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TECHNICAL NOTE 56.3

Design of a pilot anaerobic thermophilic reactor

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1. Introduction

The MELiSSA loop has five compartments. At the University 'Autonoma' in Barcelona, a MELiSSA pilot plant was built to demonstrate, evaluate and improve the validity of the MELiSSA loop concept on ground conditions. At the moment the pilot plant consists of 3 compartments: Compartment II, the photoheterotrophic reactor containing *Rhodospirillum rubrum*, Compartment III, the nitrifying reactor containing *Nitrosomonas europaea* and *Nitrobacter winogradskyi* and Compartment IVA, the photoautotrophic reactor containing *Spirulina platensis*. At bench scale these three compartments are connected with each other.

In the near future the validity of the entire MELiSSA loop will be studied. In this test, 4 rats will replace the crew. The rats will be fed with *Spirulina platensis* coming from compartment IVA. Compartment I will be fed with human faecal material, non-edible parts of higher plants, *Spirulina platensis, Rhodospirillum rubrum* and a percentage of urine. The amount of urine is not fixed yet.

The purpose of this technical note is to design a thermophilic anaerobic reactor, Compartment I, which can be connected to the other compartments in order to create a close loop. The pilot reactor will also be used to study the filtration technology, to separate the non-biodegraded organic matter from the produced ammonia and VFA and to ameliorate the percentage of degradation.

2. Present operational conditions and results

At the moment compartment I consists of a fed-batch thermophilic anaerobic reactor. The reactor is fed with human faecal material collected from 8 different people between age 24 and 40. The average composition of this faecal material is reported in Table 2-1. The human faecal material is diluted with water at a ratio 1/10 and three times a week, 150 ml is fed to the demonstration reactor. In other words, about 1.7 g DW faecal material is fed to the demonstration reactor every day.

Table 2-1 Composition of the diluted faecal material

Faecal material	**Value**
pH	6.9
Dry matter (g/l)	27
Ash (g/l)	3.9
Organic matter (g/l)	23.1
Total nitrogen (mg/l)	1106
NH_4-N (mg/l)	80
VFA (mg/l)	868
Acetic acid (mg/l)	354
Propionic acid (mg/l)	218
Iso butyric acid (mg/l)	29
Butyric acid (mg/l)	167
Isovaleric acid (mg/l)	46
Valeric acid (mg/l)	33
Caproic acid (mg/l)	20
Isocaproic acid (mg/l)	0

The biological performances of the reactor are gathered in Table 2-2.

Table 2-2 Biological performances of the anaerobic thermophilic reactor

Reactor	T	V	HRT	θ_x	Load	DW	VFA	Total Biodegradation Efficiency
	(°)	(l)	(d)	(d)	(kg COD/m³.d)	(g/l)	(mg/l)	(%)
	55	1.5	20	30	1.2	20.5	4525	55

with: T: temperature
V: volume
HRT: hydraulic retention time
θ_x: sludge age
DW: dry weight
VFA: volatile fatty acids

Since the biodegradation efficiency of the anaerobic reactor is about 55%, the non-biodegraded organic matter (solids) needs to be separated from the produced ammonia and VFA (liquid) before feeding it to compartment II. The non-biodegraded organic matter can be subjected to further treatment.

At the moment preliminary investigations are performed with a microfiltration membrane WWF 4385. The physical and chemical properties of the WWF 4385 microfiltration membrane are gathered in Table 2-3.

Table 2-3 Physical and chemical properties and performance data of the WWF 4385 membrane

WFF4385	
Physical and chemical properties	
Membrane material	polyvinylidene fluoride
Structure	asymmetric/microporous
Membrane carrier	composite polyester fabric
Geometry	tubular
Performance data	
Initial flux (l/m².h)	>1000
Transmembrane pressure (bar)	-1...3
Mean pore size (nm)	30
pH	2-10
Chlorine exposure (ppm.h)	250000
Temperature (°C)	1-70
Hydraulic diameter (mm)	5.2

In present conditions, three times a week the reactor content was recycled through the microfiltration membrane using a peristaltic pump. With a membrane valve a pressure of about 1 bar could be obtained. The set-up of this experiment is represented in Figure 2-1. The permeate was collected and analysed.

From the preliminary results could be concluded that the membrane retained 75% of the non biodegraded organic matter. About 97% of the produced ammonium and VFA were in the permeate. The purpose of the recycle is to create higher solid retention times and therefore better biodegradation efficiencies. This subject is still under investigation.

Based on the obtained separation efficiencies the importance of inserting a microfiltration unit when constructing a thermophilic reactor is shown.

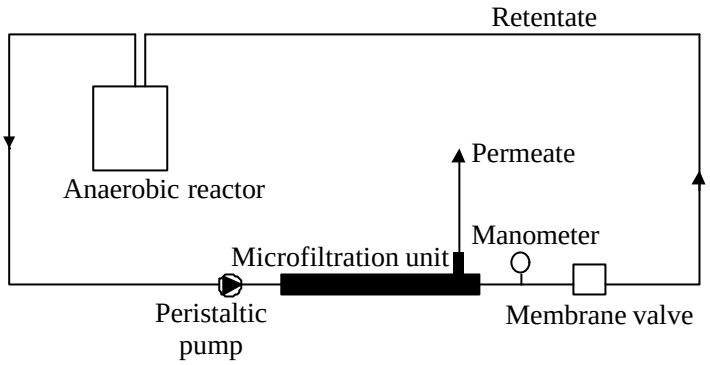

Figure 2-1 Schematic overview of the microfiltration set-up

3. Sizing compartment I

3.1 Introduction

Based on experimental data obtained until now in each MELiSSA compartment, the preliminary sizing of the first compartment was possible. The amount of VFA necessary for compartment II is 3 g a day (Albiol et al.,2000). Next to VFA, compartment I has to produce enough NH_4-N for compartment II and III. In order to produce the biomass required for 4 rats, 0.396 g NO_3-N /h is needed in compartment IV. This means that compartment III requires 0.4 g NH_4-N /h. Compartment II consumes 0.01 g NH_4-N /h. Therefore compartment I has to produce 0.42 g NH_4-N /h or 10.08 g NH_4-N /d.

With the present configuration compartment I is producing 270 mg VFA and 46 mg NH_4-N a day. The amount of NH_4-N necessary in compartment II and III can be supplied by the conversion of urine in NH_4-N and/or by the degradation of the organic waste in the anaerobic process.

3.2 Waste diluted with water

At the moment compartment I produces 0.046 g NH_4-N a day. In the future the reactor has to produce 10.08 g NH_4-N/day for compartment II and III. Assuming that all NH_4-N has to come from the degradation of the waste and in order to obtain the same load the reactor volume has to be increased until 330 litres. In Table 3-1 the new reactor design is represented when the waste materials are diluted with H_2O.

Table 3-1 New reactor design and performances

Reactor	**Lab reactor**	**Pilot reactor**
Wet Volume (l)	1.5	330
VFA production (g/d)	0.27	59
NH_4-N production (g/d)	0.046	10.08
HRT (d)	20	15
Concentration of feed (DW g/l)	27	17
Volume of feed (l/d)	0.064	14
Daily load (g DW/d)	1.7	238
Load (kg COD/m^3.d)	1.2	1.2

These calculations are based on the reactor performances of the past year, when the reactor was fed with faecal material. Preliminary research showed that the biodegradation efficiencies of a solution of faecal

material, non edible parts of higher plants, *Spirulina platensis*, *Rhodospirillum rubrum* are comparable with the biodegradation efficiencies of faecal material.

It is advisable to take into account a safety factor in case lower biodegradation efficiencies are measured. Therefore a reactor volume of 350 litres is recommended.

3.3 Waste diluted with urine

The VFA production can be increased, by increasing the reactor volume, and to obtain the same load, the flow of the influent. Since the VFA production is 270 mg (TN 43.2) a day and a production of 3 g a day is necessary, the reactor volume has to increase from 1.5 litres to 18 litres. In order to obtain the same load, the volume of waste material, fed to the reactor, has to be 770 ml a day, instead of 64 ml a day with a 1/10 dilution rate.

In order to increase the ammonia production, the faecal material will be diluted with urine instead of water. The composition of the urine is presented in Table 3-2. One person excretes 1500 ml of urine per day.

Table 3-2 Amount and composition of the urine excreted per person and day

Components	**Urine (excreted per day)**
Water	1500 ml
Proteins	0.1 g
Sodium (Na^+)	4.6 g
Chloride (Cl^-)	6.3 g
Urea	25 g
Potassium (K^+)	2.0 g
Uric acid	0.8 g
Creatinine	1.6 g

Assuming that for each mol of urea and uric acid two moles of ammonia are produced, 12 g NH_4-N /day can be produced out of 1500 ml urine.

Taking into account the increase of the reactor volume and influent flow, the reactor will produce 0.552 g NH_4-N /d. Therefore 9.528 g NH_4-N/d has to come from the conversion of urea and uric acid. Since 12 g N-NH_4 can be produced out of 1500 ml, 1200 ml urine a day is necessary to provide enough NH_4-N for the further compartments. Therefore to obtain the same load (1.2 kg COD/m³.d), the faecal material has to be diluted at a ratio 1 g waste material wet weight and 17 ml urine. With a feed of 1200 ml a day and a reactor volume of 18 litres, the hydraulic retention time is 15 days. In Table 3-3 the old values are compared with the new calculated values.

Table 3-3 New reactor design and performances

Reactor	**Lab reactor**	**Pilot reactor**
Wet Volume (l)	1.5	18
VFA production (mg/d)	270	3000
NH_4-N production (g/d)	0.046	10.08
HRT (d)	20	15
Concentration of feed (DW g/l)	27	17
Volume of feed (l/d)	0.064	1.2
Daily load (g DW/d)	1.7	20.4
Load (kg COD/m³.d)	1.2	1.2

These calculations are based on the reactor performances of the past year, when the reactor was fed with faecal material. Preliminary research showed that the biodegradation efficiencies of a solution of faecal material, non edible parts of higher plants, *Spirulina platensis*, *Rhodospirillum rubrum* are comparable with the biodegradation efficiencies of faecal material.

It is advisable to take into account a safety factor in case lower biodegradation efficiencies are measured. Therefore a reactor volume of 25 litres is recommended.

3.4 Conclusion

The volume of the reactor will fluctuate between 25 litres and 350 litres.

If no urine is added to compartment I and all the necessary NH_4 for the further loop has to come from the biodegradation of the waste, the pilot reactor will have a volume of 330 litres.

In case urine is introduced into the reactor, the reactor will have a volume of 25 litres. The ammonium concentration in the reactor will be 8 gNH_4/l. This high value is toxic for the anaerobic bacteria (maximum concentration of 2 gNH_4/l).

The volume and toxicity problem has to be further discussed in the near future with all MELiSSA partners.

4. Design of reactor

4.1.1 Schematic overview

In Figure 4-1 the set-up of the biomembrane reactor is represented. The waste material is fed into the reactor. The reactor content is send continuously through the membrane unit. In this unit the non-biodegraded organic matter is separated from the ammonia and VFA. The filtrate is removed and fed to Compartment II. The concentrate is send back to the bioreactor. By way of a valve surplus can be removed from the system.

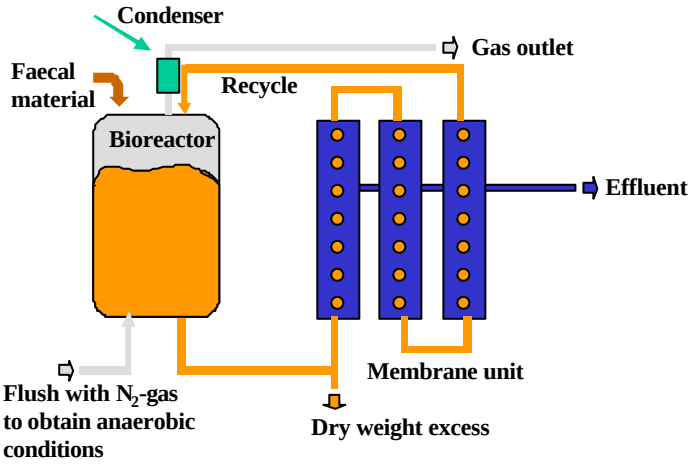

Figure 4-1 Schematic overview of the reactor design

4.1.2 Equipment

In Figure 4-2, Figure 4-3 and Figure 4-4 a more detailed set-up is shown. In this set-up all sensors and actuators are included.

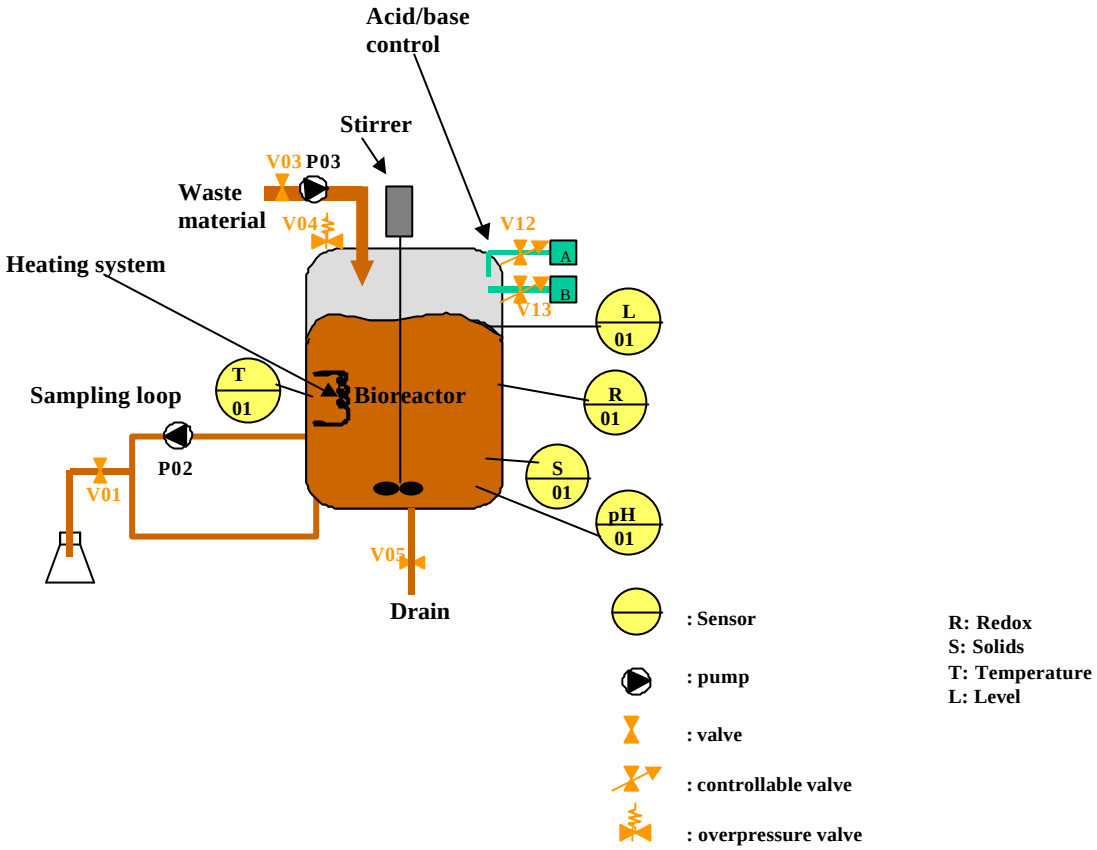

Figure 4-2 Overview of the sensors and actuators of the bioreactor

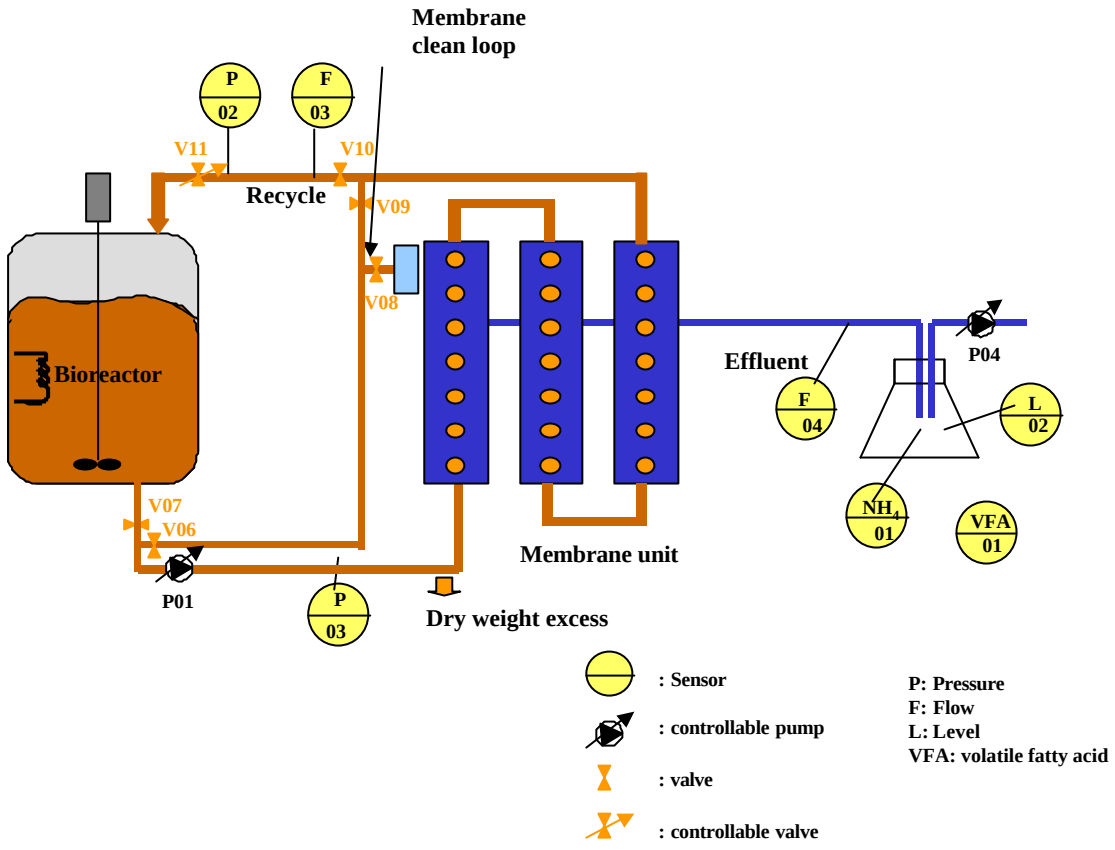

Figure 4-3 Overview of the microfiltration unit

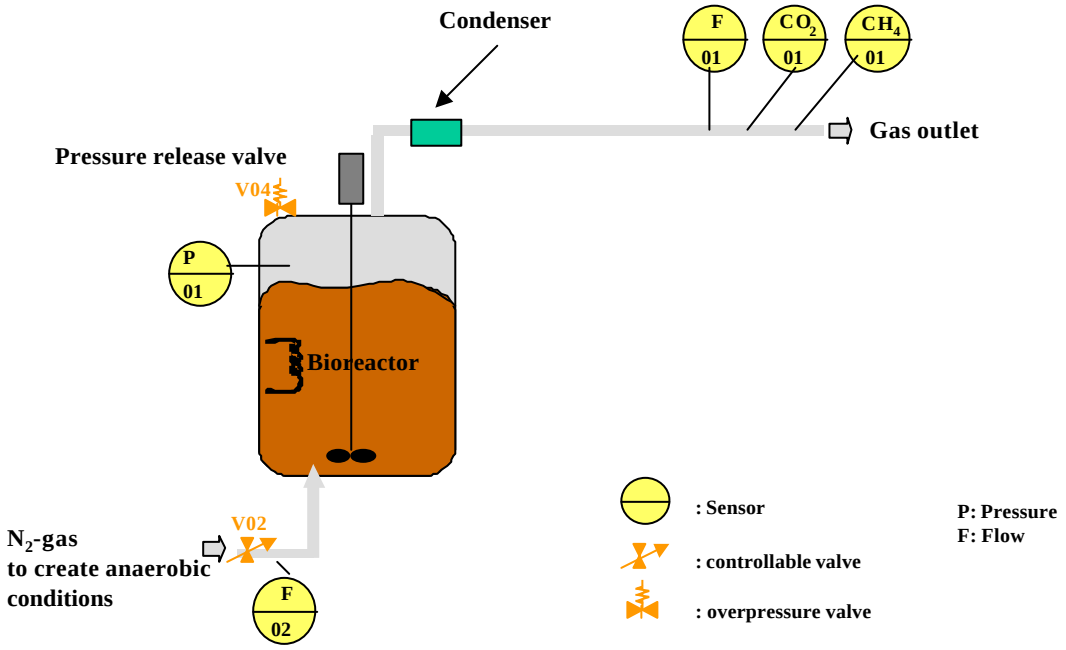

Figure 4-4 Overview of the sensors and actuators of the gasloop

4.1.2.1 Waste preparation

The waste of the new anaerobic thermophilic reactor will consist of human faecal material, *Spirulina platensis*, *Rhodospirillum rubrum* and non-edible parts of higher plants. Per day 20.4 g DW of waste will be fed into the reactor in case urine will be introduced into the reactor. The waste will contain the following elements:

Faecal material:	1 g DW/day
Non edible parts of higher plants:	15.4 g DW/day
Spirulina platensis:	3.2 g DW/day
Rhodospirillum rubrum:	0.8 g DW/day

The human faecal material, collected from different persons, has to be stored in a freezer. The non edible parts of higher plants will be dried in an oven at 105°C, during 2 days. Afterwards the dried higher plants will be grounded in a kitchen grinder until small pieces are obtained. The *Spirulina platensis* and *Rhodospirillum rubrum* will be dried and mixed together with the faecal material and non edible parts of higher plants at the desired concentration.

To prepare the waste for compartment I, the mix of faecal material, non edible parts of higher plants, *Spirulina platensis* and *Rhodospirillum rubrum* will be diluted with urine and grounded with a grinder until a homogenous liquid is obtained. The dilution rate of the mixture is 20.4g of waste material and 1200 ml urine. In Figure 4-5 a set-up of the food preparation unit is represented.

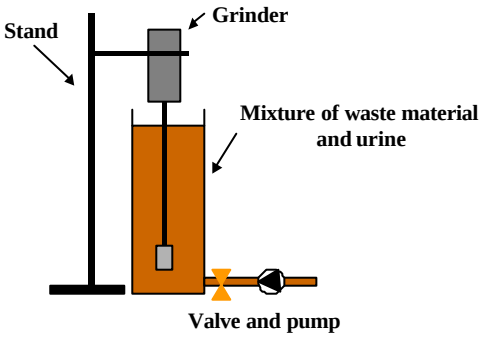

Figure 4-5 Set-up of food preparation unit

In case no urine is introduced in compartment I, 238 g will be fed into the reactor every day. This means that the following quantities of faecal material , non edible parts of higher plants, *Spirulina platensis* and *Rhodospirillum rubrum* are necessary every day:

Faecal material:	11.7 g DW/day
Non edible parts of higher plants:	179.7 g DW/day
Spirulina platensis:	37.3 g DW/day
Rhodospirillum rubrum:	9.3 g DW/day

4.1.2.2 Measurements in reactor

The installation of sensors are important to:

- ✓ give information about the performance of the membrane bioreactor
- ✓ control the system
- ✓ notify when alarm values are measured

The different sensors and its function are represented in Table 4-1. All sensors will be connected to alarm signals.

Table 4-1 Measurements in bioreactor

Sensors	Measurement	Control
Temperature (T)	on line	X (Heating system)
pH	on line	X (base/acid)
Pressure (P)	on line	X (safety valve)
Gasproduction (F)	on line	
Gascomposition		
CH_4	on line	
CO_2	on line	
Redox (R)	on line	X (N_2-gas)
HCO_3/buffer	titration	X
Solids (S)	on line	
Level (L)	on line	

4.1.2.3 Microfiltration unit

With a flow meter and a level sensor installed at the permeate side and connected to a PC, the flux can be measured and followed up. VFA and NH_4-N will be measured in the permeate. The membrane unit loop will be provided with pressure and flow sensors. Two pressure sensors will be installed. One in front of the membrane unit and one after the unit in order to calculate the transmembrane pressure. The pressure can be controlled by means of a controllable valve. The flow can be controlled by means of an adjustable pump. In Table 4-2 the different sensors necessary in the membrane unit are shown.

Table 4-2 Sensors in membrane unit loop

Sensors	Measurement	Control
Pressure (P)	on line	X
Level (L)	on line	X
Flow (F)	on line	X
VFA	on line	
NH_4-N	on line	

The membrane unit loop will be equipped with a cleaning loop in order to bypass the bioreactor and clean the membrane unit to avoid fouling of the membrane.

4.1.3 Control system

Several parameters will be controlled others will just be followed up. The values measured by the sensors will be stored in the PC. The list of parameters is shown in Table 4-3.

Table 4-3 List of parameters

Parameters	**Function**	**Controller**	**Actuator**	**I/O PC**
Temperature *T01*	C,A,I	SA	heater	AI 01, DI01, DI02
Pressure *P01*	C,A,I	SA	safety valve	AI02, DI03
P02	C,A,I	(SA) PC	valve UF	AI03, AO01
P03	C,A,I			AI04, DI05
Flow *F01*	A,I			AI05, DI06
F02	A,I			AI06, DI07
F03	C,A,I	(SA) PC	pump UF	AI07
F04	C,A,I			AI08
pH *pH01*	C,A,I	SA	valve	AI09, DI08
Redox *R01*	C,A,I	SA	valve	AI10, DI09
Ammonia NH_4*01*	A,I			AI11
VFA *VFA01*	A,I			AI12
Solids *S01*	A,I			AI13
Level *L01*	C,A,I			AI14
L02	C,A,I			AI15
Carbon dioxide CO_2*01*	A,I			AI16
Methane CH_4*01*	A,I			AI17
Flux	A,I			AI18

C: control; A: alarm; I: indication; SA: stand alone; PC: computer; AI: analog input; DI: digital input; AO: analog output;

In Table 4-4 the different actuators are listed and if they are controlled or not.

Table 4-4 List of actuators

Actuators	Mode	I/O PC
Pump		
P01	A	AO01
P02	M	no
P03	M	no
P04		
Valves		
V01	M	no
V02	A	DO01
V03	M	no
V04	A	DO02
V05	M	no
V06	A	DO03
V07	A	DO04
V08	A	DO05
V09	A	DO06
V10	A	DO07
V11	A	AO02
V12	A	DO08
V13	A	DO09
Balance	A	
Heater	A	

M: manual; A: automatic

4.1.4 Sterilisation of biomembrane reactor

To avoid contamination in the further loop, the effluent of compartment I has to be sterile. The microfiltration membrane has a mean pore size of 0.03 µm and therefore the membrane should retain bacteria and no other precautions are necessary. This will be investigated in the near future and the preliminary results will be represented in TN 56.1.

5. Feed collection programme

Urine and waste material are the two components necessary to feed the new anaerobic demonstration reactor. Faecal material and urine are excreted by human beings. Per day about 20.4 g DW of waste material and 1200 ml of urine will be fed to the reactor.

For 1 year the following quantities are necessary, when using urine (Table 5-1) :

Table 5-1 Waste materials necessary for one year

Waste	g DW a day	kg DW a year
Faecal material	1	0.35
Non edible parts of higher plants	15.5	5.66
Spirulina platensis	0.8	0.29
Rhodospirillum rubrum	3.2	1.16
Urine (l)	1.2 litres	440 litres

For 1 year the following quantities are necessary, if no urine is introduced in compartment I (Table 5-2) :

Table 5-2 Waste materials necessary per year

Waste	g DW a day	kg DW a year
Faecal material	11.7	4.3
Non edible parts of higher plants	179.7	65.6
Spirulina platensis	37.3	13.6
Rhodospirillum rubrum	9.3	3.4

6. Cost calculations

6.1 Biomembrane reactor

The biomembrane reactor consists of a bioreactor and a membrane unit, consisting of a few membranes in parallel and costs about 124 KEURO. This includes the hardware and construction costs, not the sensors, pumps, PC hardware and software.

6.2 Sensors

A rough cost estimation for the different sensors is shown in Table 6-1.

Table 6-1 Cost estimation of sensors in Euro

Parameters	Sensors	Controller	Actuators
Temperature T01	250	370	370
Pressure			
P01	250	185	100
P02	250	185	100
P03	250		100
Flow			
F01	1200		
F02	400		

F03	400		250
Level *L01*	740		
Redox *R01*	496	495	
Solids *S01*	2970		
VFA *VFA01*	21000		
pH *pH01*	496	370	495
CH_4, CO_2	5950		
NH_4	15514		
		Total price:	**53186 EUR**

6.3 PC hardware and software

In order to follow-up and control the system different hardware and software is necessary:

- ✓ PC
- ✓ PLC/communication card (compatible with University 'Autonoma' of Barcelona)
- ✓ Supervision/user interface (FIX)
- ✓ Software
- ✓ Power supplies/electronics

In Table 6-2 an indicative cost calculation of the hard- and software is shown.

Table 6-2 Hardware and software cost calculations

Hardware and software	**Price (EUR)**
PC	2974
PLC/communication card	2974
Supervision/user interface (fix)	2479
Software	13634
Power supplies/electronics	3718
Total price:	**25779**

7. Conclusion

In the near future, the validity of the entire MELiSSA loop will be studied with an experiment with 4 rats, replacing the crew. Since the present thermophilic demonstration reactor at Epas NV is too small to fit within the pilot plant at the University of Barcelona, this compartment had to be redesigned. Based on the results of the PHOTOSIM simulator from the University 'Blaise Pascal', the fourth compartment could be designed taking into account the requirements of 4 rats. Once this compartment was estimated the other compartments, among which compartment I, could be estimated.

Based on the calculations in this technical note it can be concluded that the bioreactor will have a volume between 25 litres and 350 litres dependent on whether urine is added to compartment I or not. A proper calculation need to be done with all the MELiSSA partners in the near future.

The reactor will be equipped with, a membrane unit to separate the non-biodegraded organic matter from the produced ammonia and VFA, several sensors, valves and pumps to control the system and to store

information about the performance of the system. The total cost of the system is estimated to 202965 EUR, of which 124000 EUR for the reactor and filtration unit, 53186 EUR for sensors, controllers and actuators and 27779 EUR for hardware and software. The cost calculations are only indicative and can not be interpreted as an offer.

8. References

Albiol, J., Creus, N. and Godia, F. Preliminary review of the pilot plant final loop. Technical Note 47.3. Draft version.ESTEC/CONTRACT11549/95/NL/FG.

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