current = 16.7 A, Reactor volume = 20 L, Reaction time = 240 min. (Membrane Filtration Methods)



Disinfection achieved after 180 min with a *4-log decrease* in coliform bacteria

Membrane Filtration Methods

- Filter water through a 0.45 µm membrane filter
- Place membrane on selective media
  - mEndo agar LES for total coliform
  - mFC agar for fecal coliform
  - mTEC agar for E.coli
- Incubate
  - 23±1 hours at 35.0±0.5°C for total coliform
  - 24±2 hours at 44.5±0.2°C for fecal coliform
  - 2 hours at 35.0±0.5°C + 22-24 hours at 44.5±0.2°C for E.coli
- Count colonies
  - Pink to dark-red color with a shiny, greenish-gold, metallic surface sheen for total coliform
  - Light or dark blue for fecal coliform
  - Red to magenta colonies for E.coli


Cercariae are released in water and penetrate the host's skin
5
Cercariae
Schistosomula
6
Two generations of sporocysts develop in the snail
4
During penetration, cercariae become schistosomula and are transported to the liver to mature
Sporocysts
Snails
Paired adult worms
3
Miracidia penetrate a snail
7
Paired adult worms migrate to intestinal veins or the GU venus plexus, where they lay eggs
Miracidia
Eggs
2
Miracidia hatch in water
Eggs pass from the host in feces and urine
1

Helminths eggs

Table 1 Helminth ova content in wastewater and sludge from different countries. Modified from Jiménez, 2007; Hays, 1977; Schwartzbrod *et al.*, 1989; Bennani *et al.*, 1992; Strauss, 1997* and Ensink *et al.*, in press.

Country/region	Municipal wastewater, HO/L	Sludge, HO/g TS
Developing countries	70-3000	70-735
Mexico	6 – 98 in cities, Up to 330 in rural and peri-urban areas	73-177
Brazil	166 – 202	75
Egypt		67 (mean); 735 (max)
Ghana		76
Morocco	214-840	
Jordan	300	
Ukraine	60	
United States	1-8	2-13
France	9-10	5-7
Germany	≤ 40	< 1
Great Britain		< 6
Pakistan (Faisalabad)	142 (*Ascaris*) 558 hookworms (*Ancyllostoma*, *Necator* and *Ascaris*)	
Russia	≤ 2000	
Irkutsk, USSR	19	

*cited as: from an oral communication with Schwartzbrod.

Standard level is ≤ 1 helminth egg per liter for agriculture irrigation