CRANFIELD UNIVERSITY

MOHAMAD WALEED NOAMAN

Design and Implementation of a Novel User Interfacing Module for the Cranfield Circular Toilet

School of Water, Energy and the Environment

MSc by Research

Academic Year: 2021 - 2022

Supervisor: Dr. Adriana Encinas-Oropesa

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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc by Research
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

Case Study Impact Statement

The Gates Foundation continues to seek addressing the global challenge of access to sanitation through its international competition: ‘Reinvent the Toilet Challenge’. Winning entries from multiple universities are to employ their latest technology and research findings to safely handle human waste. Novel solutions and creative approaches to this problem are needed now more than ever, to help empower communities globally with accessible methods and competitive products to safely deal with human waste and achieve decentralized sanitation.

Executive Summary

This thesis presents empirical research on the development and implementation of a novel, water-saving user-interfacing module, that operates as a part of a comprehensive non-sewered sanitation system, the Cranfield Circular Toilet, that performs decentralized human waste evacuation and treatment. Building upon previous knowledge in this project, a prototype was designed, manufactured and assembled. It boasts new automated features that augment the functions of its mechanical evacuation subsystems, utilisation of water for interface flushing from the liquid purification process, and a streamlined design for manufacturability, in preparation for volume production and commercialization.

Laboratorial tests were carried out to validate its main functionalities in self-cleaning and waste evacuation of solid and liquid human wastes to the backend treatment modules. Being a first prototype, findings from those tests were substantial in informing future design decisions in the module's evolution, through selection of suitable and cost-effective operational features, optimisation of its geometric designs, and achieving further rationalisation in using resources, in aim to achieve higher levels of performance and user appeal, and a successful integration with the rest of the sanitation system.

Keywords: *Reinvent the Toilet, Cranfield Circular Toilet, User-interfacing module, surface self-cleaning, mechanical waste evacuation, rotating bowl, auger screw*

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Table of Contents

Table of Figures

1. INTRODUCTION

1.1. Global challenges in sanitation

According to a recent report by UNICEF and the World Health Organization (WHO, 2017), around 2.2 billion people globally do not have drinking water that is free from contamination and available when needed, 4.2 billion people live without proper sanitation services from which wastes are treated and disposed of safely, and 3 billion with no basic facilities installed in their own households (WHO, 2021). The existing lack of infrastructure for sanitation and water circulation in developing countries globally is incurring economic losses of USD 260 Bn annually (Kamranvand, 2018), and implementing in-house piped water supply with connections to sewage lines and treatment would require USD136.5 Bn of annual investments (Kamranvand, 2018). Left untreated, socio-economic inequalities across communities will exacerbate the situation and lead to undesirable practices such as open defecation (Coffey, 2014). Making matters worse, such reparations would put strain on water resources when relying on a 19^{th} century toilet evacuation system that does not correspond to modern day challenges, as currently a single flush in a conventional toilet consumes around 9 litres of water to evacuate around 128g of faeces and/or 0.5 litre of urine in a single use (Woolley, 2014).

All of these factors raise the necessity for developing solutions for decentralized and comprehensive sanitation that can serve individual households in developing countries, work independently from sewage systems or service centres, reduce and reuse its own water resource and require a minimal cost on the users for waste treatment and safe disposal. In response to the above challenges, the Water, Sanitation & Hygiene program of the Gates Foundation initiated the Reinvent the Toilet Challenge in 2011 to promote the development of modern and sustainable sanitation systems (Kone, 2012).

1.2. Cranfield University's contributions

Cranfield University has been a leading institute in developing such systems, starting with the Nano-membrane toilet firstly introduced in 2014 (Tierney, 2014). This work had to go in line with the Foundation's requirements in creating a marketable toilet product that fulfils the following:

- Operation without connection to the sewage system.
- Phase separation of the human waste, removal of germs, and recovering of valuable resources such as clean water and biochar.
- Eventual cost of the final market product at 500USD as a capital expense, and 0.15USD per user per day as operational expense.
- Aiming for energy efficiency at <1kWh$_e$/day, <15A, <1.8kW
- Promotion of sustainable and profitable sanitation services and businesses.
- Aspirational white-goods product of an elegant and intuitive design, that is desirable for its ease of installation and use, minimal servicing and maintenance.
- Conformity of the final market product to the ISO-30500 standard (ISO, 2018) and therefore contributing to the United Nations Sustainable Development Goals: 1, 3, 4, 5, 6, 8, 9, 10, 11, 14, and 15 (ISO, 2020).

This had led the Cranfield team to develop a unique sanitation system and continuously evolve its operation over the years. The user-interfacing module of that system has the following design and functional features:

- A bowl that interfaces with the sitting pan. This bowl rotates upwards when the lid is opened, to receive the wastes (both urine and faeces) when the toilet is used, and then rotates downwards to deposit the wastes in a sedimentation tank, or collection tank, underneath. A mechanical swipe works in conjunction with the bowl, turning in a synchronized motion to remove soiling on the bowl's surface from residing faeces during toilet usage. The bowl's intermediate position between the sitting pan and collection tank acts as a blocker of odour and sight of the waste that is to be transferred in the next step.
- An auger screw that is situated diagonally in the frame, resting on the bottom of the collection tank to collect the waste and lift it upwards as it rotates. At the end of the screw, the solids are then channelled to a solids treatment module (previously it was designated as a small-scale combustor (Fidalgo, 2019)) whereas the liquids are channelled through a series of filtration and distillation steps, both of which to be sterilized and safe for disposal or reuse, respectively.

- The design focuses on the seat lid’s movement (opening and closing) to be the only input from the user into the system (Tierney, 2017), in efforts to minimize the user’s involvement in the toilet’s functionalities, thus maintaining user behaviour toward traditional toilets when using the Cranfield designed toilet.

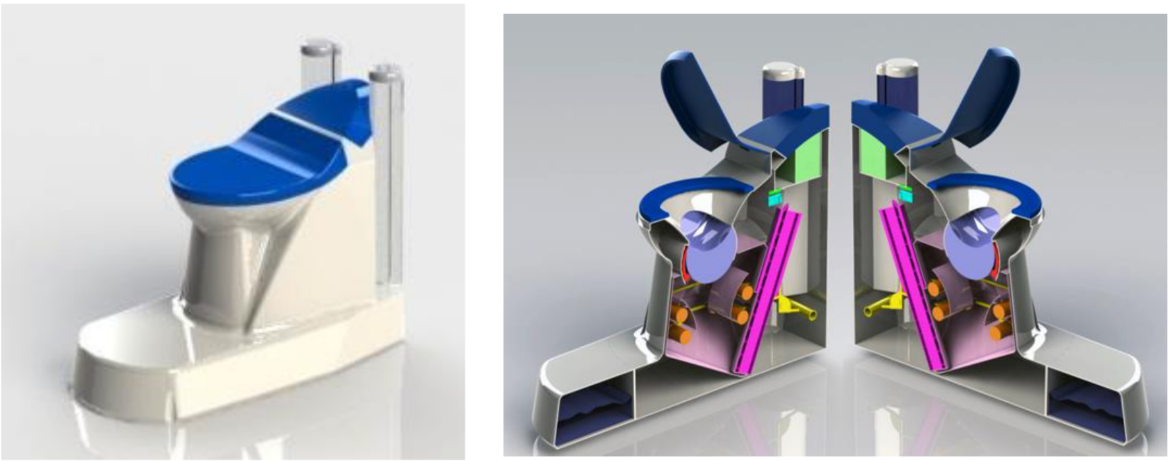


Figure 1 Nano-Membrane Toilet CAD renderings (Tierney, 2014)

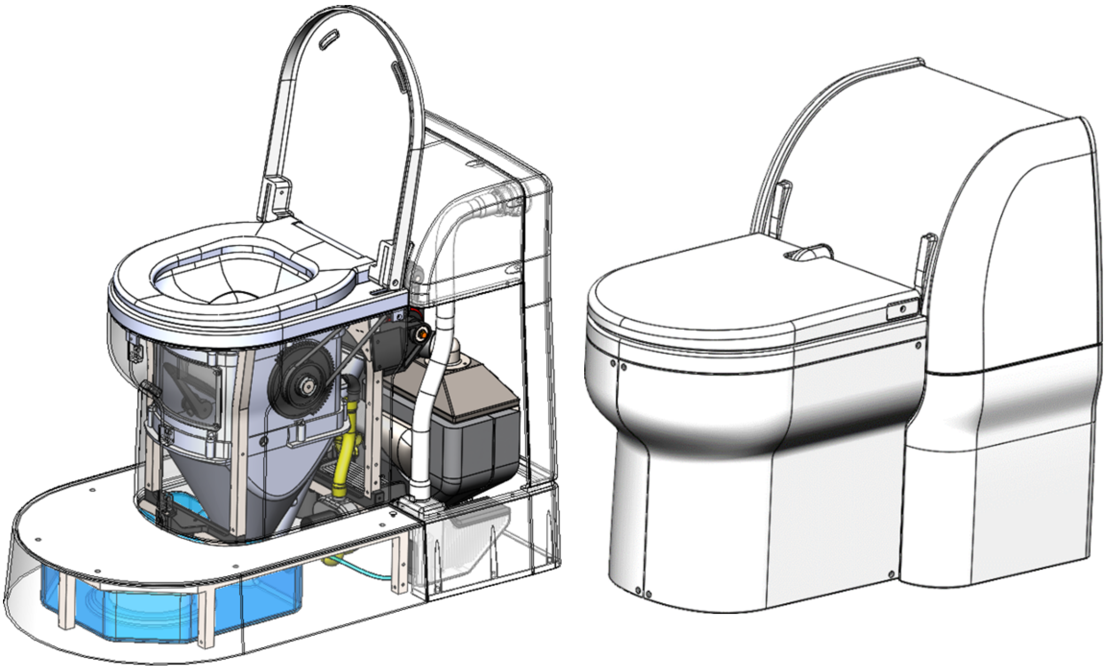


Figure 2 CAD models of the VC Toilet (left) and HUT3 Toilet (right) - © Cranfield University

With continual research efforts, the project took multiple directions and made progress in different related fields, leading to the development and adoption of new liquid and solid waste treatment systems. Their working concepts are briefly described below.

1.3. Brief description of new liquids and solids treatment technologies

For purifying effluents, direct-contact membrane distillation (DCMD) relies on the principle of two water circuits (feed and permeate) which have a temperature difference as hot and cold respectively, running in opposite directions and intersecting inside the MD unit where they make direct contact with the membrane (Ashoor, 2016). Given the oil-water separation characteristic of the membrane, the hot water molecules from the feed passes through to the cold circuit, leaving the impurities behind (Ashoor, 2016). Membrane distillation (MD) technology is growing in popularity, with companies such as AQUASTILL Netherlands, pushing pilot systems for research and commercialization. For this project, they produced a small-scaled version of their MD unit to fit within the volume provided in the backend structural frame and meet the usage intake, with the aspired production capacity of 2 Litres / hour.

For sterilizing solid wastes, torrefaction (mild pyrolysis) is an oxygen-deprived heating process where it operates at low temperatures of 200 degrees C and in ambient pressure, requiring no consumables in the process, and converting the human faeces into biochar (Serio, 2016). These conditions were found to be sufficient for eradicating pathogenic organisms in faeces, and are beneath the thresholds of releasing synthetic gases as well as ceasing the production of gases associated with other processes such as combustion due to the lack of oxygen, thus eliminating the need for extending ventilation in households (Serio, 2016).

1.4. Opportunity to reinvent the user-interfacing module

With the above-described developments, and in the university's renewed endeavour to bring the sanitation system closer towards production and commercialisation, research and industrial works proceeded towards delivering the Single-User Reinvented Toilet (SURT) also known as the Cranfield Circular Toilet. This sanitation system is made with the intention to work in private residences, with operating capacity to take and process human waste in a household of 5 people.

Previously, the human waste treatment technologies were imbedded within the volume of the user-interfacing module, which was considered as a comprehensive sanitation system at the time. However, the incorporation of the direct-contact membrane distillation module for liquid treatment, and torrefaction module for solids treatment, required bringing significant changes to the overall mechanical architecture of the sanitation system. It was found that moving those modules out of the user-interfacing module was necessary in making the system easier for development, where design complexities such as spacing and component collision were obviated, as well as modular, where installation, maintenance and upgrading of the individual modules can be achieved with a lesser extent of dependency on one another.

This had then created an opportunity to revisit the user-interfacing module, where the design of its components and subsystems could be streamlined for manufacturability and a higher overall performance. The final non-sewered sanitation system was then developed, built and installed, consisting of the user-interfacing module, the front of the system, and a closet, the back of the system, where the membrane distillation and torrefaction modules are installed. The final outbound dimensions of the whole system (width x depth x height) are 76 x 111 x 130 cm, making it adequate for indoor installation and usage. This is shown in figure 3, and the produced prototype is further elaborated in the Methods and in Appendix-A.

1.5. Research scope

This research paper focuses on developing and measuring the performance of the functions in the newly developed user-interfacing module. It does not present the waste treatment modules and does not evaluate the system’s performance as a complete interconnected product, as this will be done in future studies.

The development process considered essential matters for the sanitation system’s commercialization and are further elaborated in APPENDIX-A in relation to the newly developed user-interfacing module. These as follows:

- Ease of acceptance: where the vision of successfully disseminating this system in global markets and creating user acceptance as a potentially novel and competitive white goods product, and therefore gradually transitioning communities worldwide towards decentralized waste treatment, could be realised.

- Installation and usability: maintaining the ease of handling the toilet, in terms of usage, servicing, cleaning and maintenance, and not disturbing the initial user behaviour and perception from conventional toilets.
- Affordability: reducing costs where possible, by referring to volume production processes such as thermoplastic injection moulding and sheet-metal forming, as well as utilising commercially available components where applicable, among other cost-saving approaches.

This research, however, does not evaluate in detail the above-mentioned points, which are to be explored in future studies. This is due to the following reasons:

- As the system is being tested for its functions, it is still subject to changes and thus not yet finalised, which could affect several aspects to varying degrees.
- Field testing that involves volunteering participants was not possible due to lockdown restrictions imposed by the UK Government at the time, and
- The sanitation system's fullest potential in fulfilling all the foundation's targets would not be realised without incorporating the backend treatment modules, which are not included in this research scope as mentioned earlier.

This research thesis will proceed as follows:

The Literature Review presents the latest contributions in developing the vital subsystems comprising the user-interfacing module: the sitting pan / rotating bowl and the auger screw, with laboratorial and field test findings on their functions, in addition to research findings on areas of interest to self-cleaning surfaces: functionalized surfaces for toilet applications, to help define the research aim and objectives.

Then, the Methods presents the list of industrial works completed during the MSc registration period for the whole non-sewered sanitation system, describes the improvements and new features made across the subsystems in the user-interfacing module, describes the planning, purpose, and preparations of the tests on the same.

Afterwards, the Results presents the findings from the laboratorial tests completed, where two sets of tests were completed: 1st and 2nd waste evacuation stages, supplemented with photographic images extracted from the video recordings of the same.

Finally, the Discussion presents the points of success in the aforementioned tests, as well the areas that need reviewing in the module to improve its performance, and practical lessons learned from the tests implemented. As a result of the test findings, a CAD model of an improved version of the user-interfacing module had been developed, mainly intended to reflect needed modifications and enhancements to the module, and suggestions for exploring areas of research in interest to the system.

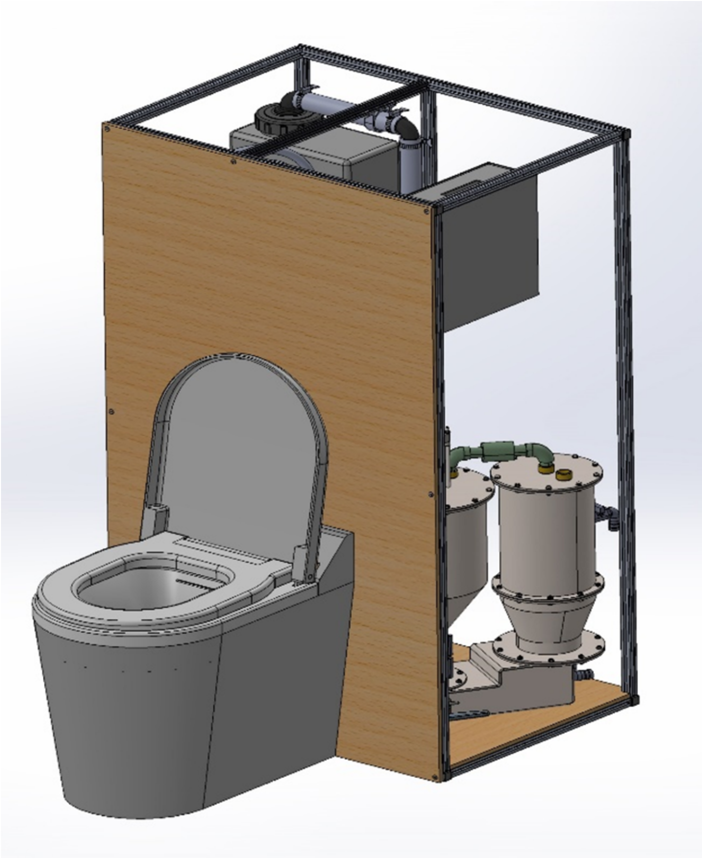


Figure 3 Cranfield Circular Toilet in CAD Assembly and complete build model

2. LITERATURE REVIEW

This section presents the most current and relevant literature material to the research in terms of designs, technologies, laboratorial and field test findings, and analyses these contributions for advantages and drawbacks, to help inform and set the direction of motion in the project's implementation.

2.1. Field and lab testing of the Cranfield waterless toilet flush

I In previous research under the same project by Cranfield University, a mechanical waterless toilet that utilises a rotating bowl was implemented for field and laboratorial testing, where it used a mechanical swipe to clean the with acceptable performances and generally favourable acceptance by the end users (Hennigs, 2019).

Three materials were used for the mechanical swipe blade: polyurethane, silicon, and oil-bleeding silicon, all of which demonstrated success in evacuating solid faeces, but varying rates of success in evacuating glutinous and soft faeces, where they relied on the addition of urine and spray water prior to defecation for a better cleaning performance. In addition, all blades had experienced fatiguing after several tests, and it was concluded that further research was needed to develop an omniphobic material with greater reliability for both surfaces of the swipe blade and the bowl. The research did not report testing the sanitation system's evacuation using only spray water and removing the swipe, as the hypothesis was to make the system work without relying on water (Hennigs, 2019).

Moreover, participants who used the dry toilet had stated their preferences to have running water in the system for better cleaning performance and perception of hygiene (Hennigs, 2019). This perceived image of hygiene goes in line with the acceptance of large populations globally for self-cleaning, where it was also found that 50% of the world's population practice wet anal hygiene (Otterpohl, 2002).

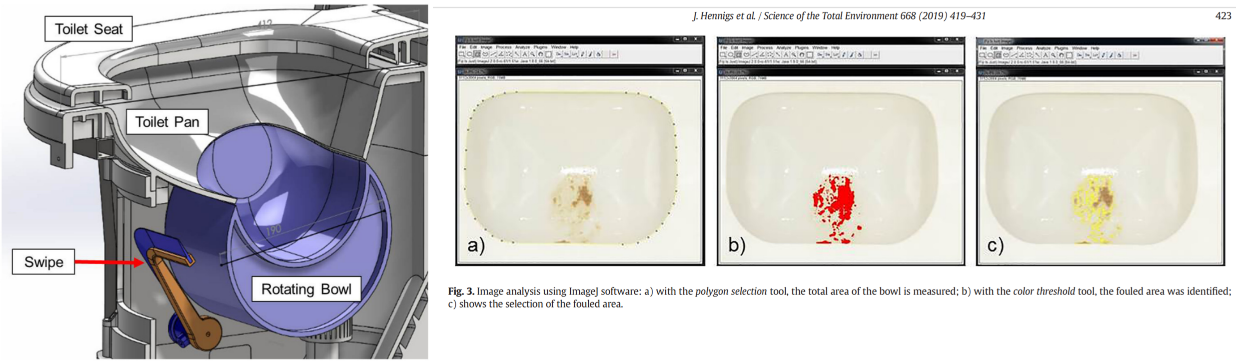


Figure 4 Mechanical waterless toilet CAD model and top photographic images (Hennigs, 2019)

2.2. Surface functionalization for toilets

In exploring new options for reducing water consumption to clean soiling surfaces, surface functionalization would come into consideration. A growing body of research has been expanding rapidly since the late 1990s with interest in re-engineering surfaces to overcome numerous types of environmental conditions, particularly in obtaining self-cleaning properties for higher performance (Zhang, L., 2014).

To present a brief understanding on functional surfaces, materials are classified depending on their interaction with water on the surface, which then determines the surface cleaning properties. On one end of the surface wetting behaviour spectrum, surfaces that attract water, called hydrophilic, cause water droplets to collapse and spread to cover the surface, therefore wetting it. On the other end, surfaces that repel water, called hydrophobic, make water droplets bead and roll over the surface if tilted by gravity, therefore keeping it dry. In addition, there are surfaces that have repellence to oil-based matters, called oleophobic, which can have higher performance in antifouling against the latter (Drelich, 2014) (He, 2021).

Due to the novelty of research on repellence of contaminating matters with high viscoelasticity in conditions similar to those for repelling human faeces in toilets, very little literature was found to date on self-cleaning surfaces in toilets with water-saving features. A recent study presented what would be the most successful solution to date in repelling viscoelastic solids using functionalized surfaces, aimed for water-saving toilet applications (Wang, 2019). In the study, a test was performed using samples of synthetic faeces that were dropped onto variously treated surface tilted at 45 degrees.

The synthetic faeces were at a viscoelasticity equivalent to real faeces at the Bristol Stool scale of 3-4, which are normally associated with a healthy diet (Woolley, 2014), and where the faeces is found to be the "stickiest" to surfaces within that scale (Wang, 2019). Five glass sheet substrates were used in the test, having the following surface treatments: nontreated, two with enhanced hydrophobic functionalities and two with enhanced oleophobic functionalities, one of them having the liquid-entrenched smooth surface (LESS) treatment, the study's main subject.

Going in line with what the literature suggests, oleophobic-functionalised surfaces are the most likely capable in repelling oil-based contaminants, superseding their superhydrophobic counterparts (Wang, 2016). This is what the test in the aforementioned study had demonstrated in repelling synthetic faeces, with the LESS treated one exceeding in performance over all other substrates, and currently recorded as the most highly repellent coating against viscoelastic solids (Wang, 2019).

Despite the promising findings, however, some oleophobic coatings could raise challenges in adoption due to maintenance requirements, which was the case observed in the LESS coating. The steps of synthesizing oleophobic surfaces normally incorporate the application of a grafting or nano-structure layer on the substrate, followed by spraying a layer of lubricant to grip on the grafting and stabilise on the surface. In the case of LESS, those are dimethyldimethoxysilane (PDMS) and silicon oil, respectively. Maintaining the surface's oleophobicity would herein require reapplying lubricant periodically, without which the self-repelling performance will reduce, and the grafting layer will be exposed and possibly be subjected to erosion.

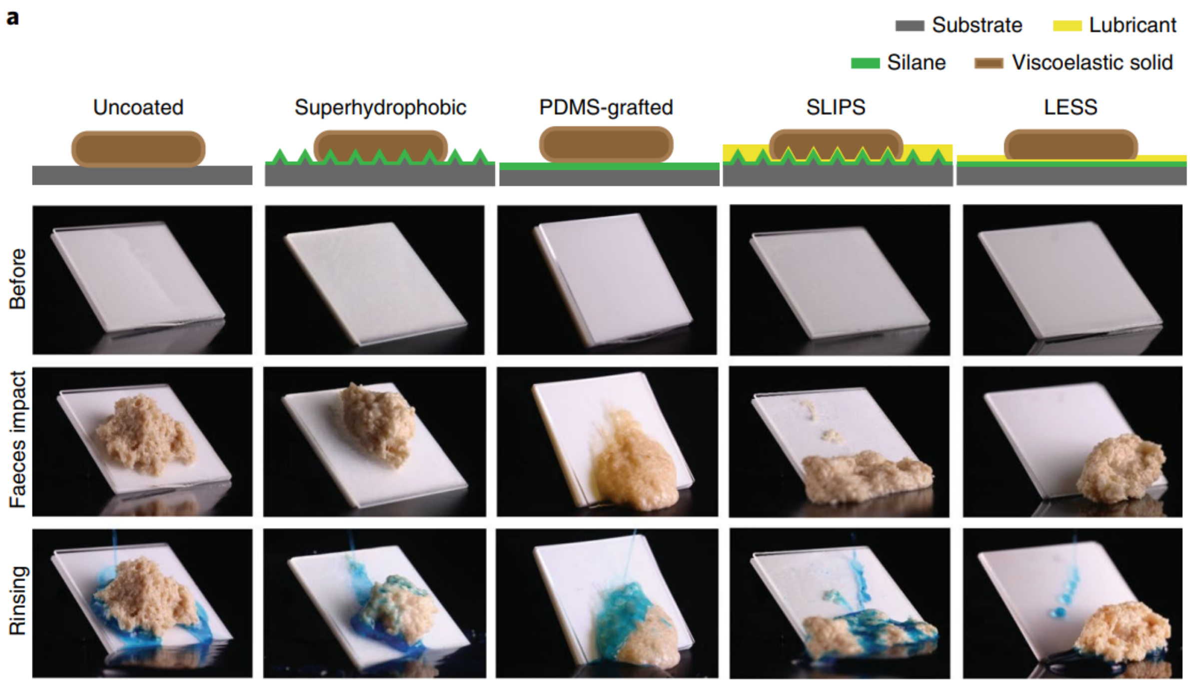


Figure 5 Images of various coatings in repelling viscoelastic waste (Wang, 2019)

Follow-up tests on the LESS's durability against continuous shear flow and impact of synthetic faeces later revealed that the lubricant coating layer starts to wear out after 50 urination and 10-35 defecation cycles. Unless the surfaces are replenished with more lubricant, either via manual spraying or by adding it in the flush water, the self-cleaning performance will reduce. At that rate, with an average of 4 toilet visits per user a day in a household of 5 people, recoating would be required almost every 2 days (Wang, 2019). Costs of consumables with then increase on the users and so will the environmental risks due to the excess synthetic oils releasing into the environment if natural alternatives were not used, despite the authors' reservations on its environmental impact.

Upon further research in this field, however, that there was no mentioning of superhydrophilicty as a potential surface functionalization strategy for repellence of viscoelastic solids (Zhang, L., 2014). In hydrophilic surfaces, water spreads and equally covers a surface as much as possible, creating a hydrogel layer. Where contaminants are located, water will seep underneath raise it above the surface, in preparation to be washed away with a change in angle or additional input of water, thus functioning indirectly as an oleophobic surface (Drelich, 2014). This suggests an opportunity for further investigation upon the release of further research in this topic of interest.

2.3. Waste Transfer and Phase Separation via Auger Screw

This section of the literature review builds upon the most recent findings from the auger screw design of the same project and highlights the limitations and potential areas for improvement, as key information from the same is acquired to inform the redesigning process in light of the recent system developments.

The auger screw was firstly proposed in the early designs of this project as a solution for 'post-flush' source separation and conveyance of urine and faeces, as it was adapted from previously existing applications of conveying high-viscosity materials, such as wastewater sludge (Rogers, 2014). This was mainly due to the increasing difficulties in introducing source-separation systems in toilet designs for users to accept and adapt, due to non-familiarity or misuse (Vinnerås, 2002). This ought to bring a post-flush separation alternative, bringing in the auger screw as the mechanical component for phase separation in post 'flush' system.

The latest study carried out at Cranfield University (Mercer, 2016) aimed to identify the screw characteristics and operational boundary conditions for extrusion of faecal sludge, to achieve phase separation with high solids concentration and consistent throughput despite the faeces' complex rheology.

The screw consists of a series of helical flights that are mounted on a central shaft and mounted inside of a tube and resting on the bottom of the collection tank. It is tilted at 60 degrees from the horizontal, which is greater than the angle range of 30-38 degrees for conveying liquids according to the literature review done by Mercer et al. (2016) to

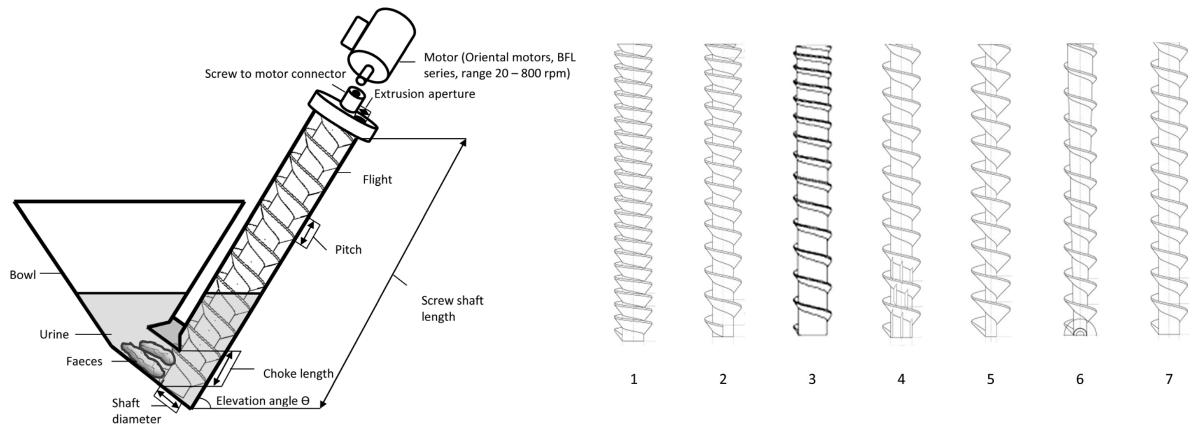


Figure 6 Experimental setup and various auger screw design configurations (Mercer, 2016)

aid in phase separation. The screw advances the sludge upstream by combination of rotation and frictional resistance (McGuire, 2009), while being operated by a motor.

Seven screw designs were made and tested, with one of the screws having an exaggerated shaft and pitch frequency, as means to compress the solids during conveyance. A rig structure that consists of a collection tank and a screw tube was used in all tests, having a fixed choke length, that is, the interface between the screw and sedimentation volume, and an extrusion aperture, i.e. the output port of solids leaving the screw, where the faecal product was collected for mass and solids analysis. The tests used both simulated and real faeces. The tests concluded favouring screw designs with smaller helical pitch of progressive tapering in the pitch and shaft.

Distinct behaviours were observed and assessed from those tests (Mercer 2016), listed herein under five performance characteristics:

1- **Comparison of screw characteristics:** The increased number of flights along the screw length increased the carrying capacity, progressive tapering of the pitch as well as the shaft diameter provided progressive reduction in the carrying capacity as the solids approach the upper end of the screw. These factors, though they increase the concentrations of solids leaving the screw, increase the compression of solids with the direction of flow, which builds up pressure behind the top outlet.
2- **Faecal sludge pre-treatment:** pre-treatment for those tests (via dicing and/or blending of faecal sludge) showed to be needed where the choke length in the test setup presented a limitation for the screw's intake. It was found that extending the choke length would provide an increase of faecal sludge flow for matters of high viscosity.
3- **Rotational speed on solids extrusion and phase separation:** an increase in rotational speed promoted the advancement of faecal sludge through the screw due to the associated increases in shear, feed pressure and vortex motion, and thus increasing the extrusion efficiency (the favourable rotational speed was found to be 300RPM.) However, the conveyance rate of solids would hit a plateau upon increasing speeds, as this would be constrained by the feed rate, conveying capacity and the outlet port's area. In the case of transporting free water, however, the tests showed the need to increase the rotational speeds of 350RPM and above,

where there will be a linear relation between the rotational speed and averaged extrusion rate.

4- **Faeces / Urine volumetric ratio on solids extrusion efficiency:** The efficiency was observed to decline with the increase of water fraction in the collection tank, which in turn reduced the faecal sludge viscosity and the friction coefficient, thus promoting back slippage along the screw helices.

5- **Application on real faeces:** with the existence of impurities in the faeces, such as indigested foods, the increase of outlet port diameter plays a role in reducing clogging and obviate blockages, which, however, will reduce the compression behaviour needed to maintain the solids concentration. Moreover, It was found that faecal sludge storage time promotes the bonding of stored sludge, thus increasing the fluid viscosity and thus the efficiency of extrusion. However, although it was observed that complete sedimentation in the tank was in 10 minutes, it was required for the sludge to sit for 24 hours in order for the conveyance rate to increase by almost a double over that of their 10-minute sedimented counterparts.

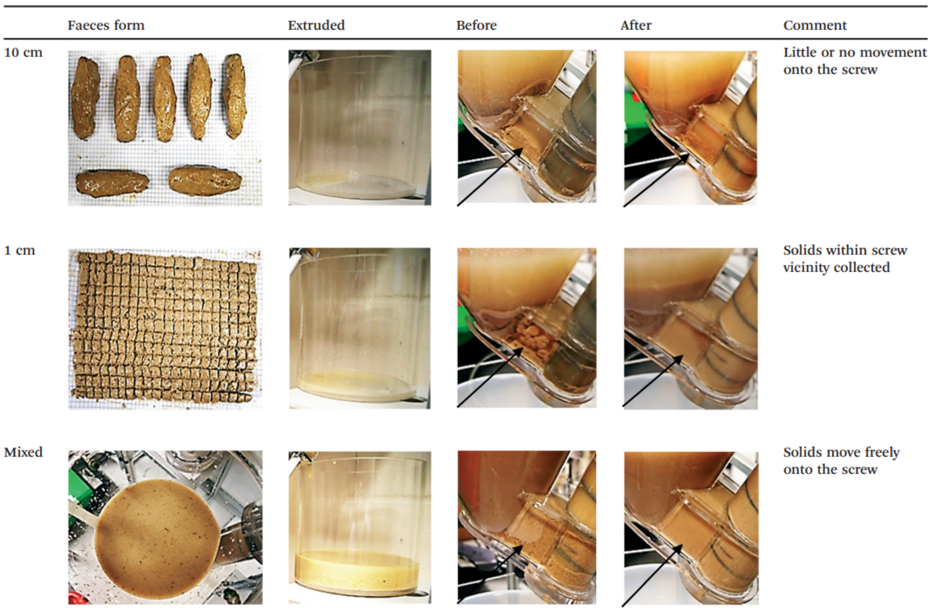


Figure 7 Various feacal outputs from the auger screw performance in various ranges (Mercer, 2016)

The above findings, despite achieving successful waste conveyance and phase separation, present a number of challenges towards promoting this solution for single household toilets. Despite that there are welcomed recommendations into the system's design -such as increasing the exposure area of the screw helices inside the collection tank volume- other changes would lead to further complications in the system's efficiency, hygiene and capability in handling varying inputs. These challenges are observed mainly in two areas:

- the research did not discuss the possibility of including toilet paper in the sludge mixture. Should the screw with tapered design features be chosen, the toilet paper, depending on the amount being dispensed after each toilet visit, will very likely create backing pressure and require additional torque on the motor.
- Moreover on the other findings, the need for motor rotation to reach high speeds such as 300 RPM (thus leading to higher power consumption), the reduction of solids extrusion efficiency with higher water fraction, and the lengthy time periods needed for solids bonding during sedimentation, are all attributed to the amount of liquids sitting in the sedimentation tank, which could otherwise be rerouted through a different route to lower the liquids quantity in the tank.

From the above, it becomes essential to introduce further design changes that would effectively maintain high efficiency in solids extrusion, accommodate to various states inside the collection tank (varying faeces/urine ratios and inclusion of toilet paper) while reducing power input into the system and preventing pressure build-ups and blockages.

2.4. Research Aim and Objectives:

The literature findings were important to inform the research, essentially, to overcome the limitations of the previous designs and setups to get the utmost potential of the user-interfacing module. Therefore, the research aim and objectives are as follows:

Aim: Define the direction of development and optimisation for the novel, water-saving user-interfacing module, to meet its industrial and performance requirements.

Objectives:

1- Achieve complete self-cleaning of the interfacing surfaces during and after usage.

2- Achieve complete waste evacuation and phase separation that is adequate for the set amount of daily usage and suitable for the subsequent treatment modules.

3- Reach performance levels that use minimal resources of time, water, and power.

The next section presents the methods used for proceeding in the project that go in line with meeting the above-mentioned objectives.

3. METHODS

This section presents the main features of the newly developed user-interfacing module as a result of the industrial works in the project, and describes the testing rationale and plans selected to evaluate its performance.

3.1. Industrial Works for the Prototype Development

The industrial project went on a very high pace, as the intention was to satisfy the Foundation's expectations in a timely manner and to make progress through the programme's objectives. Because of that, the project followed a simple methodology of designing, building, and testing the new sanitation system, as informed from the literature, practical knowledge, and the incorporation of the new liquid and solid waste treatment modules.

In order to bring the user-interfacing module closer to commercialization, a number of criteria were to be fulfilled, which are as follows:

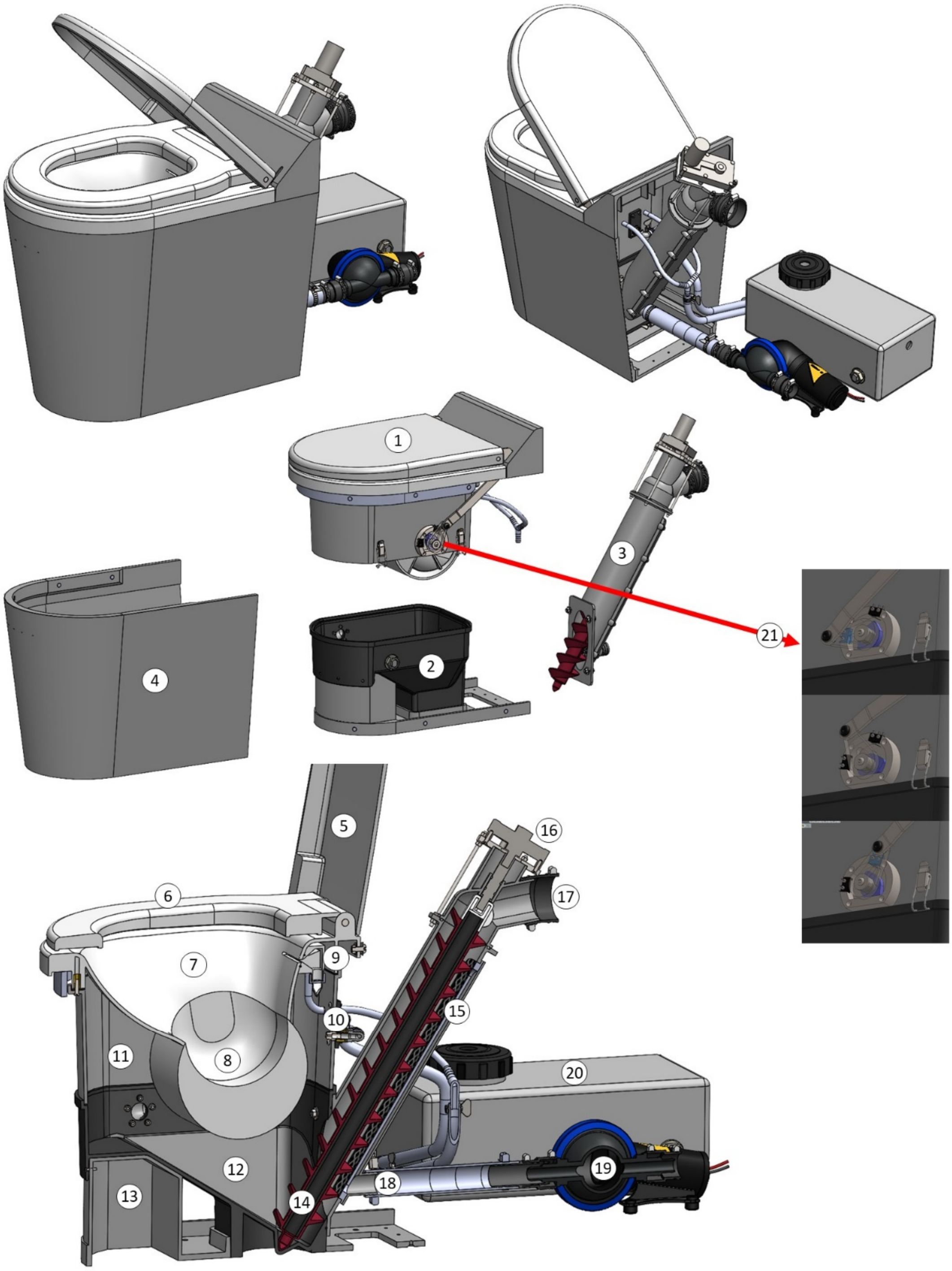
- Introducing new operational features that can augment the functionalities of existing components in the mechanical waterless sanitation system, and replacing components with ones that are more suitable for performance under the new operational settings.
- Streamlining the module's design for manufacture and assembly by reducing part count and variety, designing the main components in readiness for volume production (e.g. thermoplastic injection moulding) and substituting complex mechanical structures and mechanisms with easier and more direct solutions.
- Bringing automation into the whole system that covers the user-interfacing module, using a programmable controls solution to monitor and control the whole system, in preparation for future applications of system integration and smart features.

As a result, the main new features that differentiate the newly built user-interfacing module from its predecessors are as follows:

- Repurposing of purified water as a by-product from the liquids treatment module for rinsing the pan and bowl, a feature that was once unavailable in the context of developing the mechanical waterless toilet.
- Significantly reducing part count in the user-interfacing module, mainly in removing the swipe in line with the above-mentioned development, and simplifying the bowl movement's linkage mechanism.
- Several changes in solid and liquid waste conveyance:
    - Change in the screw design, where it has more waste carrying capacity for conveying solids.
    - Auger screw is driven be a DC motor at a lower RPM, as the requirement herein is to only lift the solids upwards by the screw, whereas the bound liquids will drip down the tube back to the collection tank and be sucked by a separate evacuation pump.
    - Incorporation of a liquids suction aperture, connected to an evacuation diaphragm pump that feeds to the liquid waste treatment module, and
    - Expanding the auger screw's exposure in the collection tank for more solids capture.

These are elaborated further in appendix-A.

It is worth noting that, from the aforementioned findings in the literature, it was determined not to proceed pursuing surface functionalization, and instead to concentrate on utilising cost-effective surface cleaning methods. Achieving this would lead to less reliance on technologies that could lead to an accumulation of costs on the end-user in terms of the manufactured product and / or any consumables needed for the same.



User-Interfacing Module Main Components:

1-Upper Portion 2-Lower Portion 3-Waste Evacuation Assembly 4- External Cover 5-Lid 6-Seat 7-Pan 8-Bowl 9-Pan Water Cascading Canister 10-Bowl Spray Nozzle 11-Mid-Section 12-Collection Tank 13-Base 14-Auger Screw 15-Liquids Port Mesh 16-DC Motor 17-Solid Waste Outlet 18-Liquids Aperture 19-Evacuation Diaphragm Pump 20-Clean Water Storage Tank (including two submersible water pumps) 21-Lid-Bowl Linkage with Oscillating Cam Mechanism.

Figure 8 User-interfacing module CAD model: Isometric and cross-section views with list of main components

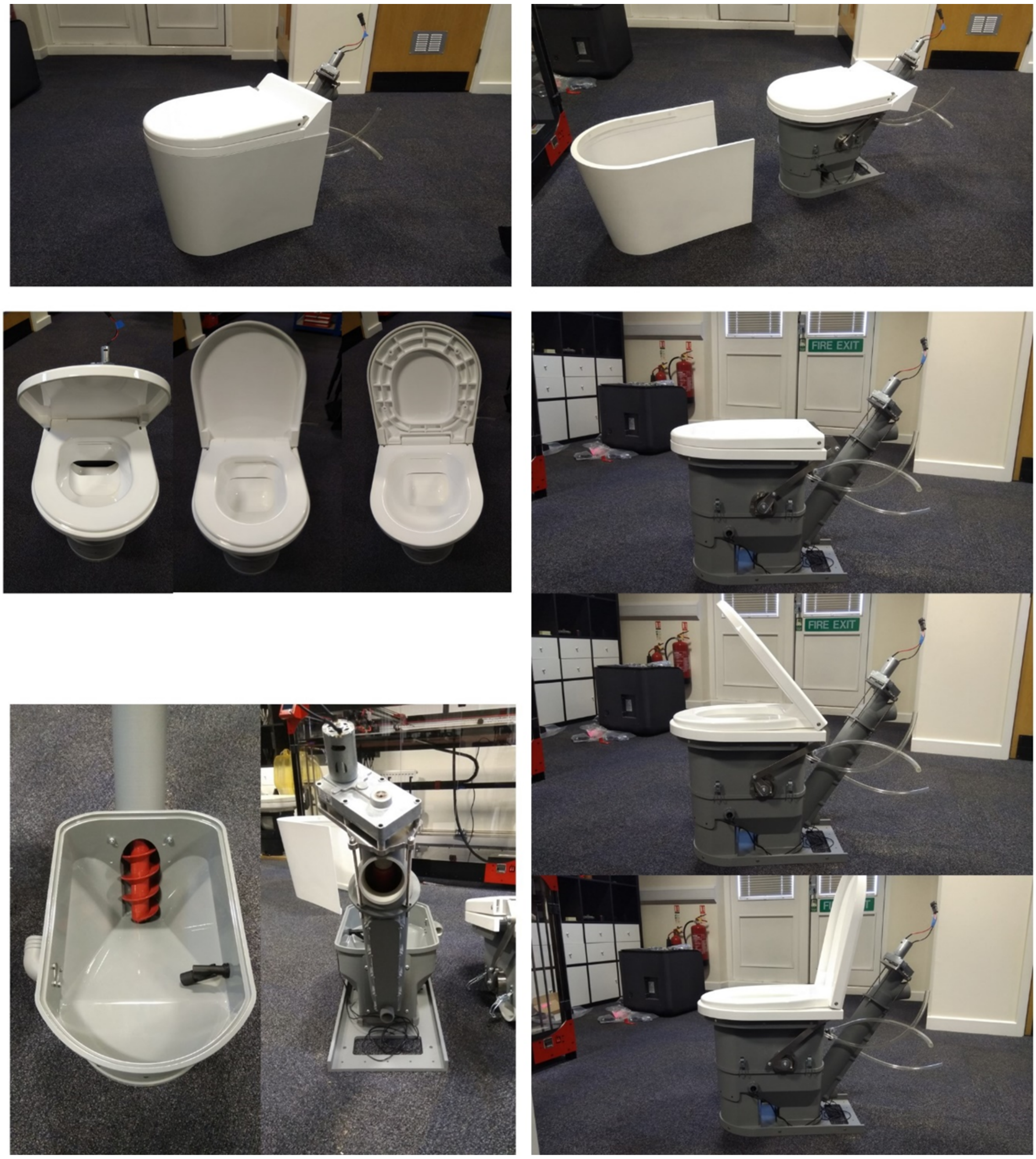


Figure 9 Physical build of the user-interfacing module

3.2. Testing Scope

The defined scope of this research is to evaluate the performance of the user-interfacing module for meeting its intended purpose: to perform complete human waste evacuation and maintain a clean interface with minimal power input and water resources. Specifically, it is to address the following questions:

- How well the pan and bowl's surface are cleaned after a toilet visit, that is, how well the waste has transferred away to the collection tank, and
- How well and quick the collection tank is emptied from deposited waste after each toilet visit using the provided waste transfer mechanisms.

Note that this research and the tests performed do not concern the condition of the waste after leaving the transfer mechanisms. This will be the subject of further research for the liquid and solid treatment modules, as the rate of phase separation prior to treatment, among other factors, will be further defined based on the pre-treatment mechanisms embedded or preceding those modules (i.e. filtration for the liquids treatment module, and partial-drying of solids for the solids treatment module).

From the above and in inspiration from the literature, it was assessed to split the main functionality of the user-interfacing module into two stages of waste evacuation, as follows:

- **The first stage of evacuation** is the transfer of waste from the sitting pan and rotating bowl interfacing with the user, into the collection tank underneath waiting for further transfer
- **The second stage of evacuation** is the movement of waste out of the collection tank through the waste transfer mechanisms, heading towards the waste treatment modules in the system's backend.

This convention is followed through the rest of this research thesis for convenience and clarity, following the boundaries of the research scope.

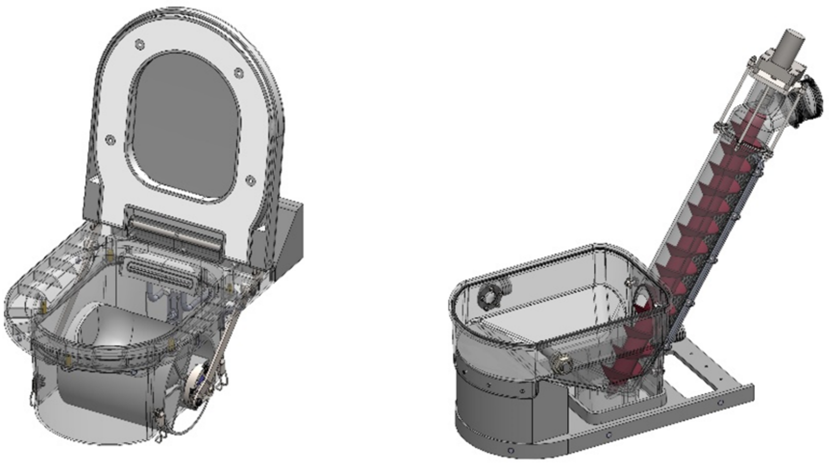


Figure 10 CAD Illustration on the 1st and 2nd stage evacuation subassemblies of the User-Interfacing Module (left and right respectively)

3.3. Defining the testing rationale

It was originally planned to implement the sanitation system for field testing, by installing it in a publicly accessible location, recruiting participants and inviting volunteers to use the toilet. This would have allowed the input of real human waste for processing in the system, serving to execute the treatment processes in the backend modules, and collecting users' observations and feedback for where improvements could be introduced. However, the UK Government's imposed social distancing restrictions at the time made this endeavour difficult to achieve. Thus, the team resorted instead to laboratorial testing, and the unit was installed in an LEV enclosure as described earlier.

Moreover, on planning the tests, it was also intended to imitate the household members' toilet visit frequencies during the day. This approach was then avoided due to limited access to the laboratorial facilities, but more importantly due to the uncertainties brought from human behaviours for visiting toilets in real life, and the need to do more research on understanding such patterns. Instead, laboratorial testing that replicates concentrated and heavy usage conditions of the module was preferred, which aimed to determine the toilet's readiness under worst conditions and identify any shortcomings in its performance. In other words, the intention was to replicate "**five consecutive, larger than average, adult defecations with rapid bowel movements."** This should pave way to prepare the module to operate under a range of circumstances that exceed average usage conditions, and increase its chances of success under such conditions.

Lastly in terms of test input consumables, the above selected approach in testing required securing human solid waste samples that are consistent in their rheological properties and volume per sample, preferably above the average output volume, and in quantities not fewer than 5 samples to be used consecutively. Since this was not possible to achieve under the given circumstance, using a synthesized alternative was then preferred, as described in the next section.

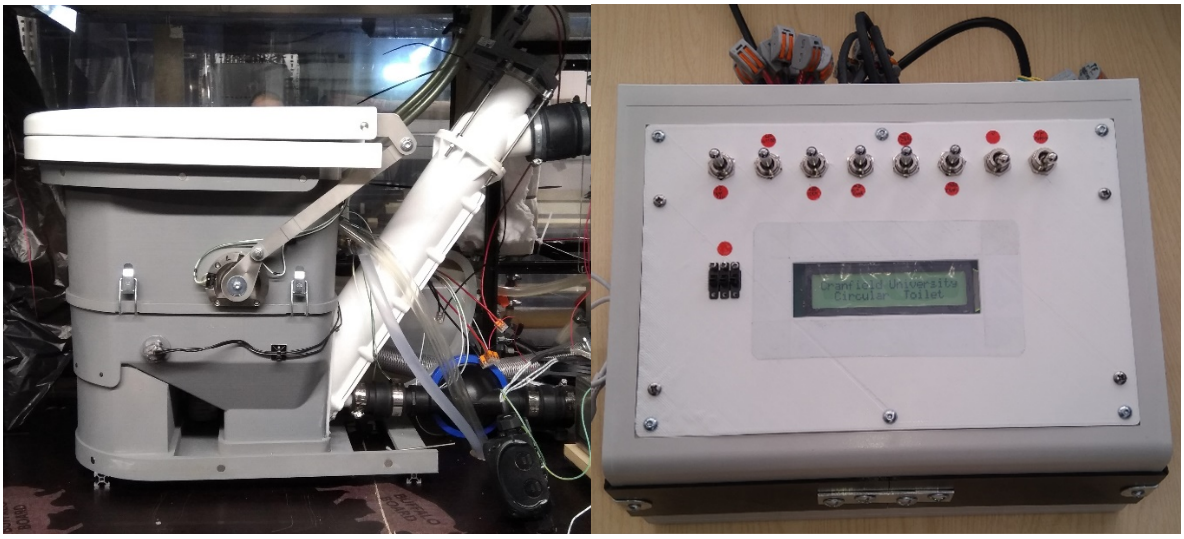


Figure 11 Laboratorial setup: User-Interfacing Module installed in the local-exhaust ventilation cabinet (left) and control box with an informative LCD display of the whole sanitation system (right)

3.4. Consumables Preparation

Given the user-interfacing module's intended application in a household of 5 people, the consumables' amounts were prepared to duplicate the scenario of heavy, concentrated usage, as follows: The toilet is visited by five adults consecutively, with 5 minutes between the start of each visit, producing defecations that are higher than the average weight of 128g and are within the range produced by adults at 51-796 g/cap/day, both as recorded by Rose et al (2015).

In inspiration from one synthetic faeces recipe developed at the University of KwaZulu-Natal in South Africa, miso paste, an essential ingredient, was used, as it was observed to be sufficient on its own to fulfil the purpose of the tests planned, and had demonstrated a rheological behaviour similar to that in faeces at the Bristol Stool Scale of 3-4, the most preferable for the testing requirements.

In addition, water was used in place of urine. Given that water comprises about 95% of a health person's urine (Rose, 2015), water was found to be sufficient to meet the testing requirements.

For that, the consumables used in the test to represent one visit (herein called a consumables set) are as follows:

- **400g of miso paste** to imitate human faeces
- **300ml of water** to imitate urination
- **250ml of water** to imitate the average amount of flush water used in the 1st stage evacuation (for the 2nd stage evacuation testing only), and
- **8 squares of 2-ply toilet paper:** In all tests, the toilet paper squares are folded and not crumbled, shredded or macerated, to maintain their structural integrity and increase chances of any potential performance issues to be observed.

These amounts are fixed per test trial in all tests, and are deposited either at a given sequence during the trial (1st stage evacuation), or as a whole at that start of a trial (2nd stage evacuation).

3.5. Test Plans

3.5.1. 1st Stage Waste Evacuation

3.5.1.1. Test Parameters

A single test trial lasts for 6 minutes, where one consumables set is used, and is then removed from the module in preparation for the next test. Test is conducted with the user-interfacing module fully assembled. the test parameters in this setup were herein divided as follows:

Fixed Parameters: The test trials in this research were carried out on the current set of manufactured parts and subassemblies (pan and bowl subassemblies) with their current geometric designs and surface properties unchanged, and no further configurations were made of the same for making comparisons.

Variable Parameters: The following set of parameters area modifiable in the control board's Arduino sketch, or by manual intervention in some cases, as follows:

- **Pan Water Deposition Method:**
  - **Cascading**: This is the water deposition method originally made in the pan, where water fills a canister situated behind the pan's surface and cascades through a slot on the pan in a gentle flow that covers the pan's back face or impact area. The maximum flow rate out of the slot is 12.7 L/min.
  - **Spraying**: This is an alternative water deposition method, where the water is ejected from a spraying nozzle in a 90-degree fan spray, that is projected to cover the impact area. This was not part of the pan's original design, and was incorporated using a removable jig structure to assist in the testing, as shown in figure 12. The maximum flow rate out of the spray nozzle is 1.187 L/min
- **Pan Water Deposition Volume:** The output volumes are controlled by setting the pump as in the table below:

Deposition Method	Cascading	Spraying
Duty cycle	30%	100%
Flow rate (mL/sec)	63.5	19.77
Deposited vol. in 0.5 sec (mL)	31.75	9.86
Deposited vol. in 1.0 sec (mL)	63.5	19.77
Deposited vol. in 1.5 sec (mL)	95.25	29.66

- **Pan Water Deposition Frequency:** In all tests, water deposition occurred once every 30 seconds during a total period of 5 minutes. This is intended to account for factors such as the total average time the user sits on the toilet and the separate instances of defecation during that time.
- **Bowl Spray Water Deposition Volume:** this is controlled by setting the pump's operation duration, as this pump is fixed to work at its maximum flow rate. This is intended to operate once, depositing the volume of 19.77mL when operating at max. duty cycle for 1 sec, but it can be actuated more than once, and in the test, will be actuated up to five times until complete bowl cleaning is achieved.

3.5.1.2. Test Execution

Events and Actions:

- The tables below show the series of actions during the 1st stage evacuation test:

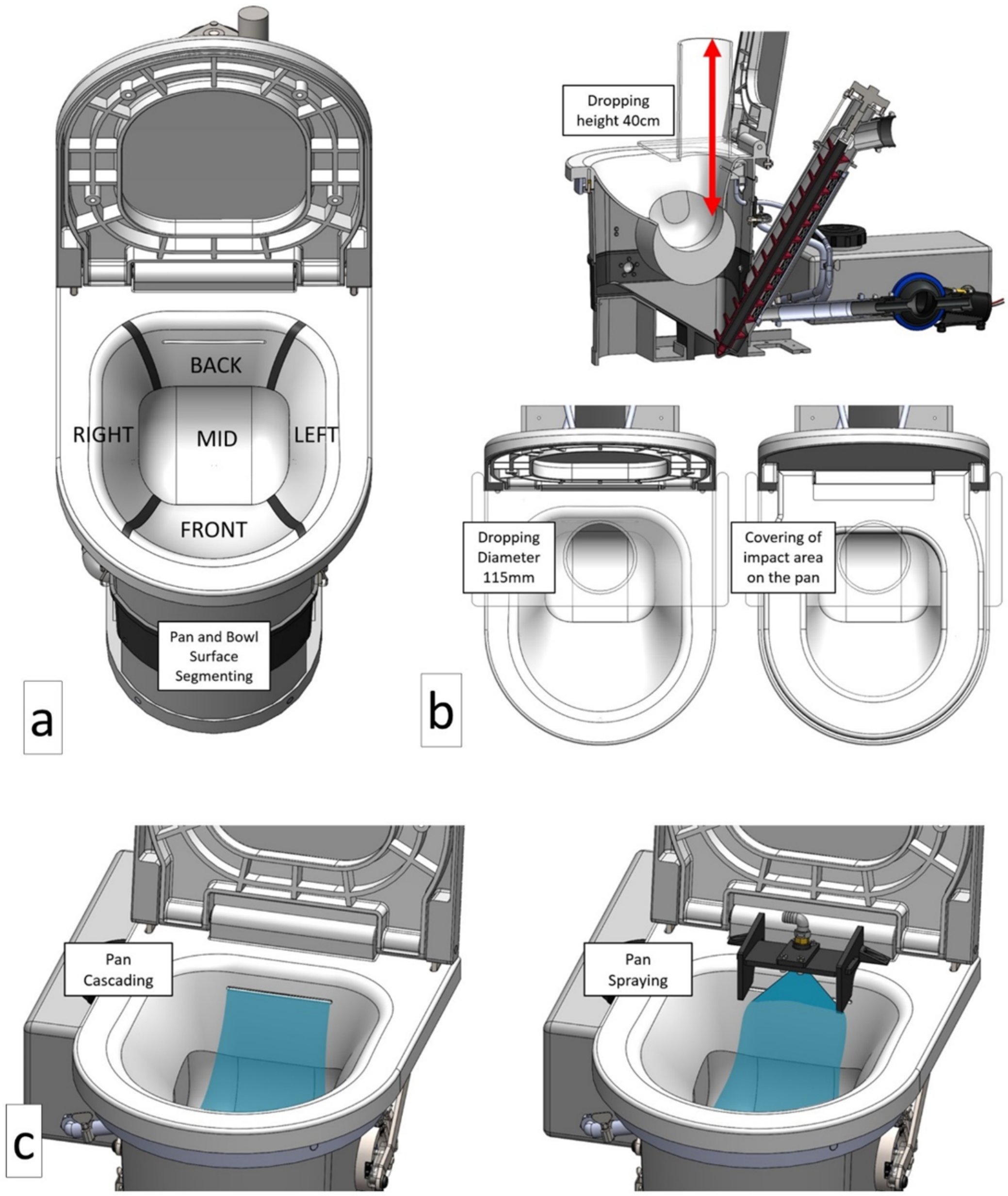
Time (sec)	Event / Action
0	Test starts with 1st pan water deposition shot
30	Pan water deposition shot – drop 400g Miso paste
60	Pan water deposition shot – pour 300 mL water
90 – 120 – 150 – 180 – 210	Pan water deposition shot
240	Pan water deposition shot – drop 8 square toilet paper
270	Pan water deposition shot
300	Pan water deposition shot – function ends – close lid
315	Bowl water deposition shot – once
330	Bowl water deposition shot – once
345	Bowl water deposition shot – 3 times
360	Test ends

Deposition of Consumables:

Dropping the solids: In part of replicating concentrated usage conditions, to achieve maximum soiling on the pan's impact area by mimicking a pressurized defecation from a rapid bowel movement, a solid waste dropping jig was made, where the miso paste is dropped from a holding cup at a fixed elevation of 40cm above the impact area, targeting the latter to achieve the desired soiling. This is done in reference to the synthetic faeces dropping and flushing test by Wang et al (2019).

Pouring the liquids: water is poured on the pan's front region to mimic urination.

Dropping the toilet paper: this is done at random and not targeting any specific point on the interface, to assimilate a real-life situation as close as possible.



Experimental preparations: a) Pan and Bowl surface segmenting for measuring cleanliness, b) Solids Sample dropping apparatus, and c) Water deposition methods for pan surface rinsing: cascading vs spraying

Figure 12 Experimental preparations of 1st stage evacuation tests

3.5.1.3. Data Collection and Outcome Measurement

Data collection in each test trial is done by top-view photographic imaging to measure the user interface's cleaning performance. For clarification, the pan and bowl surfaces were segmented into 5 regions. For convenience, these are: Back, Left, Right, Mid, and Front, as shown in figure 12. Each region has its distinct geometric characteristics, and currently the back and mid regions (pan's impact area and bowl respectively) have designated water deposition features as described earlier.

The level of cleanliness is graded on each zone throughout the test by following a traffic-light convention as follows:

- **Green (No Soiling):** no cleaning required or cleaning is completed successfully
- **Amber (Minor Soiling):** observable faecal stains or contaminated liquid droplets no larger than 5mm in diameter, and
- **Red (Major Soiling):** waste residues that are larger than those observed in amber, such as soiling that was not removed, or faeces / toilet paper remaining on the bowl even after closing the lid.

Data from each test trial is then logged in reference to the table headings below:

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade

The above table headings are as follows:

- Time stamps (increments in intervals of 30 sec when seat is open, and 15 sec when lid is closed) is when water deposition shots take place
- Deposition volumes used on each region are recorded, and then summed to calculate the total flush waster used, and
- Cleanliness grades are recorded to display the staining/cleaning progress on each region throughout the experiment.

Photographic images for the above can additionally serve for recording any other observations related to the evacuation performance and are noted accordingly.

Power consumption can be calculated from the times and duty cycles of the pumps when in operation, assuming that they would operate in nominal conditions all the time.

Once a successful self-cleaning pattern is identified, the test and data collection process is then to be repeated multiple times, to further identify the durability self-cleaning performance and locate any potential trends in the process, such as areas for gradual waste accumulation, to present future design recommendations accordingly.

3.5.2. 2nd Stage Waste Evacuation

3.5.2.1. Test Parameters

A single test trial consists of 5 sub-trials of 6 minutes each, each using one consumables set, and lasting for 30 minutes total. Tests are conducted with the upper portion of the user-interfacing module removed, to gain direct access to the collection tank's interior. The test parameters in this setup were herein divided as follows:

Fixed Parameters: The test trials in this research were carried out on the current set of manufactured parts and subassemblies (collection tank and waste transfer subassemblies) with their current geometric designs, features and surface properties unchanged, and no further configurations were made of the same for making comparisons.

Variable Parameters: The following set of parameters are modifiable in the control board's software, which are as follows:

- **Auger screw motor:** This will operate at full rotational speed (100% duty cycle), non-stop for a period of 5 minutes, then rests for 1 minute. This repeats 5 times.
- **Diaphragm Pump:** This will operate in patterns (10 sec ON, 10 sec OFF), at 50% duty cycle producing a flow rate of 9.8L/min or 163 ml/sec. This operation takes place between the minutes 2:30-4:00 in the test sub-trial. The pump then rests for minute. This repeats 5 times.

3.5.2.2. Test Execution

Events and Actions:

The tables below show the actions needed during the 2nd stage evacuation test:

Time (min)	Event / Action
0	Test starts: 1st consumables set deposited, evacuation devices start
5	Evacuation devices stop, pending waste amount measured
6	2nd consumables set deposited, evacuation devices start
11	Evacuation devices stop, pending waste amount measured
12	3rd consumables set deposited, evacuation devices start
17	Evacuation devices stop, pending waste amount measured
18	4th consumables set deposited, evacuation devices start
23	Evacuation devices stop, pending waste amount measured
24	5th consumables set deposited, evacuation devices start
29	Evacuation devices stop, pending waste amount measured
30	Test ends

Deposition of Consumables:

The solids are dropped from a holding cup at the foot of the auger screw in the collection tank, followed by the plies of toilet paper, and then water to wet the solids and paper.

3.5.2.3. Data Collection and Outcome Measurement

Data collection would be done by measuring the weight of waste pending in the collection tank at the end of each sub-trial and at the end of the trial (that is, the weight of all consumable substances in each set, which sum up to about 950g). This would be supplemented with photographic imaging to visualise the waste transfer performance and capture any further observations.

Data from each test trial is then logged in reference to the table headings below:

Time (sec)	Newly added weight (g)	Prev. Pending weight. (g)	Current Pending weight (g)

The above table headings are as follows:

- Time stamps are the increments of 5 and 6 minutes, i.e. at the start and finish of each sub-trial
- Newly added weight represents a new batch of consumable set added into the collection tank

- Previously pending weight is the weight of substances remaining in the tank before new consumables are added, and
- Current pending weight is the weight of substances remaining in the tank after new consumables are added

Power consumption can be calculated from the times and duty cycles of the diaphragm pump when in operation, assuming that it would operate in nominal conditions all the time. As for the auger screw motor, this will be measured experimentally, in anticipation for any peaks in current withdrawal in the event of transferring hard objects up the screw such as toilet paper.

3.5.3. Experimental Preparation and Administrative Approvals

The test rig was installed in a local exhaust ventilation (LEV) enclosure at Cranfield University's laboratories building B43a, as a risk mitigation measure, given that lab tests on the waste treatment modules would use contaminated matter, and the LEV would help in safely containing and ventilating any contamination.

Lab tests were conducted in ambient temperature ranges of 10-15 degrees C and an average of 75% humidity.

Risk assessments were developed and authorised for the prospected laboratorial tests. In addition, COSHH assessments were authorised for the overall handling of real human waste, which was obtained for purposes beyond the scope of this research, all of which is available on Intelex. These are as follows:

RA-2700-0321: Assembly and Testing of Novel Non-Sewered Sanitation System

RA-2977-0621: Novel SURT system

COSHH-1540-0919: Chemical characterisation of human faecal waste and the products from the pyrolysis of human faecal sludge

COSHH-2220-0621: Use of environmental samples including storage, handling, sample processing and sample analysis

Approval was obtained for carrying out the research and related tests from the Cranfield University Research Ethics System (**CURES/12867/2021**).

4. RESULTS

This section presents the results found from tests on the 1st and 2nd evacuation stages in the user-interfacing module as described in the Methods section, lists the issues observed in all tests, and interprets the outcomes of the test runs.

4.1. 1st Stage Evacuation Testing

Eight tests were completed on the first stage evacuation process following the steps described in section 3.5.1, with the tables below describing the settings and outcomes in reference to the conventions presented in the Methods:

4.1.1. Test Tables

Test 1:

Pan Water Deposition Method: Cascading

Pan Water Deposition Volume per Shot: 31.75mL

Total Cleaning Water Used: 416.35 mL

	Back Region		Left Region		Right Region		Front Region		Mid Region	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	31.75		0		0		0		0	
60	31.75		0		0		0		0	
90	31.75		0		0		0		0	
120	31.75		0		0		0		0	
150	31.75		0		0		0		0	
180	31.75		0		0		0		0	
210	31.75		0		0		0		0	
240	31.75		0		0		0		0	
270	31.75		0		0		0		0	
300	31.75		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	317.50		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, solid chunk clinging on edge of bowl

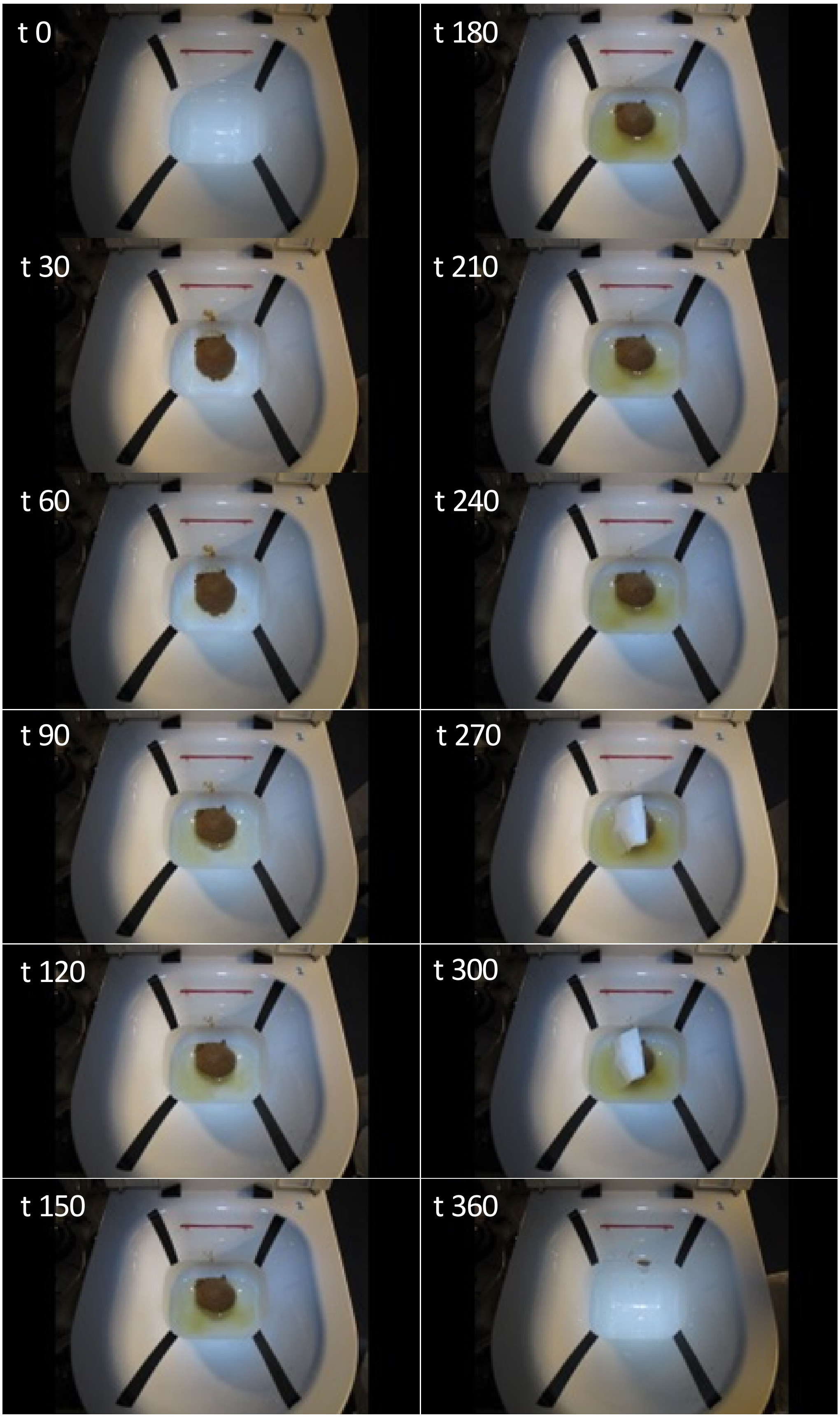


Figure 13 Top view photographic images of 1st Stage Evacuation Test 1 (t in seconds)

Test 2:

Pan Water Deposition Method: Cascading

Pan Water Deposition Volume per Shot: 31.75mL

Total Cleaning Water Used: 416.35 mL

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	31.75		0		0		0		0	
60	31.75		0		0		0		0	
90	31.75		0		0		0		0	
120	31.75		0		0		0		0	
150	31.75		0		0		0		0	
180	31.75		0		0		0		0	
210	31.75		0		0		0		0	
240	31.75		0		0		0		0	
270	31.75		0		0		0		0	
300	31.75		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	317.50		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, side of bowl not cleaned

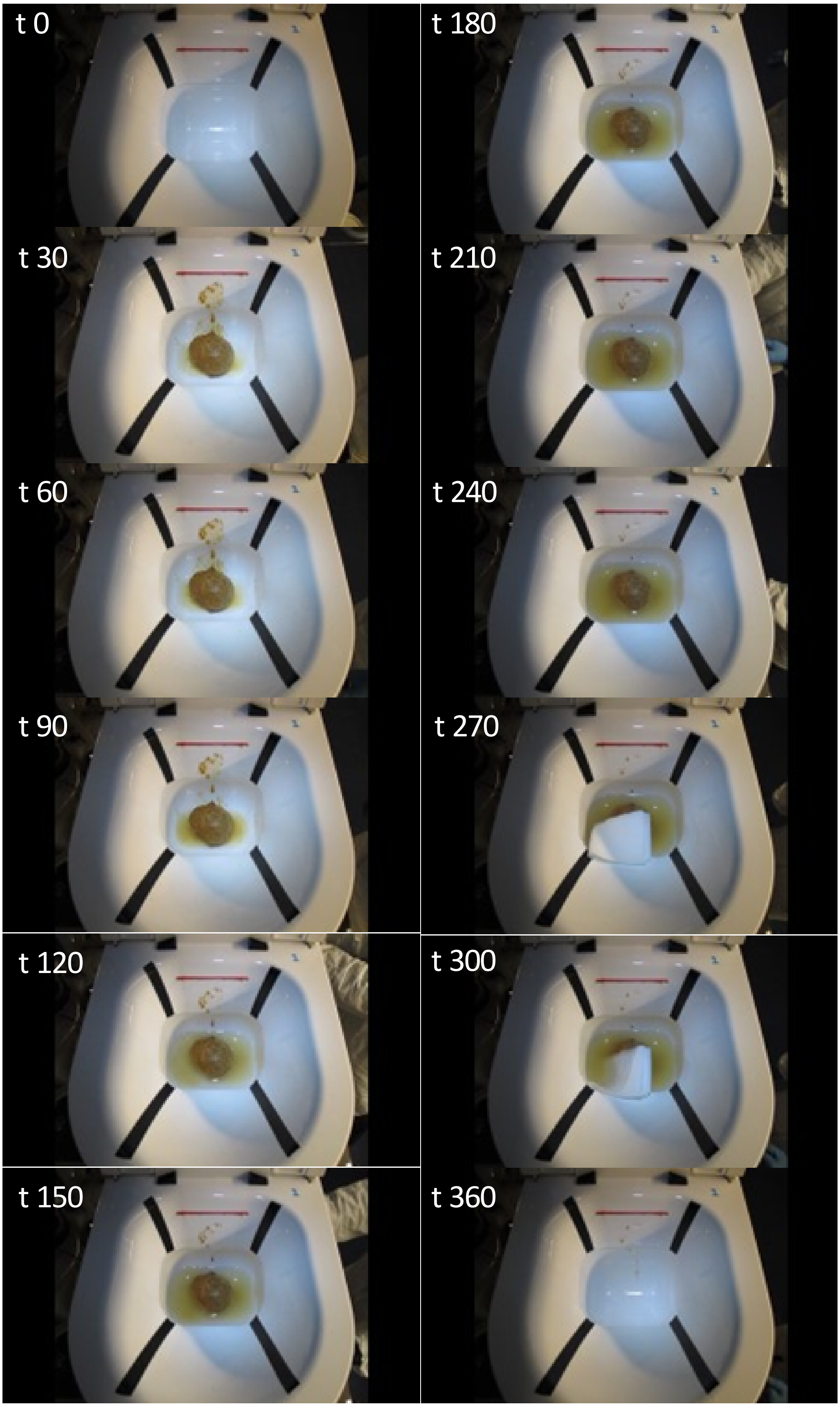


Figure 14 Top View Photographic images of 1st Stage Evacuation Test 2 (t in seconds)

Test 3:

Pan Water Deposition Method: Cascading

Pan Water Deposition Volume per Shot: 63.5mL

Total Cleaning Water Used: 733.85 mL

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	63.50		0		0		0		0	
60	63.50		0		0		0		0	
90	63.50		0		0		0		0	
120	63.50		0		0		0		0	
150	63.50		0		0		0		0	
180	63.50		0		0		0		0	
210	63.50		0		0		0		0	
240	63.50		0		0		0		0	
270	63.50		0		0		0		0	
300	63.50		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	635.00		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, stubborn solids on bowl, sides of bowl not cleaned.

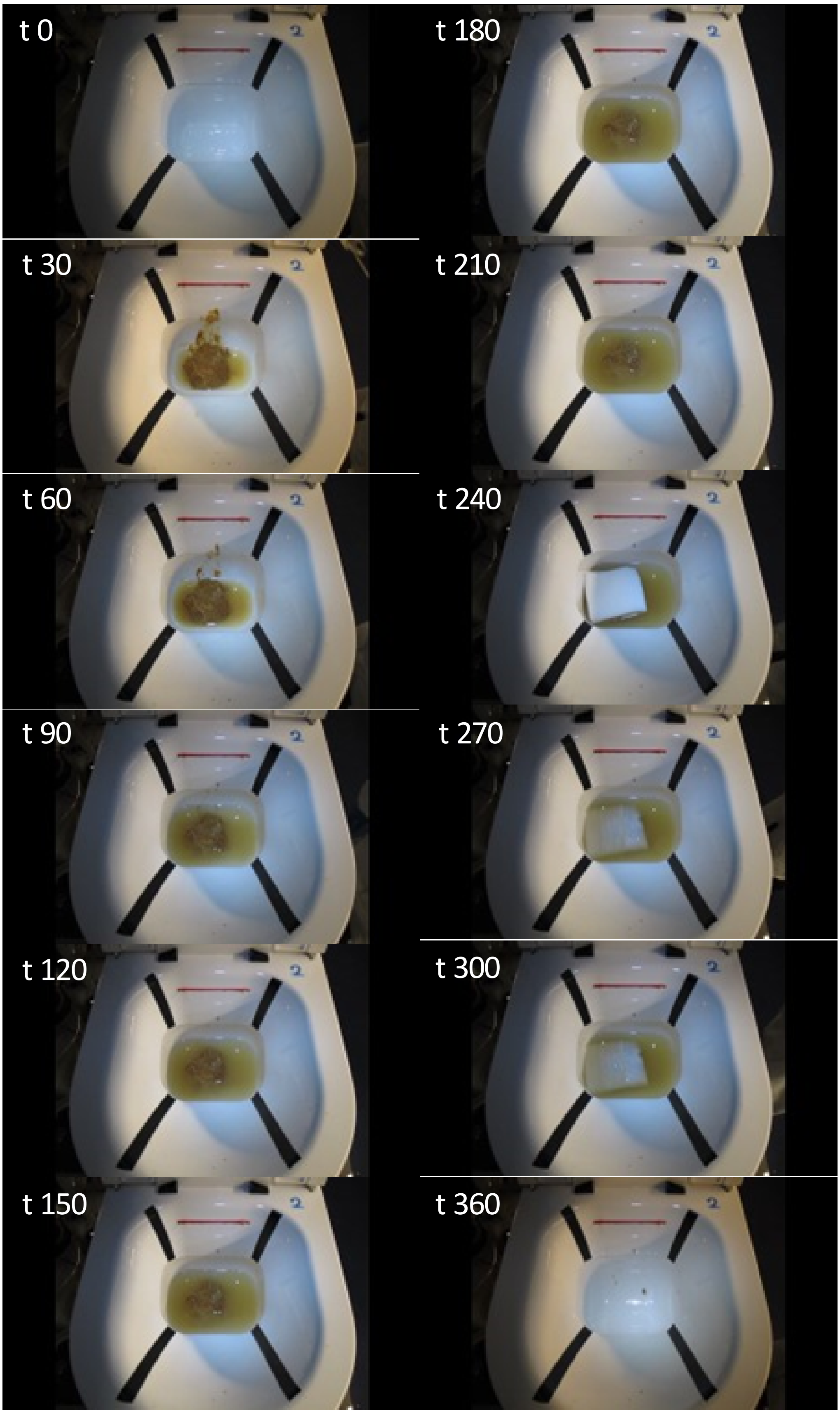


Figure 15 Top View Photographic images of 1st Stage Evacuation Test 3 (t in seconds)

Test 4:

Pan Water Deposition Method: Cascading

Pan Water Deposition Volume per Shot: 63.5mL

Total Cleaning Water Used: 733.85 mL

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	63.50		0		0		0		0	
60	63.50		0		0		0		0	
90	63.50		0		0		0		0	
120	63.50		0		0		0		0	
150	63.50		0		0		0		0	
180	63.50		0		0		0		0	
210	63.50		0		0		0		0	
240	63.50		0		0		0		0	
270	63.50		0		0		0		0	
300	63.50		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	635.00		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, splashing on and out of the pan, solid chunk clinging on edge of bowl

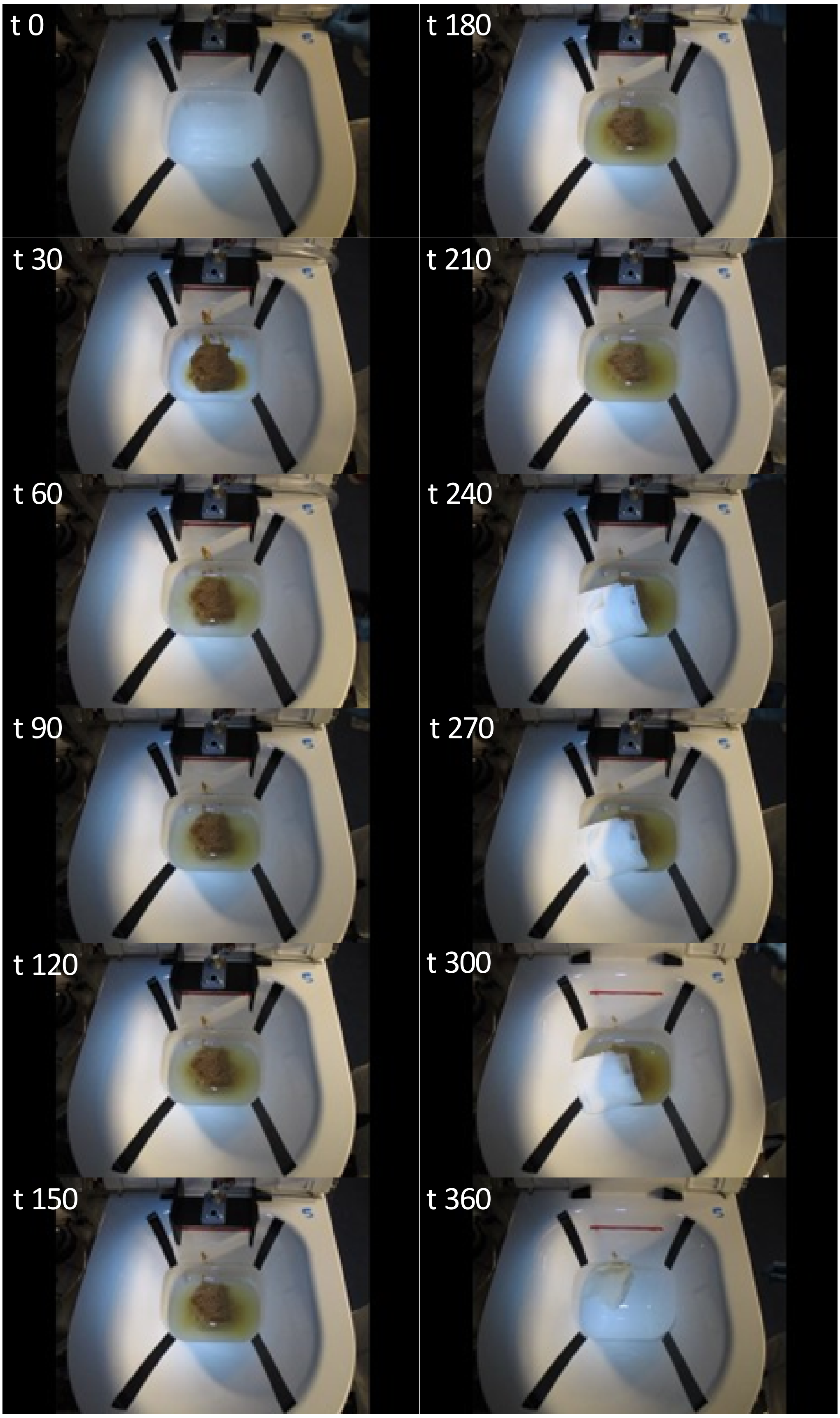


Figure 16 Top View Photographic images of 1st Stage Evacuation Test 4 (t in seconds)

Test 5:

Pan Water Deposition Method: Spraying

Pan Water Deposition Volume per Shot: 19.77mL

Total Cleaning Water Used: 296.55 mL

	Back Region		Left Region		Right Region		Front Region		Mid Region	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	19.77		0		0		0		0	
60	19.77		0		0		0		0	
90	19.77		0		0		0		0	
120	19.77		0		0		0		0	
150	19.77		0		0		0		0	
180	19.77		0		0		0		0	
210	19.77		0		0		0		0	
240	19.77		0		0		0		0	
270	19.77		0		0		0		0	
300	19.77		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	197.70		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, toilet paper not dropping down, solid chunk clinging on edge of bowl

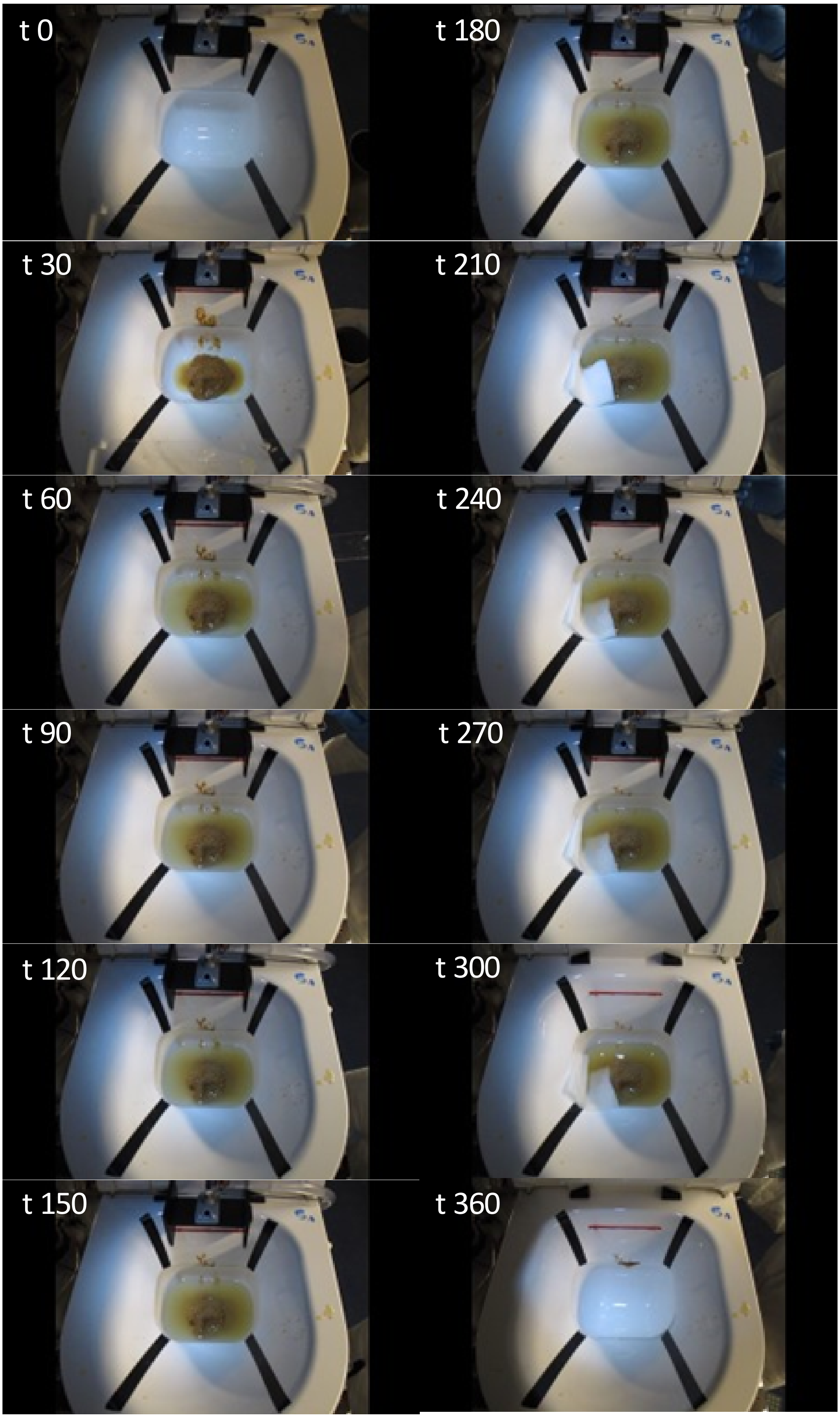


Figure 17 Top View Photographic images of 1st Stage Evacuation Test 5 (t in seconds)

Test 6:

Pan Water Deposition Method: Spraying

Pan Water Deposition Volume per Shot: 19.77mL

Total Cleaning Water Used: 296.55 mL

	Back Region		Left Region		Right Region		Front Region		Mid Region	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	19.77		0		0		0		0	
60	19.77		0		0		0		0	
90	19.77		0		0		0		0	
120	19.77		0		0		0		0	
150	19.77		0		0		0		0	
180	19.77		0		0		0		0	
210	19.77		0		0		0		0	
240	19.77		0		0		0		0	
270	19.77		0		0		0		0	
300	19.77		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	197.70		0		0		0		98.85	

Issues Observed: Remaining solid bits on back region, splashing on and out of pan, solid chunk clinging on edge of bowl, toilet paper jamming bowl motion

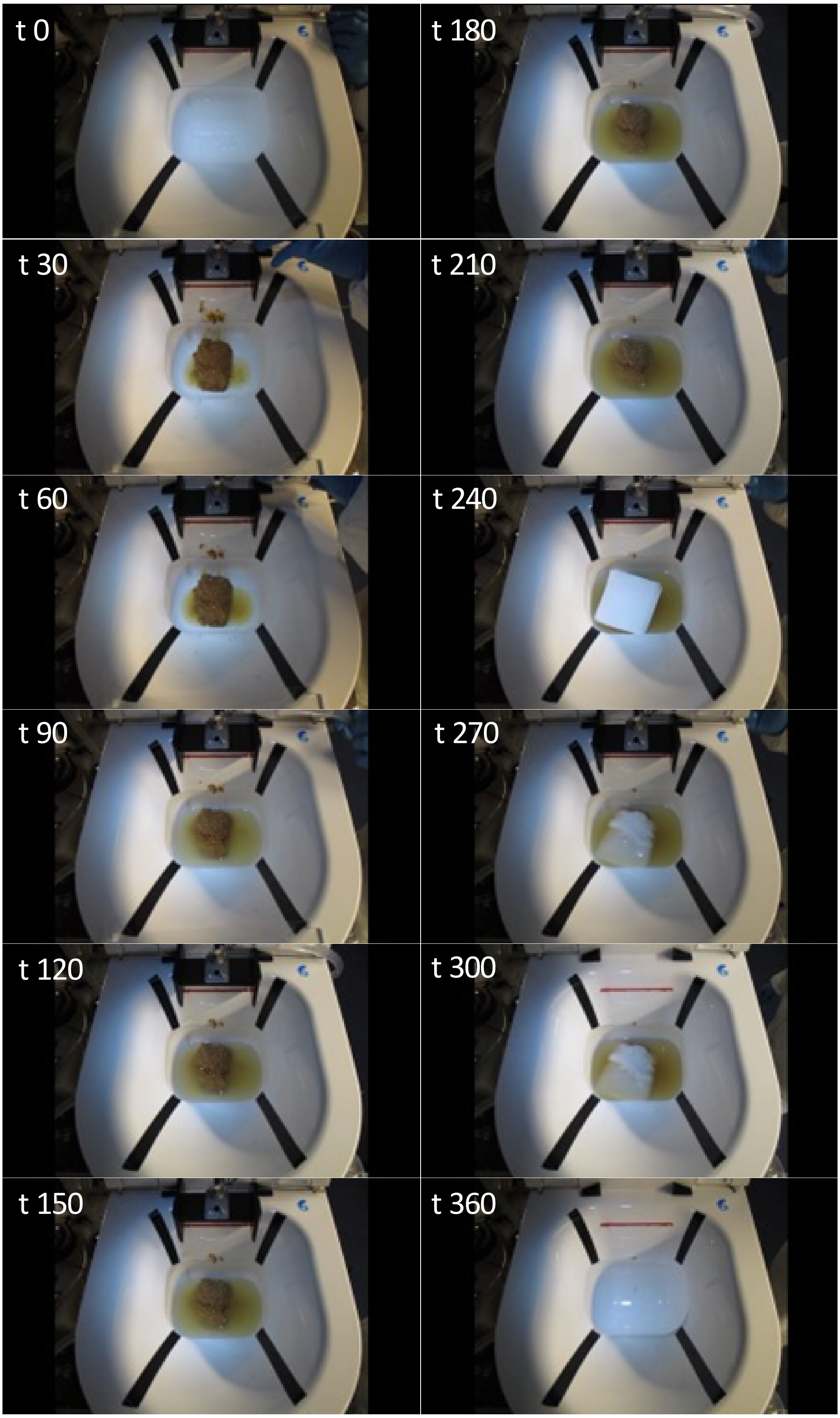


Figure 18 Top View Photographic images of 1st Stage Evacuation Test 6 (t in seconds)

Test 7:

Pan Water Deposition Method: Spraying

Pan Water Deposition Volume per Shot: 29.66mL

Total Cleaning Water Used: 395.45 mL

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	29.66		0		0		0		0	
60	29.66		0		0		0		0	
90	29.66		0		0		0		0	
120	29.66		0		0		0		0	
150	29.66		0		0		0		0	
180	29.66		0		0		0		0	
210	29.66		0		0		0		0	
240	29.66		0		0		0		0	
270	29.66		0		0		0		0	
300	29.66		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	296.60		0		0		0		98.85	

Issues Observed: Small solid bits remained in back region and bowl

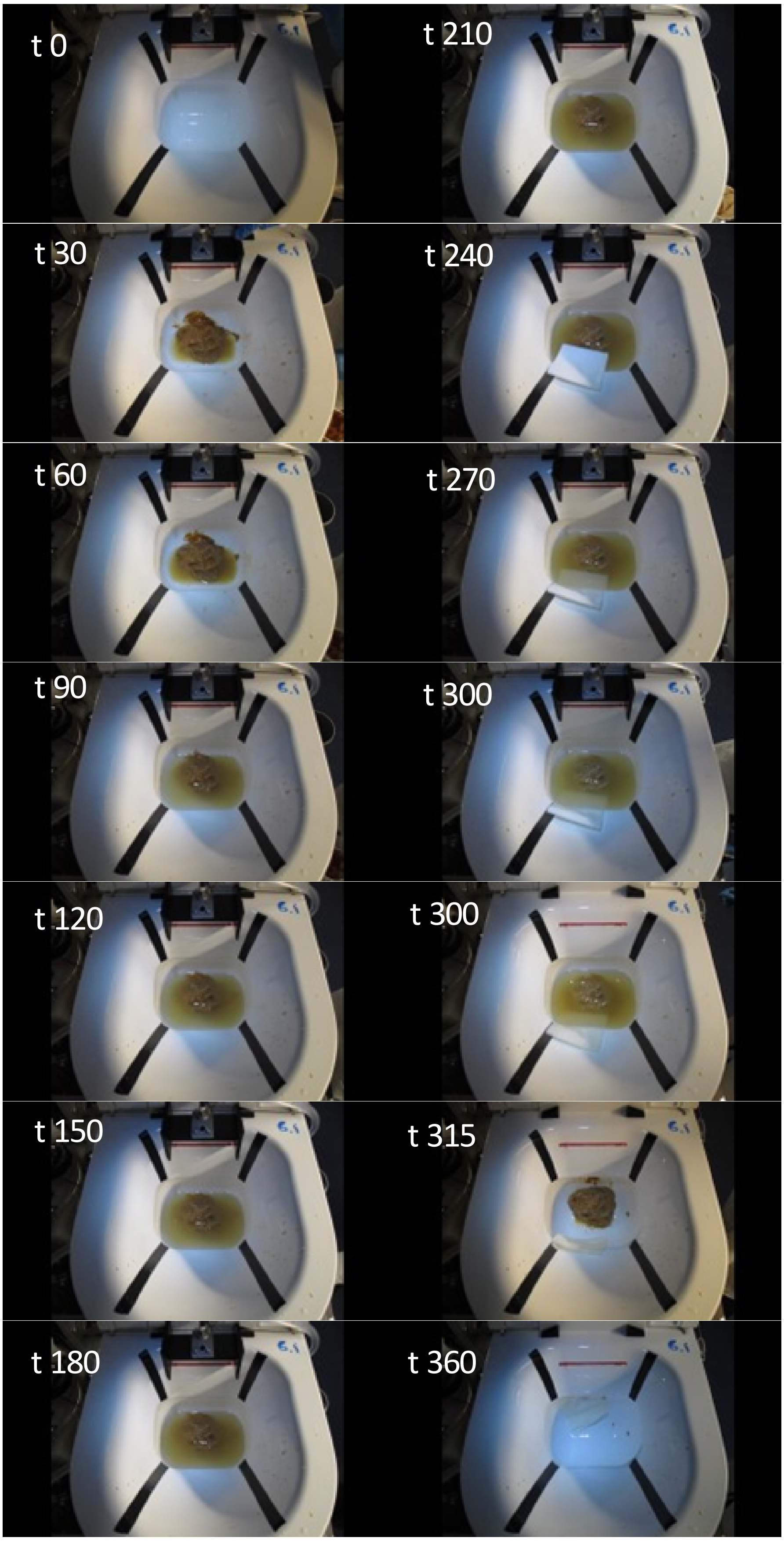


Figure 19 *Top View Photographic images of 1st Stage Evacuation Test 7 (t in seconds)*

Test 8:

Pan Water Deposition Method: Spraying

Pan Water Deposition Volume per Shot: 29.66mL

Total Cleaning Water Used: 395.45 mL

	Back Region		**Left Region**		**Right Region**		**Front Region**		**Mid Region**	
Time (sec)	Dep Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade	Dep. Vol. (mL)	Clean. Grade
0	0		0		0		0		0	
30	29.66		0		0		0		0	
60	29.66		0		0		0		0	
90	29.66		0		0		0		0	
120	29.66		0		0		0		0	
150	29.66		0		0		0		0	
180	29.66		0		0		0		0	
210	29.66		0		0		0		0	
240	29.66		0		0		0		0	
270	29.66		0		0		0		0	
300	29.66		0		0		0		0	
315	0		0		0		0		19.77	
330	0		0		0		0		19.77	
345	0		0		0		0		59.31	
360	0		0		0		0		0	
TOTAL	296.60		0		0		0		98.85	

Issues Observed: Splashing on and out of pan, toilet paper curtaining in front of spray nozzle, solid not falling to collection tank, solid chunk clinging on edge of bowl.

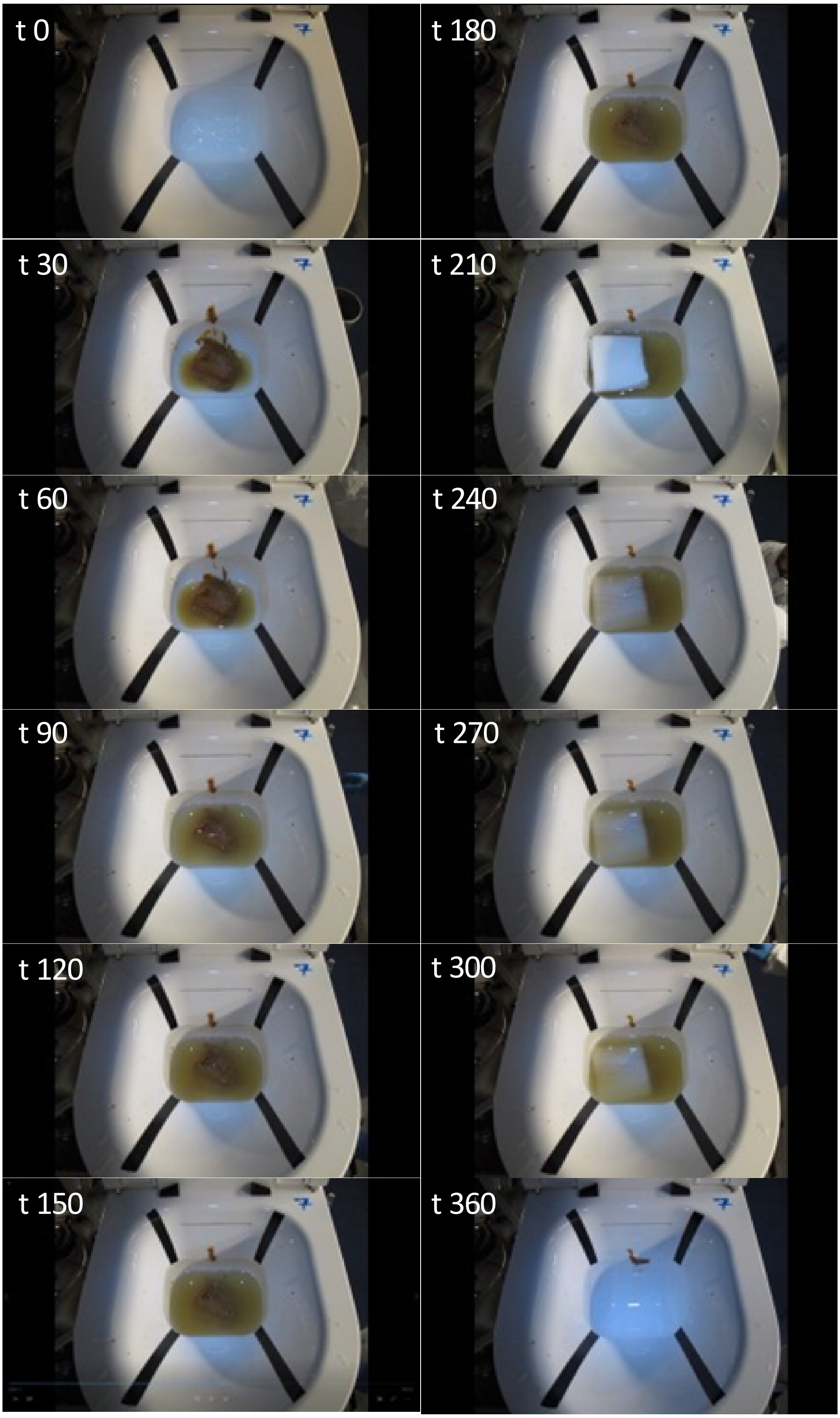


Figure 20 Top View Photographic images of 1st Stage Evacuation Test 8 (t in seconds)

4.1.2. Outcomes Interpretation

Although waste was able to transfer to the collection tank in these tests, multiple issues were observed where the 1st stage evacuation process had produced unpredictable and inconsistent outcomes that affect the hygiene of the surface, toilet and surrounding, and it was not possible to draw any concrete trends in behaviour from the system to build upon. The module therefore cannot yet be concluded as ready for optimisation testing using real faeces.

In terms of surface cleaning water consumption, there was a challenge in obtaining shot volumes consistently from the cascading function, in contrast to that from the spraying function where it was more reliable. The photos of the interface show that deposited water does attack the soiling area and gradually washes the soiling. In all tests where the back region was soiled, small bits of solids remain at the end of the test, that become harder and harder to remove.

Because of that, it is not yet clear on what would be the optimal amount of water for cleaning the pan and bowl, or whether an increased output water pressure will enhance cleaning. Although further testing using larger volumes could benefit determining the average flushing volume, a number of modifications to the design need to be completed to ensure successful performance in the long term, as will be presented in the Discussions.

From the above also, it is not yet possible to determine the required power consumption to achieve interface surface cleaning as conclusive from these tests, as the powered devices, their operation times and duty cycles, could all be subject to change with improvements, until desired cleaning performance is reached.

4.1.3. Observed Issues in 1st stage evacuation

The following issues were observed, which were all pertaining to points related to geometric designs, pressure of flush water, and the need for handling toilet paper:

Toilet splashing after large defecations: In some trials when the miso was dropped on the pan and bowl, splashing occurs that extends beyond the toilet boundaries.

Decreasing pan water cleaning performance: The efficacy of pan cleaning through water deposition, whether via cascading or spraying methods, decreases over the course of 1st stage evacuation. Most of the soiling gets washed away, with some remaining in the mid-bottom on the pan's skirt.

Jamming bowl movement by toilet paper: Toilet paper that falls close or onto the contact areas between the bowl and pan, would cause in some instances to jam the bowl movement.

Wet toilet paper laying flat on surfaces: In some instances, toilet paper would get wet and lay flat on both the bowl thus becoming difficult to remove by spraying unless the water pressure is increased.

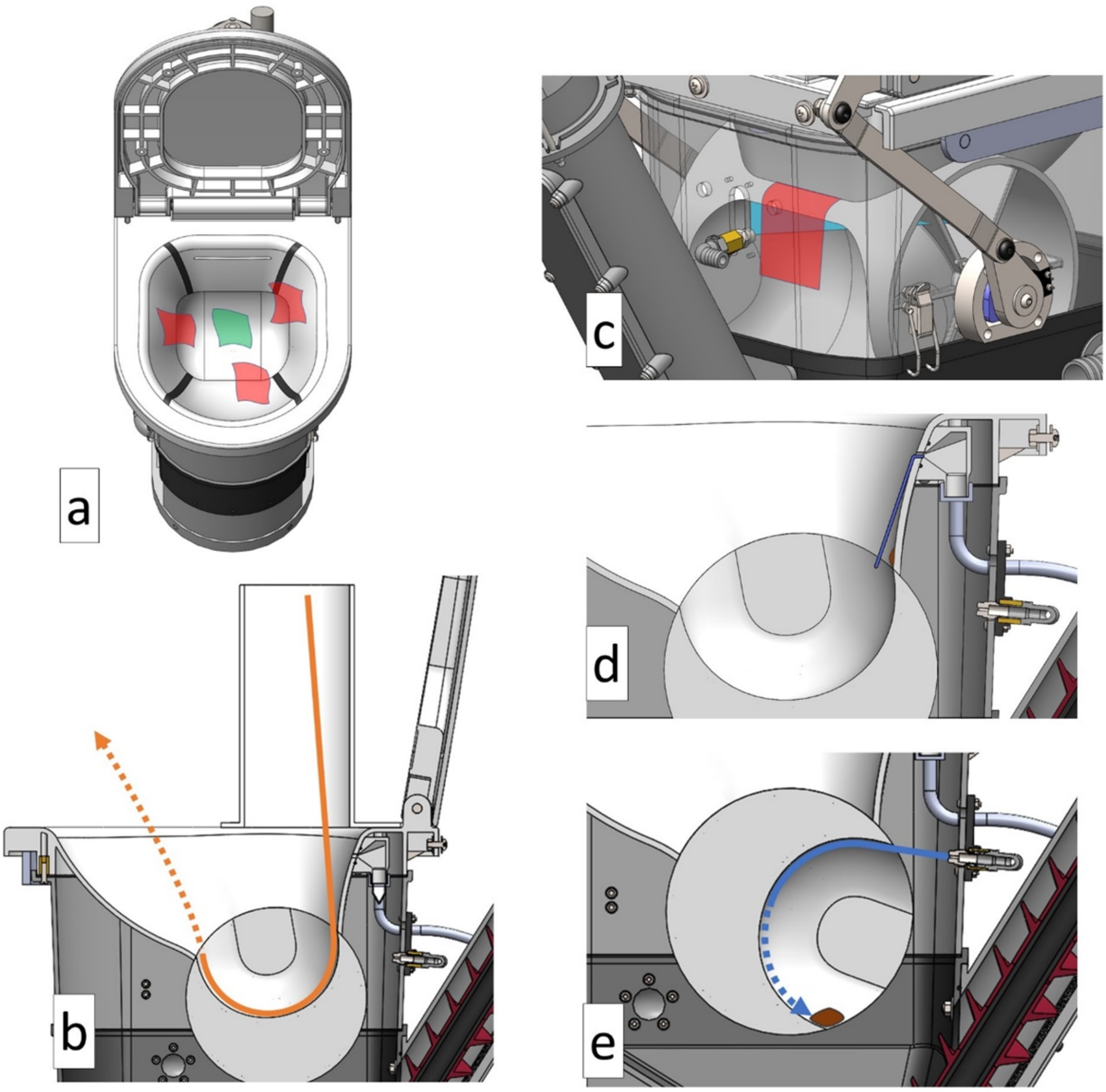
Bowl spray cleaning blocked: In other instances, toilet paper would cling onto the bowl's edge during closing and creates a curtaining barrier in front of the bowl spray nozzle, leaving the bowl's surface uncleaned from usage.

Stubborn solids sticking on the bowl: The solids in some instances would remain adherent to the bowl's surface, which sometimes causes it to not fall to the collection tank when rotated to the fully-closed position, or to slide away slowly, leaving a small bit of solids that get caught on the edge of the bowl.

Recapture of solids from the collection tank: It was suspected in some instances that the bowl recaptured some of the solids deposited in the collection tank when it rotates to the fully-open position, as some solids were observed on the bowl's edge.

Bowl drum staining from the collection tank interior: When the toilet lid is closed, the drum's cylindrical face points upwards. It was observed after testing, however, that stains are apparent on this face which leads to an unpleasant sighting.

Bowl Movement not satisfactory: The cams introduced on the bowl's shafts were observed to deter the bowl from reaching its end position when the lid is fully open, where there was a distance between the bowl's edge and pan's skirt that required manual intervention to achieve alignment. Moreover, the bowl was not yet reaching towards the pan's skirt to fully close the gap between the two parts.



Reasons for Issues – 1st Stage evacuation: a) toilet paper not flushing to centre of bowl, b) no rim provided to prevent over-splashing, c) toilet paper adhering to surface, d)water rinsing trajectory not covering surface, e) insufficient spray pressure.

Figure 21 Reasons for issues observed in 1st stage evacuation

4.2. 2nd Stage Evacuation Testing

One test was completed on the 2nd stage evacuation process, following the steps described in section 3.5.2.

4.2.1. Outcomes interpretation and observed issues

At the beginning of the test trial, there was high success in liquids absorption by the diaphragm pump, and limited success in the solids transfer up the screw. Upon adding more consumables sets, those success rates then dropped to limited and no success, respectively. As the auger screw rotated, it tended to carry whatever solids that landed on it, but also pushed some the solids around on either one of its sides whenever there was space available. More time was given well beyond the allotted test trial time of 30 minutes, but no progress was observed.

When the solids in the collection tank were then manually pushed towards the auger screw, a significant improvement was observed, where the rate of waste capture and transfer has increased. Moreover, the recording showed that suction of liquids during the process allowed the solids to get closer to the collection tank's floor and to the auger screw if it were floating above it. This demonstrates that sedimentation of liquids with the solids in the tank is no longer required, as was suggested from the Literature, and that evacuation of solids and liquids can be done more quickly when each matter is extracted in its separate path.

Despite the above, however, some liquid was no longer passing into the liquids extraction aperture, and some volume was remaining stationary in the tank. There are a number of reasons for this:

- The accumulation of small solids behind the perforated sheet was likely creating partial sedimentation, and blocking any liquids from passing through into the pump. The brushing action of the auger screw against the perforated sheet during rotation, to clean the sheet from any accumulating solids, did not prove to be successful, as a gap of nearly 1mm was remaining between the two parts.
- The height of the liquid suction aperture from the bottom of the tank, was leaving a volume of at least 0.5L that is unreachable by the diaphragm pump, and thus will remain in the tank unless manually removed.

- The accumulation of solids on the tank's floor and are not captured by the screw could temporarily lead to splitting the liquid into more than one volume, which could also become unreachable by the pump.

If the above is left unchanged, this would lead to a partial sedimentation of solids in the liquids volume, which will make the capture of those solids by the screw more difficult, and this could lead to an increasing rate of contamination in the tank interior.

In terms of the toilet paper in the collection tank, it was observed that it took time for the auger screw to capture and convey the paper, as the screw helix has a smooth profile that runs on the toilet paper's face and not capture it. As a result, this paper stands as a temporary barrier between the screw at the bottom and dropping solids from the top, thus delaying the transfer process, and potentially causing the solids content in the tank to exceed the holding limit where it could reach up to the bowl.

This suggests that improvements can be made to the 2nd stage evacuation, from which performance can then be optimized as planned, as will be presented in the Discussions. Until then, performance measurements of the test completed cannot be utilised for comparison with future test findings and are considered invalid.

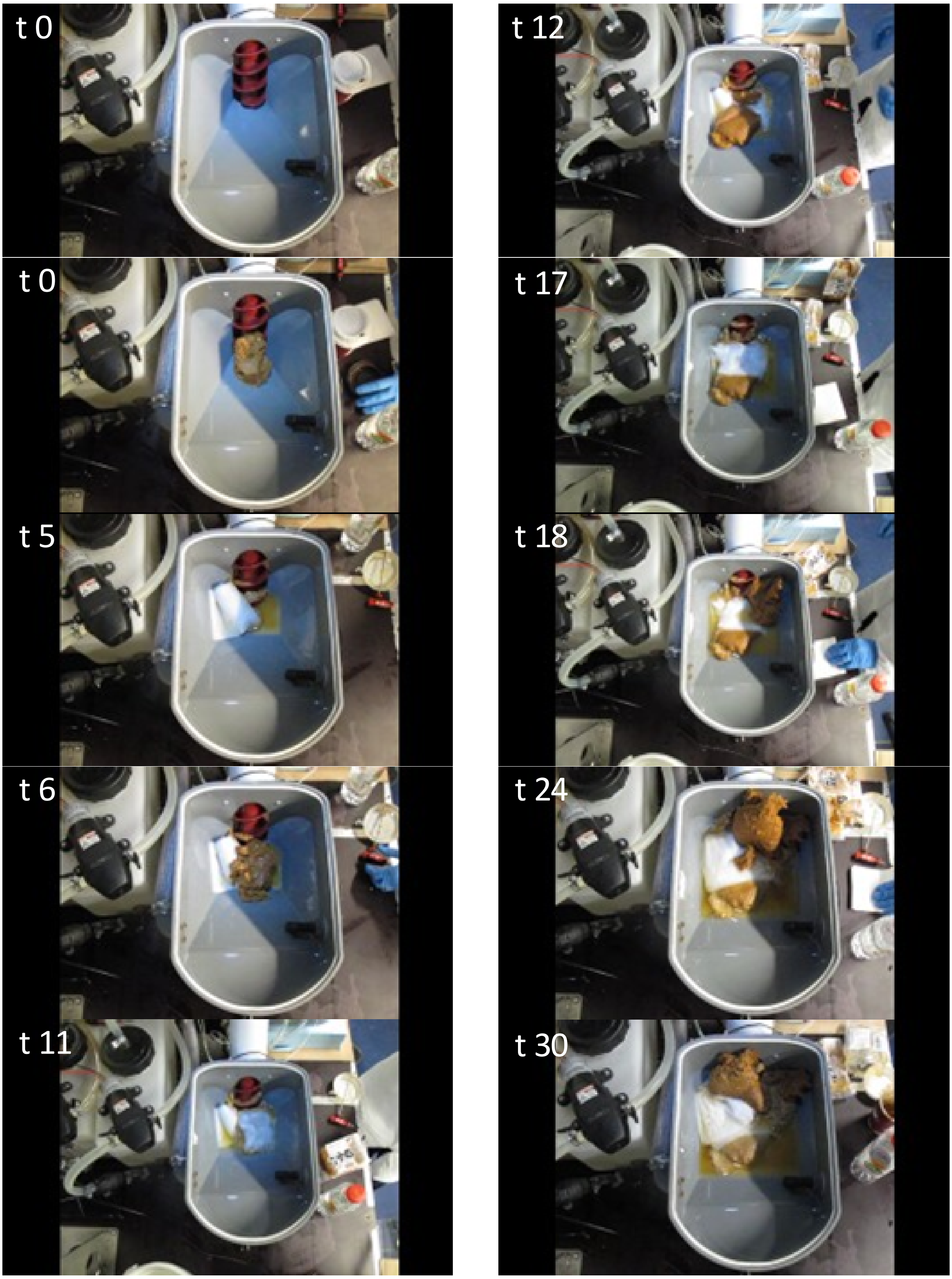


Figure 22 Top View Photographic images of 2nd Stage Evacuation Test (t in minutes)

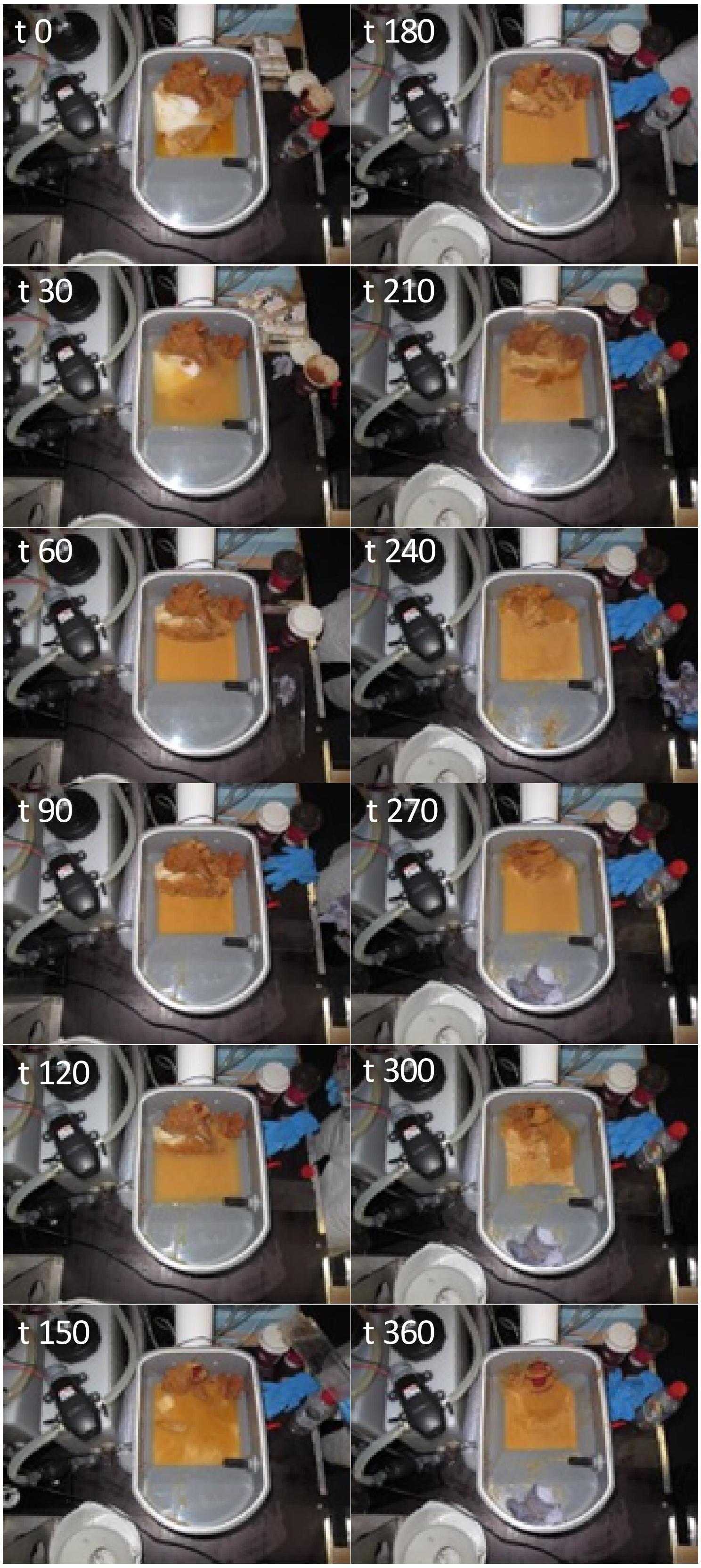
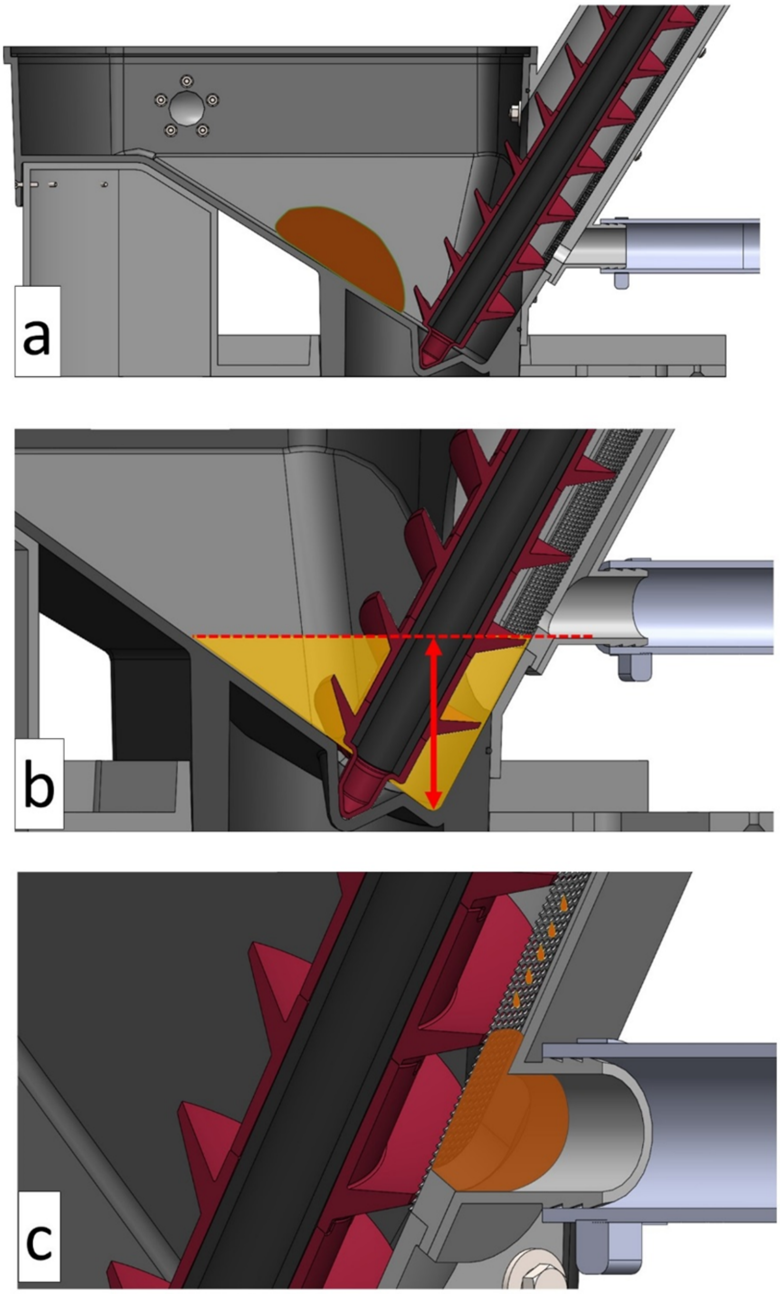


Figure 23 Top View Photographic images of 2nd Stage Evacuation Test after manual intervention (t in minutes)



Reasons for Issues – 2nd Stage Evacuation: a) collection tank slopes not steep enough to push solids towards auger screw, b) liquids aperture too high to absorb all liquids, c) no pushing action available to remove solids accumulating behind the mesh.

Figure 24 Reasons for issues observed in 2nd stage evacuation

5. DISCUSSION

The tests conducted on the two stages of evacuation presented the possibility to achieve waste movement across consequent parts of the user-interfacing module, with some design features showing more success than others, suggesting a range of enhancements for future prototypes. However, the tests in total were fewer than intended, due to vital observations that became apparent early in the process as described in the Results. A number of undesired outcomes were recurring during those tests, which would lead to inconvenient sensations during normal usage and require attention for future improvement. This section investigates the issues observed with possible reasons presented for their occurrences and how they may be mitigated or eliminated.

5.1. Discussion on 1st Stage Evacuation

5.1.1. Observations on pan water deposition methods

Of the two followed water deposition methods, the spraying approach was found to be more promising than cascading to remove soiling off the impact area.

Similarities between cascading and spraying methods:

- the amounts of water used in ejections are within similar ranges, as presented in the Methods.
- the count and variety of components used to make each subsystem are nearly the same.

Advantages of spraying over cascading method:

- More control on the volume of water ejected in the spraying method was achieved during the test trials than in the cascading one. This is likely due to the pump's operation at 100% duty cycle in spraying -versus 30% duty cycle in cascading- thus operating in nominal settings that bring the pump close to its utmost efficiency, and overcome constraints from variables such as the length of plumbing and head lift to raise water from the purified water storage tank to the pan.

- Cavities in the cascading water design, such as the holding canister and slot on the pan, make potential regions for fouling, microbial growth, or even a potential target for aiming urine or faeces upon misuse of the toilet, inadvertently or otherwise. These areas are difficult to access and clean without disassembly or use of special tools, as was experienced in the laboratory works. These issues are less likely to occur in the spraying method design, which can help avoid these potential health hazards.
- Pressurised water was observed to bring better surface cleaning performance over the cascading, potentially bringing better repellence of microbial growth on surfaces.

5.1.2. Explanations on observed issues in 1st stage evacuation

Toilet splashing after large defecations: The undesired splashing that reaches out of the pan and beyond the toilet is likely due to the proximity of the bowl's bottom surface, currently at 235mm from the top face of the seat. Unlike in traditional toilets where the dropped faeces would normally continue falling to the bottom of the S-bend (which could reach almost to the floor level depending on the toilet make model, the landing of the faeces on the bowl's surface from such height increases the chances for splashing to go outwards. In addition, the pan does not have a rim like in traditional toilets, which could deter some of the splashing, to promote easier cleaning. Both these design points were intended to promote easier post-cleaning of the toilet by the user, which seem otherwise to raise other issues in the process.

Decreasing pan water cleaning performance: It is believed that the surface geometry of the pan's back face plays a role in altering the deposited water's streaming trajectory, due to being a convex profile, thus driving the water flow away from the middle and above the surface, thus making it difficult to clean the remaining bits of soiling in the mid-bottom. If the back face were of a straight or concave profile, this problem would have less chances of occurring.

Jamming bowl movement by toilet paper: This issue presents an interesting design challenge in moving components, where part of the toilet paper lies flat on the pan's surface instead of falling in full inside the bowl. The cam mechanism that delivers the bowl's oscillating motion creates a gap where the toilet paper could fall into, thus causing the bowl to jam, urging for this odour-blockage feature to be revised. Otherwise, the toilet paper's overreach to the pan's regions is due to the lack of means that push waste to the centre of the bowl, such as more water spray nozzles.

Wet toilet paper laying flat on surfaces: The issue of stubborn toilet paper was assessed to be a matter of insufficient spraying pressure from the pump, where the spray water seems not to have enough push-force that covers all areas and remove adherent paper.

Bowl spray cleaning blocked: Similar to the above, where toilet paper curtains in front of the spray nozzle, the lack of means to push it to the centre of the bowl has lead to this jamming problem, as well as the low pressure on the pump that could not overcome the toilet paper's adhesion.

Stubborn solids sticking on the bowl: This also presents another design challenge, where it was previously solved using the rotating swipe in earlier versions, but currently, given the water spray's trajectory on the bowl's concave surface, this last bit becomes difficult to reach and remove due to the water's travel distance required. The likelihood herein is that, like in previous points, the pump's pressure is insufficient to make the pressurized water reach to the entire bowl.

Recapture of solids from the collection tank: This observation may likely do with the solid's landing on the auger screw instead of falling to the bottom of the collection tank, making it in proximity to the bowl and increasing the chances of recapture. This point requires further investigation to be confirmed, and to recommend a solution for the same accordingly.

Bowl drum staining from the collection tank interior: This issue is likely due to the splashing that occurs inside the collection tank when waste is dropped, with this face being exposed inside the tank, and has no fending or wiping solution to prevent soiling.

Bowl Movement not satisfactory: Due to the test rig's current installation inside an LEV, where air ventilation was always switched on, testing on odour blockage was not possible and is not within this research test scope. That said, the above issues could lead to a failure in odour blockage until an improved mechanism for bowl vertical oscillation is developed.

5.2. Aspired performance of 2nd Stage Evacuation

It is possible to enhance the geometries and features of the 2nd stage evacuation to achieve more streamlined waste transfer, where the collection tank can be emptied much faster before the next user sits on the toilet. This would be a desirable performance feature that minimizes the solids' exposure inside the tank, thus minimising the chances of odour diffusion and potential cross-contamination.

Given that the diaphragm pump was able to absorb the liquids inside the collection tank in as little as 10 seconds, this raises the question as of why not optimise the solids transfer rate to a similar time frame.

Currently, the auger screw has 14 screw helix flights, each with a carrying capacity of 100ml. As the screw rotates at 5RPM, this gives it a maximum solids transfer rate of 500ml/min. Given that the approximate density of human faeces at a Bristol Stool Scale of 3-4 is 1g/ml (Rose, 2015) that maximum transfer rate translates to 500g/min. As 4 of these screws are exposed inside the collection tank, in an ideal situation, where faeces from one average defecation (plus toilet paper) perfectly lands on the entire exposed screw, liquids are all extracted through the liquids aperture, and all other surrounding environmental factors are ignored, solids waste transfer out of the collection tank's interior after each toilet visit should herein be completed in no more than 1 minute.

The above hypothetical could be achieved with a series of modifications, as it was evident from the laboratorial recordings that part of the solids that landed on top of the auger screw were then getting conveyed up its flights, whereas the solids that laid next to the screw or away from it in the tank's interior was sitting in place idly by, thus the manual intervention.

5.3. Connecting with the Literature:

This research referred mainly to the previous literature on the Cranfield sanitation system project, given the unique design and intended functions of the current user-interfacing module in waste evacuation and interfacing surface self-cleaning. Given the project's high pace, there was significant pressure to produce the prototype very early in the project for the university's team and the external industrial partners, and it was not possible under the time constraint to attend to and assess all aspects from previous design iterations. The next two subsections present connections of the issues observed in the tests with the literature.

5.3.1. Dated designs of the pan and bowl:

The 2014 study (Tierney, 2014) acknowledged the complication of designing the bowl with a mechanical swipe, where the intersection between the two gave the bowl its crescent-shaped cross-section. It was not possible to reduce the crescent thickness any further to utilise the unused volume and increase the bowl's carrying capacity, and instead the bowl itself had to be enlarged in diameter (at 190mm) and elongated in length (at 180mm) in order to reach the 1.15 litre carrying capacity. This resulted in a part that is larger than necessary, which needed to be distanced from the bottom of the collection tank, thus pushing it, and the adjacent interfacing surfaces, closer towards the sitting user, and so contributing to the over-splashing problem.

Moreover, because the swipe needed to pass across the entire bowl's concave surface, the bowl cannot rotate to a fully downward direction. This resulted in some urine to remain in the bowl that was not pushed by the swipe when closing the lid, as reported from field tests by Hennigs et al. (2019) as well as solids that would cliff-hang on the bowl's edge as found in this research's tests.

Lastly, the pan surfaces, being all convex as they approach to the bowl in the centre, were not optimised for water rinsing, as using water was not previously considered in the flushing process.

These design aspects were carried onwards into later prototypes. Despite currently removing the swipe, other design aspects in this area were not revised, and thus the aforementioned disadvantages were still realised.

5.3.2. Suboptimal interior of the collection tank:

In the study of Mercer et al. (2016) the holding chamber was made as a steep-angled cone at a height of 50cm, upper and lower inlets with diameters of 35cm and 7cm respectively, giving a downward slope angle with the horizontal of 74 degrees. Such steep angle is a likely contributing factor to drive the waste downward toward the screw. However, this was not discussed nor expanded on in the study, for it has investigated various auger screw designs but used only one holding chamber, thus missing out an opportunity on taking measurements to find any trends in that area. Other likely reasons that prevented investigating that area was the fact that the waste mixture had to travel through a choke between the collection tank and the foot of the auger screw, and that the waste had to be treated beforehand, as described in the literature, to allow for its conveyance through the choke and up the screw. The design information on the collection tank's interior geometries was not carried onward into later prototypes, resulting in collection tanks with less steep wall angles, which were then repeated in this prototype.

5.4. Proposed design changes:

There were several lessons learned from the designing, implementation, and testing in this project, which prompted producing a CAD model of a new and improved version of the user-interfacing module. Almost every part of this module that is related to the scope of this research was revisited, with changes made in terms of both geometries and features, in aim to streamline the performance and manufacturing process wherever possible. Figures 25, 26, and 27 present the proposed CAD model that was created by the researcher, and is further described in appendix-B.

The proposed improved model aims to bring the following potential advantages over the current built version:

- Improved interfacing surface geometries for more effective rinsing and are deeper away from the sitting user for a better sitting sensation that minimizes over-splashing during usage.
- Water rinsing that covers a larger interfacing area to further push waste and toilet paper towards the bowl.
- Better bowl cleaning performance via larger rotation angle for dropping waste, as well as several cleaning options (closely targeting spray nozzles, motor-driven small swipe … etc.) enabled by the new structural architecture.
- Smaller, more insulated collection hopper as part of the auger screw tube that replaces the currently larger collection tank, with steep wall angles to drive the waste towards the auger screw, intended for evacuating waste after each toilet visit.
- More equipped auger screw to capture and quickly transfer all waste, continuously clear the liquids aperture mesh, and avert jamming on hard objects when entering the screw tube.
- Smaller liquids aperture brought to the lowest point in the auger screw tube and directly connected to the evacuation pump, aimed to capture all liquids and push any solids that accumulate behind the mesh.
- Reduced overall part count and sizes where applicable, and easier assembly steps, while maintaining current desirable user-centric features.

It should be noted that the proposed model might require more volumes of water for pan and bowl rinsing, given the increased number of spray nozzles. However, this must be validated via laboratorial testing. Moreover, as development is ongoing on the liquids treatment process to improve its efficiency, it is aspired to achieve a daily production rate of purified water that is reciprocate to the average volume needed for a single day’s use by a household of 5 people, once determined from laboratorial testing on the proposed model.

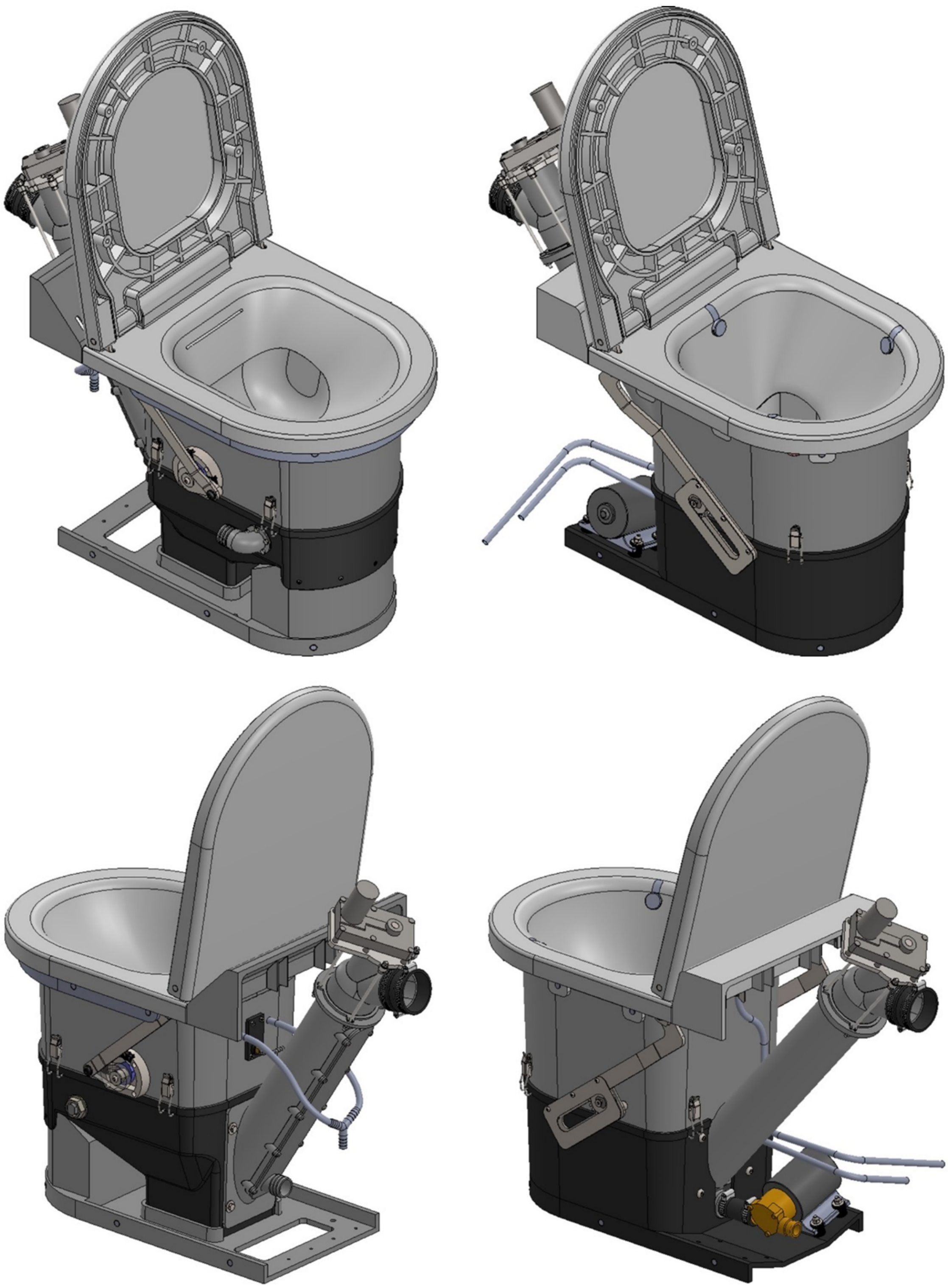
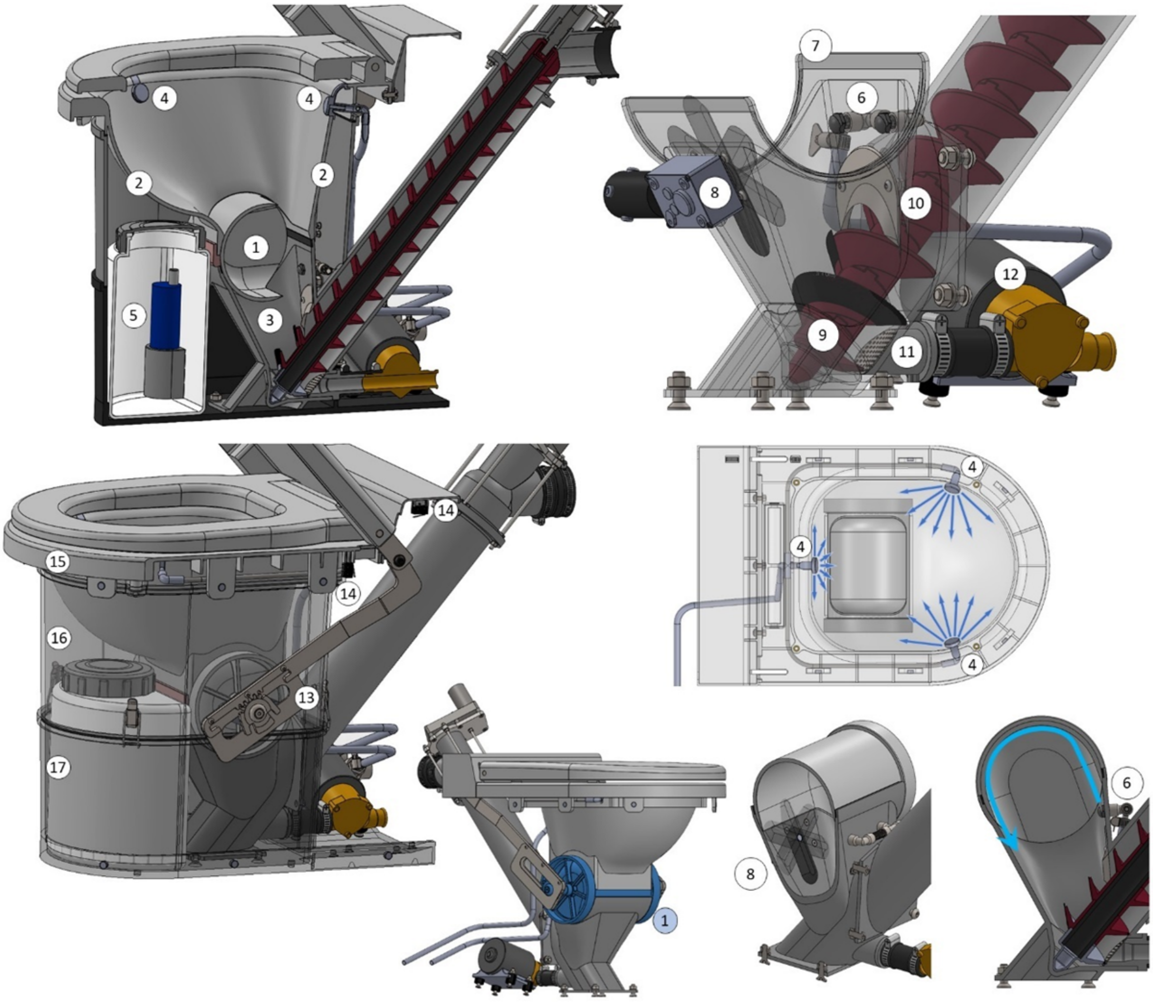


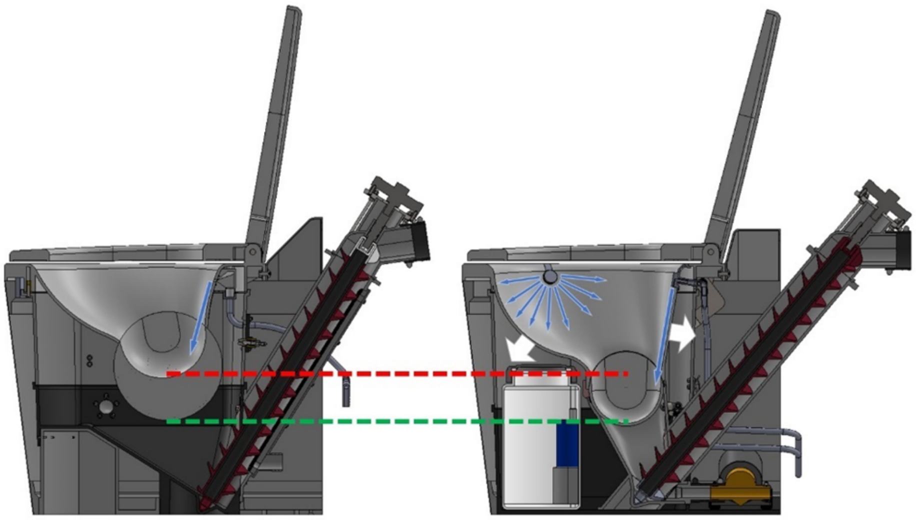
Figure 25 Isometric views of CAD models of current version (left) and proposed version (right)



Main Areas of Improvement:

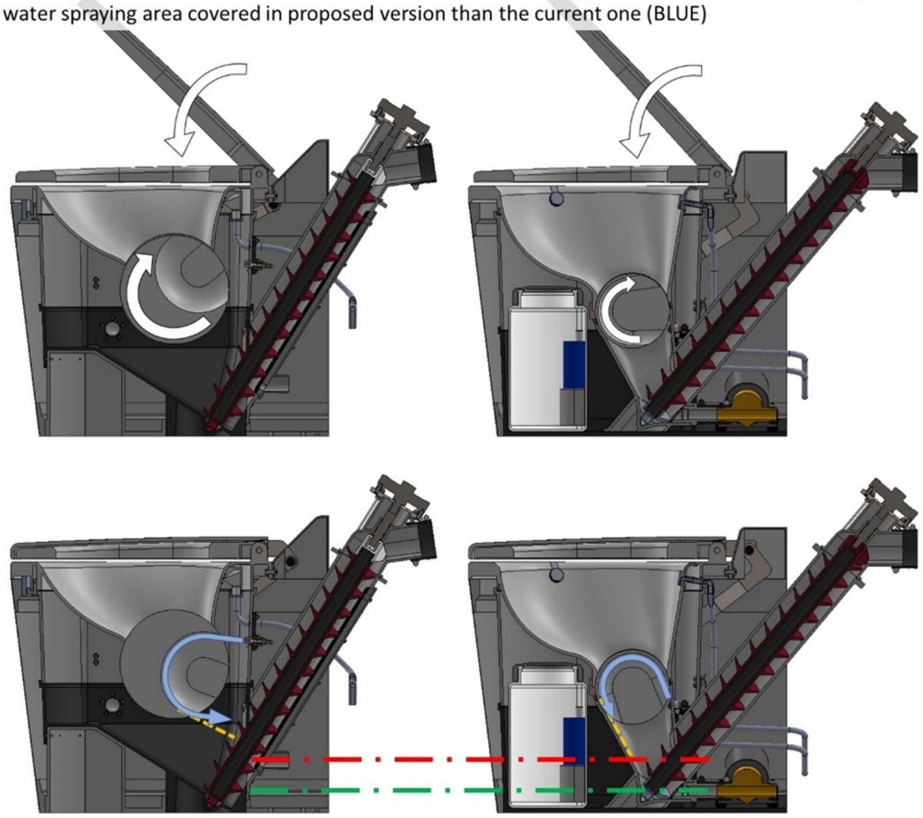
1. Smaller, lowered rotary bowl, and secured in position between pan and collection hopper
2. Deeper pan surfaces to improve water rinsing and distance dropped waste from sitting user
3. Improved auger screw tube including small collection hopper as a reduced and more insulated waste holding chamber, with steep wall angles to better drive solid waste towards the auger screw
4. Three snap-in spray nozzles for further pan surface coverage, concentrating waste to the bowl
5. Auxiliary 5L water tank with pump - for anal hygiene – in newly created space in the module (optional feature)
6. Two spray nozzles (industrial or commercial types) brought closer to the bowl for more effective rinsing
7. EPDM felt with all-round contact with the bowl, for complete odour blockage and cylindrical surface wiping
8. Rotary swipe –motor driven- for further bowl surface cleaning (optional feature)
9. Auger screw equipped with bristles for brushing liquids port mesh and more effective pulling of toilet paper
10. Blade at the auger screw tube inlet for slicing toilet paper to prevent jamming
11. Liquids aperture reduced and moved to lowest point in the auger screw tube
12. Compact evacuation pump positioned closest to the liquids aperture in the user-interfacing module's volume
13. Customised rack-pinion linkage mechanism to assure complete bowl rotation between seat lid end positions
14. More securely located limit switches to indicate the seat lid end positions
15. Improved pan geometric features for assembling with the external cover panel and mid section
16. Improved mid-section geometries for assembly and manufacturability
17. Improved base geometries for assembly and manufacturability

Figure 26 Main areas of improvement in proposed user-interfacing module



Arrow indications of main areas of improvement – Lid Open:

1. Deeper pan surface geometries in proposed version (pulling directions in WHITE)
2. Waste landing point on bowl is lowered from the current version (RED) to the proposed one (GREEN) by 8cm
3. More water spraying area covered in proposed version than the current one (BLUE)



Arrow indications of main areas of improvement – Lid Closed:

1. Shorter path of bowl rinsing spray deflection in proposed version in comparison to current one (BLUE)
2. Waste dropping line (AMBER) increased in angle with the horizontal from 20 degrees in current version to 70 degrees in proposed one
3. Liquids aperture in current version (RED) is brought to the lowest point of the screw tube in the proposed one (GREEN)

Figure 27 Main areas of improvement in proposed user-interfacing module, cont.

5.5. Further Recommendations

For the purposes of planning and executing future waste evacuation tests, it is highly recommended to continue using miso paste as a sufficient and safe alternative to human-faeces, as it brings near-matching mechanical and rheological properties consistently, and obviates the need for further research ethics and administrative approvals. Following this route, tests can be carried out as many as needed more safely, flexibly and productively, until the desired performance features are reached, and system robustness is maintained for real-waste and field testing.

In addition, unless optimal flushing water rationalization is achieved in future prototypes, it would be worth investigating the option of superhydrophilic surface coating for the pan and bowl (Zhang, Y., 2019), where the combination of functionalized surface treatment and UV lighting to both actuate sterilize the surface, would bring dual functionality of surface pre-wetting and constant interface hygiene (Maric, 2016).

6. CONCLUSION

This research presented the development of a novel toilet user-interfacing module as part of a comprehensive non-sewered sanitation system, the Cranfield Circular Toilet, which was based on the latest version of the Nano-membrane toilet previously developed at Cranfield University. Given the recent introduction of new human liquid and solid waste treatment modules, the user-interfacing module was revised to accommodate its integration with the rest of the system and bring it closer towards manufacturability and commercialization.

The literature review presented previous research and development efforts on developing Cranfield University's sanitation system, as well as an overview on technologies for water-saving purposes related to this project, setting the direction for industrial works to adopt solutions and features that are practical and cost-effective in the module's structure and functionality.

A new prototype was developed, manufactured and assembled, with the aim to perform complete human waste evacuation, with the intended processing capacity of a daily output from a household of 5 people. While continuing to use the waste transfer mechanisms of a rotating bowl and an auger screw from the nano-membrane toilet concept, the new design had several improvements over previous versions: module was automated by incorporating powered devices, instrumentations and controls, that assist in the mechanical components' functions, the design was further streamlined by reducing its part count, variety and complexity, and purified water produced from the liquids treatment module was utilised for flushing the interfacing surfaces.

Laboratorial tests were carried out on the user-interfacing module, where it was split into two stages of operation: 1st stage evacuation, where the waste is transferred from the interfacing pan and rotating bowl into the collection tank, while the interfacing surfaces perform self-cleaning functions, and 2nd stage evacuation, where the waste is transferred out of the collection tank into the backend modules. The following consumables were used in testing: miso paste and water as replacements to human faeces and urine, and squares of toilet paper.

The module was tested by replicating conditions of heavy, concentrated usage by 5 adults. This was intended to verify its readiness under worst-case scenarios, identify the metrics to obtain the most adequate performance possible, and uncover the limits of the current design, potentially to help further pronounce any such issues that might otherwise go undetected under normal usage conditions.

The module was able to perform its intended functions through the two stages of evacuation. However, this came with a number of limitations across the module's design. Although some evacuation trials were completed successfully within the desired operation boundaries, other trials were not as successful, and required intervention that ranged from repeating automated processes to manually pushing the waste to its destinated location. Moreover, there were observations where sanitation was compromised, mainly in relation to the geometric and feature designs made in the module. As a first prototype of its kind, issues are expected as an outcome in the development process, and those were discussed in detail.

The issues found led to completing fewer test trials than planned. That said, the findings from those tests had brought forward valuable observations and lessons learned to improve the module's design towards reaching its intended performance metrics. As a result, an updated complete CAD model of the user-interfacing module was produced, bringing several geometric design and feature changes to overcome the issues experienced from the laboratorial tests.

With further improvements on geometric designs and operational features, future testing will become possible on more advanced areas in the sanitation system's functions. The presented user-interfacing module has high potential to achieve successful waste evacuation with minimal stress on water and power resources, in aim to become a deployable solution that integrates into a comprehensive non-sewered sanitation system for decentralized human waste treatment.

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APPENDIX-A: Industrial Works and Prototype Development

Industrial Works:

As the industrial aim in this project was to deliver a comprehensive non-sewered sanitation system that is close towards production and commercialization, several improvements were needed on the user-interfacing module prior to producing the prototype. The target herein was to bring automation into the module and augment its existing features' functionalities, streamline the design for manufacturability and assembly, and repurpose the purified water from the liquids treatment module for flushing the interfacing surfaces.

The industrial works that were completed by the researcher towards setting the sanitation system are listed below:

- Concept and build strategy development in the user-interfacing module
- CAD modelling in SolidWorks of all three sanitation system modules
- Complete 2D technical drawings with critical dimensions
- Documentation of complete system assembly instructions
- Building, electrical wiring and looming of the test rig
- Troubleshooting of integrated PCB, controlled by Arduino Micro
- Programming, debugging, and updating the Arduino IDE sketch for controlling the whole sanitation system
- Producing test instructions for all three sanitation system modules
- Installation of built test rig in a lab local-exhaust-ventilation (LEV) cabinet
- Running tests, maintenance, and retrofitting of the test rig in the lab

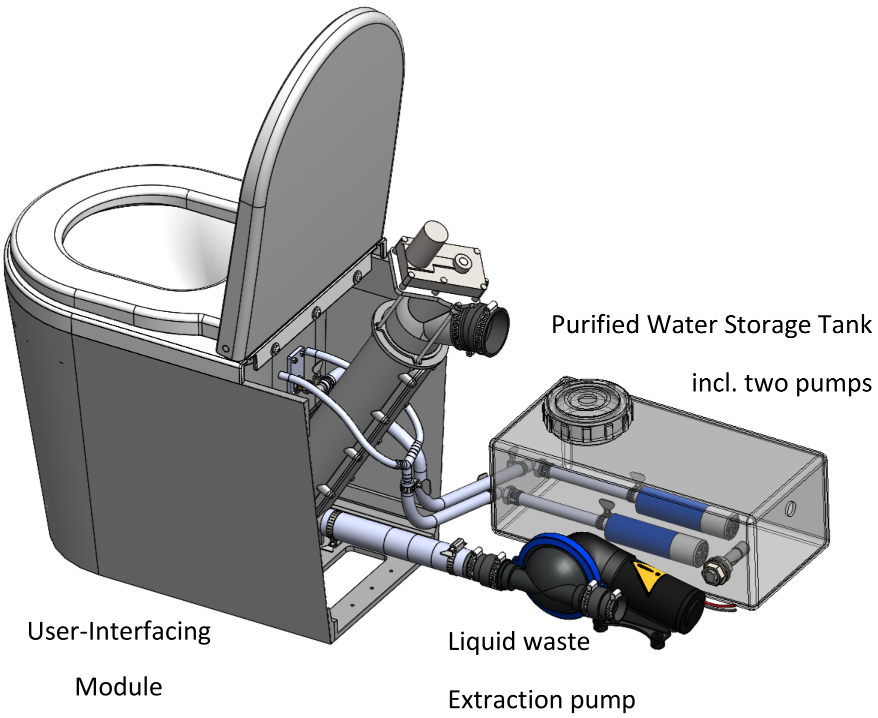

Figure 28 Complete set of components of User-Interfacing Module testing

Design Developments in Prototype:

Several developments were made on the user-interfacing module to achieve the targets previously mentioned, with improvements spanning across the following areas:

Main Body Parts Fabrication:

The structural body of the module was split into stackable parts, designed for quick assembly by the end-user by means of snap-locking the parts into one another. Those were manufactured as follows:

- 3D printing the master parts using EOS P730 selective laser sintering (SLS) machine, using polyamide powder PA2200 (Nylon 12)
- Making silicon moulds from the masters
- Vacuum-casting the final parts from the moulds using resin
- Surface-finishing of the surfaces in contact with liquid and solid waste

Several sets were fabricated in this method beside the one used in the university for testing, in part of making several completed units that were distributed to the industrial partners involved in this project. The 3D printed main stack consists of the following main parts (excluding the waste transfer set) listed from top to bottom: seat, lid, pan, bowl, mid-section, and collection tank. In addition, there is an external cover panel to that assembles to the main stack to disguise the interior using magnets, and a back panel that disguises the space between the main stack and the wall.

Pan Surface cleaning:

A new feature is introduced in the pan's surface cleaning: a water cascading slot, that is 120mm long, was introduced on the pan's back face or impact area, and a dispensing canister is mounted behind it, in aim to wet the surface area underneath it during toilet usage, where faeces is likely to impact and soil that area during defecation. The water is pushed to the holding canister by a pump (LVM Nile Pump LVM118 24V) situated in the purified water tank, which has maximum flow rate of 12.7L/min or 211.7 mL/sec, and maximum pressure of 0.75 bar. The pump's flow rate is adjustable via a set program in the control board, as will be described later.

Bowl Movement:

Previously, the bowl and the swipe were connected to the toilet seat lid via a series of gears and belts to provide synchronized rotational motion for both parts. In aim to reduce complexity in this design iteration, the bowl is now connected using a few linkage bars, that were developed to provide the angular motion required, where bowl rotates a full motion of 120 degrees. In addition, the bowl oscillates vertically during rotation, using a pair of cams situated on its shafts and interfacing with the mid-section. This is intended to reduce friction between the bowl and pan in rotation, while pressing the bowl against the pan at the end positions to achieve odour blockage (This was not yet tested for reasons explained in the Discussions). Finally, the bowl's rotation direction is reversed to deposit the waste in the collection tank towards the auger screw and away from the user, adding further to the evacuation performance and the user's visual appeal.

Bowl surface cleaning:

In continuation to the above, the mechanical swipe had been removed, thus reducing the mechanical complexity it brought. It is replaced by a spray nozzle (Bete Spray Nozzle, 1/8" BSP, NF0690, 303 St/Steel) mounted in a position to sweep across the entire bowl's surface when it is in the fully-closed position. The water is pushed to the spray nozzle by another pump like the one for the pan's cascading, situated in the purified water tank, where it is set to always operate at maximum flow rate. With that, the water nozzle provides high-impact spray angle of 90 degrees, at a flow rate of 19.77 mL/sec (circa. 20mL/sec).

Collection Tank redesign:

The tank's interior geometry was modified to achieve the following: orientate the surfaces to slope towards the auger screw, and maximize the exposure of the screw flights inside the tank. This goes in contrast to the previous design iterations where the screw was exposed to the raw waste through a small aperture at the bottom of the tank, whereby here it is intended to land as much of deposited solid waste as high up the screw flights as possible for quicker waste transfer out of the collection tank.

Waste Transfer redesign:

Previously, the extraction of the waste up the auger screw was done by manipulating negative/positive pressures on the waste mixture as it transitions to a semi-liquid state. This required high rotational speeds and tightening geometries in the screw and its enclosing tube's apertures, which meant high power consumption, loud operation noises, and most of all, high chances of failure in the real-world. In this design iteration, a different approach is taken in aim to achieve waste transfer and phase separation more efficiently, by applying geometric design modifications and new operational features. These are as follows:

- **Solids conveyance:** the auger screw helix's design was changed from its tapered design as in the literature, into one with a constant pitch and base diameter, having larger carrying volume of 1400ml (or 100mL / flight x 14 screw flights). Moreover, the screw is driven by a DC motor that runs at a rotational speed bandwidth much lower than those mentioned in the literature. Here, it is set at 5 RPM. In addition, the solids ejection aperture at the top of the auger screw is now expanded, to facilitate the solids movement out of the screw to the solid waste treatment.
- **Liquids conveyance:** The auger screw tube has an additional aperture for extracting liquid waste located at the bottom, which is connected to a diaphragm pump (Jabsco 50890-1100 Self-priming diaphragm waste pump 24V DC) that

feeds to the liquid treatment module. The pump has a maximum flow rate of 19 L/min.

- **Phase separation:** the auger screw tube includes a channel on its back face that leads to the liquids extraction aperture. The liquids bound to the conveyed solids will flow down this channel and into the lower aperture, thus participating in the solids' partial drying during conveyance. A perforated sheet is mounted on the channel along its length to act as a filter that prevents solids from passing into the liquids extraction aperture. The sheet is in contact with the auger screw, such that the latter will scrape on its face, preventing any accumulation of solids that block its perforations.

Instrumentation and Controls:

The following sensors were introduced for controlling and actuating the functions in the user-interfacing module:

- two limit switches on the cam's interfacing block: for indicating that the toilet seat lid is at a fully open or fully closed position
- a float switch in the collection tank to indicate that the tank is full and needs evacuation, and
- a float switch in the purified water storage tank to indicate the level of purified water in the tank to enable the flushing actions.

Moreover, a controls board was developed for controlling the processes of the entire sanitation system, using Arduino micro at its core to control all events that take place in the system. A simplified description of the controls of the sequence of events in normal operation is presented in the table below:

Name of Function	Condition(s) to Start Function	Condition(s) to Finish Function	Function Outcome
Pan Water Cleaning	Seat fully open AND Pan cleaned = false	- 5 minutes passed OR - Lid closing	Pan cleaned = true
Bowl Water Cleaning	Seat fully closed AND Bowl cleaned = false	- 5 seconds passed OR - Lid opening	Bowl cleaned = true
Collection Tank Evacuation	(Pan cleaned = true AND Bowl cleaned = true) OR Collection tank full = true	- 5 minutes passed AND - Collection tank full = false	Reset Bowl and Pan cleaning states to false

Note that conducting the tests required developing a modified version of the Arduino sketch than that for normal operation, to enable manual control of the devices in the module as per the intended test plans.

Figure 29 Waste Evacuation Steps in User-Interfacing Module

APPENDIX-B Main features of proposed improved user-interfacing module

Smaller, Lower Bowl:

The bowl’s overall dimensions are reduced (outer diameter from the current 190mm to 120mm) while maintaining the same carrying capacity of the current version at 1.1 litres, which allowed positioning it further down in the toilet’s architecture, lowering the bowl’s bottom point further from the seat by 80mm. Moreover, it rotates to a larger angle of 70 degrees with the horizontal (in contrast to 20 degrees with the horizontal in the current version) to match with the wall angle of the screw tube’s hopper in the fully closed position.

This will allow to achieve the following:

- Lower landing contact point of the solids during defecation to lessen chances of over-splashing, thus contributing positively to the sitting sensation.
- More dropping of solids from the bowl in its fully-closed position, and reducing the cliff-hanging effect of solids on the bowl’s edge.
- Smaller part than the current version, thus less expensive to manufacture.

Multiple improvements to the Pan:

- As a result of repositioning and resizing the bowl, the pan’s skirt surfaces are improved. The skirt is straight in the back, and more concave in the front, in aim to obtain more effective pan water rinsing and a reduced proximity to the user for a better sitting sensation (increasing scrotum clearance).
- The pan incorporates 3 water spray nozzles for rinsing, easily installable with snap-in features, where the water spreads from each nozzle as a flat fan spanning up to 180 degrees.
- The magnet holding arch for interfacing with the external panel has become part of the pan as magnet-holding tabs, as means to reduce the manufacturing and assembly cost of an additional part.

More Controlled Bowl Movement

- Secured positioning of the bowl with the pan on its upper side, and with the screw tube's hopper on its lower side using drum-and-lip features on all aforementioned components.
- Improved linkage mechanism: a rack and pinion arrangement is developed, to assure a complete bowl rotation to either end-position, regardless of how far backwards the toilet lid is opened (the bowl's vertical oscillation approach is discontinued.)

Streamlined, multi-purpose Design of the Auger Screw Tube:

- The tube has a solids collection hopper, that interface with the bowl to directly receive the waste, with steep wall angles to drive it towards the auger screw, having an angle of 70 degrees with the horizontal, which is close to that found in the literature by Mercer et al. (2016).
- The evacuation process will occur after each toilet visit, thus allowing to use a small-sized hopper.
- The current collection tank is modified as a base for holding the toilet structure.
- The tube's hopper incorporates two spray nozzles and an optional rotary swipe, turned by a DC motor, for cleaning the bowl when in the fully closed position.
- The tube has an arch-shaped blade that is mounted on the inlet, to allow slicing toilet paper before entering the tube, reducing chances of motor stalling.
- Improved interface with the auger screw's tip to prevent residual liquids.
- Liquids suction aperture is brought to the lowest point in the screw tube and connected directly to the evacuation pump.

Improved Auger Screw Performance:

- The screw will rotate at a higher speed than the current 5RPM (e.g. 20-30 RPM), for quicker solids evacuation, as the design direction is to evacuate waste after each toilet visit
- The first two screw stacks have bristles. As the screw rotates, the bristles can assist in capturing toilet paper, brushing the liquid inlet's mesh and tube interior.
- Detection of jamming in the auger screw tube (e.g. stuck toilet paper between the auger screw and tube inlet). When this happens, the screw can move in a

back-and-forth rocking motion until the hard object is cleared or sliced by the blade in the hopper.

Odour and Bowl Splashing Blockage:

- The screw tube hopper has an EPDM rubber felt that constantly contacts the bowl's cylindrical surface to maintain odour blockage and insulates the hopper as the solids holding chamber, as well as wiping off any stains from splashing inside the auger screw tube hopper on the bowl's cylindrical face.

Instrumentation Improvement:

- The limit switches are mounted more securely on the pan and back cover.
- Incorporation of a hand gesture sensor for rinsing the pan, as many times as needed to concentrate the solids and toilet paper in the bowl
- Utilising water pumps with larger pressure, to help move out stubborn solids and flat toilet paper

Additional hygiene feature:

- An auxiliary water tank of 5 litre capacity is introduced with a submersible pump within, intended to provide water through a hand-held sprayer for anal hygiene. The tank occupies the unused volume of the user-interfacing module for proximity to the users, to easily fill the tank when needed.

A note on the auger screw tube's design that it had to be tilted downward from 60 to 50 degrees and had to be elongated by an additional stack, which is still above the angle range for phase separation as found earlier in the literature.

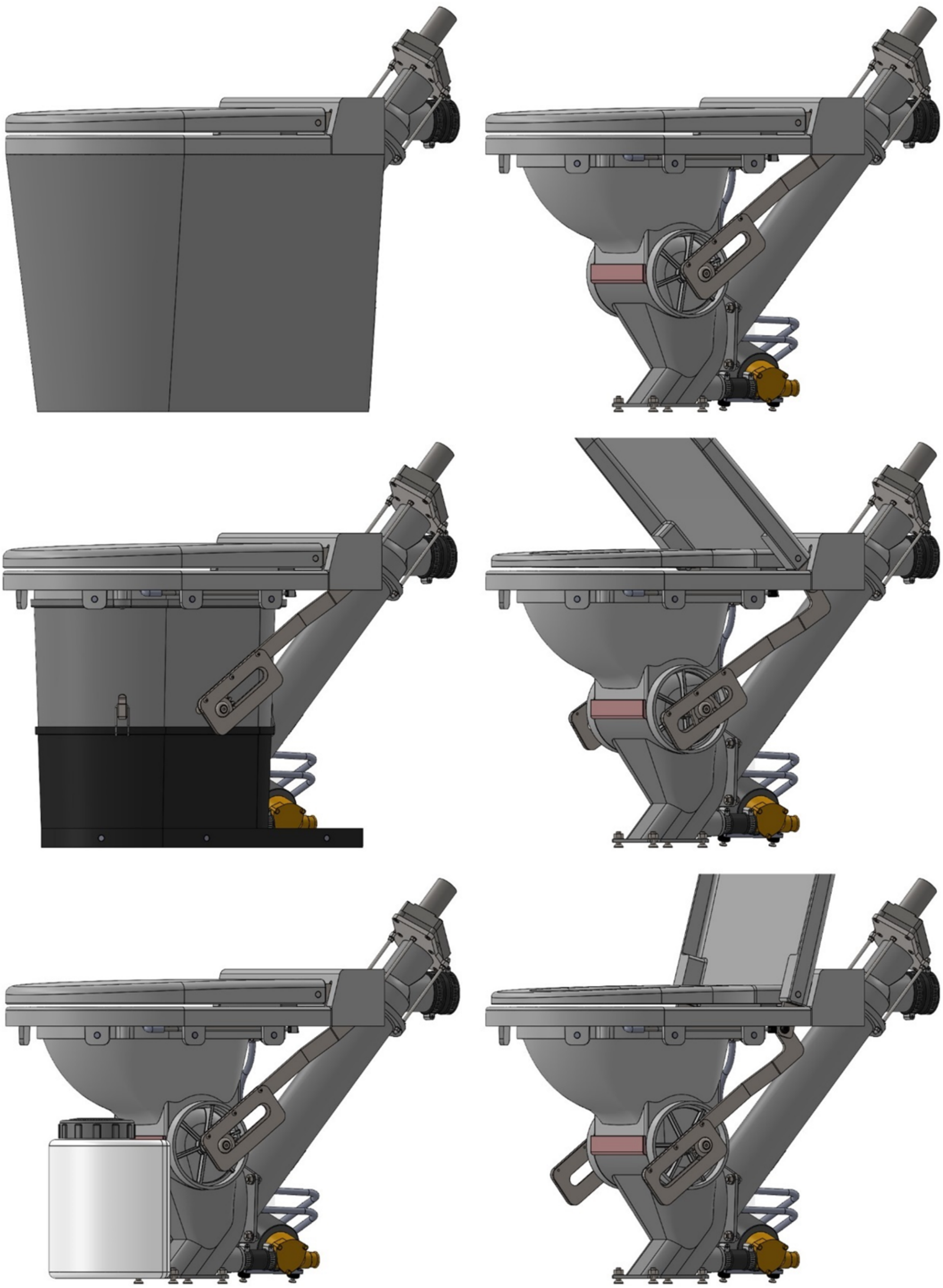

Figure 30 Proposed updated user-interfacing module – views of internal components in motion

Figure 31 Proposed user-interfacing module - lid motion sequence with components on transparent view

Figure 32 Proposed user-interfacing module - lid motion sequence with cross-section view