Reinvent the Toilet Challenge – Round 1 Final Report

Data and design – mineralisation of sanitation wastes from community ablution blocks

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Summary Information

Grant Information

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General results

The Reinvent the Toilet Challenge (RTTC) project at the University of KwaZulu-Natal (UKZN) has aimed to ground the research work in the real-world context of informal settlement community ablution blocks. The characterisation of human excreta samples from these settings provides the basis for producing the data necessary to design excreta-processing systems suitable for operation in these contexts.

A decision was made to separate excreta waste streams at source, to facilitate downstream processing. To achieve this, a new source-separation pedestal was developed and two prototype versions of it manufactured.

The concept design for a three-stage processing system for the drying and combustion of the faecal and non-faecal solids was developed and the first stage (extruder-separator) prototyped.

Construction is underway of experimental rigs for work on a forward osmosis membrane system for urine processing. Experimental work has not yet started.

The excreta characterisation work has not progressed to the extent that was planned, due to a number of factors external to the project. These are summarised in Appendix A2, along with the current status of each issue. This in turn has limited the work that could be carried out on the design of the excreta processing systems.

Sustainability

A proposal is being negotiated with the BMGF for second phase funding for the project. The emphasis of the research will be modified from the project's first phase, in the following ways:

- The excreta characterisation work will continue, and will be expanded to include analyses requested by other grantees to support their RTTC and other sanitation work;
- There will be increased emphasis on collaboration with other grantees to field-test toilet pedestals and partial or complete excreta-processing systems. The design of a purpose-built community ablution block with facilities for testing different systems will form part of the work;
- Based on the excreta characterisation data generated, an integrated model for the toilet system will be developed;
- The pedestal will be further developed to improve the wash water distribution (over the existing plastic surface) and to design an improved pedestal shape which will reduce the fouling down the back face of the pedestal while presenting the material into the collection hopper. The emphasis will be on the physical form of the pedestal, rather than new materials or coatings.

The following resources will remain in place after the end of the Phase 1 grant period:

- Two Masters students working on the faeces and urine processing sections of the project will continue through to March 2013, providing a resource to continue characterisation work after the end of the Phase 1 grant period, and time to recruit replacements for any future phases;
- A new project manager has been recruited for a possible second phase of the project, and is currently employed part time, both to support Phase 1 activities and enable a smooth transition to a second phase;
- Discussions have taken place with the current project partners (Envirosan - pedestal development, eThekwini Water and Sanitation - support for sampling and field testing, and Hering - community ablution block design) about a possible Phase 2 project – all have expressed a desire to continue their involvement with the project. eThekwini Water and Sanitation would receive a sub-grant under the proposed RTTC Phase 2 budget.

A significant issue exists with retaining contract staff after the end of Phase 1 (specifically a senior workshop technician and laboratory assistant).

Scalability

The project design for a second phase envisages the scale-up of (i) the excreta characterisation work and (ii) collaborative work with other grantees. To enable this, the following actions are being taken:

- A revised team structure has been proposed for Phase 2, based on lessons learned during the current phase. The team, overseen by the principal investigator, would consist of: a project manager (with an administrative focus), a project engineer (overall technical management), two post-doctoral fellows (supervising the technical aspects of the urine and faeces processing activities respectively), an increased number of Masters students (each with responsibility for specific sections of experimental work) and two full-time skilled laboratory technicians;
- A separate budget (outside the RTTC project funding stream) is being compiled for the necessary health and safety infrastructure improvements that would have to be made to allow increased numbers of samples to be handled safely by the Group's laboratory.
- Health and safety review of laboratory and fieldwork procedures.

Challenges

The major challenges to the project were the external issues detailed in Appendix A2. The extent and duration of the impact of these factors on project progress could not be anticipated. The intervention of the Foundation in June 2012 (a meeting with the university Research Office staff and a representative from the Foundation) assisted with the resolution of some of the issues.

The issue remains of attracting and retaining good staff in the research group when only short contracts can be offered (because the contract is tied to the length of the project funding). Discussion with the Foundation has covered the possibility of separate grant funding for longer term (e.g. two year) contracts for skilled administration and laboratory staff to support Foundation-funded projects. Alternatively the RTTC Phase 2 budget could include for employing support staff beyond the length of the project.

The time and infrastructure required to put in place systems to handle and analyse a large number of hazardous samples was not properly anticipated. The lessons learned from this process will facilitate the continuation of the characterisation work.

Lessons learned

Key points to note for future work are listed under the review of each of the project work areas, however the following general points are noted from the first phase of RTTC work at UKZN:

- Setting up systems for the routine collection and analysis of excreta samples is time-consuming, even in a laboratory that already handles other bio-hazard samples.
- Human excreta is classified (unofficially or officially) as a different biohazard to sewage sludge – with the result that the majority of external (non-medical) labs refuse to analyse it.

Attachment:

RTTC Phase 1 Results Framework

1 Background

The study area is within the eThekwini municipality, located in the province of KwaZulu-Natal, South Africa, and covering an area of approximately 2300 km^2. In 2002, of a population of 3.5 million, approximately 175,000 households were estimated as not having access to basic sanitation (Roma et al. 2011). The South African constitution guarantees access to free basic water and sanitation to all. In dense, informal urban settlement areas one of the few viable ways for the government to provide sanitation is through community ablution block facilities.

Community ablution blocks typically serve around 300 users (75 households), in a radius of 200 m from the facility. Toilet, shower and clothes-washing facilities are provided. The toilets may be on a sewer or septic tank system or be ventilated improved pits (VIPs). The implementation context for the RTTC project at UKZN is an ablution block of this type.

The Pollution Research Group (PRG) at UKZN partnered with the following organisations for Phase 1 of the RTTC project:

- **eThekwini Water and Sanitation**: municipality water and sanitation department. Facilitate access to community and household sanitation facilities;
- **Envirosan**: plastic toilet pedestal manufacturer and distributor in multiple countries. Partner for design of a new toilet pedestal;
- **Hering**: public toilet facility designers. Partner for design of a purpose-built community ablution block for field-testing.

This report describes the work carried out during Phase 1 of the RTTC project at UKZN, divided across the following workstreams:

- Conceptualisation of the toilet system
- Characterisation of the toilet input streams
- Toilet pedestal development
- Faeces and solids processing
- Urine processing
- Health and safety
- Community ablution block design

2 Toilet system

Figure 2.1 overleaf summarises the concept design of the toilet system. The following should be noted:

- An initial design decision was made to implement source-separation of the excreta streams. This facilitates the downstream processing of the influent, but creates additional challenges for the user interface section of the system;
- Three main processing sections exist, for the following streams that are produced from the toilet pedestal: (i) urine, (ii) contaminated washwater used for rinsing the toilet bowl and (iii) faeces and non-faecal solids;
- The overall energy flow is from the solids processing section (recovered energy from the combustor) to the liquids processing side (to drive membrane separation and dehydration processes);
- The following product streams result: potable water, concentrated nutrient products and sterile, nutrient-rich ash.

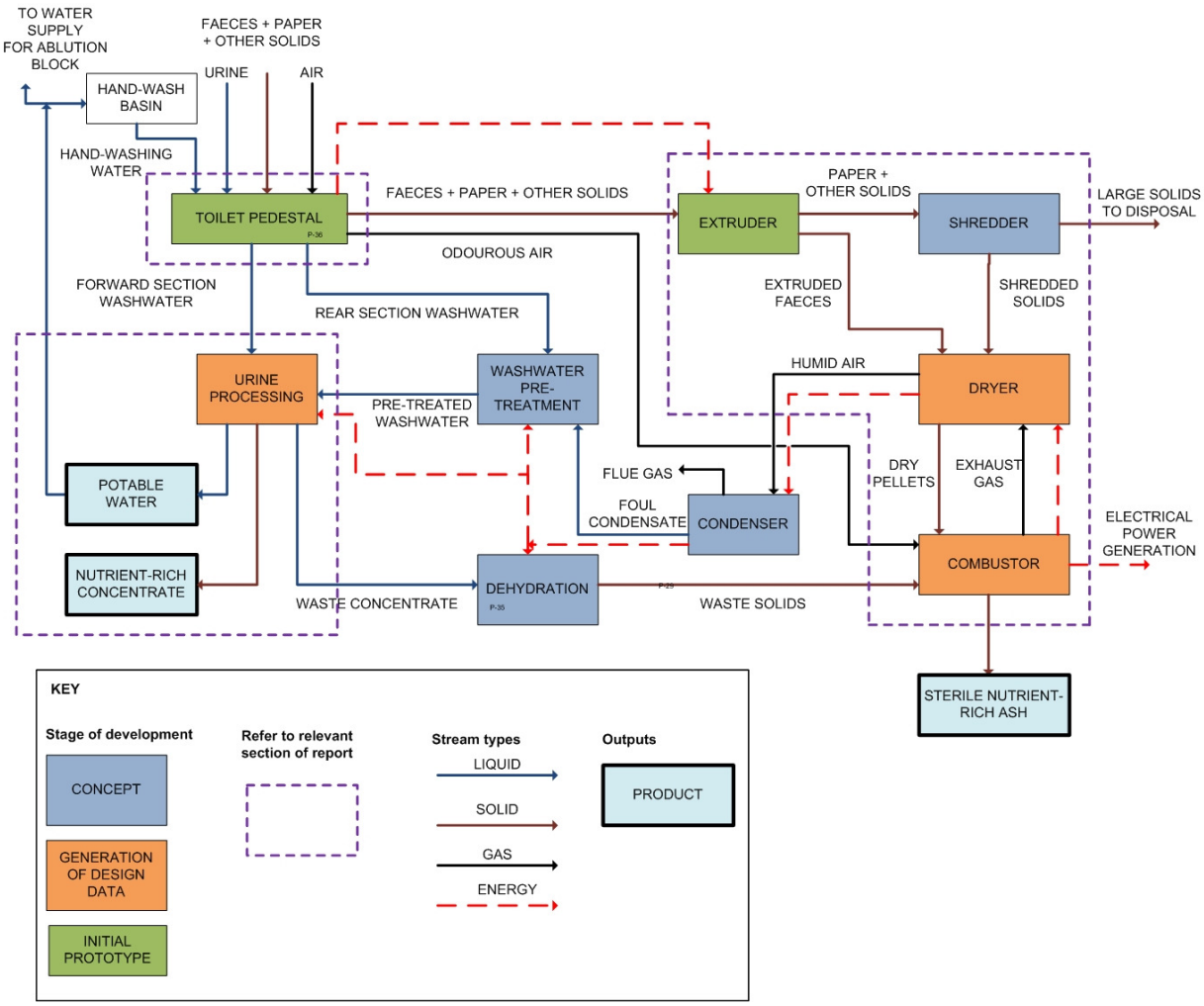

FIGURE 2.1 GENERAL PROCESS FLOW DIAGRAM OF THE TOILET SYSTEM

Under the current phase of the project, prototypes of the new toilet pedestal and the solids separation-extrusion system have been manufactured . Human excreta characterisation data for the influent streams has been generated. Equipment has been built and purchased to generate design data for the drying and combustion of the solids stream, and for the membrane processing of the urine stream.

3 Characterisation of toilet input streams

3.1 Review of existing property data for faeces

Limited literature exists on the mechanical and thermal properties of human faeces. Table 3.1 summarises data reviewed from several studies on the chemical composition of faeces.

TABLE 3.1 CHEMICAL PROPERTIES OF HUMAN FAECES

Parameter	Unit	Reference		
		Lopez Zavala et al. 2002	**Chaggu 2004**	**Buzie-Fru 2010**
Water	%	73.4 – 84.7	66 – 85	70 – 85
Total Solids (TS)	%	18.2	33 (avg)	15 – 30
Volatile Solids (VS)	%	84.4	88 – 97	88 – 97
pH	-	7.5	-	-
EC	µS/cm	115.9	-	-
COD	mg/mg	1.45	46.23 – 78.31 (g/L)	33
Total Carbon	g/g		-	44 - 55
Total Nitrogen	mg/g	60.1	5.0 – 7.0	5.0 – 7.0
NH_3-N	mg/g	3.4	-	-
NO_3-N	mg/g	0.03	-	-
Cl	mg/g	4.2	-	-
SO_4	mg/g	1.1	-	-
PO_4-P	mg/g	4.5	-	3.0 – 5.4

The following can be noted:

- The major components of excreted faeces are: water, bacteria, excreted waste from the blood stream and glands and organic material from ingested food that has not been completely digested and absorbed by the intestines;
- The organic, nutrient and water content of faeces are dependent on diet, age, health, lifestyle and geographic region (Lopez Zavala et al. 2002, Buzie-Fru 2010);
- Intestinal transect time (itself connected to the diet and state of health of the subject (Bowen 2006)) has been shown to vary from 20.9 to 197.7 hours (Lewis & Heaton 1997), and has a major impact on water content of excreted faeces;
- Whilst the majority of nutrients are excreted via urine, a significant proportion are contained in faeces: 20 to 50% of phosphorus, 10 to 20% of nitrogen and 10 to 20% of potassium (Berger 1960);
- The properties of faeces change significantly post-excretion, mainly due to water loss and biodegradation. Bai and Wang (2011) observed a 63% reduction in organic content over a 2-week period.

Based on the review of existing data, the aims of the RTTC faeces characterisation work were to:

- Quantify the nutrient and organic content, mechanical and thermal properties of faeces from two populations of different socio-economic sectors, between which diet and general state of health are assumed to differ significantly;
- Investigate the changes in properties with (i) water content and (ii) age of samples.

- Investigate the types of non-faecal material the toilet system will have to process in a community ablution block context.

3.2 Sampling programmes

Excreta samples from different sources were collected. These sources and the rationale for collecting samples from them are detailed in Table 3.2.

TABLE 3.2 TYPES OF HUMAN EXCRETA SAMPLES COLLECTED

Sample type	Sample source	Single / multiple donor	Reason for collection	Status
Faeces only	University students & staff (relatively affluent)	Single	Relatively easy to collect and handle samples Representative of higher-income diet	Ongoing (started March 2012)
Mixed excreta (faeces, urine, cleansing material)	Informal settlement community ablution block (ventilated improved pit latrines)	Multiple – single gender	Representative of lower-income diet Likely to be higher incidence of diarrhoeal disease Significant quantities of non-faecal solids disposed of into toilet Allows analysis of real mixed stream samples with no water addition	Ongoing (started June 2012)
Faeces and solid cleansing material	Rural household urine diversion toilet	Multiple – mixed gender, single household	Representative of lower-income diet & health condition Segregated faeces samples	Not started

Appendix A3 details the process of setting up the sampling programmes and methods used for collections.

3.3 Sample analyses

The following sets of analyses were carried out on the excreta samples detailed above:

(i) Chemical property analyses: to determine potential for fertiliser application of the toilet system end-products;
(ii) Mechanical property analyses (including rheology): to provide data for the design of any part of the toilet system which requires mechanical processing of excreta and to calculate the energy requirements of these processes;
(iii) Thermal properties: to provide data for the drying, combustion and potential energy recovery from the solids stream of the excreta.

Table 3.3 details the status of the individual analytical tests being carried out.

TABLE 3.3 STATUS OF ANALYTICAL TESTS

Property group	Analytical tests	Status
Mechanical & rheological properties	Basic characterisation (mass, photo, Bristol stool categorisation)	In progress
	Rheology (flow curve, oscillatory tests, temperature dependency, stress recovery, variation with water content and age of sample)	In progress
	Solids (total, suspended, volatile)	In progress
	Density	In progress
	Particle size distribution	External laboratory required – suitable service provider not yet found
Chemical & biological properties	Total Kjeldahl Nitrogen (TKN)	In progress
	Ammonia	
	Chemical Oxygen Demand (COD)	
	pH	
	Total phosphate	External laboratory sourced – test samples underway
	Orthophosphate	
	Potassium	

	Volatile Fatty Acid (VFA)	
	Viable Ascaris	
Thermal properties	Drying curves under controlled environmental conditions (air flowrate, humidity and temperature; varying flow regimes and drying geometries)	Construction underway of purpose-built drying rig; awaiting final parts from supplier
	Thermal conductivity	Ongoing
	Specific heat	Ongoing
	Calorific value	Calorimeter awaiting final installation from supplier

Fresh excreta samples had not been previously handled by the Pollution Research Group laboratory. New standard operating procedures (SOPs) were developed or existing methods modified to carry out the analyses listed above.

3.4 Analytical data

Table 3.4 summarises the analytical tests carried out to date. All tests were carried out in the Pollution Research Group laboratory, unless otherwise indicated.

TABLE 3.4 LIST OF ANALYTICAL TESTS PERFORMED

Analytical test	Number of samples analysed	Comments
Basic characterisation	85	Includes mass of sample, Bristol stool classification, photograph
Rheological tests	64	
Total and volatile solids	139	Includes sub-samples of individual stool samples
Density	77	
Chemical Oxygen Demand (COD)	81	
Ammonia	87	
Total Kjeldahl Nitrogen (TKN)	54	
pH	91	pH of dilution of solid sample
Thermal conductivity & specific heat	13	
Total phosphate	3	Awaiting initial test results from external laboratory – analysis to now be ongoing
Orthophosphate	3	

Potassium	3	
Volatile Fatty Acid (VFA)	3	
Viable Ascaris	4	

Standard literature methods were used for all chemical characterisation tests. The appropriate concentration of faeces dilution to be used had to be established for each test. New standard operating procedures (SOPs) were written for basic handling and characterisation of samples, density and rheological measurements and sample disposal. SOPs are provided as attachments to the report.

The property data generated has been compiled into a database. A summary of the rheology study is given in Section 5 and in the document attached to this report.

Further analytical data, particularly on samples from community ablution blocks, is required to able to make a comparison between the properties of the faeces from the two sample groups. This will be addressed in the next stage of the project. The rheological study gives details of correlations between rheological and other tested properties of samples.

The majority of samples (68%) collected from individuals were classified as having a Bristol Stool Form Scale (BSFS) index of 4 (see Lewis & Heaton 1997 for explanation of scale). BSFS classifications for mixed excreta samples from community ablution blocks are less useful, as faeces and urine are combined together in the collection container.

The average mass of the stools collected (from individual donors) was 129g (σ = 52g; n = 75; min = 32g; max = 304g), with an average total solids content of 26.95% (σ = 8.77%; n = 131; min = 11.32%, max = 53.81%). Average volatile solids content was 22.99% (σ = 7.42%; n = 130; min = 7.91%; max = 45.85%). Average approximate density was 1.06 g/ml (σ = 7.42%; n = 64; min = 0.17g/ml; max = 1.16 g/ml).

Average chemical oxygen demand (COD) for faeces samples from individual donors was 1062.69 mg O_2 / g dry sample (σ = 634.33 mg O_2 / g dry sample; n = 68; min = 12.46 mg O_2 / g dry sample; max = 3088.08 mg O_2 / g dry sample). Average ammonia content was 11.17 mg NH_3-N / g dry sample (σ = 7.67 mg NH_3-N / g dry sample; n = 74; min = 1.03 mg NH_3-N / g dry sample; max = 30.64 mg NH_3-N / g dry sample). Average total Kjedhal nitrogen (TKN) was 40.19 mg TKN / g dry sample (σ = 184.80 mg TKN / g dry sample; n = 47; min = 0.56 mg TKN / g dry sample; max = 1291 mg TKN / g dry sample). COD, ammonia and TKN are dependent on age of sample and it should be noted that the samples analysed for this dataset varied in age at the point of analysis.

Attachments

Standard Operating Procedures for:

- Basic faeces handling and sample preparation
- Density measurement of faeces
- Rheological measurements on faeces
- Sample disposal
- Total Kjeldahl Nitrogen (TKN)
- Chemical Oxygen Demand (COD)
- Ammonia
- Total and volatile solids; ash content

4 Pedestal development

A new design of toilet pedestal was developed in partnership with Envirosan.

The objectives of the new toilet pedestal were to:

(i) Achieve a three-way source separation of:
   a. Urine
   b. Faeces and non-faecal solids
   c. Contaminated washwater from rinsing the toilet bowl;
(ii) Prevent odours;
(iii) Provide an attractive, easy to clean toilet that a user would wish to own and use.

Urine is diverted via the front section of the pedestal (Figure 4.1B). When the toilet lid is open, faeces and non-faecal solids drop through the rear portion of the toilet bowl (Figure 4.1B and 4.1C). Used water from hand-washing is diverted to the toilet to provide a rinsing system for the front and rear portions of the toilet bowl (Figure 4.1A). The mechanism of closing the toilet lid causes a bowl to swing underneath the pedestal and locks onto the bottom of the toilet (Figure 4.1C - E). The bowl catches the soiled washwater, which is diverted by pipe to a separate washwater processing system. The bowl also provides an odour seal.
The outer shell for the toilet pedestal body was injection-moulded from high density polypropylene (this is standard part already produced by Envirosan, therefore moulds already existed). New prototype parts, including the diversion system for the washwater, were machined from acrylonitrile butadiene styrene (ABS) plastic, as producing moulds for one-off parts is infeasible. ABS was a suitable material for most parts that were prototyped, but was not rigid enough for sections undergoing torsion (e.g. the strut joining the toilet lid to the washwater diversion bowl).

Two versions of the toilet prototype were manufactured and workshop-tested. Further revision to increase the robustness of the design is necessary before field-testing in an ablution block setting could be carried out.

Appendix A5 provides further detail on the pedestal design. Further detail on the manufacturing processes used by Envirosan is available at www.envirosan.co.za.

FIGURE 4.1 **TOILET PEDESTAL: THREE-STREAM SOURCE SEPARATION (A) DIVERSION OF USED HAND-WASHING WATER TO RINSE TOILET PEDESTAL (B) URINE SEPARATION SECTION (C) – (D) MECHANISM FOR CONTAMINATED WASHWATER DIVERSION**

5 Faeces and solids processing

Various types of non-faecal solids (in addition to toilet tissue) have been observed deposited in community toilets, including newspaper, plastic packaging, clothing and hair (Figure 5.1). The solids processing system must account for these. Figure 5.2 summarises the concept design for the solids processing section of the toilet system. The mixed solids (faeces and non-faecal solids) pass through a three-stage processing system: (i) extrusion-separation, (ii) drying and (iii) combustion with energy recovery.

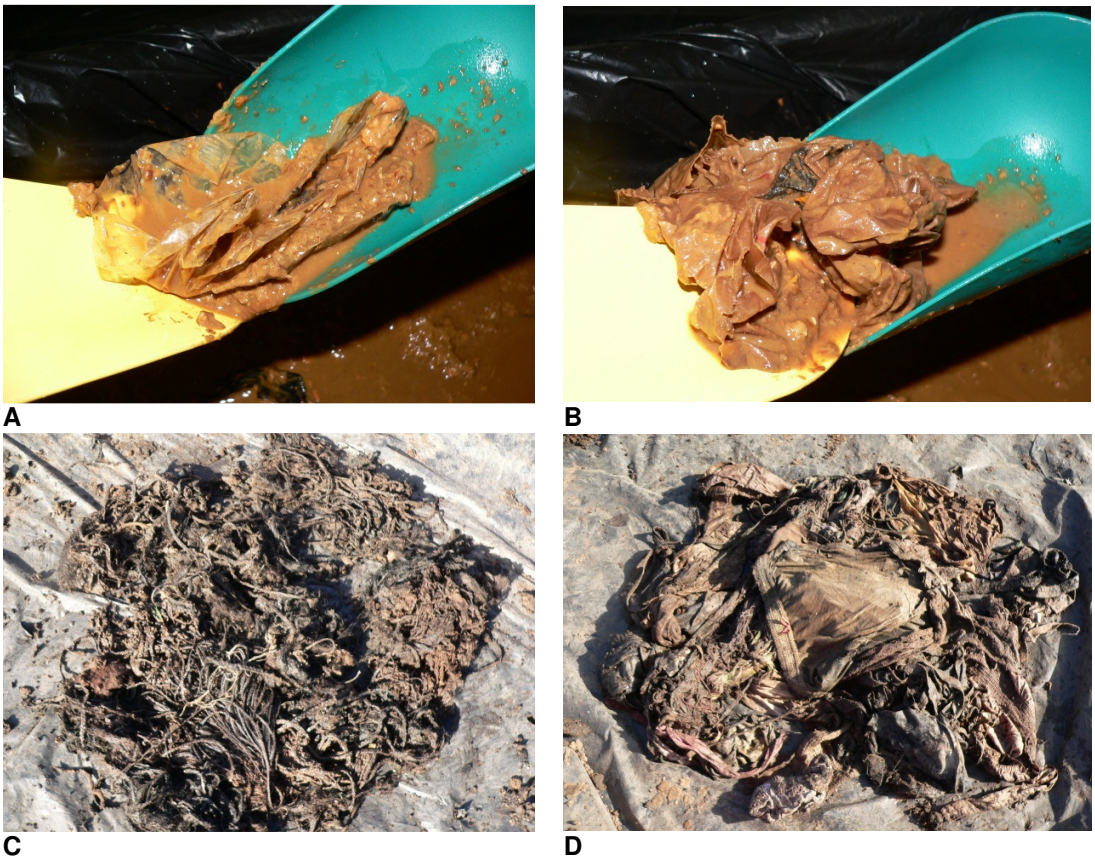

FIGURE 5.1 **NON-EXCRETA SOLIDS FOUND IN TOILET FACILITIES: (A) PLASTIC PACKAGING; (B) NEWSPAPER; (C) HAIR EXTENSION; (D) CLOTHING & FABRICS**

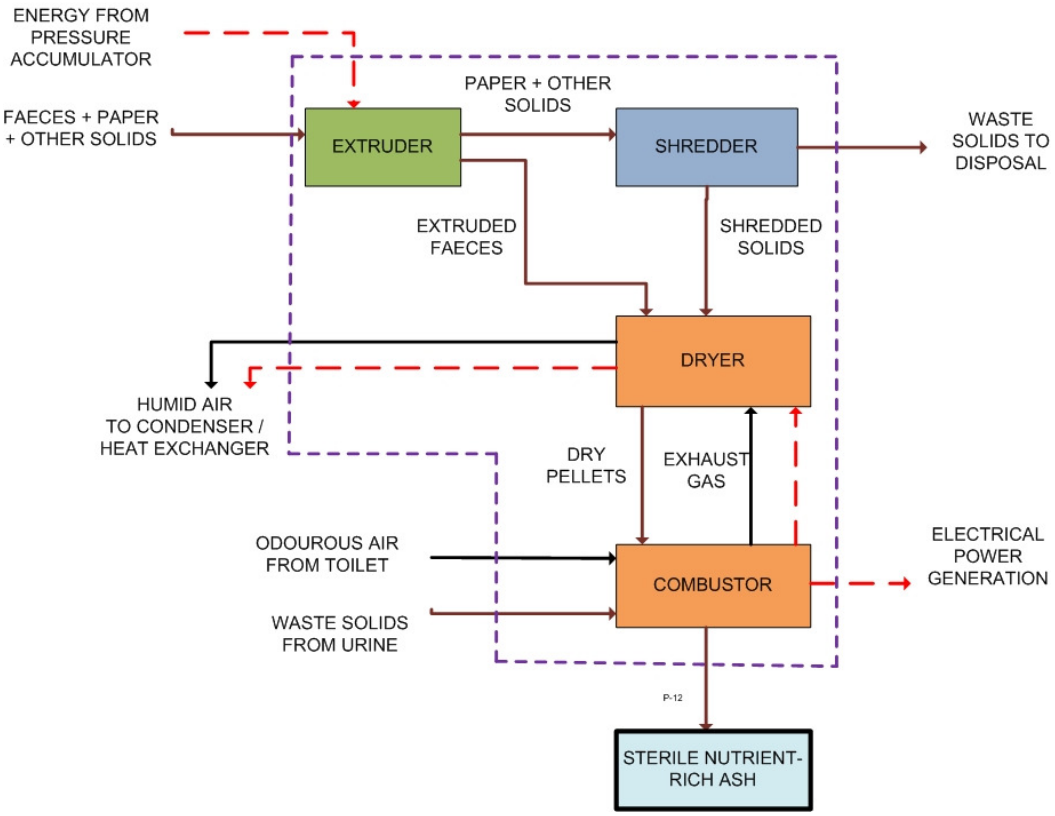

FIGURE 5.2 PROCESS FLOW DIAGRAM OF SOLIDS-PROCESSING SECTION OF TOILET SYSTEM

5.1 Extrusion-separation system

The first stage of the solids processing system has two aims:

(i) To separate non-faecal solids from faeces – these are processed separately (non-combustibles are disposed of separately, combustibles are shredded before being sent to the dryer);
(ii) To prepare the faecal paste into a form where it can be efficiently dried and combusted.

This is achieved via a ram extrusion system, shown conceptually in Figure 5.3.

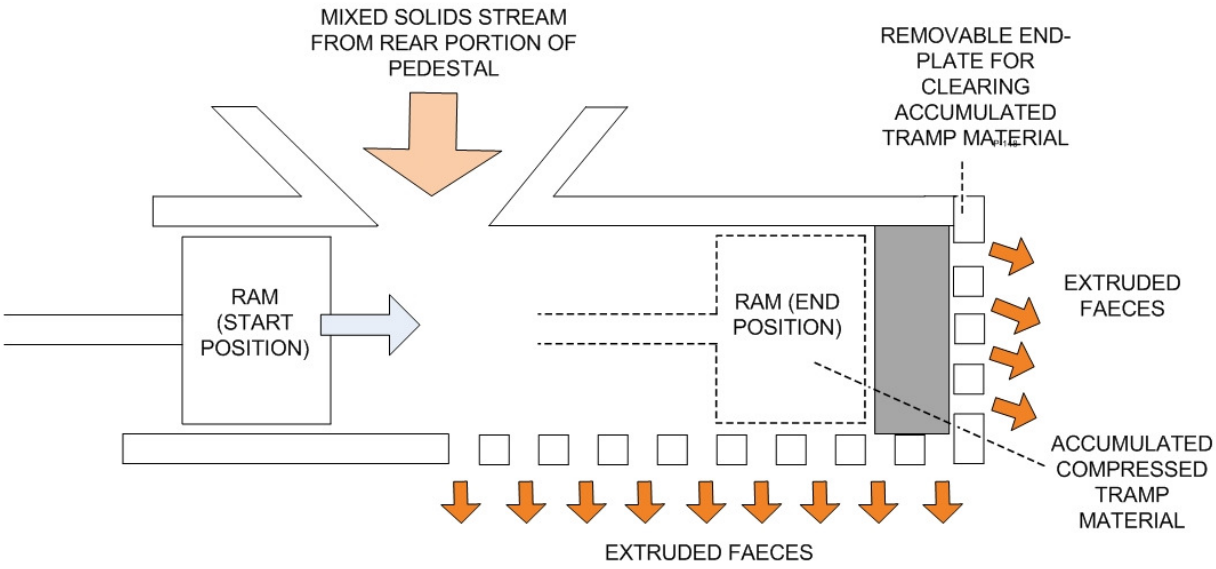

FIGURE 5.3 CONCEPT FOR EXTRUSION–SEPARATION SYSTEM

Mixed solids are pushed by a ram through a pipe and pressed against a fixed end-plate. Faecal paste is extruded through holes bored into the pipe, and the pellets caught on a belt below. Non-faecal tramp material accumulates at the end of the pipe and is removed at intervals (manual removal in the first prototype) for separate processing. Figure 5.4 shows the prototype extruder operating on a mixture of faeces simulant and newspaper.

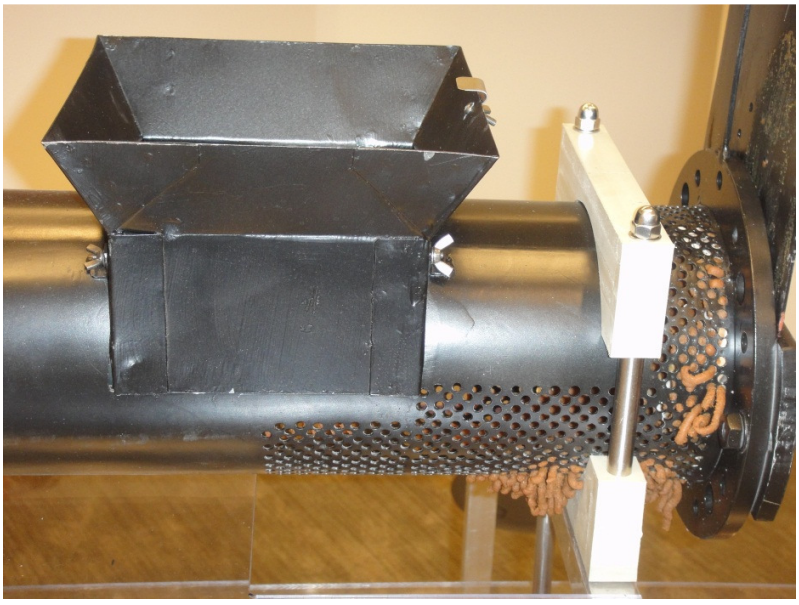

FIGURE 5.4 EXTRUDER OPERATION: FAECAL SIMULANT EXTRUDED FROM RAM

Two options for powering the ram were trialled – compressed air and electrical motor. The energy requirements for powering the ram to achieve extrusion are extremely dependent on the rheology of the

material being processed. The next stage of the work would link the rheology study to the design of the extruder system. It is envisaged that in future systems mechanical energy could be harnessed from the toilet system (e.g. the action of closing the toilet cubicle door or sitting on the toilet seat) and used to power the ram.

5.2 Rheology study of human faeces

The rheological properties of fresh human faeces from individual donors were measured using a rotational rheometer. The same samples were further tested for water content, total solids, volatile and ash content and density.

All stool samples were found to have a yield stress; there was a decrease in apparent viscosity with increasing shear rate. For any given shear rate, higher apparent viscosities were associated with lower moisture contents.

During constant shear tests, the apparent viscosity of all faeces was found to decrease asymptotically to a minimum value, where the minimum apparent viscosity value increased with decreasing moisture content or decreasing shear rate.

An analysis of structural recovery tests and flow curve hysteresis data indicates that human faeces is rheomalaxic (Hackley & Ferraris 2001) in behaviour.

A linear relationship between viscosity and temperature was found, with lower viscosities at higher temperatures, over a temperature range of 10°C to 50°C.

The results and discussion from the rheology study, 'Some Rheological Properties of Fresh Human Faeces with a Variation in Moisture Content' (Woolley et al. 2012), is provided as an attachment to this report.

6 Urine processing

The design principles behind the urine processing system were as follows:

- To maintain the feed streams in as concentrated form as possible (via the diversion of soiled washwater and solids as separate streams from the urine);
- To combine streams for processing when their compositions were most similar;
- To use power sources readily available from other portions of the toilet system (i.e. heat recovered from the combustion process);
- To design a failsafe process, that would still function under significant levels of cross-contamination from the faeces stream;
- To design a robust and modular process, that would be simple to maintain;
- No requirement for regular addition of non-standard consumables (e.g. chemical dosing agents);
- Process to be universal, i.e. not dependent on geographical location, time of day or season.

The concept for the urine processing system is summarised in Figure 6.1.

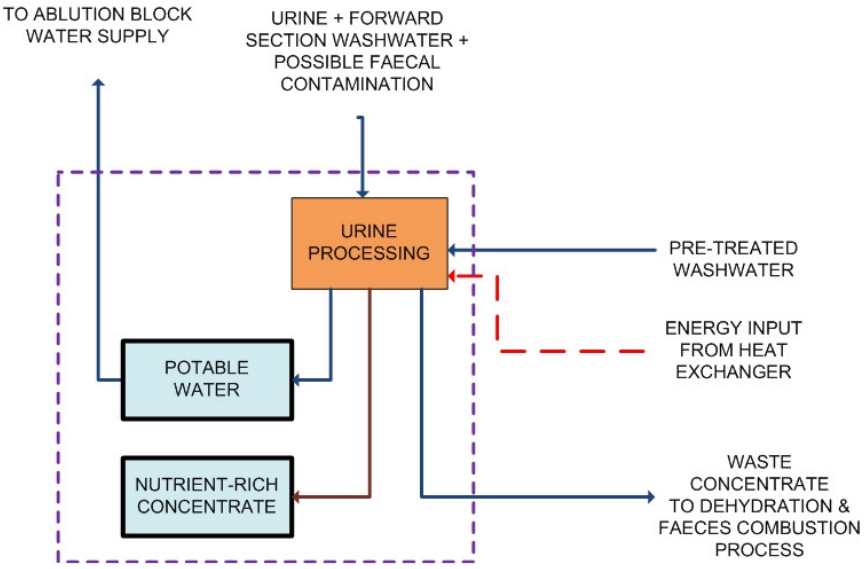

FIGURE 6.1 CONCEPT FOR URINE PROCESSING SYSTEM

The following treatment process objectives were defined for the processing system:

- Hygienisation;
- Water recovery;
- Stabilisation (preventing loss of nitrogen);
- Phosphorus and potassium recovery;
- Nitrogen recovery;
- Separation of micropollutants from the other components;
- Elimination of micropollutants.

Based on the literature, thirty different processes were judged on the extent to which they fulfilled these objectives. A summary of the evaluation process is given in Appendix A8.1. Evaporation systems scored well against the treatment objectives, but are highly energy-intensive. Membrane systems achieved the best scores across the broadest range of treatment objectives, and the majority of the design constraints did not apply. Energy requirements of membrane systems vary by the membrane used.

A further literature review was carried out on the use of membranes for urine and wastewater treatment. A summary of this review is given in Appendix A8.2. Based on this work, three different membrane process combinations were considered, with the nutrient product, waste and water streams being recovered at different stages.

Forward osmosis (with microfiltration and nanofiltration pre-treatment) was chosen for investigation, for the following reasons:

- No high pressure driving force is required to separate water from the feed stream;
- Low fouling rates of the membrane;
- Potential for obtaining the draw solution components (ammonium bicarbonate) from the urine itself;
- Availability of low-grade heat from the toilet system for driving the recovery of the draw solution.

The concept process flow diagram is shown in Figure 6.2. Particulate fouling components are first removed by the first stage (microfiltration or loose ultrafiltration). The nanofiltration provides secondary separation of the majority of dissolved components (including pharmaceutical products), apart from urea (Cath et al. 2005). The forward osmosis stage provides separation of potable water and urea (Parker & West 1973, Bahnemann 2004, Water Desalination International nd).

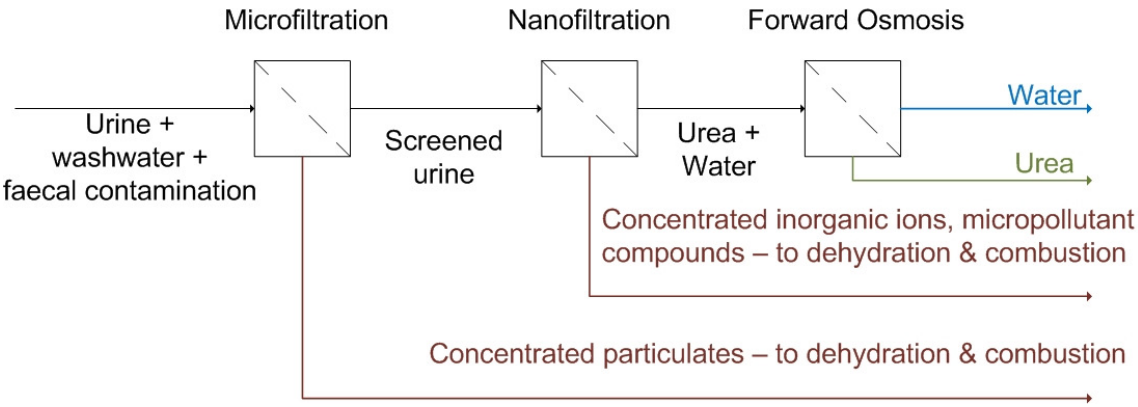

FIGURE 6.2 HIGH-LEVEL PROCESS FLOW DIAGRAM FOR MEMBRANE PROCESSING OF URINE

Experimental rigs for microfiltration and nanofiltration have been constructed and a purpose-built membrane cell has been manufactured for the forward osmosis rig. Details are given in Appendix A7.2. Experimental work has not yet commenced.

7 Laboratory health and safety

Upgrades to laboratory infrastructure have been required to be able to be able to store and analyse a large volume of hazardous samples. These have included:

- Installation of a laboratory ventilation system, providing odour removal from workstations, ovens and experimental rigs;
- Purchase of accessories to existing analytical equipment to improve health and safety (e.g. TKN and COD analysers);
- Installation of a sluice for disposal of solid excreta samples;
- Design and construction of a purpose-built ventilation cabinet for sorting of mixed excreta samples from community ablution blocks;
- Purchase of protective clothing and sampling equipment for field sampling programmes;
- Inoculation and preventative de-worming of staff and students.

Further infrastructure work is planned to provide facilities for collaboration with other RTTC grantees on sample characterisation and field-testing of prototypes.

8 Community ablution blocks

Prototype components of toilet systems (pedestals and unit treatment processes for excreta) will move through laboratory testing stages into field-testing programmes. Initial field-testing will require a relatively controlled environment. Purpose-built community ablution blocks can provide a space where different systems can be trialled by 'real' users whilst still allowing designers the flexibility to monitor and modify designs with relative ease.

In partnership with Hering, a concept design was developed for a community ablution block suitable for field-testing prototype pedestals and excreta treatment unit processes (Appendix A6).

A central service corridor allows toilet maintenance to be carried out without having to gain access via the cubicle. Removable, pre-fabricated panels around the base of the pedestal and in the wall behind it allow different models of pedestal to be interchanged easily. Head-height space beneath the toilet cubicles allows easy installation and removal of different excreta processing systems. The block would be connected to sewer, to allow easy disposal of wastes generated by prototype systems.

Budget Progress Narrative

General Budget Progress

Overall project spending has been below budget. This is mainly due to the significant delays experienced in the purchase of equipment and services, for reasons outlined in Appendix A2.

A proportion of the un-spent funds are committed to areas of the project work that will be on-going after the end of the Grant period. These areas include: work on the membrane system for urine processing, completion of the mechanical properties study on faeces, further sample characterisation work and improvements to laboratory health and safety. This work can be carried out within budget.

Budget Variances

The reasons for variance between the 2012 budget and actual expenditure are as follows:

- Expenditure on personnel was higher than budgeted as the senior technician, laboratory assistant and project manager were employed for additional time to compensate for delays to the project. Expenditure on personnel was lower than budgeted for in 2011, with some of this staff time passing to the 2012 period;
- A sub-grant was made to only one partner organisation (Energy Engineering International), in the 2011 budget period. A second partner, Hering, have not been actively involved in the project during this phase (due to delays with other sections of work on which their contribution would have built) and therefore no grant has been made to them. The third sub-grantee originally listed, Envirosan, is offering time pro-bono, with UKZN paying only for materials and services involved in producing prototype parts. Costs for the prototype parts are now covered under 'Other Direct Costs';
- No consulting fee is now being paid to eThekweni Water and Sanitation;
- No expenditure on capital equipment was originally budgeted for. The principal spend in this category was on two items of laboratory equipment for the sample characterisation work (thermal conductivity analyser and calorimeter). This budget variance was approved by the Foundation (Frank Rijsberman via email 19 December 2011).
- Expenditure on other direct costs is currently under budget, for reasons outlined in Appendix A2.

Budget or Financial Challenges

The main financial challenges for the project have been associated with inefficiencies in the internal university systems, rather than a lack of funds availability. These issues and actions taken to resolve them (including intervention from the Foundation) have been summarised in Appendix A2.

Attachment

Budget Template

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A2 Status of external factors impacting on project progress

TABLE A2.1 STATUS OF EXTERNAL FACTORS IMPACTING ON RTTC PROJECT PROGRESS

Factor impacting on project progress	Current status (November 2012)
Impacts of university restructure (January 2012)	
Orders for supplies and equipment have been significantly delayed in the university buying office – in some cases taking up to 10 weeks to be processed and a purchase order sent to supplier.	Procedures recently changed and majority of orders now being processed in a reasonable timeframe.
Long delays (in one case 5 months) in adding new suppliers (of which we have multiple for the Reinvent the Toilet project) to the university approved vendors list. Until suppliers are on the vendors list we are unable to order from them.	Outstanding applications from new vendors now cleared (as of July 2012).
Financial policy on petty cash changed, resulting in minimal or no petty cash being available to the Pollution Research Group. This caused significant delays in buying low-value items (particularly parts for experimental rigs).	Ongoing issues with adequate supply of petty cash.
Delays in the university paying suppliers has resulted in some companies no longer being willing to supply the university, or being unable to fulfil orders until previous invoices have been paid.	Ongoing.
Under-staffing in critical support services roles – particularly purchasing and legal services.	Ongoing.
The University has been unwilling to release funds for basic maintenance work on laboratory infrastructure (e.g. air compressors and fume extraction filters) that should be covered under the overheads paid from project funds.	Infrastructure in question now functional (as of June 2012). Further infrastructure upgrade work planned to be carried out under a separate grant from BMGF.
Other issues	
Significantly increased administration load for the RTTC project team, due to the above factors, reducing time available for project work.	Additional part time staff member employed (as of July 2012) to take on some of the administration workload. Team structure for any future RTTC work will take into account the administration time required for a project of this nature within the UKZN structure.
Insufficient laboratory infrastructure capacity to handle the number and type of samples required	Budget for necessary health and safety upgrade work has been compiled, for application for funds

for the RTTC work.	from BMGF under a separate capacity-building grant (based on the understanding that the PRG laboratories are to be used in future as a staging area for other BMGF grantees to do fieldwork and testing). An external laboratory has been identified that is willing to undertake some of the work in the interim.
Delays in achieving necessary staff capacity to carry out the project work. Without a positive balance in a cost centre account, it is not easy to convince the Human Resources division to offer an employment contract to a potential employee. Therefore active recruitment for the RTTC project manager could only take place after the contract was in place. The academic year starts in February, therefore Masters students involved in the RTTC work only started 8 months into the project cycle. An additional laboratory technician was required to be able to handle increased analytical workload associated with the RTTC project. However, because salary is paid from the project funds we are only able to offer short contracts, and therefore find it difficult to attract and retain the best candidates.	Discussion underway with BMGF about a grant to be able to fund a longer-term (2 years minimum) contract for a laboratory staff member.
Partner organisation involved in the drying and combustion work has failed to fulfil commitments. This has resulted in delays to the faeces processing work due to lack of staff time.	Partner organisation is no longer part of the RTTC project. Should the project continue to a second Phase, a post-doctoral fellow would be recruited to supply the necessary expertise in this area.
External laboratory that was to be involved in some of the analytical work has been unable to fulfil commitments due to staffing and procurement issues.	An alternative laboratory has been identified and is currently taking samples for analysis.

A3 Excreta sampling programmes

A3.1 Faeces samples from individual donors

A pool of approximately 20 university staff and students were recruited to participate in the faeces donation programme.

Participants were required to attend a briefing and sign an agreement form to participate in the programme. The following points were highlighted during the briefing:

- The background to and importance of the research being carried out;
- Samples should be kept as free from urine as possible;
- Full sample containers should be transferred to a cooler box with ice-packs directly after excretion, and brought to the laboratory as soon as possible (and as a maximum within 18 hours of excretion);
- The date and time of excretion should be marked on the sample container.

Each participant was provided with a cooler box, ice packs, permanent markers and sample containers. A donor number was assigned to each participant. Figure A3.1 summarises the process required of each participant when providing a sample to the project (as included on the donor information sheets).

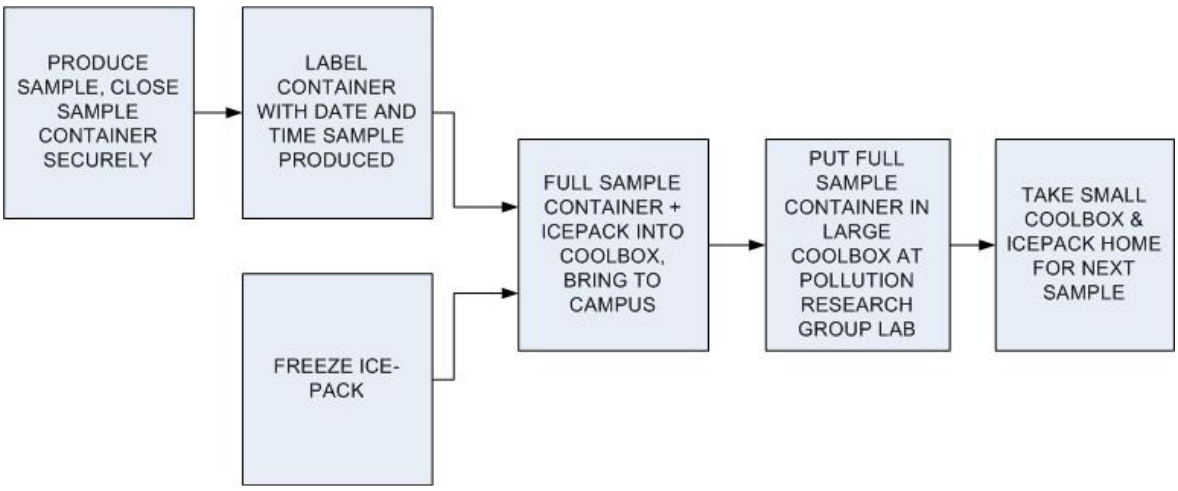


FIGURE A3.1 FAECES SAMPLE DONATION PROCESS (EXTRACT FROM PROGRAMME PARTICIPANT INFORMATION SHEET)

Participants were paid ZAR 50 (USD 5.60) per sample provided. Each sample was assigned a 6-digit sample ID number (composed of the donor number and a sample number).

Donor numbers were linked to donor names for the purposes of payment for participation in the programme. Analytical data on the samples were only linked to the sample ID number.

Samples were transferred to the cold room (storage temperature 2 °C) on receipt at the laboratory.

A3.2 Field sampling programme: community ablution blocks

The eThekwini Water and Sanitation Department facilitated access to a community ablution block in the Durban metro area. The block selected was a ventilated improved pit (VIP) facility, in an informal settlement area approximately 10km from Durban city centre. A VIP facility was selected to enable collection of excreta free from flush water.

Sample containers were designed and purpose-built from steel, to hang underneath the toilet pedestals (Figure A3.2).

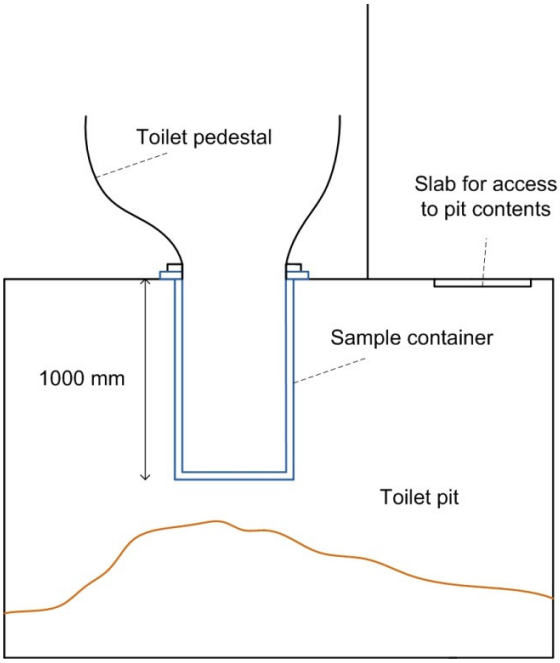


FIGURE A3.2 POSITIONING OF SAMPLE CONTAINER IN VIP COMMUNITY ABLUTION BLOCK

The containers were lined with plastic bags to facilitate sample removal. When in position, the sample containers were not visible to the toilet user (Figure A3.3D). This was designed to prevent facility users from favouring or avoiding a particular cubicle.

A

B

C

D

E

FIGURE A3.3 **SAMPLE CONTAINER IN VIP COMMUNITY ABLUTION BLOCK FACILITY**

(A) CUBICLE
(B) PIT CONTENTS
(C) TOILET PEDESTAL REMOVED TO INSERT SAMPLE CONTAINER;
(D) SAMPLE CONTAINER AND LINER IN PLACE
(E) CONTAINTER AND LINER UNDERNEATH TOILET

Each ablution block in the eThekwini metro area has a caretaker who is responsible for the maintenance of the facility. Researchers carrying out sampling activities at the block coordinated with the caretaker. Sample containers were left in the facility for approximately 24 hours. Urine, faeces and solid cleansing material were collected in the plastic liner. The full liner was transferred to a sealed container for transport to the laboratory. The sample container was removed off-site between collections.

Slight odour and presence of flies was observed on removal of the full sample container from the cubicle (as there was no ventilation from the sample container to the outside, except via the toilet pedestal). No complaints were received from users, however sample containers were always removed after a maximum period of 24 hours to restore proper ventilation from the cubicle promptly.

Samples were transferred to the cold room (storage temperature 2 °C) on arrival at the laboratory. The samples were later processed as follows:

- The total mass of the sample was recorded;
- The mixed excreta sample from one container was spread out in a tray, photographed, and non-excreta material noted (e.g. newspaper and packaging);
- Individual faeces samples were separated into different sample containers;
- Non-faecal material was separated into a separate container;
- A sample of the remaining liquid was separated into a separate container.
- Separated samples were stored and later analysed.

A4 Status of analytical tests

TABLE A4.2 STATUS OF ANALYTICAL TESTS

Property group	Analytical tests	Status
Rheological / mechanical properties	Basic characterisation (mass, photo, visual categorisation)	In progress
	Rheometer tests (5x characterisation tests)	In progress
	Solids (total, suspended, volatile)	In progress
	Density	In progress
	Particle size distribution	Agreement being sought from external laboratory to handle faeces samples
Chemical / biological properties	TKN	In progress
	Ammonia	
	COD	
	pH	
	Total phosphate	To be done by external laboratory – need to source alternative facility as eThekwini municipality laboratories have informed us that they are unable to do the work due to staffing issues
	Orthophosphate	
	Potassium	
	VFA	
	Ascaris	
Drying / thermal properties	Drying curve	Awaiting delivery of thermal conductivity analyser and calorimeter from supplier. Drying rig designed and built (see Appendix A7.1), commissioning in progress.
	Thermal conductivity	
	Specific heat	
	Calorific value	

A5 Source-separation toilet pedestal design

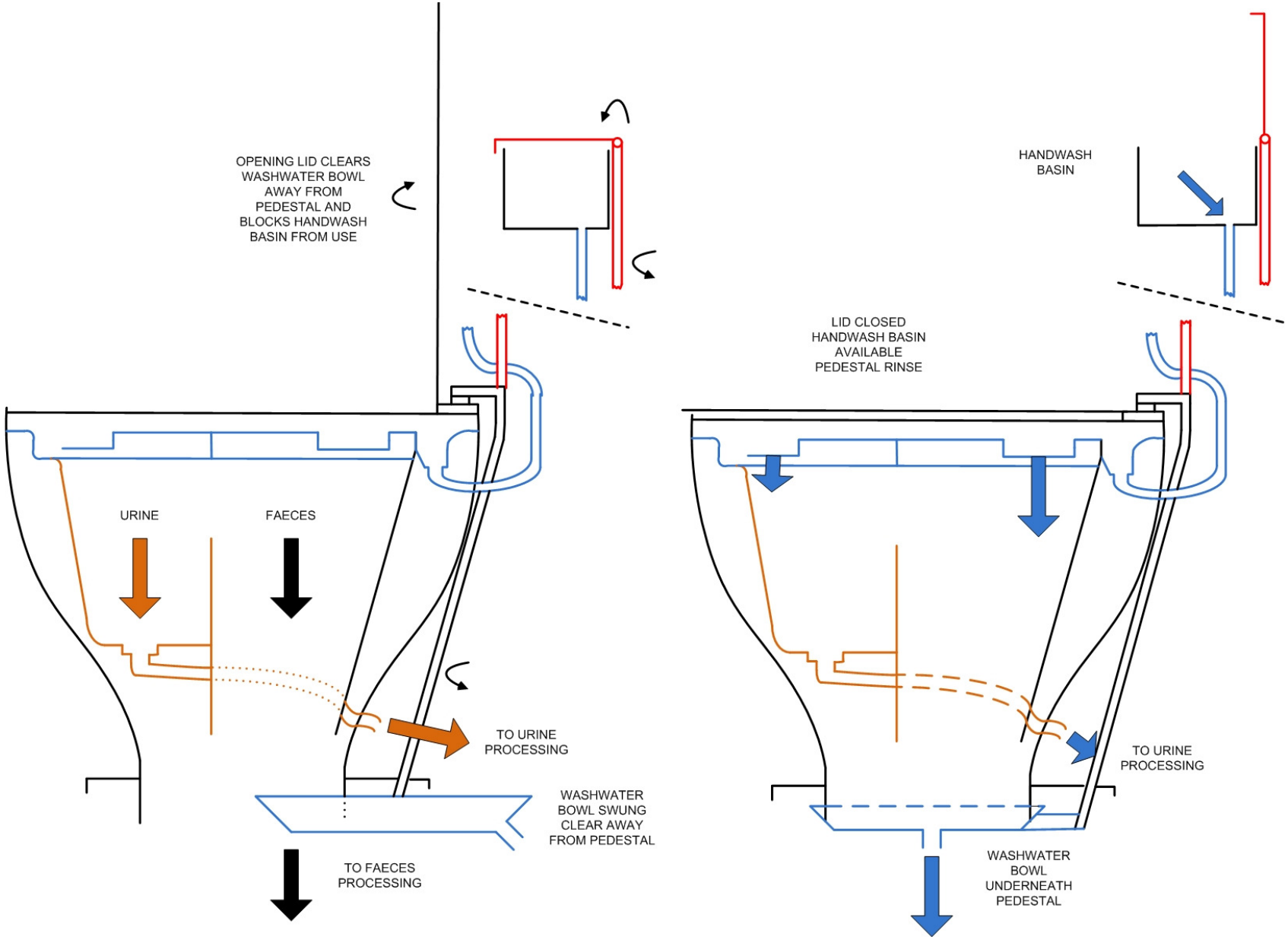


FIGURE A5.1 DESIGN CONCEPT FOR SOURCE-SEPARATION PEDESTAL

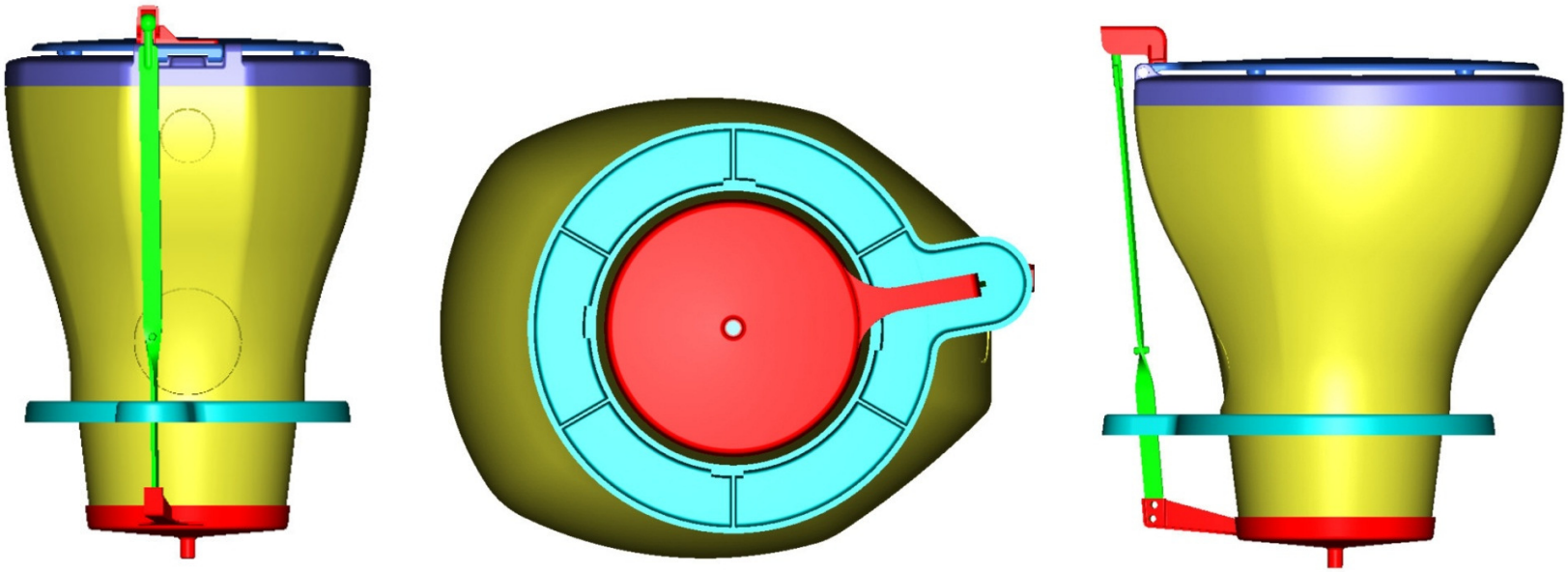


FIGURE A5.2 **DESIGN DRAWINGS FOR FIRST STAGE PEDESTAL PROTOTYPE. STRUT SECTION (GREEN) CONVERTS TOILET LID-LIFTING ACTION INTO A ROTATIONAL MOTION TO SWING THE WASHWATER DIVERSION BOWL (RED SECTION) AWAY FROM THE BOTTOM OF THE PEDESTAL, ALLOWING SOLIDS TO DROP THROUGH THE PEDESTAL TO THE PROCESSING SECTION BELOW.**

A6 Design of community ablution block

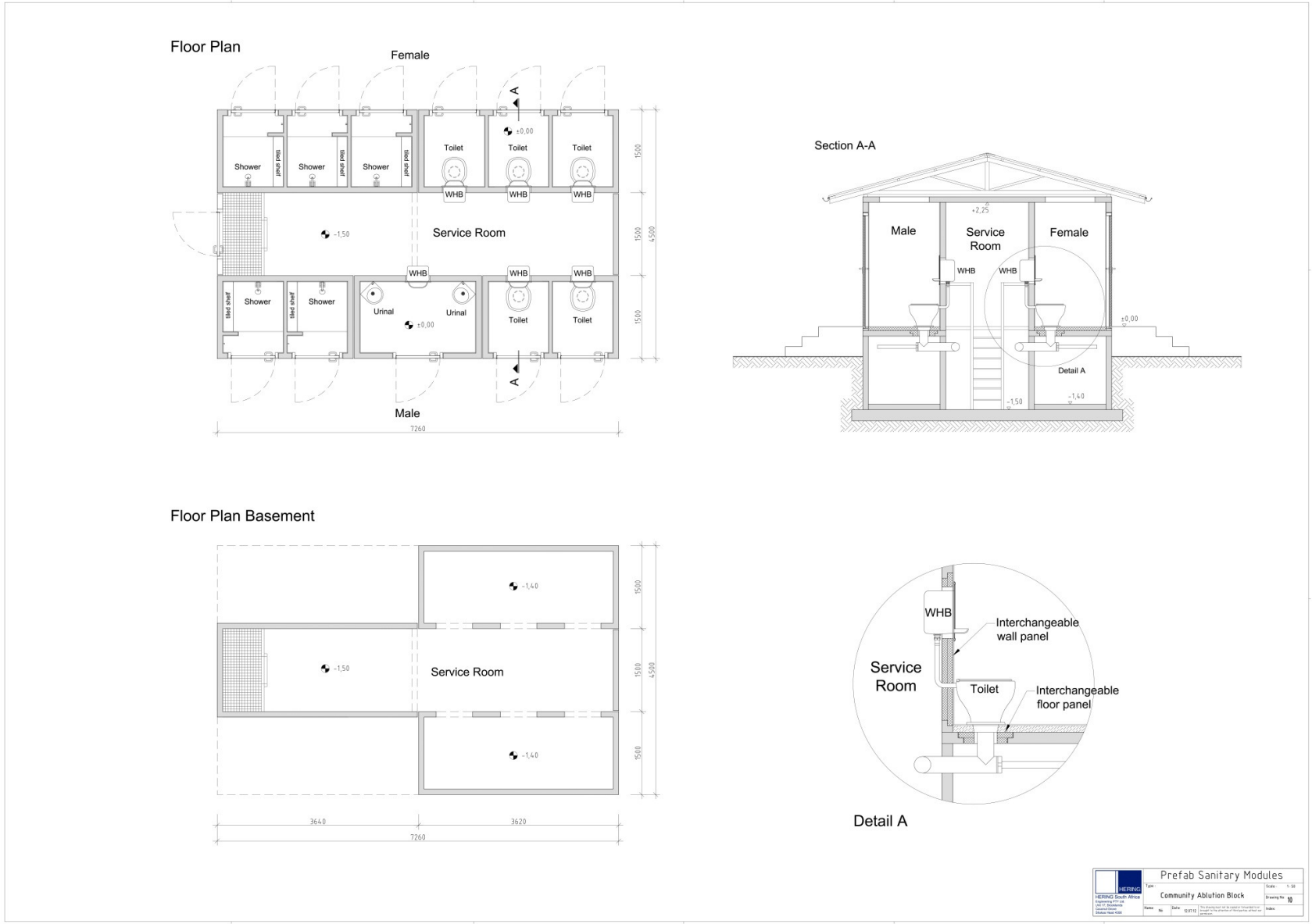


FIGURE A6.1 DESIGN FOR COMMUNITY ABLUTION BLOCK FOR FIELD-TESTING OF TOILET SYSTEMS

A7 Equipment designs

A7.1 Drying rig

A7.1.1 Background and design

Rates of drying are generally limited by heat transfer rates, although in some instances mass transfer of water may be the limiting factor. The aim of the drying experiments being carried out is to produce drying curves for a variety of faeces samples under a range of different, well-defined environmental conditions (temperature, humidity and and flow velocity of the air used for drying). For a given set of environmental conditions, a particular sample will dry up to a moisture content that is in equilibrium with the relative humidity of the air surrounding it. The equilibrium moisture content of a sample at a specified air relative humidity is extremely substance-specific.

Foodstuffs exhibit significant differences in the shape of their equilibrium moisture content curves. Variation therefore may be expected between faeces samples from subjects with different diets. The equilibrium vapour pressure above a sample is determined by temperature, the water content of the sample, the way that the water is bound within the material and by the presence of dissolved solutes in the water (Earle 1983).

The purpose of the drying rig is to dry faeces samples at specified, controlled environmental conditions and accurately measure the rate of drying. Dry air is passed through a packed column with water flowing through the column counter-currently, to bring the air to 100% relative humidity. The humidified air is passed over heaters to reduce humidity and raise air temperature to the user-specified values. The air stream passes to the sample chamber and flows over samples suspended on load cells. Mass change of the samples with time is automatically logged by the PC, together with the process conditions (air flow, temperature and relative humidity). Figure A7.1 shows the design of the rig.

The shape of the sample water content v. time curve allows various drying properties of the sample to be identified – e.g. whether a dry crust is quickly forming on the exterior of the sample, with the interior remaining wet for a longer period of time.

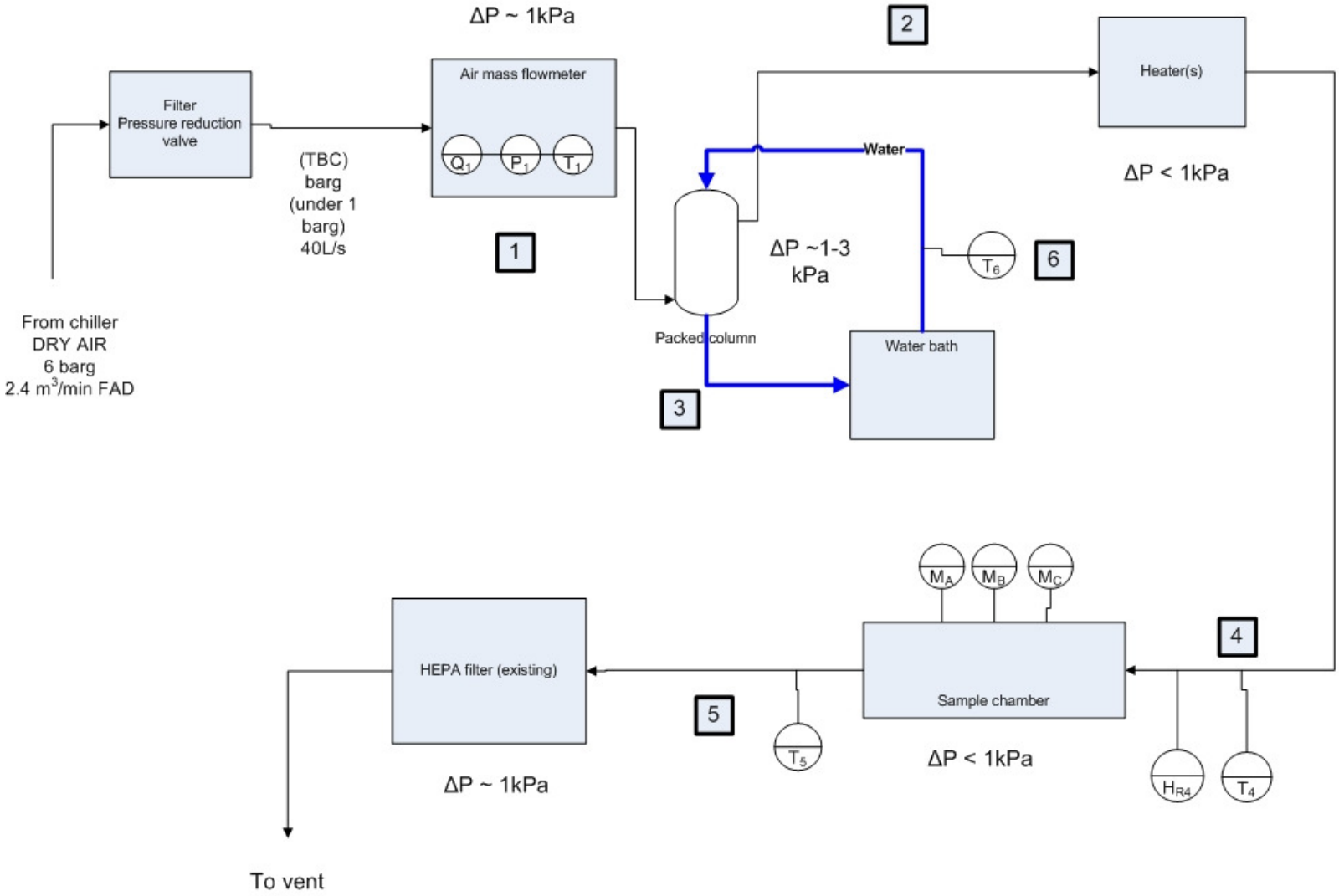


FIGURE A7.1 PROCESS FLOW DIAGRAM OF DRYING RIG

A7.1.2 Control system

The aim of the control system is to control the temperature and humidity condition of the air as it enters the sample chamber (point 4 on the process flow diagram), to user-specified values.

1 Nomenclature

A	Antoine coefficient	Pa
B	Antoine coefficient	Pa
C	Antoine coefficient	K
e	Constant	
H_R	relative humidity of air	%
j	user input	%
m	mass	g
M_a	molecular weight of air	g/mol
M_w	molecular weight of water	g/mol
p	partial pressure	Pa
p_s	vapour pressure	Pa
P	total pressure	Pa
ΔP_{column}	pressure drop across packed column	Pa
ΔP_{4_atm}	pressure drop point 4 to atmosphere	Pa
Q	mass flowrate of air	kg s^{-1}
r	user input	K
T	temperature	K
T_{db}	dry bulb temperature of air	K
u	user input	%
v	user input	%
W	absolute humidity	g water / g air
x	user input	s
y	user input	K
z	user input	K

Numbered subscripts (e.g. $T_{db,4}$) refer to numbered points on the process flow diagram.
Subscript t (e.g. $T_{db,4,t}$) refers to a target (as opposed to measured) value of a parameter.

2 Values for constants

TABLE A7.1 VALUES FOR CONSTANTS

Symbol	Constant	Value	Units
A	Antoine coefficient	2440.236	Pa
B	Antoine coefficient	508807.781	Pa
C	Antoine coefficient	227.02	K
e	Constant	2.71828	
M_a	Molecular weight of air	28.97	g/mol
M_w	Molecular weight of water	18.02	g/mol
ΔP_{column}	Pressure drop across packed column	3000 (TBC)	Pa
ΔP_{4_atm}	Pressure drop from	1000 – 2000 (TBC)	Pa

	point 4 (before sample chamber) to atmosphere		

3 Instrumentation

TABLE A7.2 INSTRUMENT LIST AND PARAMETERS TO BE LOGGED

Instrument	Stream	Parameter	Symbol	Unit	Log / control
Air mass flowmeter	Air	Mass flowrate	Q_1	kg s^{-1}	Log
		Temperature	$T_{db,1}$	K	Log
		Pressure	P_1	Pa	Log, control
Relative humidity (4)	Air	Relative humidity	$H_{R,4}$	%	Log, control
Temperature (4)	Air	Temperature	$T_{db,4}$	K	Log, control
Temperature (5)	Air	Temperature	$T_{db,5}$	K	Log
Water bath temperature (6)	Water	Temperature	T_6	K	Log, control
Water bath pump rate	Water	Flow rate			
Load cell A	n/a	Mass	m_A	g	Log
Load cell B	n/a	Mass	m_B	g	Log
Load cell C	n/a	Mass	m_C	g	Log

4 Control philosophy

4.1 Data-logging

System will log all parameters listed in Table 2.

User should have ability to specify time interval for logging for each individual parameter.

System will log all calculation results. Calculations to be performed at user-specified time intervals.

4.2 Process control

The aim of the control system is to control the temperature and humidity condition of the air as it enters the sample chamber (point 4 on the process flow diagram), to user-specified values.

Air conditions at point 4 are referred to as the 'target conditions' of temperature and relative humidity. At point 4:

- Temperature is logged and compared against the target value by the control system;
- Pressure is logged and used in the control calculations;
- Relative humidity is logged and compared against the target value by the control system.

Control sequence

1. At the start of each experimental run, user inputs target values for temperature and relative humidity ($T_{db,4,t}$ and $H_{R,4,t}$)
2. Pressure at point 4, P_4 , is a user-input value (units Pa)
3. Calculate target vapour pressure at point 4, $p_{s,4,t}$

$$p_{s,4,t} = e^{A-\frac{B}{C+T_{db,4,t}}} \quad [1]$$

4. Calculate target partial pressure at point 4, $p_{4,t}$

$$p_{4,t} = \frac{H_{R,4,t}p_{s,4,t}}{100} \quad [2]$$

5. Calculate target absolute humidity, W_t

$$W_t = \frac{M_w p_{4,t}}{M_a(P_4 - p_{4,t})} \quad [3]$$

6. Calculate pressure at point 2, P_2

$$P_2 = P_1 + \Delta P_{column} \quad [4]$$

7. Calculate target partial pressure at point 2, $p_{2,t}$

$$p_{2,t} = \frac{M_a P_2 W_t}{(M_w + M_a W_t)} \quad [5]$$

8. Check calculation: calculate relative humidity at point 2, $H_{R,2}$

   (i) Calculate vapour pressure at point 4, $p_{s,4}$

$$p_{s,4} = e^{A-\frac{B}{C+T_{db,4}}} \quad [6]$$

   (ii) Calculate partial pressure at point 4, p_4

$$p_4 = \frac{H_{R,4}p_{s,4}}{100} \quad [7]$$

   (iii) Calculate absolute humidity at point 4, W_4

$$W_4 = \frac{M_w p_4}{M_a(P_4 - p_4)} \quad [8]$$

   (iv) Absolute humidity same value at point 4 and point 2

$$W_2 = W_4 \quad [9]$$

   (v) Calculate partial pressure at point 2, p_2

$$p_2 = \frac{p_4 P_2}{P_4}$$

[10]

(vi) Calculate vapour pressure at point 2, $p_{s,2}$

$$p_{s,2} = e^{A - \frac{B}{C + T_{db,2}}}$$

[11]

(vii) Calculate relative humidity at point 2, $H_{R,2}$

$$H_{R,2} = \frac{100 p_2}{p_{s,2}}$$

[12]

(viii) If relative humidity at point 2 is less than a user-input setpoint, j, then raise alarm flag

$$H_{R,2} < j$$

[13]

9. Let partial pressure at point 2 equal the vapour pressure at point 2 (this is based on the assumption that $H_{R,2}$ is 100%, i.e. that the packed column is functioning properly – if it is not then user will be alerted by the alarm flag in 8viii).

$$p_{s,2} = p_2$$

[14]

10. Set target vapour pressure at point 2, $p_{s,2,t}$

$$p_{s,2,t} = p_{2,t}$$

[15]

11. Calculate target dry bulb temperature at point 2, $T_{db,2,t}$

$$T_{db,2,t} = \frac{B - C(A - \ln p_{s,2,t})}{(A - \ln p_{s,2,t})}$$

[16]

12. Set water bath temperature, T_6

$$T_6 = T_{db,2,t}$$

[17]

13. Wait x minutes (user-input)
14. Compare measured air temperature at point 4, $T_{db,4}$, to target temperature, $T_{db,4,t}$
15. If

$$T_{db,4,t} - T_{db,4} > r$$

[18]

Where r is a user-defined difference (units of K), then increase heater power until $T_{db,4} = T_{db,4,t}$
OR
If

$$T_{db,4,t} - T_{db,4} < -r$$

[19]

Then decrease heater power until $T_{db,4} = T_{db,4,t}$

16. Compare measured $H_{R,4}$ to target relative humidity at point 4, $H_{R,4,t}$
17. If

$$H_{R,4,t} - H_{R,4} > u$$

[20]

Where u is a user-defined difference (units of %), then increase value of $T_{db,2,t}$ by a user-defined increment, v.
OR
If

$$H_{R,4,t} - H_{R,4} < -u \quad [21]$$

Then decrease value of $T_{db,2,t}$ by a user-defined increment, v.

18. Repeat 12 through 17 until

$$\left|H_{R,4,t} - H_{R,4}\right| < u \quad [22]$$

AND

$$\left|T_{db,4,t} - T_{db,4}\right| < r \quad [23]$$

19. When target values for $H_{R,4}$ and $T_{db,4}$ are reached, raise flag – user will then introduce samples into sample box.

3.3 Alarms

Alarms will be tagged as process control alarms or safety alarms. Summary list is included below.

Safety alarms

- Low pressure alarm for P_1
- High pressure alarm for P_1
- Low temperature alarms for T_1 , T_6 , T_4
- High temperature alarms for T_1 , T_6 , T_4
- Low flow alarm for Q_1
- High flow alarm for Q_1
- Heater alarms? TBC
- Water bath alarms? TBC

Process control alarms

- If $H_{R,2}$ is less than a user-input setpoint, j, then alarm
- If target values of $T_{db,4,t}$ and $H_{R,4,t}$ not reached after a (user-specified) time period then alarm
- If more than a user-specified number of high and/or low flow alarms are raised for Q_1 within a specified length of time then alarm.

Outputs

- .csv file recording all logged and calculated parameters
- Drying curve plots for each sample – charts of mass recorded by each load cell against time

A7.2 Membrane processing systems for urine

Test rigs have been designed and built to generate design data for the microfiltration and nanofiltration membrane stages of the proposed urine treatment process. A membrane cell has been designed and manufactured for the forward osmosis system, with the remainder of the rig under construction. The following sections provide detail on each of the systems.

A7.2.1 Microfiltration rig

The aim of the microfiltration stage is to remove particulate matter which would cause fouling downstream. Urine will be fed from a tank to a membrane chamber containing six commercial microfiltration membranes. Permeate will be collected and mass logged. Rate of fouling, rejection of particulates and flux across the membranes will be measured.

Figures A7.2 – A7.4 describe the experimental setup.

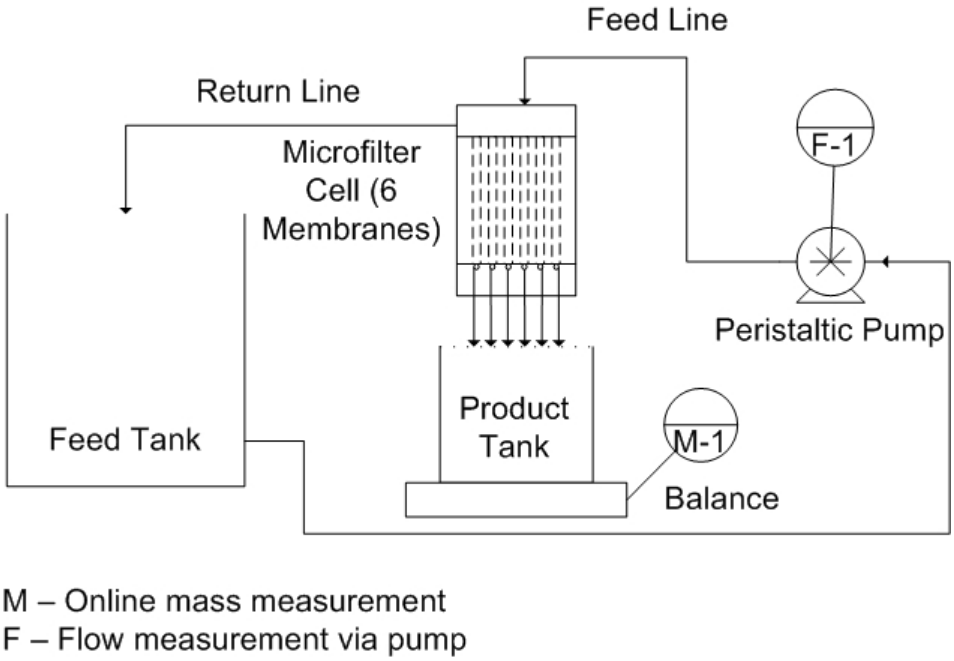


FIGURE A7.2 PROCESS FLOW DIAGRAM – MICROFILTRATION TEST RIG

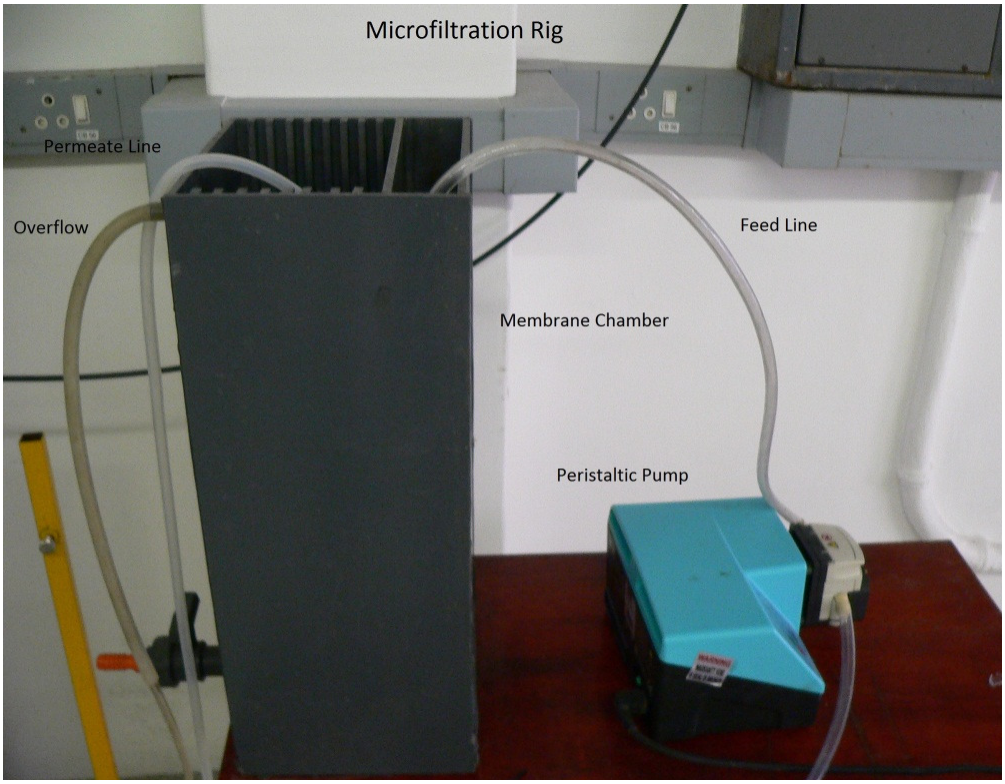


FIGURE A7.3 MICROFILTRATION TEST RIG

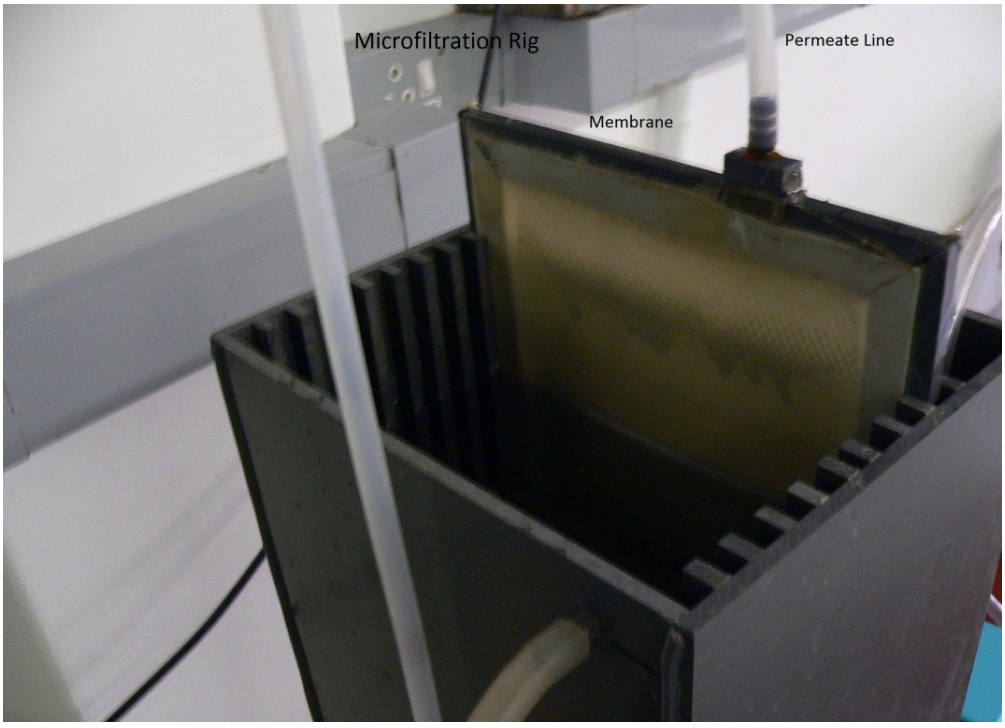


FIGURE A7.4 MICROFILTRATION TEST RIG – MEMBRANE HOLDER

A7.2.2 Nanofiltration membrane rig

The nanofiltration stage aims to separate the major portion of the undesired salts and pharmaceutical compounds from the water and urea. The laboratory set-up consists of 3 cells in series, each containing a 300D molecular weight cut off (MWCO) nanofiltration membrane. The feed is pumped from a tank, which may be heated or cooled via a coil, and fed into the cells. The permeate is collected and mass logged. The retentate is sent to the next cell in the series and finally is fed back to the feed tank, with flowrate measured on the return stream. The pressure is measured across the cells and the temperature, conductivity and pH of the feed tank and beaker are logged.

Figures A7.5 – A7.7 describe the experimental setup.

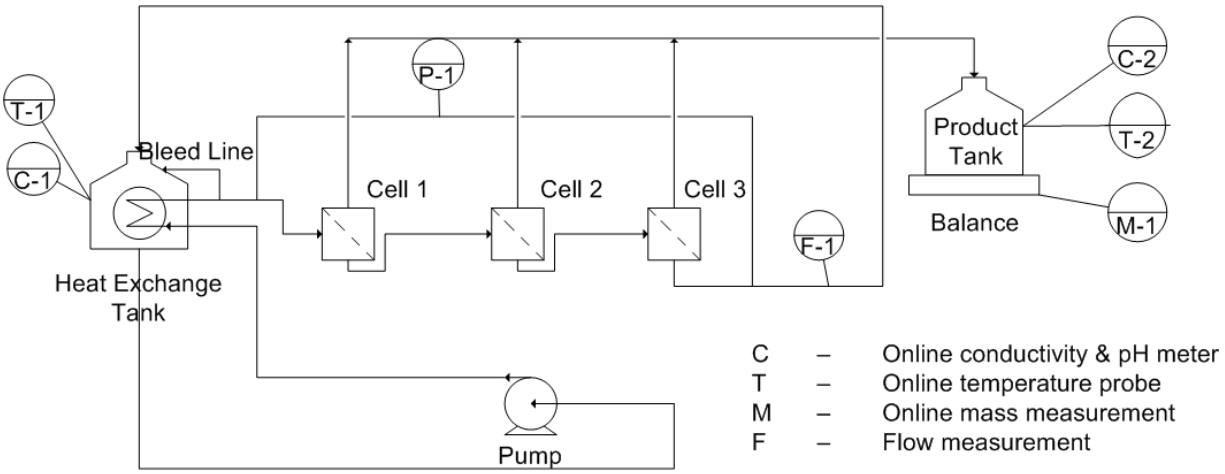


FIGURE A7.5 NANOFILTRATION RIG PROCESS FLOW DIAGRAM

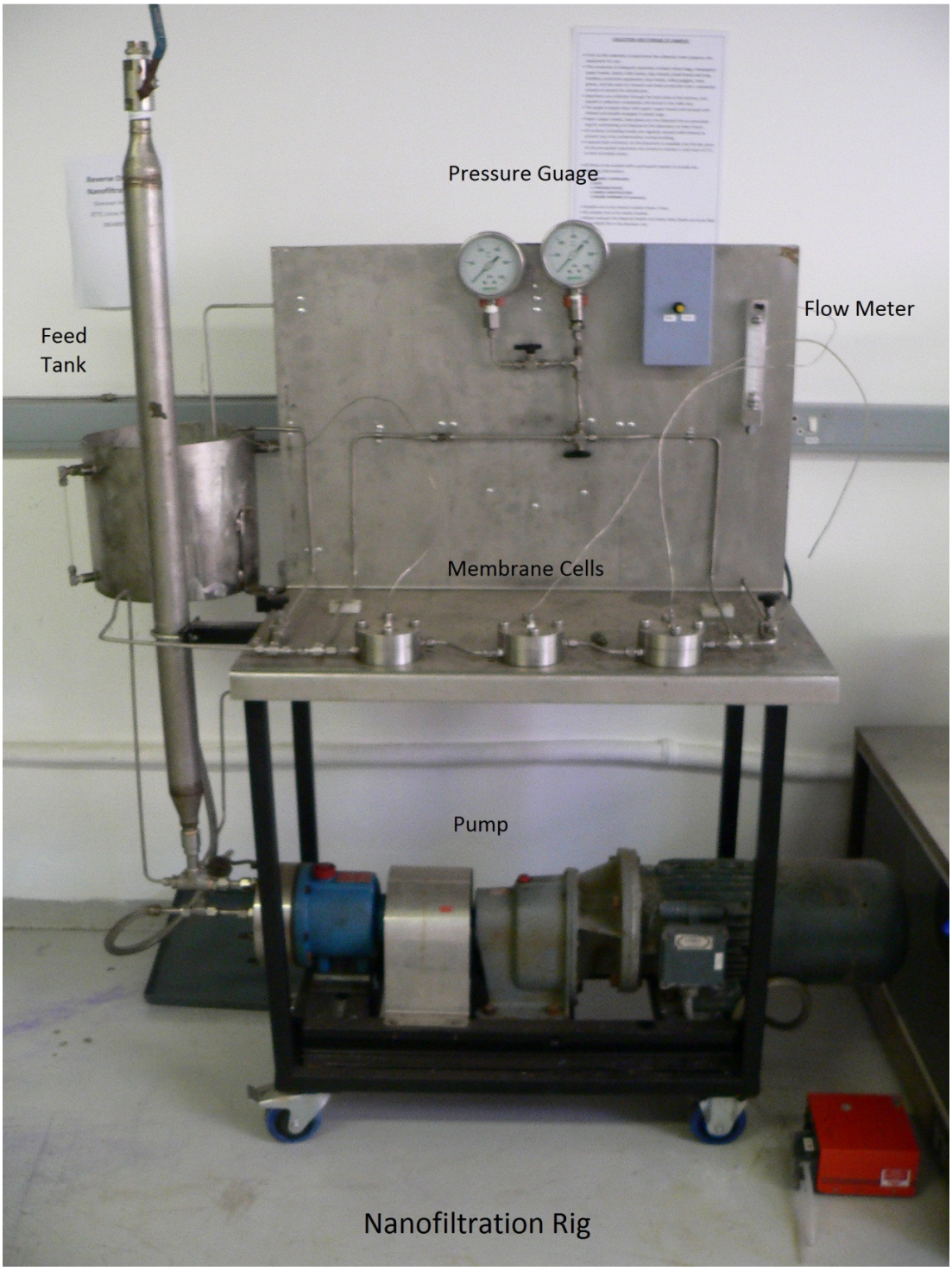


FIGURE A7.6 NANOFILTRATION MEMBRANE RIG

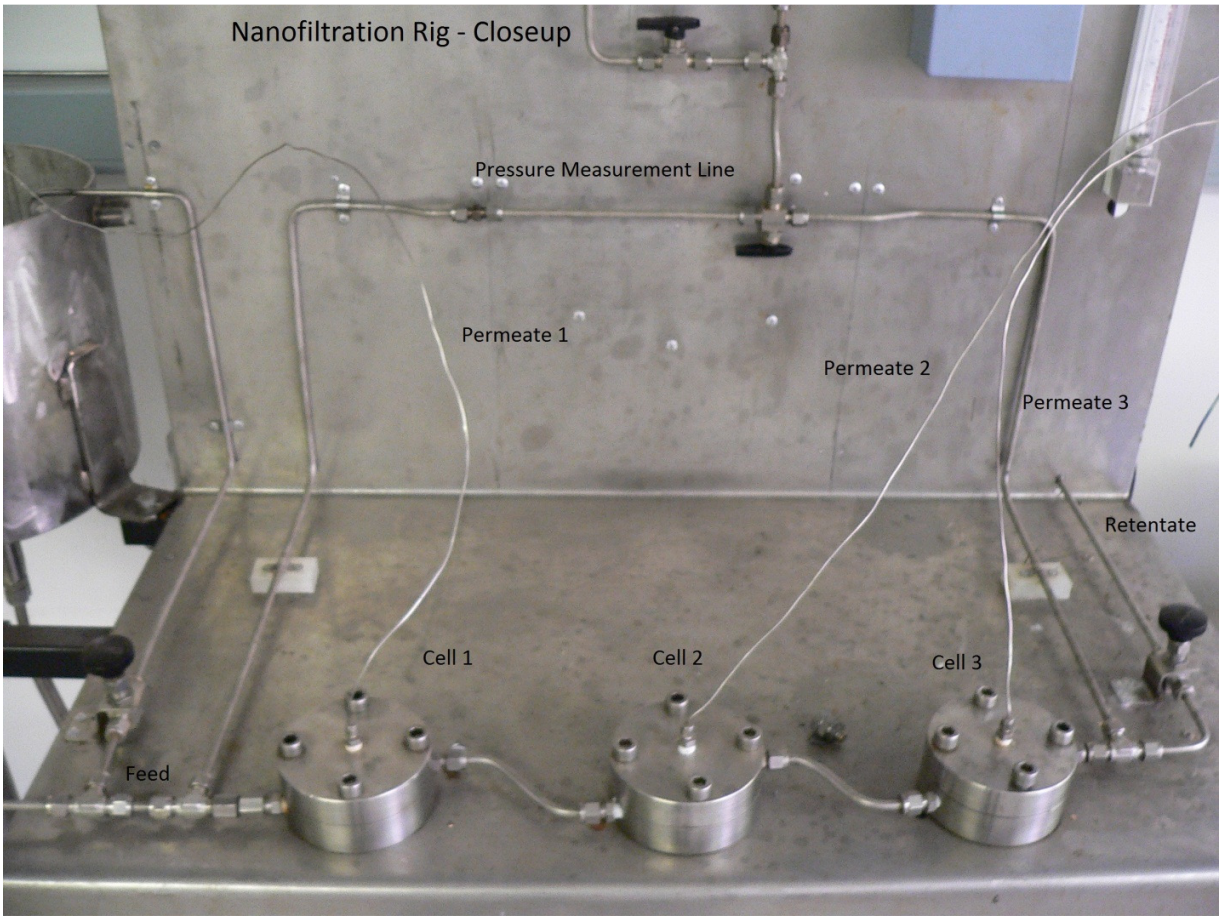
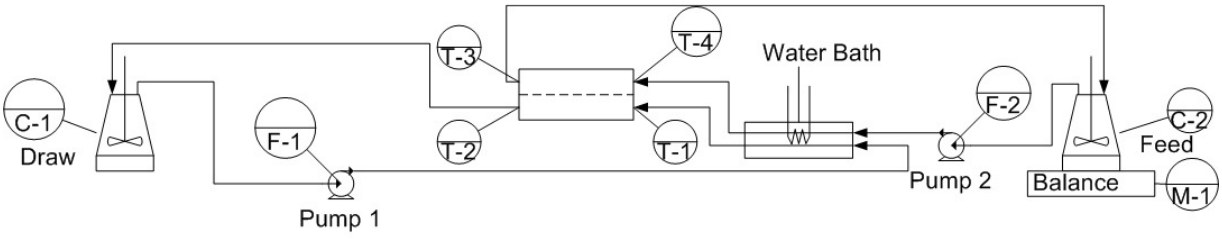


FIGURE A7.7 NANOFILTRATION RIG MEMBRANE CELLS

A7.2.2 Forward osmosis membrane rig

The forward osmosis (FO) stage aims to separate the water and urea, forming a potable water stream and a highly concentrated urea stream. The feed and draw solutions are pumped, via the water bath, through the FO cell. The two streams are separated by the FO membrane. Water flows down the osmotic gradient from the feed solution across the membrane into the more concentrated draw solution. The mass, conductivity, pH and temperature of the feed and draw solutions are logged. The urea concentration change in the draw and feed solutions, fouling rates and flux through the membrane will be studied. The rig does not currently incorporate recovery of the draw solution.

Figures A7.8 – A7.10 summarise the experimental setup.



C – Online conductivity & pH meter
T – Online temperature probe
M – Online mass measurement
F – Flow measurement via pump calibration

FIGURE A7.8 FORWARD OSMOSIS RIG PROCESS FLOW DIAGRAM

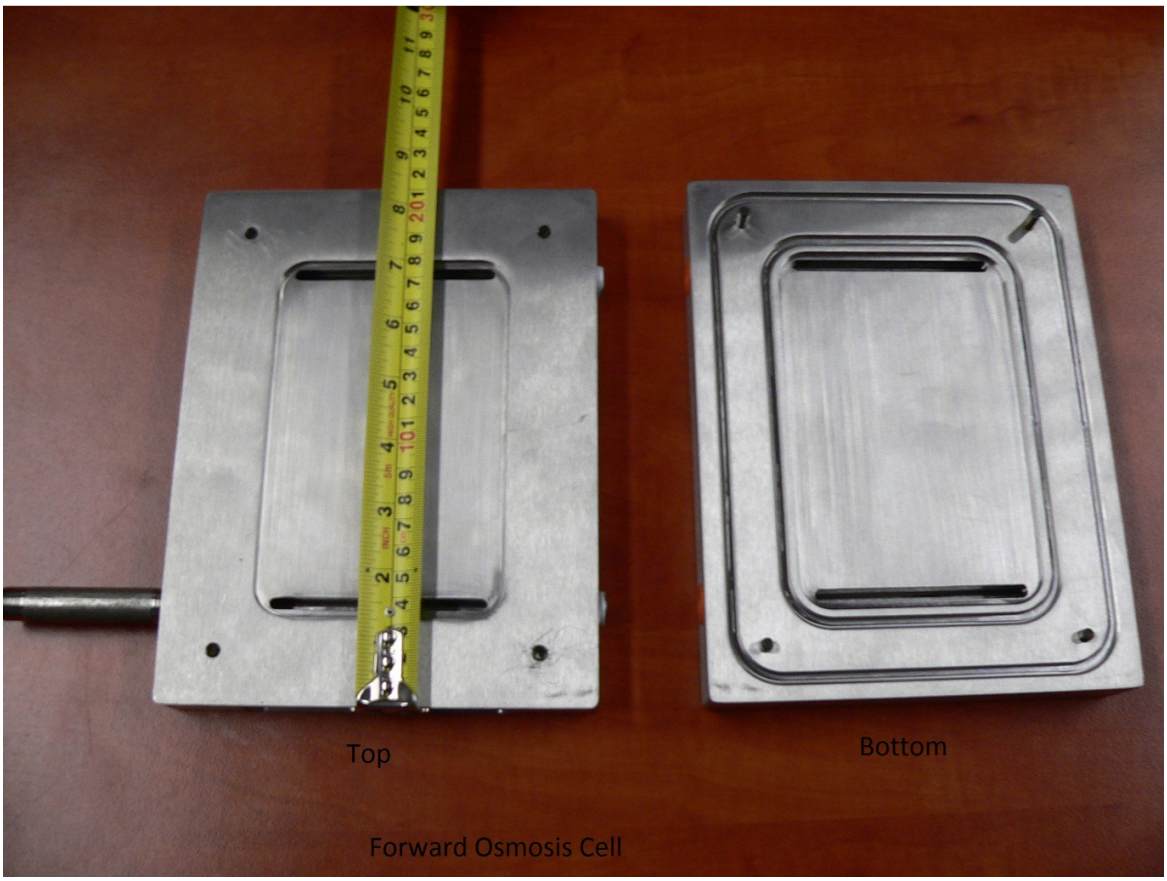


FIGURE A7.9 FORWARD OSMOSIS MEMBRANE CELL

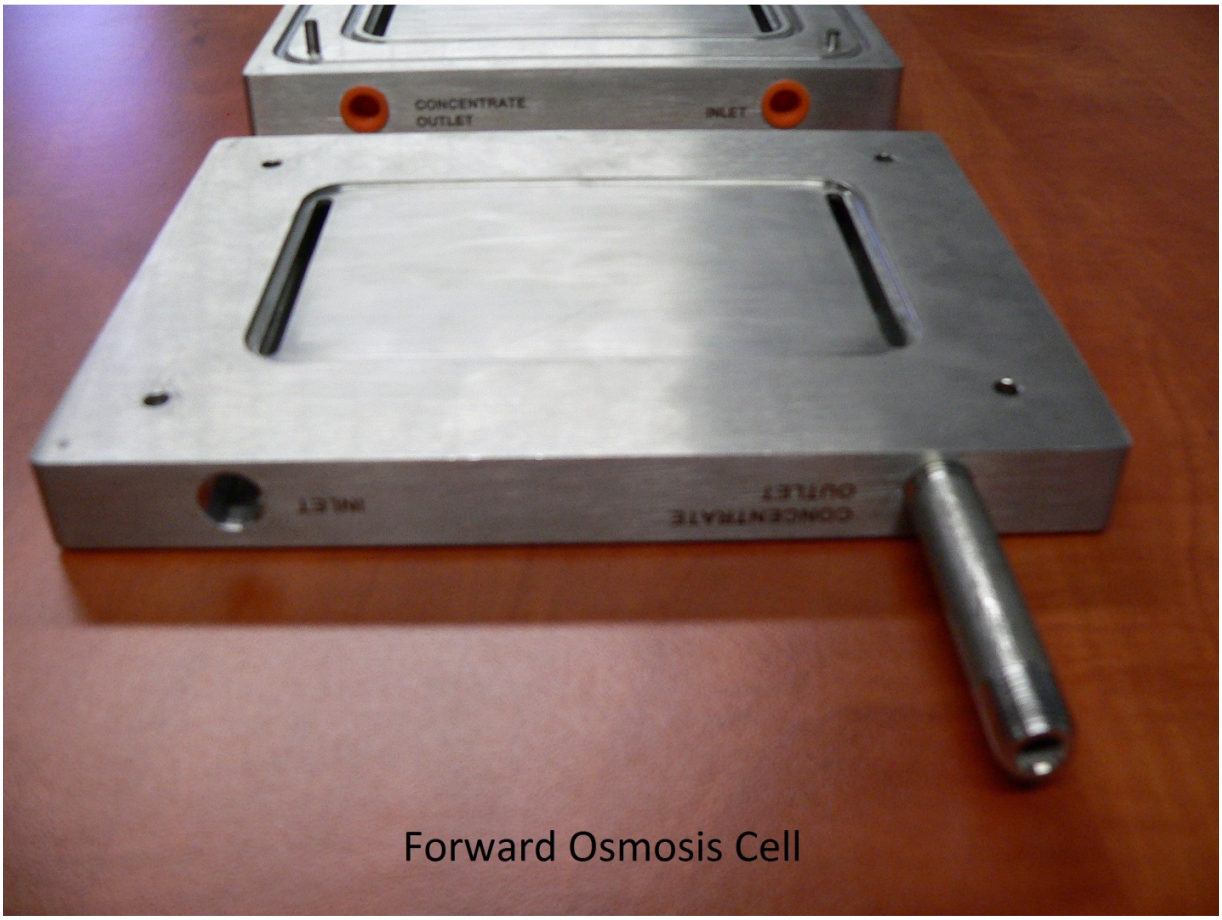


FIGURE A7.10 FORWARD OSMOSIS MEMBRANE CELL SHOWING FEED INLET AND CONCENTRATE OUTLET

A 7.3 References

Earle, RL 1983, Unit Operations in Food Processing, viewed 20 July 2012, http://www.nzifst.org.nz/unitoperations/drying4.htm

8 Urine processing: selection of system

A8.1 Evaluation of processes for urine treatment

Thirty different processes were judged against the extent to which they fulfilled the treatment objectives, with the screening process summarised in Table A8.1.

TABLE A8.1 SCREENING SELECTION TABLE OF PROCESSES FOR URINE TREATMENT

Group	Process	Hygienisation	Water Recovery	Stabilisation	P,K Recovery	N Recovery	Micropollutant /Nutrient Separation	Micropollutant Elimination	References
Evaporation	Vapour Compression Distillation	2	3	2	3	3	1	1	[3], [5], [6]
	TIMES	2	3	2	3	3	1	1	[3], [7]
	Air Evaporation System	2	3	2	3	3	1	1	[3]
	Multi-stage Flash	3	3	2	3	3	1	1	[3]
	Freeze-thaw	2	2	1	3	3	1	1	[3]
	Solar Evaporation	3	2	2	3	3	1	1	[8–11]
	Passarell Process	3	2	2	3	3	1	1	[12]
Membrane	Membrane Distillation	4	2	1	4	4	4	1	[5], [13], [14]
	Reverse Osmosis	4	3	1	3	3	4	1	[3], [5], [14]
	Forward Osmosis	4	3	1	3	3	4	1	[5], [14], [15]
	Electrodialysis	3	2	2	2	2	2	1	[3], [16]
	Micro/Ultra Filtration	2	1	3	1	1	1	1	[3], [17]
	Nanofiltration	3	1	2	1	1	3	1	[3], [18]
Nitrogen/ Ammonia recovery	Ammonia Stripping	1	2	1	1	3	3	1	[3]
	Anammox Process	2	1	3	1	1	2	?	[3]
	Acidification	2	1	3	1	1	1	1	[3]
	Partial Nitrification	2	1	3	1	1	1	?	[19], [20]
	Sand Bed Nitrification	2	1	3	1	1	1	1	[19], [20]
	Struvite	1	3	1	3	3	3	1	[3]
	IBDU Precipitation	1	2	1	1	3	2	1	[3]
Other	Ion-Exchange	1	2	1	1	3	2	1	[3]
	Ozonation/Advanced Oxidation	2	1	2	1	1	1	4	[3]
	UV Treatment	4	1	3	1	1	1	4	[21]
	Storage	2	1	1	1	1	1	2	[3]

KEY			
No effect / Not Feasible	Some Effect	Strong Effect	Greatest Effect
1	2	3	4

A8.2 Evaluation of membrane processes for urine treatment

Table A8.2 compares the ability of different membranes to separate the principal components of urine, based on previous work using membranes to treat raw and diluted urine.

TABLE A8.2 COMPARISON OF MEMBRANE PROCESSES FOR URINE TREATMENT

Function	Unit operation					
	Membrane Distillation	Reverse Osmosis	Forward Osmosis	Microfiltration	Ultrafiltration	Nanofiltration
Pathogen Removal	4	4	4	2	2	3
Enzyme/Microbe Rejection	1	1	1	3	3	1
P, K Retention	4	3	3	1	2	3
Urea Retention	4	3	3	1	1	2
Micropollutant/P, K Separation	1	1	1	1	2	1
Micropollutant and Pharmaceuticals Rejection	4	4	4	1	1	4
Requirement for pre-treatment	2	4	3	1	1	3
Flux ([l/m^2.h]	1	20	12			100
Available Literature	2	2	3	1	1	2
Extent Tested on Urine	2	2	2	2	2	3
Energy Required [kWh/m^3 water]	2	24	6	0.3	3	6
Primary energy source	Heat	Pressure	Heat	Pressure	Pressure	Pressure
Cost	2	3	2	1	2	2
Simplicity of System	3	4	2	1	2	3
Requirement for Chemical Addition	1	2	1	1	1	1
Nutrient Product Stream Usability	3	3	3	1	1	2
Product Water Stream Quality	4	3	3	1	1	2
References	[5], [13], [14]	[3], [5], [14]	[5], [14], [15]	[3], [17]	[3], [17]	[3], [18]

KEY

No effect or Not Feasible / Low	Some Effect / Medium	Strong Effect / High	Most Effect / Very High
1	2	3	4

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A9 Attachments

The following documents are attached to this report:

- Key milestones spreadsheet;
- Budget report spreadsheet;
- Standard operating procedures for analytical tests on faeces;
- Short Communication: Some Rheological Properties of Fresh Human Faeces with Variation in Moisture Content (Woolley et al. 2012);