

ABSTRACT

ROGERS, TATE WESTON. Modification of Power Earth Augers for Pit Latrine Extraction in Developing Countries. (Under the direction of Robert C. Borden).

There are hundreds of thousands of pit latrines in the developing world that require regular emptying to control disease and reduce childhood mortality. Unfortunately, many of these pits are in difficult to access locations (down narrow alleys, inside buildings, hillsides, etc.) and cannot be accessed using currently available equipment (e.g. large vacuum trucks). As a result, many pits are emptied manually exposing the workers and surrounding communities to a broad array of fecal borne pathogens.

Low cost, effective methods are needed to empty waste pits in difficult to access locations. The Extraction Auger was developed to meet this need. The basic design consists of a motor that rotates an auger inside of a pipe, lifting waste from a pit and depositing it in containers through a wye fitting at the top of the mechanism. Laboratory testing of the Extraction Auger with a simulant waste (bentonite clay) shows increases in flow rates with increases in the rotational speed of the auger and the viscosity of the material. During Field-testing of the auger, the mechanical drive gasoline powered engine generated rotational speeds up to 260 rpm with flow rates of over 45 liters per minute (lpm) for a 7% bentonite clay mixture. Using a hydraulic drive system generating 450 rpm, over 125 lpm of dairy waste was lifted over 2.5 m out of a 1-m³ container.

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Modification of Power Earth Augers for Pit Latrine Extraction in Developing Countries

by
Tate Weston Rogers

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APPROVED BY:

Robert C. Borden
Committee Chair

Tarek N. Aziz

Francis De Los Reyes III

DEDICATION

This thesis is dedicated to my mother Shelley, father Dale, and sister Tess for their continued love and support.

BIOGRAPHY

Tate Rogers is a graduate research assistant at North Carolina State University fulfilling the requirements for his MS in Environmental Engineering under the supervision of Dr. Robert C. Borden. He is from Lawsonville, North Carolina. Tate received his BS in Environmental Engineering from North Carolina State University.

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TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	viii
CHAPTER 1	1
1. INTRODUCTION	1
1.1 Global Sanitation Crisis	1
1.2 Extraction Auger Concept.....	4
CHAPTER 2	8
2. PROPOSED EXTRACTION AUGER DESIGN	8
CHAPTER 3	15
3. METHODS	15
3.1 Laboratory Testing.....	15
3.1.1 Simulant Waste	15
3.1.2 Setup	16
3.2 Field-testing	17
3.2.1 Rogers Farm.....	18
3.2.2 NC State Dairy Farm	18
CHAPTER 4	19
4. EXTRACTION AUGER OUTCOMES	19
4.1 Hydraulic Performance	19
4.1.1 Flow Output	19
4.1.2 Jamming.....	20
4.2 Usability of Extraction Auger.....	21
4.2.1 Maneuverability	21
4.2.2 Cleaning	21
4.2.3 Deterioration of Extraction Auger Components	22
4.2.4 Modularity.....	23
CHAPTER 5	24
5. LABORATORY TESTING WITH SIMULANT WASTE.....	24
5.1 Laboratory Testing.....	24
5.1.1 Results from Laboratory Testing	24
CHAPTER 6	30
6. FIELD-TESTING	30
6.1 Initial Field-testing of Mechanical Drive Auger.....	30
6.1.1 Rogers Farm.....	30
6.2 North Carolina State University Dairy Farm	31

CHAPTER 7	34
7. CONCLUSIONS AND RECOMMENDATIONS	35
CHAPTER 8	37
8. REFERENCES	37
APPENDICES.....	40
APPENDIX A – The Global Sanitation Crisis, the Development of Pit Latrine, and the Development of Pit Latrine Emptying Technologies	41
A.1 Introduction.....	41
A.2 The Pit Latrine	43
A.3 Pit Emptying Complications	45
A.4 The Need for New Pit Latrine Emptying Technologies	52
A.5 Current Pit Latrine Emptying Technologies	52
A.5.1 Pit Screw Auger	57
APPENDIX B – Laboratory Testing	61
B.1 Formulation of Simulant Waste	61
B.2 Initial Design Process of Extraction Auger.....	66
APPENDIX C – Field-testing.....	77
C.1 One man 43 cc 2 HP Mechanical Drive Engine.....	77
C.1.1 Description	77
C.1.2 Rogers Farm Testing	78
C.1.3 Dairy Farm Testing	80
C.2 Hydraulic Drive Motor with Gasoline Engine	83
C.2.1 Engine and Hydraulic Motor.....	83
C.2.2 Dairy Farm Testing	83
C.3 Two man 160 cc 5.5 HP Mechanical Drive Engine.....	90
C.3.1 Engine Description.....	90
C.3.2 Dairy Farm Testing	90
C.4 Moisture, Organic, and Inorganic Content of Dairy Farm Waste Procedure.....	94

LIST OF TABLES

Table 6.1	Average flow rates for the exposed 6-inch choke and with a half-trough design for a constant and variable lift height.	32
Table 6.2	Extraction Auger performance on dairy waste for 1/32-inch and 1/8-inch clearances with a 6-inch exposed choke.	33
Table A.1	Human waste characteristics for various countries	48
Table A.2	Characteristics of Current Pit Latrine Technologies	55
Table B.1	Viscosity measurements of bentonite mixtures for varying shear rates	63

LIST OF FIGURES

Figure 1.1	Final Extraction Auger design.....	4
Figure 1.2	Basic screw conveyor variables.....	6
Figure 2.1	Schematic of steel coupling for connecting pipe sections.....	10
Figure 2.2	Section of double helix reverse flights connected to the HDPE single flight auger before the addition of the pipe casing.....	11
Figure 2.3	Hydraulic motor version of Extraction Auger recycling dairy waste from a 1230 L container.....	14
Figure 3.1	Experimental setup of Extraction Auger	16
Figure 5.1	Flow rate vs. auger rotational speed with a 5.1 cm (2 in) choke length for shallow (120 cm lift height) and deep (105 cm lift height) settings for three different bentonite mixtures.	25
Figure 5.2	Flow rate vs. auger rotational speed for 5.1 cm (2 in) and 10.2 cm (4 in) choke lengths in the deep setting (105 cm lift height) for three different bentonite mixtures.....	26
Figure 5.3	Observed flow rates for a 5.1 cm (2 in) choke length and deep setting (105 cm lift height). Theoretical flow rates are based on Roberts (2001) derivation for flow through a screw conveyor for varying material friction coefficients (μ_c).....	28
Figure 6.1	Field-testing the Extraction Auger at the Rogers farm with the 43cc 2 HP engine.	31

Figure 6.2	Dairy waste being recycled into the 1 m ³ container with the Hydrdraulic drive version of the Extraction Auger with a 2.7 m auger length.	34
Figure A.1	Proportion of the population using improved sanitation in 2010.	42
Figure A.2	An example of an improved sanitation facility, the Ventilated Improved Pit latrine and of an unimproved sanitation facility, a hanging latrine.	43
Figure A.3	Manual pit latrine emptying or "scavenging" in Dar es Salaam, Tanzania.	45
Figure A.4	Densely populated community that presents a difficult task for large pit emptying equipment to gain access.	46
Figure A.5	Pit latrine that must be accessed from the side because of a design not compatible with pit emptying.	47
Figure A.6	A "dry" pit latrine and a "wet" latrine found less than one mile apart.	50
Figure A.7	Pit latrine with high solid waste content near Durban, South Africa.	51
Figure A.8	Current pit latrine technologies.	56
Figure A.9	Pit Screw Auger being tested in a pit latrine.	57
Figure A.10	Pros and cons of the Pit Screw Auger design.	59
Figure B.1	Viscosity versus shear rate profiles for the high yield bentonite mixtures used for simulant waste.	61
Figure B.2	7% bentonite clay mixture in a 210 L drum.	66
Figure B.3	Initial prototype of the Extraction Auger.	68
Figure B.4	Initial Extraction Auger schematic.	70
Figure B.5	Bentonite clay mixture being lifted with the Extraction Auger and recycled into a 210 L drum.	72

Figure B.6	Schematic of the inlet of the Extraction Auger with the metal double helix bit..	73
Figure B.7	The head produced at the outlet (port 4) for varying bentonite concentrations at the deep setting (105 cm lift height) and with a 5.1 cm choke length.....	75
Figure B.8	Head produced at each port for the 7% bentonite mixture, deep setting (105 cm lift height), and 10.2 cm choke length.....	76
Figure B.9	Flow rates produced for single versus double helix metal inlet tips at the deep setting (105 cm lift height) with a 10.2 cm choke length.....	76
Figure C.1	10% bentonite mixture being mixed in the simulated pit.....	78
Figure C.2	7% bentonite mixture with the addition of horse manure	79
Figure C.3	The Extraction Auger prototype with the 43cc engine recycling dairy waste from the settling basin after the addition of the section of reverse flights	81
Figure C.4	Schematic of the reverse flights within the wye fitting and the metal double helix reverse flighted section before pipe is attached.....	82
Figure C.5	Hydraulic unit mounting front at multiple views.	84
Figure C.6	Dairy farm setup to simulate emptying from a 1.6 m deep pit.....	85
Figure C.7	Deterioration of a section of pipe after testing with the hydraulic motor in dairy waste.	88
Figure C.8	The inlet of the auger after a piece was snapped off when using the hydraulic motor in the dairy waste..	88
Figure C.9	Gearing and reverse mechanisms for 5.5 HP160cc engine setup.....	92
Figure C.10	Extraction Auger setup with the 5.5 HP 160cc mechanical drive engine.	93

CHAPTER 1

1. INTRODUCTION

1.1 Global Sanitation Crisis

The lack of proper sanitation in the developing world causes an estimated 2.5 billion yearly cases of diarrhea, resulting in the death of over 1.5 million children (WHO and UNICEF 2009). The Millennium Development Goal set in 1990 of halving the global population without access to proper sanitation is projected to fall well short, leaving an estimated 2.6 billion still without as of 2010 (UN 2010).

Pit latrines provide improved sanitation at a relatively low cost. Ventilated improved pit latrines (VIP) and pit latrines with a slab that ensure the hygienic separation of humans from their excreta are considered an improved sanitation source by the World Health Organization (WHO and UNICEF 2008). Pit latrines can have various superstructures and pit designs. Pit volumes vary between 1 and 4-m³ with typical depths of up to 2 m (Still 2002; Mara 1984). The accumulation rates in these pits vary tremendously within the same area and between areas with fill times ranging from 3 to 20 years (Still 2002). The fill rate is dependent upon the drainage, the degradation of the waste, and the addition of rubbish (trash) to the pit. Proper pit maintenance is necessary to extend the life of the pit and decrease the frequency of pit emptying, making the process more affordable and manageable for the users (Still and Foxon 2012b). The Ethekewini municipality in South Africa is able to offer free pit emptying to users every five years (Eales 2005). The makeup of the pit waste is highly

variable between pits and within a specific pit. Every pit latrine has specific characteristics; however, most pits form three layers from top to bottom: floating scum, liquid, and sludge layers. If the pit is “dry” or well drained, then it is typical for only a sludge layer to be present. The consolidated sludge layer is reported to have densities up to 1,750 kg/m³ and behaves more like a soil as it does not readily flow (Hawkins 1982)(Radford 2011). “Dry” pit latrines generally show a trend of decreasing moisture content from the surface of the pit to a 1 m depth and little to no change past that depth (Still and Foxon 2012a).

Pit emptying is a necessary service for the hundered of thosands of pits that are filling annually in the developing world. However, pit emptying is a difficult process for the users and laborers. Typical sewage removal technologies, such as large vacuum tankers, are often prohibitively expensive or incapable of reaching the pits in dense urban slums and difficult rural terrain. In some cases, the pit contents are only accessible through the toilet hole within the superstructure or by drilling holes in the side of the latrine (Still 2002). Up to 20% of the pit contents may be solid waste (trash) in some countries (Still 2002). Large amounts of trash can cause severe operational problems in with many mechanical pit emptying devices. The lack of user capital and access to a proper emptying technology often results in manual excavation of the pit waste. Manual excavation often exposes the laborers and users to pathogens contained within the pit contents including: *Ascaris*, *Giardia*, *Trichuris*, *Cryptosporidium*, and *Taenia*. These pathogens survive for long periods and transmit through the air or contact with a contaminated source (Still and Foxon 2012a). It frequently takes manual excavators longer than a day to empty a single pit and as a result pits are often left uncovered overnight (Still and Foxon 2012a). For these reasons, organizations are exploring

new pit emptying technologies to provide an effective, affordable, and sanitary option for the pit emptying labor force.

Several organizations are developing new mechanisms in an attempt to provide effective and sanitary pit emptying. These technologies fall into three categories: manual, semi-mechanized, and fully mechanized (O’Riordan 2009). Manual pit emptying ranges from only a bucket to elongated shovels and tools used from outside the pit. Most of the existing semi-mechanized technologies are manually powered mechanisms to pump or lift the waste out of the pit. The fully mechanized equipment involves primarily smaller and more maneuverable vacuum pumps compared to the large vacuum trucks. Vacuum tankers are often limited to typical empty depths of only 0.8 m below the ground surface by the available suction power and have difficulty with the dense bottom sludge due to air entering the hose (Still and Foxon 2012a). Excluding the manual pit emptying methods, most of the new technologies have proven effective at removing the liquid and scum layers but have difficulty with the dense sludge layer (Thye et al. 2011; Still and O’Riordan 2012; O’Riordan 2009).

The objective for this research was to develop a mechanism to meet as many of the following criteria for an effective pit emptying technology as possible:

- Portable - easily able to access most any pit latrine location
- Sanitary – provides hygienic protection of the operator
- Effective – quickly removes a wide range of waste
- Affordable – produced with cost effective and easily replaceable materials
- Maneuverability – easily operated by two or less people within the pit
- Modularity – ability to be assembled within a latrine superstructure

1.2 Extraction Auger Concept

The Extraction Auger was developed to provide a user friendly and effective method for pit emptying in the developing world. The basic design models the common screw conveyor or screw pump used in the food processing and wastewater industries. As shown in Figure 1.1, the design consists of a gasoline engine powered hydraulic motor that rotates a screw within a pipe that is fastened to the engine mounting. The bottom of the pipe sits at the bottom of the pit and when rotated it would lift the waste up through the pipe and out through a tee fitting. A fabricated attachment piece holds the pipe rigid, attaches it to the engine mounting, and forces the waste out of the pipe through the wye fitting.

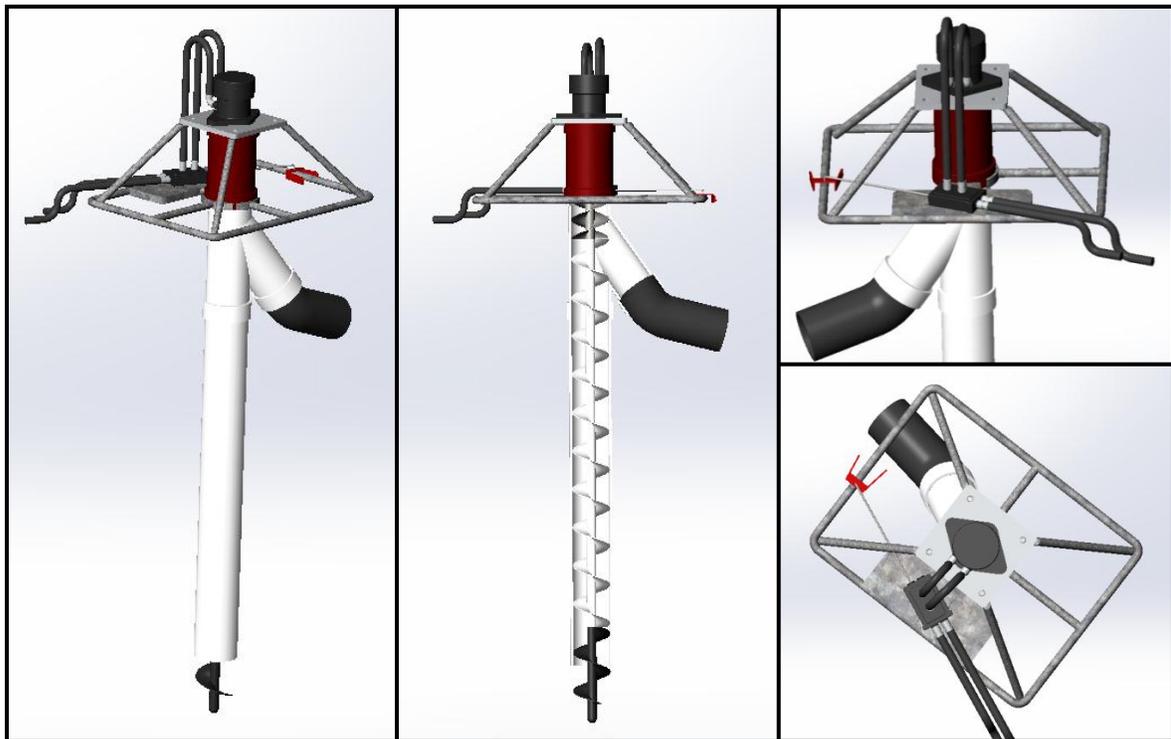


Figure 1.1 Complete final Extraction Auger design (left), auger configuration within the pipe (center), back view of the hydraulic unit (top right), and the overhead view of the hydraulic unit (bottom right) (Gasoline engine not shown).

Roberts (1964, 1999, 2001) described the mechanics of enclosed screw conveyors for moving bulk materials and developed Equation 1.1 to estimate flow through screw conveyor based on the geometry and the rotational speed of the screw. Vortex efficiency (η_{VR}) is the most important parameter in determining flow in Roberts' model. η_{VR} must be positive to generate flow.

$$Q = \Gamma \omega D^3 \eta_v \quad (1.1)$$

Where,

$$\Gamma = \frac{1}{8} \left[\left(1 + 2 \frac{C}{D} \right)^2 - \left(\frac{D_i}{D} \right)^2 \right] \left[\frac{p}{D} - \frac{t_s}{D} \right] \quad (1.2)$$

$$\eta_v = \eta_{VR} \eta_F \quad (1.3)$$

- Q_t maximum theoretical throughput
- η_v volumetric efficiency
- η_{VR} rotational or vortex efficiency
- η_F fullness efficiency
- h_{av} average height of material on the screw surface
- p screw pitch (m)
- D screw diameter (m)
- D_i shaft diameter (m)
- ω angular velocity of screw (rev/s)
- C radial clearance (m)
- t_s thickness of screw blade (m)

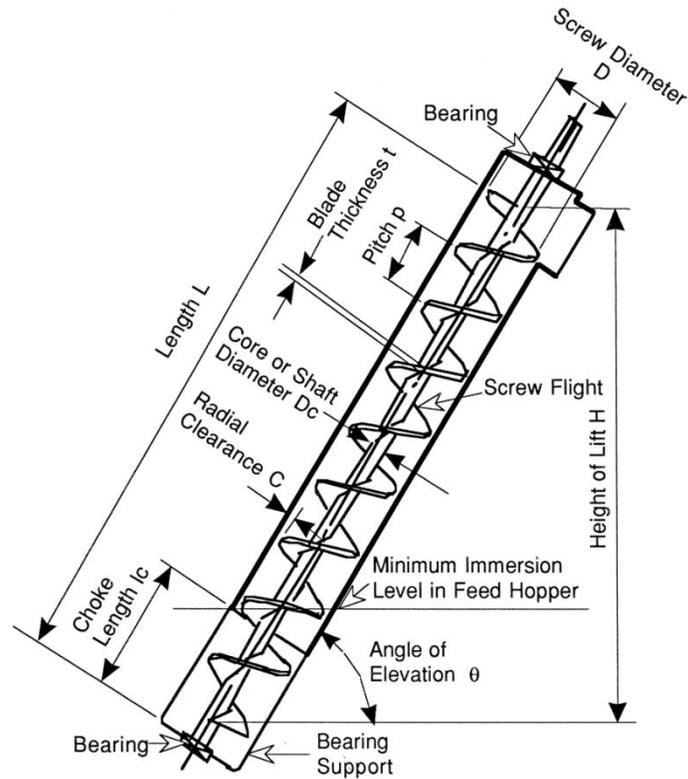


Figure 1.2 Basic screw conveyor variables (Roberts 1999).

3-Dimensional modeling of small particles through screw conveyors at different inclinations have shown the rate of material passed through the screw conveyor decreases with an increase in inclination (Owen and Cleary 2009). Screw pumps used for lifting wastewater are typically set at an inclination between 22 and 40 degrees (Lakeside 2004). This implies that the operation of the Extraction Auger should be with as little inclination as possible, although a vertical orientation will be most common in the field.

The objectives for the development of the Extraction Auger included:

- Demonstrate that the Extraction Auger can lift simulated waste vertically using a typical gasoline powered motor.
- Identify critical variables to improve performance.
- Develop a robust, maneuverable, and user-friendly design that can rapidly and safely empty pits.

CHAPTER 2

2. PROPOSED EXTRACTION AUGER DESIGN

The following performance criteria for the proposed Extraction Auger were developed from reviews of published literature, discussions with field practitioners, and our own laboratory and field tests:

- a) Sanitary – To achieve the overall objectives of improving sanitation in developing countries, the Extraction Auger must improve separation of the operator from the waste. This includes equipment set up, transferring the waste from the pit into the transport containers, transport of the waste to suitable disposal location, equipment cleanup, and removal from the site.
- b) Portable – Pit latrines are often located in very difficult to access locations such as dense slums or steep terrain with little to no road access. Therefore, a pit emptying mechanism should be able to fit down narrow alleys and operate in tight working areas. The transportation and operation of the mechanism should require a maximum of two laborers meaning that the total weight of the mechanism should not exceed 50 kg.
- c) Hydraulic performance – A typical pit holds 1 – 4 m³ of waste. To be cost effective, the Extraction Auger should have an average waste throughput of at least 40 liters per minute (lpm) allowing a typical pit to be emptied in 1-2 hours. Higher flow rates would allow multiple pits to be emptied in one day including setup, cleanup, and transport times. The mechanism should be capable of lifting waste 2-3 m from the bottom of a 1-2 m deep pit and into a 1 m tall transport container. Ideally, a single machine should also be able to

remove a wide range of waste viscosities and densities including liquid at the top of the pit and dense bottom sludge. If possible, the Extraction Auger should be able to handle trash within the pit by either 1) passing it through the mechanism with the waste or 2) rejecting large solids from entering the mechanism. At a minimum, the Extraction Auger should allow easy removal of trash that does enter the auger.

- d) **Maneuverability** – In addition to the mechanism being portable, it should also be easy for the operator to maneuver within the pit. One operator should be able to run the mechanism after it has been placed in the pit while another directs the waste into an appropriate transport container. A mechanism weighing less than 25 kg would provide easy maneuverability and reduced strain on the operator.
- e) **Durability and Simplicity** – A pit emptying mechanism should be robust enough to handle the day-to-day wear experienced in the field. It should also be easy to repair and replace parts in a developing region with limited resources. Simple to understand and operate designs are optimal for easy comprehension of the mechanism by the labor force.
- f) **Modularity** – Many pit latrines do not have access to the pit outside of the superstructure. Rigid mechanisms will be required to be almost 3 m in length to empty a typical pit. Therefore, rigid mechanisms should be capable of assembly within a superstructure while still eliminating contact between the human and the pit contents.

The development of several iterations of the Extraction Auger occurred through trial and error procedures during lab and field-testing. The proposed design described below has shown to meet the majority of the criteria for a proper pit emptying mechanism. Chapter 4 discusses the specific outcomes discovered through the trial and error process.

The most effective version of the Extraction Auger consists of a 4-inch (10.2 cm) extraction screw enclosed in a pipe. Waste sludge is transported up the pipe by the rotating action of the screw and then discharges to a collection container through a downward oriented 45-degree wye fitting. A hydraulic motor powered by a remotely located gasoline engine rotates the screw.

The main body of the Extraction Auger consists of a 4-ft (1.2 m) long straight section of high-density 4-inch (shaved down to 3.75-inch (9.5 cm)) high-density polyethylene (HDPE) auger flights mounted on a 1-inch (2.5 cm) stainless steel hex center shaft (Lundell Plastics Corp., Odebolt, IA). The HDPE flights are enclosed in 4-inch (10.2 cm) schedule 40 polyvinyl chloride (PVC) pipe. The top end of the PVC pipe is glued to a 4-inch x 4-inch x 4-inch (10.2 cm x 10.2 cm x 10.2 cm) PVC wye fitting. Waste moves upward through the auger to the wye, turns 270 degrees, and discharges out the wye through a collapsible 4-inch

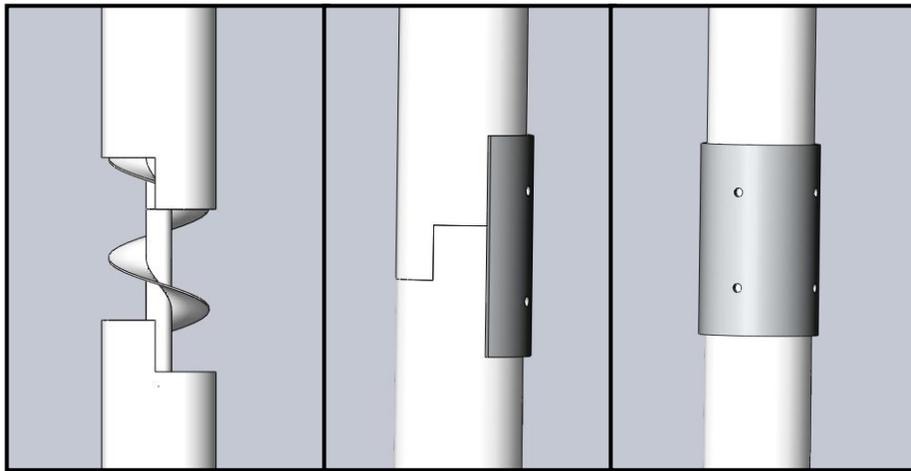


Figure 2.1 Diagram of steel coupling that connects two sections of 4-ft lengths of pipe. Not shown are the set screws that are threaded into the pipe to hold the pipe in place.

PVC hose. A handle attached to the discharge end of the collapsible hose to assists in directing the waste into a suitable collection container.

At the bottom (intake end) of the auger, two flights (8-inch or 20.3 cm) of steel auger extend past the end of the PVC pipe to convey waste into the solid pipe portion of the auger. Steel replaces the HDPE in this section to improve the durability of the exposed flights. A 1-inch (2.5 cm) steel ball is welded on a 1 ½-inch shaft that protrudes from the bottom of the steel flights to prevent the auger from damaging the bottom of the pit, if it is lined. The length of the Extraction Auger is easily increased to empty deeper pits by attaching additional lengths of HDPE auger and PVC pipe. The HDPE auger comes in 12-inch (30



Figure 2.2 Section of double helix reverse flights connected to the HDPE single flight auger before the addition of the pipe casing.

cm) lengths. The PVC pipe can be connected with 8-inch (20.3 cm) long steel couplings as shown in Figure 2.1.

Inside the wye at the top of the screw, there is an 8-inch (20.3 cm) long section of double helix reverse flights to aid in discharging the solids through the wye into a collection container. In the current version, the reverse flights are manufactured from $\frac{1}{16}$ -inch (1.6 mm) thick steel plate welded to a 1 $\frac{1}{2}$ -inch outer diameter (3.8 cm) (1 $\frac{1}{4}$ -inch inner diameter) steel tubing that slides over an exposed section of hex shaft above forward HDPE flights (Figure 2.2). The steel tubing is mounted to the hex shaft with one $\frac{5}{16}$ -inch bolt. In future versions, the reversed steel flights could be replaced with a lighter weight material (i.e. HDPE) if available.

The auger and wye fitting are connected to the hydraulic motor using a specially fabricated coupling machined from a 6-inch diameter nylon piece. The top 2 inches of the PVC wye fitting slides into the coupling to provide a secure fit and is held in place by four $\frac{3}{8}$ -inch bolts that are screwed through the fabricated attachment piece into small indentations in the wye fitting. A fabricated steel shaft passes through the fabricated coupling, connecting the output shaft of the hydraulic motor to the auger. This shaft steps down to $\frac{7}{8}$ -inch after the connection to the hydraulic unit so the 1-inch steel hex shaft of the auger was able to slide over and fit tightly. This fabricated shaft protruded 6 inches below the fabricated attachment piece, as shown in Figure 1.1, so that the auger could be fastened to the shaft using two $\frac{5}{16}$ -inch bolts.

The hydraulic motor used to drive the Extraction Auger is an Eaton Char-Lynn model 103-1034 with a displacement 75 cm^3 per rotation and a weight of 6.8 kg (15 lbs.). The motor

is rated for the following maximum continuous conditions: speed of 493 rpm, flow of 37.9 lpm (10 gpm), and torque of 148 Nm (1308 lbs.-in) at a maximum pressure of 138 bar (2000 psi). Hydraulic power to drive the motor is supplied by a 10.7 HP (at 3600 rpm) Honda GX340 gasoline engine (Little Beaver Inc., Livingston, TX). Hydraulic fluid is transferred from the hydraulic pump to the hydraulic motor through 7.6 m (25-foot) lengths of hydraulic hoses with Quick-connect fittings. The hydraulic motor, forward and reverse controls, pressure gage and Extraction Auger are mounted to a frame handle bar constructed from $\frac{3}{4}$ -inch (1.9 cm) steel pipe (Figure 1.1).

The final version of the Extraction Auger shown in Figure 2.3 was tested in the field at the North Carolina State University Dairy Farm on Lake Wheeler Road, near Raleigh, NC in January and February of 2013.

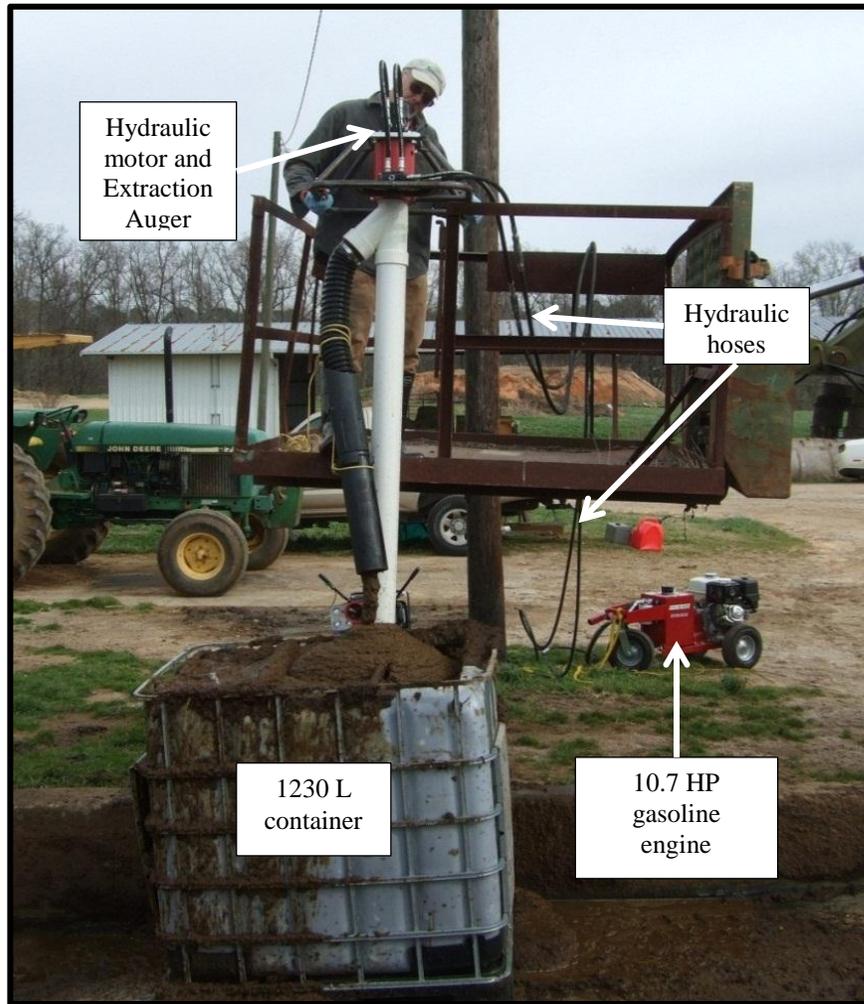


Figure 2.3 Hydraulic motor version of Extraction Auger recycling dairy waste from a 1230 L container.

CHAPTER 3

3. METHODS

This research evaluated the performance of the Extraction Auger in both the laboratory and the field. Construction of the initial prototypes took place mostly in the lab with some fabrication completed through a local machine shop.

3.1 Laboratory Testing

3.1.1 Simulant Waste

A high yield bentonite clay and water mixture was used as a simulant for human waste during the laboratory-testing phase.

Data provided by Stuart Woolley et al. (personal communications, August 2012) indicates that the viscosity of fresh feces varies between 2,200 and 70 Pascal-seconds (Pa-s) for shear rates of 0.2 and 21 1/second (1/s). Preliminary testing in the laboratory at NCSU (see Appendix B) showed that mixtures of bentonite clay and water have similar thixotropic properties with effective viscosity varying from 700 to 0.3 Pa-s for the same range of shear rates. Important advantages of bentonite mixtures over actual feces include: (a) the bentonite will not biodegrade over time allowing testing of the material for an extended amount of time in a laboratory setting and (b) the bentonite mixture does not contain pathogens, which could expose workers to unnecessary hazards. Three different mixtures were prepared of 5, 6, and 7% bentonite clay by weight in 210 L drums. These represented a

wide range of viscosities with the higher percentage bentonite mixtures yielding higher viscosities.

3.1.2 Setup

All laboratory tests were completed with the Extraction Auger using the experimental setup shown in Figure 3.1. All tests were run with the auger oriented vertically for two reasons: (1) flow rate usually decreases dramatically with increases in inclination of the

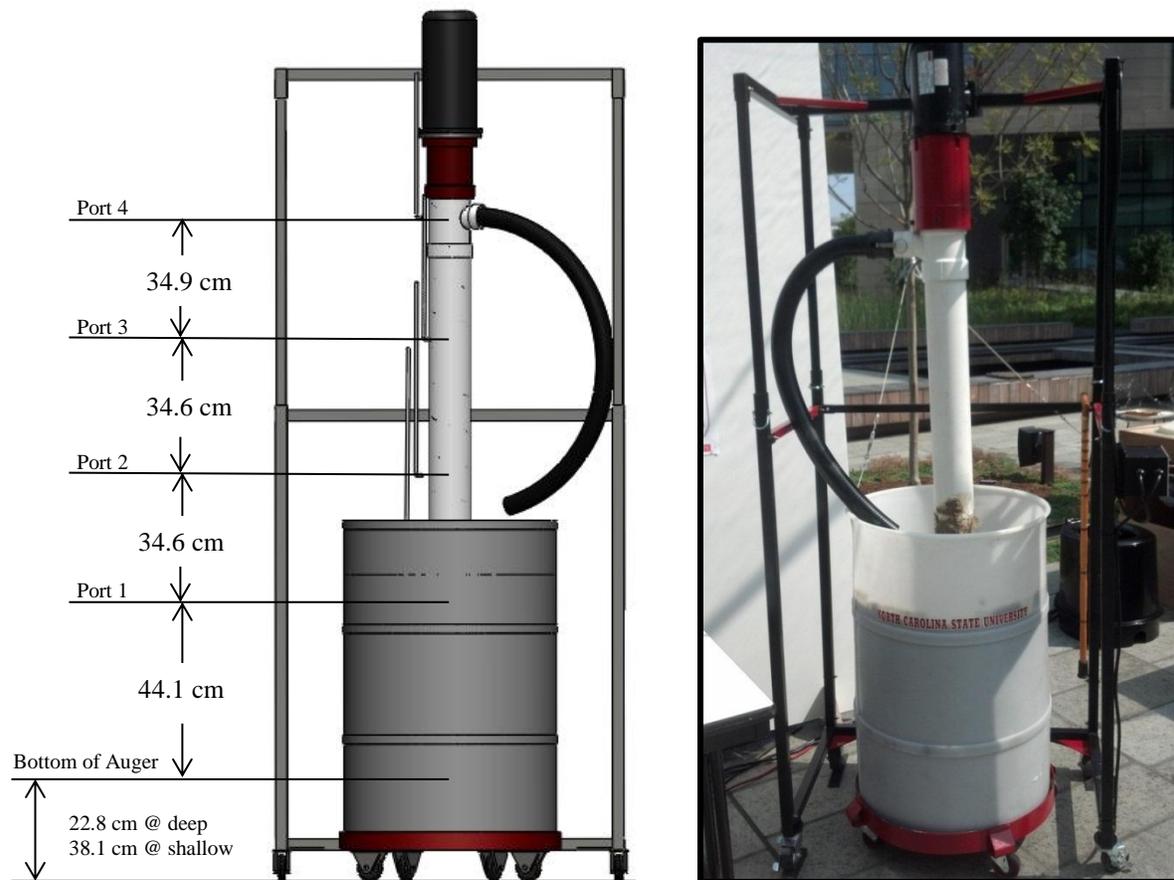


Figure 3.1 Experimental setup diagram for Extraction Auger with port locations (left) Display version of Extraction Auger presented at The Reinvent the Toilet Fair in August 2012 (Right).

auger; and (2) operation the Extraction Auger will be at very steep inclinations in the field (Roberts 1964; Dixon Jr. and Humphries 1995).

Several iterations of the initial prototype design were tested using a 43cc 2 HP engine as the power source until adequate flows were produced. Once a feasible design was developed, a 1 HP electric motor was used in subsequent laboratory tests. A rheostat was used to control the rotational speed of the auger allowing testing at different speeds. The motor attached to a metal stand that held the prototype vertical and allowed for different height settings. In all of the laboratory tests, a 5-ft (1.52 m) long auger was used with a 4-inch x 4-inch x 2-inch tee fitting outlet. Clear manometer tubes were attached to the sites of the auger at four locations to examine the change in head produced over the length of the auger. A laser tachometer was used to measure the rotational speed of motor shaft that was marked with a piece of reflective tape. Auger discharge rate was measured in duplicate and averaged by monitoring the time required to fill a 19 L (5-gallon) pail. The laboratory experiments examined the variation in flow rate and discharge pressure with motor speed, auger choke length (auger exposed at pipe bottom), lift height (height from the material level to the outlet), and bentonite solids content.

3.2 Field-testing

After completion of the laboratory tests, the Extraction Auger was tested in the field at two different sites (Rogers Farm and North Carolina State Dairy Farm). Development of alternative versions of the Extraction Auger generated improvements in its functionality and output.

3.2.1 Rogers Farm

An Extraction Auger powered by a 43cc 2 HP gasoline engine with a 2.44 m (8 feet) auger was tested with three different materials: 7% bentonite-water, 10% bentonite-water, and 7% bentonite-water with the addition of horse manure. A simulated pit was constructed by burying a 1.52 m (5 feet) long by 46 cm (18 in) diameter section of PVC pipe vertically in the ground and filling with simulated waste. Once filled with waste, the auger was inserted into the larger PVC pipe and used to lift waste out of the simulated pit and into a container to measure discharge rate.

3.2.2 NC State Dairy Farm

Three different versions of the Extraction Auger were tested at the North Carolina State University Dairy Farm waste settling basin. The material used for testing consisted of cow manure and a small amount of sand or wood shavings submerged in a settling basin. This material had a moisture content of 80.9%, and organic content of 9.7%, and an inorganic content of 9.5%. This moisture content is within the range of moisture content for fresh human feces (Still and Foxon 2012a). Testing of a 1.83 m (6-ft) version with the 43 cc 2 HP engine occurred directly in the settling basin with a water level of 46 cm. Later versions were tested with lift lengths greater than 2.44 m (8-ft) in a 1 cubic meter (1.1 m x .9 m x 1.0 m) container (shown in Figure 2.3) filled with the cow manure to better simulate a pit latrine that would be encountered in the field.

CHAPTER 4

4. EXTRACTION AUGER OUTCOMES

Several complications and resolutions emerged through the development of the Extraction Auger. The two main areas of focus for the optimization of the Extraction Auger were hydraulic performance and usability.

4.1 Hydraulic Performance

4.1.1 Flow Output

Several parameters influence the flow rate produced by the Extraction Auger including the auger rotational speed, viscosity of the waste, and removal of the waste from the pipe at the outlet. Initial laboratory testing with simulated waste showed that the auger operating at reasonable speeds (100 – 500 rpm) does not generate significant pressure and that continuous flights from inlet to the outlet are needed to produce flow. The rotational speed and viscosity of the material had the greatest effect on the flow produced. A threshold rotational speed of approximately 350 rpm is necessary to attain flow rates greater than 15 lpm during lab testing with the 5% bentonite mixture. The threshold speed decreases to approximately 225 rpm to obtain flows greater than 15 lpm with the more viscous 7% bentonite mixture (discussed in Chapter 5).

Field-testing showed that a motor that provides at least 10.7 HP (8 kW) is adequate for lifting thick sludge up several meters. The 43cc 2 HP gas engine used for initial testing did not provide enough power to lift highly viscous materials over long lift heights. The

389cc 10.7 HP gasoline engine that powers the hydraulic unit has shown to provide enough power during field-testing.

Field-testing indicated that material with high solids content that did not readily flow would become compacted at the top of the auger and not flow out of the 4-inch x 4-inch x 2-inch sanitary tee fitting. Attaching a short section (8 inches) of reverse flights at the top of the auger above the outlet prevented waste from jamming at the top of the pipe (Figure 2.2). A 4-inch wye fitting angled downward for the outlet fitting appeared to help the material be removed from the pipe by gravity instead of being forced through a 2-inch fitting.

4.1.2 Jamming

During lab and field-testing, the auger would often jam (stop rotating within the pipe) causing flow to stop. This was assumed to be due to two possible problems: 1) the auger wobbling within the pipe causing the system to bind and 2) material wedging between the edge of the auger flights and the pipe. Two modifications were made to the auger to reduce binding: 1) the coupling between the drive head and the screw auger was modified to provide a more rigid connection (Figure 1.1); and 2) the gap between the HDPE auger flights and the PVC pipe was increased from $\frac{1}{32}$ -inch to $\frac{1}{8}$ -inch, by shaving down the HDPE auger. These two modifications greatly reduced friction and associated binding.

Lockup or jamming of the auger was also reduced by increasing the maximum hydraulic pressure (controlled by a pressure relief valve) from 1500 psi (103 bar) to 2000 psi (138 bar). The increased torque provided by the higher pressure was able to dislodge most material without locking up the auger. When the auger did jam, the hydraulic controls on the handle bar allowed the auger rotation to be easily reversed and dislodge any trapped material.

In all cases, a 1-2 second reversal of the auger was effective in dislodging trapped material. This allowed continued pumping of the waste without any other action.

4.2 Usability of Extraction Auger

4.2.1 Maneuverability

For efficient operation, the auger should be easily transported and used by two men. A 4-inch pipe and auger were selected to provide adequate flow while still being maneuverable with one or two operators. Wrap-around handle bars were fabricated (Figure 2.1) for the operator to easily move the system around within the pit. The use of a hydraulic unit decreased the weight of the Extraction Auger since the gasoline engine powered unit is separate from the hydraulic motor and operators do not have to lift the gas engine. The total weight of the hydraulic unit with an 8.8-ft (2.7 m) auger length is approximately 48 kg (106 lbs.). However, the operator does not have to hold this weight once the auger is resting on the pit bottom or semi-solid material in the pit. An adjustable stand was also developed to help support the auger. The gasoline power hydraulic pump can be located a short distance away from the pit when access is restricted using hydraulic hoses to carry fluid between the hydraulic pump and Extraction Auger. The gasoline powered hydraulic pump is mounted on wheels for easy transport.

4.2.2 Cleaning

Once the pit has been emptied, the Extraction Auger should be easy to clean and transport away without contaminating the pit area. The reverse mechanism on the final hydraulic unit allowed the waste still inside the auger to be discharged back into the pit,

reducing the equipment weight and waste spillage outside the pit. If water is available, pouring a steady stream of water through the outlet while running the mechanism in reverse is effective in removing most waste before disassembly. We suggest capping the inlet and outlet of the Extraction Auger between pits to minimize the frequency of cleaning the interior of the system and exposing the operators to the waste. A rubber squeegee with a long handle allows the operator to wipe down the outside of the pipe during emptying. Further work is necessary to develop a good system that prevents contact between the waste and the operator.

4.2.3 Deterioration of Extraction Auger Components

The Extraction Auger should be durable, allowing daily use of the equipment with few repairs. When repairs are needed, required materials should be low cost and readily available in developing areas. Laboratory and field-testing showed significant scoring of the inside of the pipe casing and some deterioration of the edge of the plastic auger. However, no observed cracking or breaking of the pipe occurred with the exception of a small piece rupturing at the inlet of the pipe. This was most likely due to a solid in the material wedging between the inlet of the pipe and the edge of auger flights (Appendix C). An 8-inch section of metal single flighted auger was used at the end of the HDPE auger to prevent exposure of the weaker HDPE material to abrasive solids that will be encountered within the pit. A small section of metal pipe can also be used at the inlet of the auger to prevent the wedging of solids that result in cracks and breaks in the pipe.

4.2.4 Modularity

Many pits are only accessible within the latrine superstructure (Still and O’Riordan 2012). Extraction Augers capable of emptying pits up to 2.5 m deep can be assembled inside a structure using several shorter lengths of auger and pipe. However, this may increase the risk of waste spillage and contact between the operator and the waste during disassembly (Still and O’Riordan 2012).

CHAPTER 5

5. LABORATORY TESTING WITH SIMULANT WASTE

5.1 Laboratory Testing

The Extraction Auger was tested in the laboratory in a vertical orientation since this is most common in the field. The simulated waste used in the laboratory was prepared with 5, 6 and 7% bentonite to represent a range of viscosities similar to human feces mixed with varying amounts of water. In the laboratory, the Extraction Auger lifted the simulant waste from 210 L (55-gallon) drums and recycled it through a 2-inch (5.1 cm) hose back into the drums.

An electric motor with a variable speed control was used to examine the effect of auger rotational speed (100, 200, 300, 400 and 500 rpm) on the flow rate and pressure head produced. Additional variables examined included two choke lengths (5.1 cm (2-inch) and 10.2 cm (4-inch)) and two lift heights (105 cm and 120 cm) at steady state. The study of only two lift heights and the small change in lift height for laboratory testing was a result of spatial constraints within the lab testing facility. A lift height of 105 cm corresponds with a deeper submergence of the pipe and auger into the material, implying a higher amount of head above the inlet of the pipe. Similarly, longer lift heights infer a shallower submergence and a smaller amount of head above the inlet of the pipe.

5.1.1 Results from Laboratory Testing

Laboratory test results showed that simulated waste could be lifted vertically using the Extraction Auger. Figure 5.1 shows the variation in flow rate for three different solids

contents and two lift heights. Sludge lift height was increased by raising the auger up 15 cm, which also reduced the intake submergence by 15 cm. The auger rotational speed and waste viscosity had a great effect on the flow produced. The Extraction Auger was capable of lifting 40 lpm of the 7% bentonite mixture at 300 rpm, allowing a typical pit to be emptied in less than 1 hour. However, a speed of over 500 rpm is required to achieve the same flow rate for a less viscous, more ‘water-like’ 5% bentonite mixture. Changes in lift height had minimal impact on flow rates for the 5% and 6% bentonite mixtures when auger speed is constant, suggesting that drainage of the fluid back down through the auger for these mixtures was not a major issue. For the 7% bentonite mixture, the lower lift height / deeper

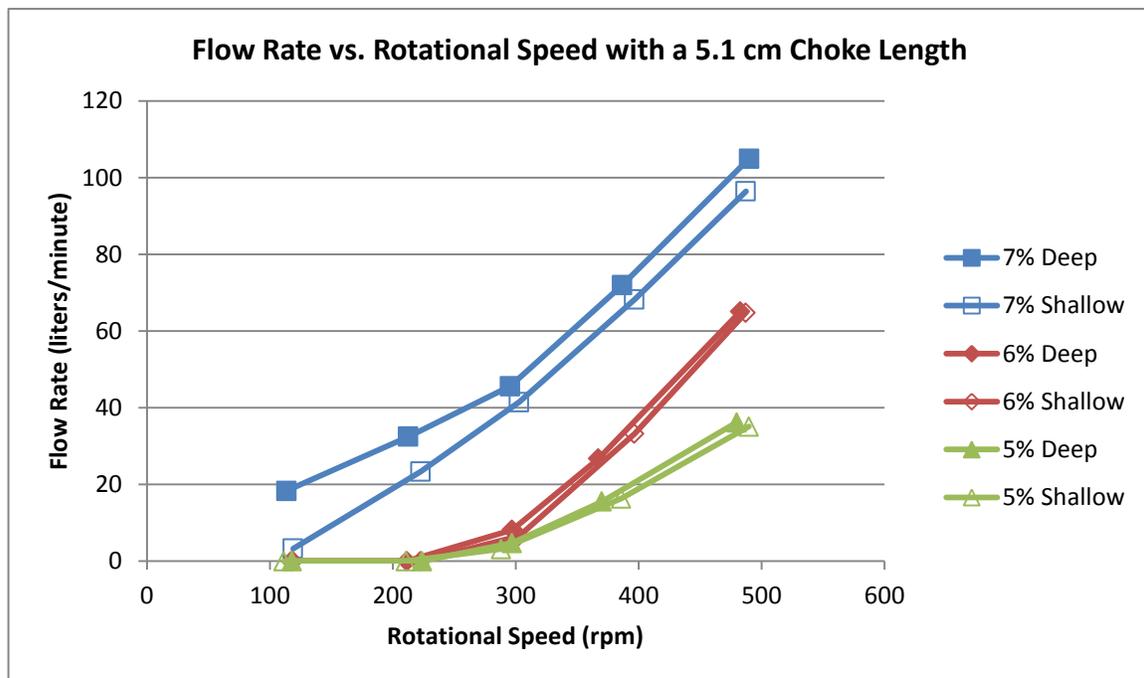


Figure 5.1 Flow rate vs. auger rotational speed with a 5.1 cm (2-inch) choke length for shallow (120 cm lift height) and deep (105 cm lift height) settings for three different mixtures (5, 6, and 7% bentonite).

intake submergence did produce some increase in flow rate at lower rpm. This most likely occurred because a larger hydraulic head is required to transport the more viscous material into the auger intake because it does not flow as freely as the lower viscosity mixtures. This could limit pumping rates as the pit is emptied, especially for high viscosity waste.

Figure 5.2 shows the effect of choke length (length of exposed auger below the solid pipe) on flow rates over a range of rotational speeds. Choke length also had minimal impact on flow rate for the lower viscosity materials, but did have some impact on flow rate for the highest viscosity material. Again, this is consistent with the idea that the pumping rate of

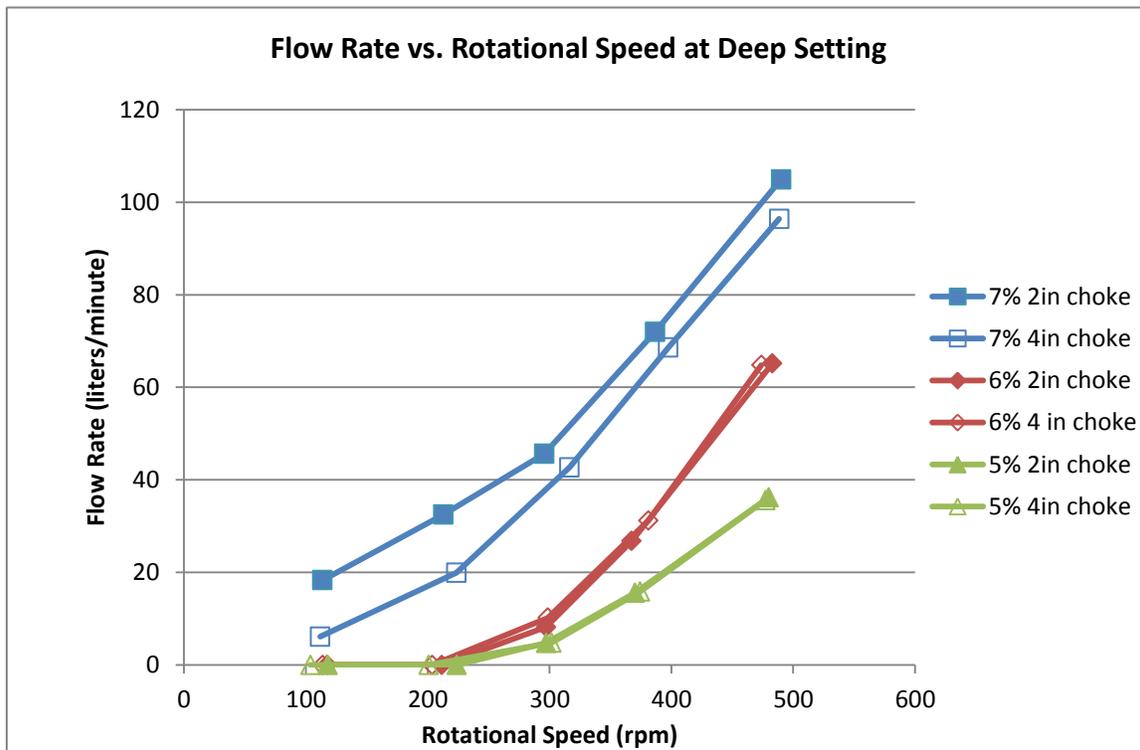


Figure 5.2 Flow rate vs. auger rotational speed for 5.1 cm (2-inch) and 10.2 cm (4-inch) choke lengths in the deep setting (105 cm lift height) for three different mixtures (5, 6, and 7% bentonite).

high viscosity materials may be limited by the rate the material enters the auger intake.

Field-testing of a similar screw conveyor in South Africa found the flow rate to decrease by 80% as the pit neared empty (Still and O’Riordan 2012). The large decline in flow in the South African tests may have been due to the higher viscosity of the pig waste used in that study. The small change in flow rate with the 7% bentonite mixture for the different choke lengths may be attributed to the decrease in submergence at the pipe inlet from the removal of 5.1 cm (2-inch) of pipe.

For each bentonite mixture, there was a threshold rotational speed required to produce any flow. Above this threshold, flow increased substantially with increases in rotational speed. Roberts (2001) derivation of flow through a screw conveyor based on fill and vortex efficiencies (Equations 1.1 – 1.3) explains this threshold. Figure 5.3 shows the observed flow compared to the expected flow based on measured and typical values for varying friction coefficients. The friction coefficient, μ_c , refers to the friction between the material moving through the screw conveyor and the casing. Roberts’s equations suggest that no flow will be obtained if the effective helix angle is negative which results in a negative vortex efficiency. As the friction coefficient increases, less rotational speed is required to achieve flow. The increasing viscosities of bentonite mixtures used during lab testing correspond with the increasing friction coefficients. This explains the smaller threshold and higher flow rates produced with the more viscous bentonite mixtures. However, Roberts’s equations for conveyor throughput are based on the conveyance of bulk materials that behave different from the thixotropic bentonite mixtures. This most likely explains why the lab data does not perfectly follow Roberts’s model in Figure 5.3. Roberts’s model is not intended to model the

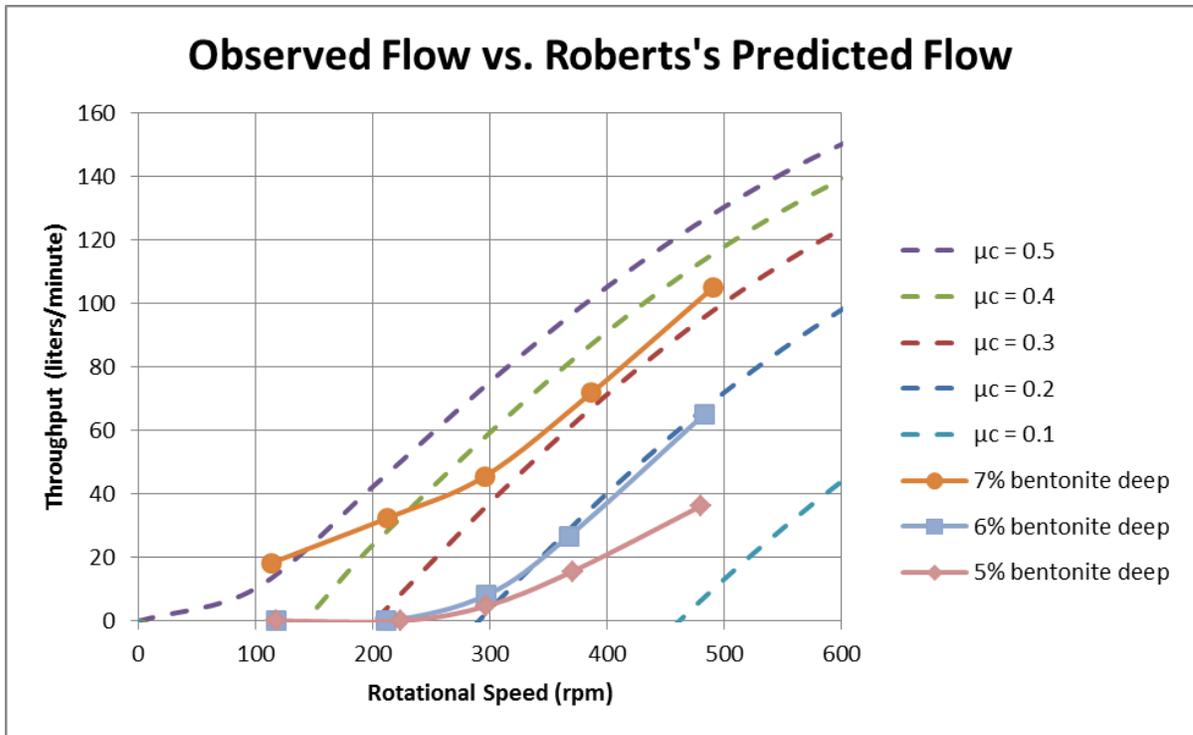


Figure 5.3 Observed flow rates for a 5.1 cm (2 in) choke length and deep setting (105 cm lift height). Theoretical flow rates are plotted based on Roberts (2001) derivation for flow through a screw conveyor for varying material friction coefficients (μ_c).

flow of bentonite through a screw conveyor. Instead, it is intended to explain the threshold rotational speed requirements and the increase in throughput due to increases in material viscosity and auger rotational speed. The volumetric efficiency achieved a maximum of approximately 26% at the highest rotational speeds and bentonite concentrations. This low efficiency in these tests is most likely due to the vertical orientation of the auger, which increases in the slip of material backwards through the auger (Roberts 1964).

The pressure head throughout the lift also showed positive correlations with increases in the rotational speed as well as viscosity. However, the greatest pressure head produced at

the outlet any setting was less than 14 cm. This implies that the Extraction Auger will not generate enough pressure to pump material through a significant length of hose and will need to discharge directly into transport containers.

CHAPTER 6

6. FIELD-TESTING

6.1 Initial Field-testing of Mechanical Drive Auger

After completion of the laboratory testing, different versions of the Extraction Auger were tested. Testing several iterations of the Extraction Auger design took place at a local farm (Rogers Farm) on simulant waste and horse manure mixtures and at the North Carolina State University Dairy Farm on cow manure. Operational problems and solutions identified through field-testing are explained further in Chapter 4.

6.1.1 Rogers Farm

Testing of the 43cc 2 HP engine version of the Extraction Auger with a total auger length of 2.4 m (8-ft) took place on a local farm. This system, weighing a total of 33 kg (72 lbs.), operated in 1.5 m (5-ft) deep pits with a total volume of 1-m³. The three different mixtures tested consisted of a 7% bentonite-water mixture, a 7% bentonite mixture with the addition of horse manure, and a 10% bentonite mixture. Flow rates of approximately 40 lpm produced for both the pure 7% bentonite mixture and with the addition of horse manure correspond with data gathered in the laboratory experiments. Testing of the 10% bentonite mixture achieved lifting, but the mixture was too viscous to flow through the 5.1 cm (2-inch) outlet hose. This was due to the inability of the 43cc 2 HP engine to move this material from a lack of available power.



Figure 6.1 Field-testing the Extraction Auger at the Rogers farm with the 43cc 2 HP engine.

6.2 North Carolina State University Dairy Farm

In the next phase of testing, a modified version of the Extraction Auger was tested at the North Carolina State University (NCSU) Dairy Farm. This modified version utilized a hydraulic motor powered by a 389 cc 10.7 HP gasoline engine. This version was designed for rotational speeds up to 493 rpm (at no load) with enough available torque (110 ft-lbs. at full speed) to lift very viscous materials.

To better recreate the constraints that would be presented by an actual pit latrine, the Extraction Auger was used to lift dairy waste out of a 1-m³ container with the top removed,

simulating a 36 cm x 90 cm opening on top of the pit. The dairy waste consisted of cow manure, water, and a small amount of bedding material (sand or wood shavings) that was collected from a settling basin and placed into the 1-m³ container. Based on visual observation, the largest particles in the waste were less than 1.0 cm in longest direction. The hydraulic unit was tested with a 2.7 m (8.8–ft) total auger length operated from a platform suspended above the 1 m deep container.

After several operational problems were resolved (Chapter 4) the Extraction Auger produced steady flows and two different inlet designs were examined: a 15.2 cm (6-inch) choke length completely exposed and a 15.2 cm (6-inch) choke length surrounded on the bottom by a half pipe (half-trough). The completely exposed choke length produced greater flow rates than the half pipe design at a lift height of 2.0 m and as the container was emptied from a lift height of 2.0 m to 2.34 m (Table 6.1).

Table 6.1 Average flow rates for the exposed 6-inch choke and with a half-trough design for a constant and variable lift height.

Lift height	Flowrate (lpm)	
	Bare	Half-trough
2.0 m	127	108
2.0 to 2.34 m	88	73

This setup of the hydraulic unit was also tested with an auger with a clearance of 3.2 mm (¹/₈-inch) compared to the previous setup of a 0.8 mm (¹/₃₂-inch) clearance. A decrease in flow and power consumption would be expected with an increased clearance due to leakage around the periphery of the pipe, especially with finer free-flowing materials

(Roberts 1964). Roberts (1999) suggests a clearance of between 1.5 and 3 times larger than the maximum particle size to prevent jamming and energy loss as well as limiting slip back and a loss of efficiency. However, the expectation was that a larger clearance would reduce the friction created inside the pipe and decrease the required pressure needed from the hydraulic motor. A steady state pressure of only 1200 – 1600 psi for the 3.2 mm clearance compared to 1800 psi for the 0.8 mm clearance validated that point. This indicates the increase in clearance caused a significant reduction on the friction occurring within the pipe. The larger clearance jammed about half as often. The larger clearance also resulted in a slightly higher rotational speed of 410 rpm compared to 380 rpm produced with the smaller clearance. This is most likely due to the reduction in friction within the pipe. However, as predicted, the larger clearance did cause a decrease in the flow with an average flow rate of 94 lpm at the 2 m lift height using the bare 15.2 cm (6-inch) choke setup. These results indicate that there is a tradeoff between the flow produced and the operating hydraulic pressure. Although higher flows are possible with smaller clearances, there is also an increased risk of jamming and deterioration of the pipe and auger.

A decline in flow rate was observed as the container was emptied. The flow rate produced by the auger with a bare 15.2 cm (6-inch) choke and 0.8 mm clearance experienced

Table 6.2 Extraction Auger performance on dairy waste for 1/32-inch and 1/8-inch clearances with a 6-inch exposed choke.

Clearance (inches)	Steady State Hydraulic	Auger speed at Steady State (rpm)	Flow at 2.0 m lift height	Jam Frequency
1/32-inch	1800	380	127	2-3
1/8-inch	1200 - 1600	410	94	< 1

a decrease from 127 lpm at a 2.0 m lift height to an average flow of 88 lpm as the lift increased from 2.0 m to 2.34 m (submergence decreased from 0.7 m to 0.36 m). This corresponds with the data presented on the screw conveyor testing on pig slurry in South Africa (Still and O’Riordan 2012). However, significant flow rates are still produced at large lift heights. Every setup encountered difficulty at removing the waste after the level in the container reached a point below the exposed choke at the bottom of the pit. Upon reaching this point, a second person moving the waste towards the inlet with a shovel allowed lifting the waste to continue. Leaving a small amount of waste in the bottom of the latrine, however, is beneficial as it permits the current microbial community to stay intact which allows to better degradation of future waste (Still and O’Riordan 2012).



Figure 6.2 Dairy waste being recycled into the 1-m³ container with the Hydraulic drive version of the Extraction Auger with a 2.7 m auger length.

CHAPTER 7

7. CONCLUSIONS AND RECOMMENDATIONS

Lab testing showed that the Extraction Auger could be effective in lifting viscous material vertically and could provide flow rates that would be effective in the field. Increases in rotational speed and material viscosity resulted in significant increases in flow rates produced after reaching the threshold rotational speed. The rotational speed threshold is higher for less viscous materials. A rotational speed of at least 350 rpm is needed to lift less viscous “water-like” wastes. The minimal pressures produced at the discharge end of the auger require that the Extraction Auger discharge directly into transport containers.

Field-testing on bentonite mixtures and dairy waste identified several operational problems that were resolved. The flow rates produced on the range of simulant wastes in the laboratory and the viscous waste at the Dairy Farm would indicate that the hydraulic unit would be capable of emptying a wide range of wastes encountered in actual pit latrines. Field-testing would also show that the Extraction Auger would be capable of emptying a typical pit of 2.5 m³ in less than 30 minutes. The Extraction Auger has also proven to lift highly viscous waste at flow rates greater than 100 lpm indicating that it could be capable of efficiently removing the dense bottom layer of sludge found in most pit latrines. This Extraction Auger with a hydraulic drive provides adequate rotational speeds, torque, maneuverability, and unjamming capabilities that are required on actual pit latrines.

Further research is needed to improve the performance and durability of the Extraction Auger. Testing is required to determine the effect of solid waste (trash) on the ability of the Extraction Auger to remove waste from a pit latrine. The development a better

method of cleaning the Extraction Auger is also necessary, as there is currently still some risk of human contact with the waste. Additional work is needed to develop procedures for assembly, use and removal of wastes from pits located inside structures. Finally, an evaluation of the functionality and durability of the Extraction Auger in an actual field environment will be very beneficial. This evaluation should occur over an extended period, using the Extraction Auger on a daily basis to empty pit latrines.

CHAPTER 8

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APPENDICES

APPENDIX A – The Global Sanitation Crisis, the Development of Pit Latrine, and the Development of Pit Latrine Emptying Technologies

A.1 Introduction

Sanitation is an essential part of a healthy life and is considered a basic human right. Unfortunately, an estimated 2.6 billion people are currently without access to proper sanitation, including 1.1 billion who are still practicing open defecation (UN 2010). There are an estimated 2.5 billion cases of diarrhea from poor sanitation practices every year, resulting in the death of 1.5 million children. Diarrhea is the second leading killer of children and kills more children than AIDS, malaria, and measles combined (WHO and UNICEF 2009). In 1990, the United Nations, in collaboration with several world development organizations, set forth the Millennium Development Goals (MGDs). These included eight target categories to begin the process of improving the developing world by eradicating poverty and hunger, ending the spread of disease, providing universal education, and several other initiatives. These initial goals were set to be complete by 2015 and many have already reached or surpassed their targets. Within the seventh category of Ensuring Environmental Sustainability, the goal was set of halving the world's population without access to safe drinking water and basic sanitation. The goal for access to clean water has already been met as of 2010 with an increase of over 2 billion people from its inception (WHO and UNICEF 2012). However, the goal set for sanitation is lagging well behind. The World Health

Organization (WHO) defines an improved source as “facilities that ensure hygienic separation of human excreta from human contact.” These include (WHO & UNICEF 2008):

- Flush or pour-flush toilet/latrine to:
 - o piped sewer system
 - o septic tank
 - o pit latrine
- Ventilated improved pit latrine
- Pit latrine with slab
- Composting toilet

Access to an improved or shared (two or more households) sanitation facility has

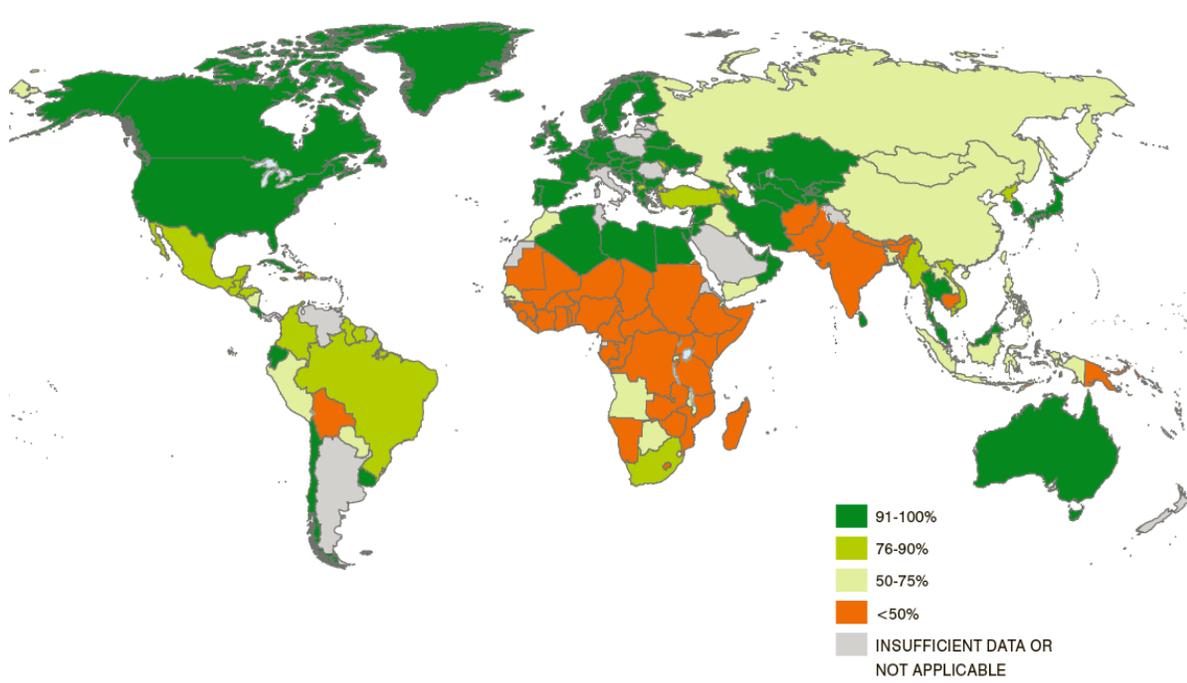


Figure A.1 Proportion of the population using improved sanitation in 2010 (WHO and UNICEF 2012)

increased from 50% to 65% as of 2008 which still excludes about a third of the world's population (WHO and UNICEF 2008).

The majority of this population without proper sanitation is located in Sub-Saharan Africa and Southeast Asia (Figure A.1). These countries are where the most concerted improvement efforts are occurring. However, urbanization in developing countries and a growing slum population has made keeping up with sanitation needs even more difficult.

A.2 The Pit Latrine

An essential part of improving sanitation in the developing world has been the implementation of hundreds of thousands of pit latrines. The basic function of the pit latrine is to isolate humans from their excreta. There are certain guidelines that a latrine design must



Figure A.2 An example of an improved sanitation facility, the Ventilated Improved Pit latrine (left). An example of an unimproved sanitation facility, a hanging latrine (right) (Photo: Wateraid / Abir Abdullah).

have to be considered an improved facility that qualifies as proper sanitation. These include a proper foundation, use of a cement slab to seal the pit, a secure super-structure, and ventilation for gases produced within the pit. An example of a very common improved facility, the Ventilated Improved Pit (VIP) latrine, is shown in Figure A.2. An example of a common unimproved facility, the “hanging latrine,” that provides privacy but little to no sanitation is also shown in Figure A.2. When built and maintained properly, pit latrines can serve as an adequate solution for sanitation in the developing world. However, an issue arises when the pits are eventually filled and the waste must be removed and processed. Typical pit volumes are 1 – 4-m³ depending on accumulation rates, number of users, and the design life (Still 2002; Mara 1984). However, the design life can fluctuate tremendously and pits have been found to fill from anywhere between three and twenty years with discrepancies in fill time noticed within the same area and between areas (Still 2002). These fill times vary depending on the size of the pit, the amount of users, amount of excreta produced by each user, the location of the water table, soil type, local climate, existence of a pit lining, material used for anal cleansing, and the amount of solid waste (trash) added to the pit (Pickford 1995; Still 2002). Once these pits do become full, the threat of poor sanitation rises again as these pits now need to be emptied. This can be a very difficult task as there are several issues encountered by the user when a pit is filled. Frequently, mechanical pit emptying devices, such as a vacuum truck, are prohibitively expensive or are too large to access the pit, which is often located in a dense slum or on a steep embankment. So, if a pit emptying service is not offered by the local government or another provider, the users are left with only a few options: build a new pit adjacent to the existing one, sluice the contents into an adjoining pit,

use a neighbor's latrine, resume unsafe sanitation practices, or have a local person empty the pit manually (O'Riordan 2009). In a rural setting, building a new pit and moving the superstructure is often feasible because land area is available, although groundwater contamination and costs are still of concern. However, in an urban setting, all of these options either postpone an inevitable need for emptying or reverse any sanitary progress that has been made to that point. For these reasons, the need for a new pit emptying technology that can affordably and sanitarily remove waste from pits is pivotal to continue on the path of improved sanitation across the developing world.



Figure A.3 Manual pit latrine emptying or "scavenging" in Dar es Salaam, Tanzania (O'Riordan 2009).

A.3 Pit Emptying Complications

In 2005, Kathy Eales wrote, "pit emptying is the dark under-belly of on-site sanitation – neglected, stigmatized, and inadequately acknowledged as an essential component of



Figure A.4 Densely populated community that presents a difficult task for large pit emptying equipment to gain access (Still and O’Riordan 2012).

sustainable sanitation, especially for the poor.” This pilloried view of pit emptying is not without reason. This difficult task often is passed on to the poorest to deal with in extremely unsanitary conditions. Several factors can make developing an adequate pit emptying technology very difficult in addition to the financial and sanitary concerns.

The first issue that a pit emptying service encounters is the ability to get their emptying device to the pit or within range to extract the material. Many of these pits are located in urban slum settings where the only access is through narrow alleys. In some areas, pits located down steep embankments without close access to streets. Both of these situations can make it very difficult for large equipment such as vacuum trucks to get in close enough proximity for pumping.

Another factor is the ability of the pit emptying mechanism to gain access into the actual pit and the pits contents. Many pit latrines were installed without considering the access points to the pit contents for when the pits would need to be emptied years later. There are also many different pit latrine configurations, even within the same service area. Some pit

latrines have the convenient access points in the back or side of the latrine with removable slabs, such as in Figure A.6. However, often the only access is through the small hole used for defecation. If the superstructure is not removable, long, rigid mechanisms are not an option unless a hole is dug in the side of the latrine as shown in Figure A.5.

If access is available to and into the pit latrine, then the pit emptier must then be able to manage the actual contents of the pit. The makeup of the contents of a pit latrine can vary tremendously depending on several factors including the materials used for the bottom and sides of the pit, local climate, the use of water or fibrous materials for anal cleansing, height of the water table, user diets, and the presence of solid waste in the pit. In general, pit latrines can be divided into two categories, “wet” latrines and “dry” latrines. Wet latrines are



Figure A.5 Pit latrine that must be accessed from the side because of a design not compatible with pit emptying (Still and O’Riordan 2012).

typically found where there is a high influx of water into the pit through rainwater, water for anal cleansing, or high water tables. Some pits may not have good drainage through the sides or bottom of the pit due to the low permeability soil or the use of impermeable materials to retain all the pit contents. Excreta stored in a wet latrine tends to separate into three layers from top to bottom: floating scum, liquid, sludge/sediment (Hawkins 1982). The floating scum layer is often 100 mm to 200 mm thick and is usually present when paper or fibrous materials are used for anal cleansing. This scum layer needs to be broken up and mixed in with the liquid layer for removal by vacuum trucks. Pits where water is used for anal cleansing have thinner, softer, or even absent scum layers. The bottom layer of sludge that forms at the in the pit latrines has proven to be the most difficult to remove (Hawkins 1982).

The sludge layer within pit latrines has shown to have unique characteristics when compared to the liquid and scum layers. A “dry” pit latrine, or well-drained pit latrine, does not have the presence of a scum or liquid layer and therefore only consists of a sludge layer (Hawkins 1982). In a “wet” latrine, a substantial sludge layer takes about 6 months to

Table A.1 Human waste characteristics for various countries (Hawkins 1982).

Country	% water		NVS%		Density (kg/dm ³)	
	mean	range	mean	range	mean	range
Japan	97	97-98	40	30-50	-	-
Taiwan	97	96-98	41	19-87	1.01	-
S. Korea	95	94-96	29	24-34	1.02	-
Thailand	86	81-89	40	12-84	1.04	0.97-1.13
Botswana	68	43-91	59	37-76	1.27	1.03-1.43
Tanzania	46	26-74	42	23-59	1.45	1.11-1.75
- % water refers to moisture content						
- NVS% refers to % of total solids						

develop and becomes more compacted over time. The composition of the sludge layer depends on several factors including organic content, the amount of urine excreted by the user, the type of anal cleansing material used, the presence of solid waste in the pits, and moisture content. The compaction and other sludge properties do not correlate with the amount of free water in the pit, meaning that sludge from wet and dry pits should be comparable. A table of moisture content, percent of total solids, and sludge densities collected by Hawkins (1982) from several pits in various countries is shown in Table A.1. This table shows the high variance of sludge densities that can be found in pit latrines, even within the same region. Higher densities result in a higher required static head for vacuum systems (Thye et al. 2011). Perhaps more important than the density of the sludge, however, are the flow properties of the sludge. Sludge has been shown to have thixotropic, shear thinning properties meaning that the material becomes less viscous and more fluid-like with increasing shear or energy input (Hawkins 1982). Therefore, if a mechanism is able to initiate the sludge moving, the sludge viscosity will drop, allowing vacuum systems to work. Addition of as little of 2% of water to the pit can reduce resistance to flow 30 – 300 fold, most likely due to thixotropy (Hawkins 1982). Although several new pit emptying technologies have been developed in recent years, most still have difficulty with removing the dense, compacted sludge. It is important to note that little research has been completed on the flow properties of sludge. Recent efforts have been made to quantify the rheology of waste throughout the pit as it can vary significantly throughout a given pit (Van Vuuren 2008). One ongoing study by Jamie Radford, Mott MacDonald UK, uses a ball penetrometer to measure the rheology throughout the depth of pit latrines which could eventually lead to a

classification system of pit emptying technologies based on their capabilities with different viscosities of sludge. Early results indicate that pit content characteristics can vary tremendously from area to area and within areas. An example of this variance is shown in Figure A.6 below, where wet and dry latrines with completely different characteristics were found less than a few miles apart. From previous pit emptying studies, it is apparent that a pit emptying technology should be able to extract as wide of range of sludge viscosities and densities as possible.

Another factor that contributes to the complications with pit emptying is the presence of solid waste (trash) in the pits. Many of the areas where pit latrines are used lack adequate solid waste collection and disposal. Therefore, inhabitants throw solid waste into the pit

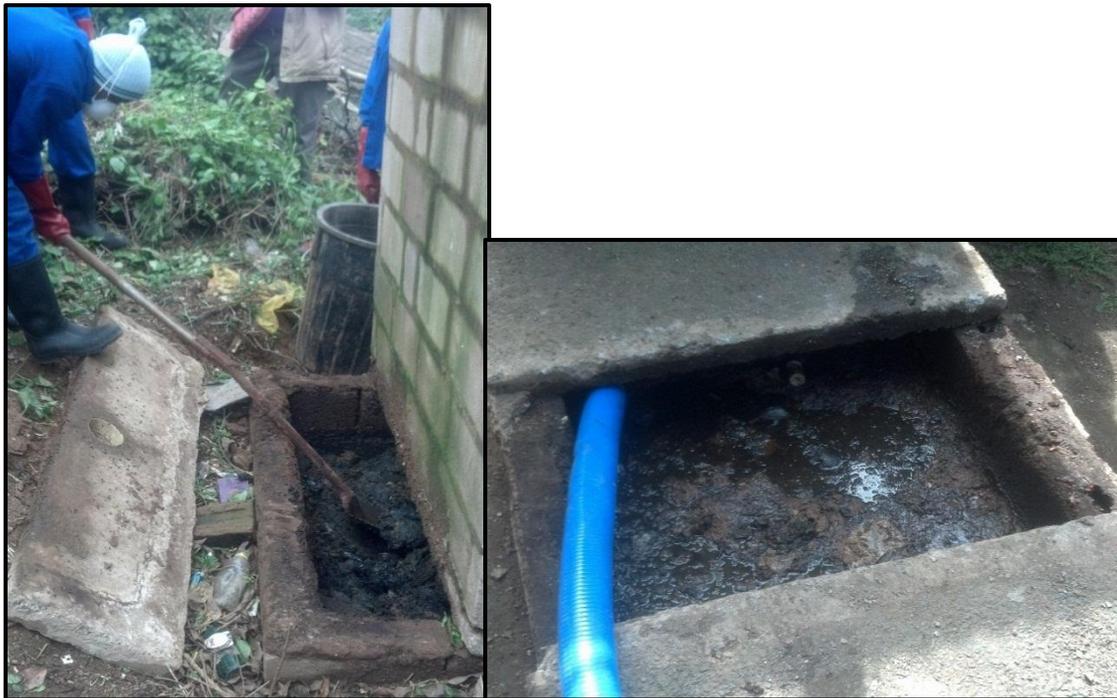


Figure A.6 A “dry” pit latrine (left) and a “wet” latrine (right) found less than one mile apart.

latrine. Still (2002) reports that, in some areas, up to 20% of the pit contents maybe solid waste. As seen in Figure A.7, a wide range of materials may be present in pits including rags, clothes, tires, etc. Large amounts of trash are most often present in areas where fibrous materials are used for anal cleansing and less frequently in regions where water is used. The presence of solid waste can make most any pit emptying technology impractical as they become frequently jammed and clogged. As a result, many pits with high amounts of solid waste must be emptied with manual tools, which can be very time consuming. Reductions in the amount of solid waste in pits have been observed in certain areas where a government utility is responsible for emptying the latrine. In the province of EThekweni in Durban, South Africa, the local utility provides a free pit emptying once every five years (WIN-SA & WRC 2012). However, if the pit fills up more than once per five-year period, the cost for emptying



Figure A.7 Pit latrine with high solid waste content near Durban, South Africa (Photo: Buckley et al.).

becomes the responsibility of the user. Since, the addition of refuse causes the pits to fill up significantly faster, this serves as an incentive to avoid adding solid waste and extend the fill time of their pit.

A.4 The Need for New Pit Latrine Emptying Technologies

Because of the growing need for the hundreds of thousands of existing pit latrines to be emptied, several prevailing and new technologies have been employed. The complications with pit latrine emptying mentioned above have made developing an affordable yet sanitary and effective solution difficult. The variability of the pit latrine locations, configurations, and contents indicate there is not currently one technology that works for every pit. The cost of emptying the latrine is also a major component of selecting the correct technology and often depends on what entity is incurring the costs. If the federal government, local municipality, or another organization is incurring the costs then often the more effective, sanitary, and expensive technologies can be used. However, when the user is required to pay for the pit emptying, manual emptying or other unsanitary practices usually occur. For these reasons, several new technologies have been explored in an effort to develop a sanitary technology that is sanitary, effective, and sustainable within the location it is being utilized.

A.5 Current Pit Latrine Emptying Technologies

The current pit latrine technologies include some that have been in use for decades and some that are just past their prototype stage. As mentioned, some technologies are effective at emptying pit latrines in certain situations, but not others. For this reason, the search for the ideal pit latrine emptying mechanism is an ongoing process.

Pit latrine emptying technologies can be divided into three groups: manual, semi-mechanized, and fully mechanized. The manual group consists of buckets, shovels, and specialized scoops that require the user to manually remove the waste from the pit latrine. The waste is usually placed into containers for transport off site. The manual method is the cheapest form of pit latrine emptying but can be time consuming and exposes humans to the waste. Semi-mechanized pit emptying technologies utilize an apparatus to move the waste but are still powered manually (O’Riordan 2009). This group includes the MAPET system, which utilizes a hand powered piston pump that creates a vacuum in a tank mounted on a small pushcart (O’Riordan 2009). This system has been used for over two decades and has proven successful in certain conditions, such as the wet pits found in Dar es Salaam, Tanzania. Another prominent semi-mechanized technology that has been used in several developing countries is the Gulper, developed by Steve Sugden of the London School of Hygiene and Tropical Health. It is a very low cost and simple design that uses a human powered lever on the top of a pipe to move a foot valve up and down to draw the waste up and out of the pit through a wye fitting at the top of the pipe (O’Riordan 2009). It has proven successful with fairly liquid or low viscosity sludge but has had difficulties with the dense bottom sludge in wet latrines and with the entirety of the contents in dry latrines. Fully mechanized technologies use an engine or motor to power the mechanism used for emptying of the pit latrine. The most commonly known mechanism of this group is the vacuum tanker such as those often used in developed countries. They use a vacuum pump and a large storage tank mounted on the back of a truck to pull the waste out of the latrine through a hose and into a tank for transport. This design has several limitations in the developing world

including high costs, the inability to access certain locations, and its inability to pump very dense sludge or the contents found in dry pits. Several smaller and less expensive variations of the vacuum tanker have been developed to access the various pit locations and empty them quickly. Many of these have proven successful in different local situations but still fail in most cases to empty very dense sludge or dry pit contents. A summary of several current pit latrine technologies is shown in Table A.2 with corresponding photos in Figure A.5.

Table A.2 Characteristics of Current Pit Latrine Technologies

	Manual	Semi-Mechanized					
	Long Handle Tools	MAPET	Gulper	Nibbler	Gobbler		
Description	Shovels, pitchforks, and scooping mechanisms with long handles	A manual pump and small tank mounted on pushcarts	Manual hand pump	Chain and Scoop mechanism	Robust version of Nibbler		
Access to most locations	Good	Fair	Good	Good	Good		
Maneuverability within pit	Poor	Good	Poor	Poor	Poor		
Possibility of human contact with sludge	High	Low	Low	Low	Low		
Capital costs	Low	Moderate	Low	Moderate	Moderate		
Operating and maintenance costs	Low	Moderate	Low	Moderate	Moderate		
Pit emptying times	Slow	Moderate	Slow	Moderate	Moderate		
Design Complexity	Low	Moderate	Low	Moderate	Moderate		
Sludge emptying capabilities	<i>Water-like</i>	Poor	Good	Good	Poor	Poor	
	<i>Thick slurry</i>	Moderate	Good	Good	Good	Good	
	<i>Dense sludge</i>	Good	Poor	Poor	Moderate	Moderate	
Ability to empty high refuse	Good	Poor	Poor	Poor	Poor		
Source*	1,2	1,3	1,3	2,3	2,3		
	Fully Mechanized						
	Vacuum Tanker	Micravac	Dung Beetle	Vacutug	NanoVac	Evac	Pit Screw Auger
Description	A vacuum pump mounted on a motorized tanker	Micro vacuum tanker designed for uneven roads and poor access	Two wheeled tractor connected to small vacuum tanker	Original smaller vacuum tanker with 500L tank	Small vacuum system with piston pump	Small vacuum system with vane pump	An auger or screw rotated within a pipe by a motor
Access to most locations	Poor	Fair	Fair	Fair	Good	Good	Good
Maneuverability within pit	Good	Good	Good	Good	Good	Good	Poor
Possibility of human contact with sludge	Low	Low	Low	Low	Low	Low	Low
Capital costs	High	High	High	Moderate	Moderate	Moderate	Moderate
Operating and maintenance costs	High	High	High	Moderate	Moderate	Moderate	Moderate
Pit emptying times	Fast	Fast	Fast	Moderate	Moderate	Moderate	Moderate
Design Complexity	High	High	High	Moderate	Moderate	Moderate	Moderate
Sludge emptying capabilities	<i>Water-like</i>	Good	Good	Good	Good	Good	Poor
	<i>Thick slurry</i>	Good	Good	Good	Good	Good	Good
	<i>Dense sludge</i>	Poor	Poor	Poor	Poor	Poor	Good
Ability to empty high refuse	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Source*	1,3	3	3	3	2	2	2

*Sources: 1: (Thye et al. 2011) 2: (Still and O’Riordan 2012) 3: (O’Riordan 2009)

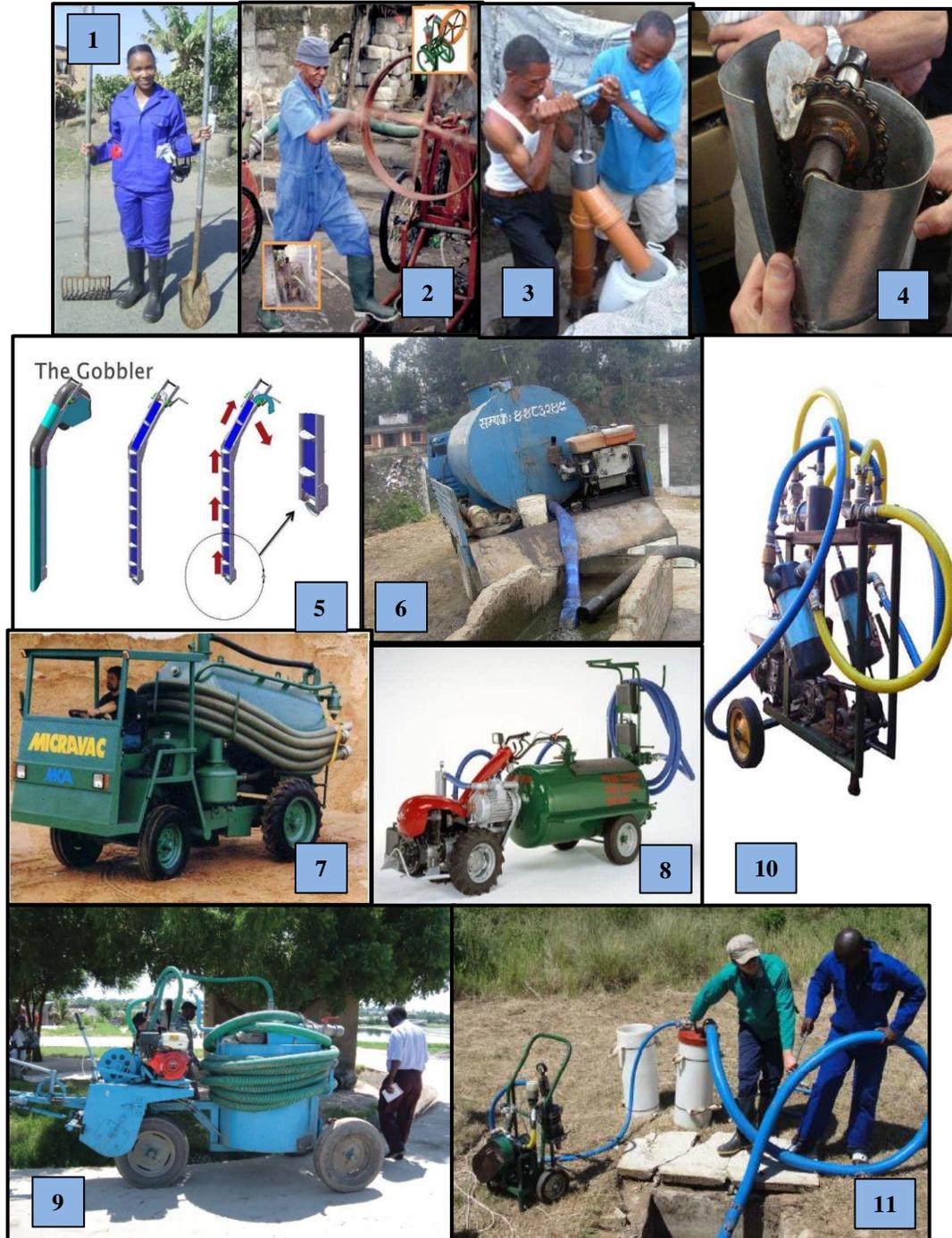


Figure A.8 Current pit latrine technologies described in Table 2. 1: Long handled manual tools, 2: MAPET system, 3: the Gulper, 4: the Nibbler, 5: the Gobbler schematic, 6: typical vacuum tanker, 7: the Micravac, 8: the Dung Beetle, 9: the Vacutug, 10: the NanoVac, 11: the EVac. Sources: (Thye et al. 2011), (Still and O'Riordan 2012), (O'Riordan 2009).

A.5.1 Pit Screw Auger

Another fully mechanized technology that has been developed by Dave Still, Mark O’Riordan and the Partners in Development team is the Pit Screw Auger. This design is very similar to the Extraction Auger and is based on the main principle of an auger being rotated within a pipe to lift the waste out of pit latrines. We were unaware of their research for a majority of our design and prototype development stage, but their findings, some very similar to ours, have proven very helpful as we move forward with our project.

The initial testing of the Pit Screw Auger on pig waste slurry was completed in a semi-mechanized fashion with the operator physically turning the auger. This yielded rotational speeds of only 50 to 60 rpm, which were not sufficient to achieve good output rates, so an electric motor was incorporated for higher speeds. They determined that there is a critical rotational speed that must be reached to achieve any flow and that above this rpm



Figure A.9 Pit Screw Auger being tested in a pit latrine (Still and O’Riordan 2012).

flow rates would increase with rotational speed. For their tests, they found this critical speed to be 60 rpm for a setup with a 700 mm long pipe with a 125 mm diameter and a 100 mm diameter auger with 100 mm pitch. However, they saw no increase in flow rate when they increased the rotational speed from 60 to 120 rpm, which remained at 25 lpm.

The pipe surrounding the auger was given consideration for improving the flow rate. The team tried using a helical lined pipe, but it showed no improvement in the flow rate and increased friction within the pipe. A hinged sleeve was produced to make it easy to remove trash that would often get jammed in the system. Insufficient clearance within the sleeve proved to cause enough friction to occasionally stall the electric motor. They found the amount of exposed auger, choke, to be 5 – 10 cm for significant sludge uptake, although they believe there to be a strong positive correlation between the choke length and flow rates produced. It is also stated that the choke length will be equal to the height of the sludge left in the pit and so a longer choke length will result in more sludge being left in the pit, which decreases the pit life. However, leaving a small amount of sludge in the pit can be beneficial as it provides a functional microbial population capable of speeding up the waste degradation process. The discharge at the top of the pipe is also addressed, as the sludge tends to continue upward and compact in the top of the system instead of moving out of the tee fitting. They propose using a small section of reverse flights above the discharge point to direct the waste out of the pipe and through the outlet. This has shown to work very well in our tests on the simulant waste and cow manure. In addition, as we found in our testing, continuous flights are needed from the inlet to the outlet to produce flow, so a gap between sections of flights will not suffice. Testing was conducted in pure pig slurry and pig slurry with the addition of

newspapers, rags, and plastics. It performed very well in all of these tests with flow rates between 25 and 40 liters per minute although they did see a decrease to 5 lpm was observed as the pit near being emptied. However, when testing on an actual pit latrine, the Pit Screw Auger was unable to remove any waste as it became immediately jammed with trash present in the pit.

Several other variations of the Pit Screw Auger were observed including different outlet hoses, the ability to extend the system, and the support to hold the system in place. In their evaluation of the Pit Screw Auger, the team determined the system to have several advantages that would encourage further testing. A diagram of the pros and cons the team found with the Pit Screw Auger is shown in Figure A.10. They provided several suggestions

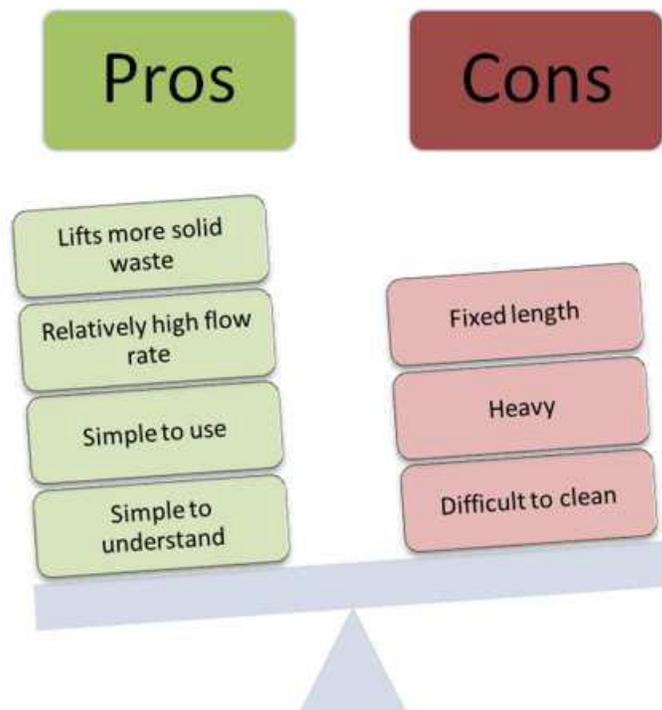


Figure A.10 Pros and cons of the Pit Screw Auger design.

based on the problems they encountered and foresaw which are summarized below (Still and O’Riordan 2012):

- **Trash in pits:** remove as much trash as possible before emptying is started or develop a waste shredder to shred all the waste before it enters the pit.
- **Reduce weight and improve maneuverability of system:** Use a smaller diameter auger or have a system where the motor is separate from the control unit.
- **Modularity:** Having a unit that is assembled in sections may facilitate too much contact between the user and waste. Having different length of auger and corresponding pipe for the different pit depths that may be encountered may be a good option.
- **Extension:** Having a system capable of lifting a total length of 2.8 m should work for most pits encountered.
- **Storage and Transportation:** Appropriate and ideal containers in addition to storage and transport methods should be identified.
- **Cleaning:** Develop equipment specifically for cleaning the auger system as it currently causes too much contact between the waste and user.
- **Support:** Develop a support that allows for good horizontal and vertical maneuverability and a support that will allow the system to be manipulated inside a toilet superstructure if necessary.
- **Accessing the pit:** If the auger is at fixed length, a method must be developed for how to empty pit latrines that do not have outside access and must be emptied from inside the superstructure

APPENDIX B – Laboratory Testing

B.1 Formulation of Simulant Waste

Little data has been gathered on the mechanical properties of human waste, especially in pit latrines. It is known, however, that human waste exhibits thixotropic tendencies implying that it becomes less viscous as more energy is put into the material (Mara 1984). A simulant waste was desired for laboratory testing that was analogous with the mechanical properties of human waste. Several formulations of simulant waste have been developed, to evaluate the use of human waste for biodegradation, energy production, etc.

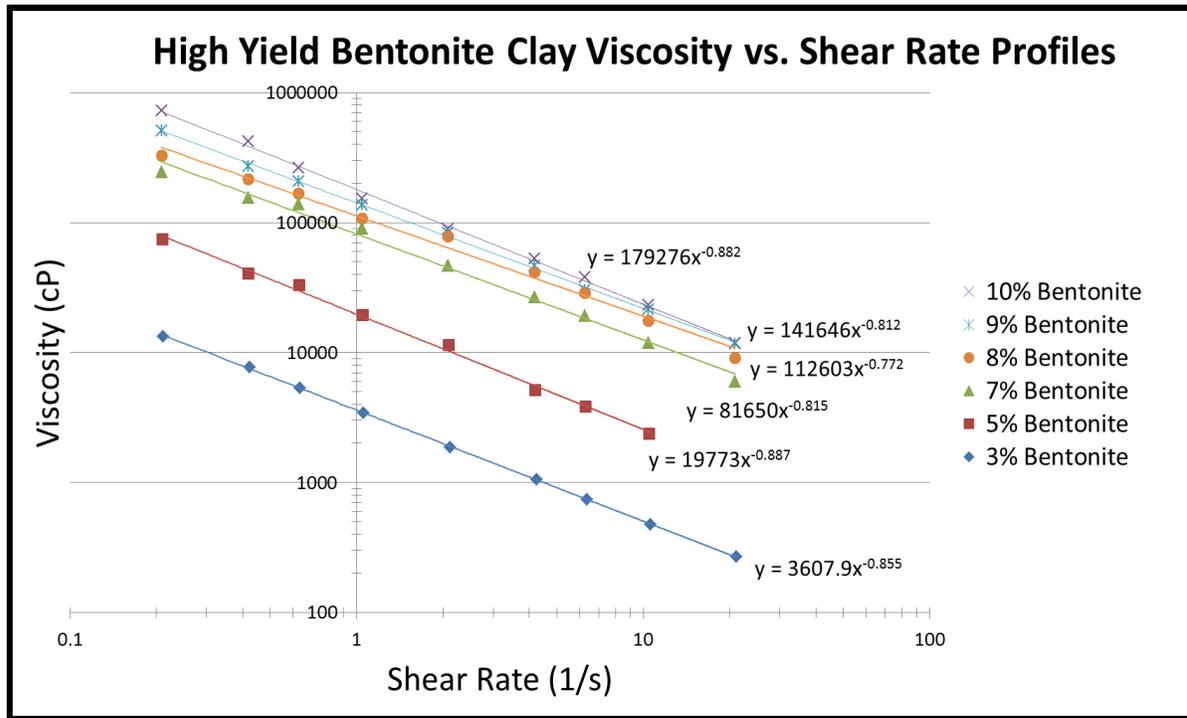


Figure B.1 Viscosity versus shear rate profiles for the high yield bentonite mixtures used for simulant waste.

In this project, simulant waste was prepared from a mixture of water and extra high yield bentonite clay (WYO-BEN Inc., Billings, MT). High yield bentonite is a powdered form of the clay that is an efficient viscosifier and mixes easily. A homogeneous mixture could not be easily prepared with the pellet form of bentonite.

To quantify the thixotropic nature of the bentonite clay, a range of mixtures were measured with a DV-E Brookfield Viscometer. Figure B.1 shows the viscosity versus shear rate curves for six different mixtures of bentonite ranging from 3 to 10% by weight. The increasing concentrations of bentonite correlate with increasing viscosities and all of the mixtures exhibited similar shear thinning (thixotropic) qualities. The figure also indicates that the change in viscosity with increasing bentonite concentration begins to diminish quickly above a solids content of 8%. For easy management, three mixtures of 5, 6, and 7% bentonite by weight were chosen for final lab testing. Stuart Woolley (personal correspondence, 2013) reported that fresh human feces with a 80% moisture content have viscosities that vary from approximately 2×10^9 to 2 centipoise (cP) as a function of shear rate. The slope of the shear versus viscosity curve is similar to the bentonite mixtures but a viscosity of about 65000 cP higher than the 7% bentonite mixture at a shear rate of 1/s. We have assumed that mixtures of human feces, urine and water present in pit latrines would have viscosities similar to mixtures of bentonite and water with 3% to 7% solids.

Table B.1 Viscosity measurements of bentonite mixtures for varying shear rates completed with a DV-E Brookfield Viscometer.

	3% Bentonite			5% Bentonite			7% Bentonite		
Speed (rpm)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)
1	0.212	44.50%	13350	0.21	61.60%	73900	0.209	40.60%	243500
2	0.424	51.50%	7720	0.42	67.40%	40430	0.418	50.40%	154800
3	0.636	53.40%	5339	0.63	82.50%	32990	0.627	69.10%	138800
5	1.060	57.20%	3437	1.05	80.70%	19360	1.045	75.10%	90100
10	2.120	62.30%	1872	2.1	94.50%	11340	2.09	76.20%	46370
20	4.240	70.00%	1050	4.2	89.50%	5153	4.18	88.50%	26540
30	6.360	73.60%	736	6.3	96.70%	3843	6.27	96.30%	19260
50	10.600	79.10%	475	10.5	98.70%	2385	10.45	97.80%	11780
100	21.200	89.30%	269.4	N/A	N/A	N/A	20.9	98.90%	5980
	8% Bentonite			9% Bentonite			10% Bentonite		
Speed (rpm)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)	Shear Rate (1/s)	Torque	Viscosity (mPa*s)
1	0.209	27.20%	326000	0.209	42.70%	512000	0.209	60.30%	723000
2	0.418	36.00%	216000	0.418	43.40%	271100	0.418	70.50%	423500
3	0.627	42.00%	168000	0.627	52.00%	206800	0.627	65.80%	263100
5	1.045	44.50%	106800	1.045	56.80%	136300	1.045	65.30%	153300
10	2.09	64.70%	78500	2.09	69.00%	83600	2.09	73.50%	88500
20	4.18	68.00%	41400	4.18	78.00%	46400	4.18	88.50%	53000
30	6.27	71.70%	28600	6.27	75.00%	30100	6.27	93.70%	37800
50	10.45	73.30%	17600	10.45	89.00%	21400	10.45	96.80%	23300
100	20.9	76.00%	9130	20.9	97.00%	11700	20.9	98.00%	11800

The procedure for measuring the viscosities of the bentonite-water mixtures is as follows:

Creating the bentonite mixtures:

- 1) Add half of the water for each mixture into an industrial blender.
- 2) Add appropriate amount of bentonite to blender.
 - a. Samples were a total weight of 600 g.
- 3) Add remaining water.

- 4) Cover with lid and mix for at least one minute or until homogenous mixture is obtained.
 - a. Mixtures greater than 7% bentonite became too viscous after approximately one minute of mixing and stopped the blender from turning. However, the mixtures still appeared to be well mixed and homogenous.
- 5) Pour mixtures into mason jars for viscosity testing.

Viscosity Testing:

- 1) Check that viscometer is level.
- 2) Attach appropriate spindle.
 - a. May have to change spindle depending on how viscous the material is to get a reading for each rotational speed.
 - b. Spindle numbers used: 3% bentonite (62), 5% bentonite (63) 7% bentonite (64) 9% bentonite (64).
- 3) Lower the spindle into the mixture to the indicated mark.
- 4) Start at low rotational speed and progress to the highest setting.
 - a. Range for this experiment: 1 rpm – 100 rpm.
- 5) Record first viscosity reading after a measureable reading is reported.
 - a. It was noticed that the viscosity reading would continue to drop over time at each rotational speed, so the first available reading was taken to be systematic.
- 6) Calculate shear rates from the rotational speeds based on the geometry of the spindle (Brookfield n.d.).

Making the bentonite mixtures for laboratory testing in 210 L drums on dollies allowed for easy transport around the lab. 126 liters of water was added to the drums (about two thirds of the volume of the drum). The appropriate amount of bentonite for the desired concentrations was added. A green lightning 0.5 HP Baldor electric mixer was used at high speed for 5 -10 minutes until mixture was homogenous. A paint mixer with a Milwaukee 10-amp electric drill was later used for mixing and proved more efficient at mixing the highly viscous material. After mixing and between testing the drums were sealed with locking lids.

Solids Content Procedure

After each day of testing with the bentonite clay, subsamples were taken to determine the actual solids content by the following process:

- 1) Take sample from well-mixed area from the top of the bentonite in the drum.
- 2) Measure weight of two crucibles for each bentonite mixture.
- 3) Transfer the bentonite mixtures into the crucibles (two crucibles per bentonite mixture).
- 4) Place in 105 °C oven for at least two hours.
- 5) Remove from oven and weigh crucibles.
- 6) Place back in 105 °C oven for at least one more hour.
- 7) Remove from oven and weight crucibles again.
 - a. Check for mass stabilization, if more mass has been lost; return the samples back in the oven.

Solids content could vary slightly between testing days from incidental water addition and loss of mass during cleaning.



Figure B.2 7% bentonite clay mixture in a 210 L drum.

B.2 Initial Design Process of Extraction Auger

Several iterations of the Extraction Auger were evaluated before reaching the design that was used for the final laboratory testing. These iterations can be summarized as follows:

- 1) First Iteration Components
 - a. 43cc 2-cycle earthquake power auger (Lowe's Home Improvement Inc.)
 - i. Maximum of 300 RPM
 - ii. 47 ft-lbs. of torque
 - iii. 30:1 gear ratio
 - b. 4 inch metal earth auger bit (Lowe's)
 - i. 4-inch standard pitch (standard referring to the outer diameter of the auger being equal to the pitch).

- ii. Flights covered approximately 50% of total lift length when assembled.
- c. 4 in PVC pipe (Lowe's)
- d. 4 in PVC sanitary tee fitting with 2-inch outlet
 - i. 2-inch flexible PVC hose with cam-lock fittings was attached to the 2-inch outlet.
- e. Fabricated attachment piece (Sun Machine Inc.)
 - i. Made from durable nylon material, although other materials could be used
 - ii. Equipped with a 2-inch ball bearing that contained a connecting shaft that attached the outlet shaft of the engine to the auger bit. The bearing was installed to keep material from entering the engine mounting and instead force it out through the tee fitting.
 - iii. The initial piece was made so that the top 2 inches of the tee fitting was fastened to its exterior.

The initial prototype was tested at a vertical orientation in water and 4.0%, 5.1%, and 6.3% bentonite mixtures. When testing with this auger bit, maximum rotational speeds were observed at approximately 260 rpm as measured by a contact digital tachometer (ENM Company) that was attached to the spark plug of the gas engine. No flows were produced for any of the mixtures. However, some rise in the fluid level above the top of the auger flights were observed for all three bentonite mixtures. This indicated that a version with continuous flights running to a level at or above the outlet was needed.

2) A continuous flighted 4-inch metal drilling bit (Giddings Machine Inc.) was obtained and attached to the current design. This setup was also tested on the 4.0%, 5.1%, and 6.3% bentonite mixtures. Maximum rotational speeds for this setup were approximately 240 rpm due to more friction between the auger bit and pipe. This friction was due to the thicker, heavier metal auger bit in addition to the excess surface area in contact with the pipe due to the continuous flights. Flow from the outlet was finally observed in the 6.3% bentonite mixture. However, the pipe containing the auger would wobble significantly causing the auger to bind within the pipe and stop spinning. Due to this inconsistent rotation, flow rates were not attained.



Figure B.3 Initial prototype of the Extraction Auger.

3) Two problems were addressed in the third iteration of the design. First, the fabricated attachment piece was redesigned so that top 2-inch of the tee and 4 additional inches of pipe would slide into the interior of the attachment piece. This allowed for rubber O-rings to be placed around the 4 in protruding section of pipe, which created a seal upon sliding the pipe into fabricated attachment piece. The pipe was held steady by four 3/8-inch bolts that were threaded through the attachment piece and fit into small groves drilled into the pipe exterior. These bolts were oriented below the O-ring seals and did not penetrate into the pipe to avoid leaking. This stabilized the pipe and minimized the wobble produced from the auger rotating inside. Secondly, the heavy auger (1 kg per feet of shaft) and cumbersome drilling bit was replaced with a 4-inch diameter high-density polyethylene (HDPE) plastic auger with a stainless steel center hex shaft (Lundell Plastics Inc.). This auger is much lighter (0.5 kg per feet of shaft), cheaper (\$21.17 per feet), causes less friction within the pipe, and is easier to clean. The hollow hex shaft allowed it to be slid tightly over a 7/8-inch shaft that was connected to the output shaft of the motor and protruded 6-inch below the attachment piece for an easy connection. Two 5/16-inch bolts were used to attach the auger shaft to the 7/8-inch output shaft. Figure B.4 shows a schematic of the initial design and the basic assembly. After these modifications, the mechanism began operating efficiently and tests were initiated to test the capabilities of the Extraction Auger.

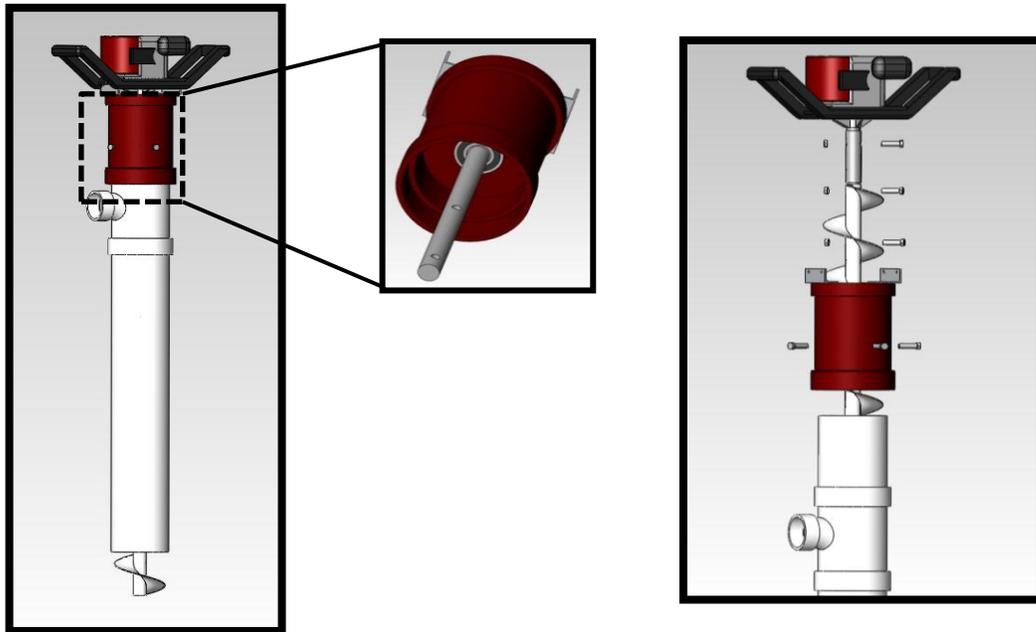


Figure B.4 Initial Extraction Auger design (left), fabricated attachment piece (center), and exploded view of the assembly (right).

B.3 Laboratory Setup

A Dayton 1 HP electric motor with adjustable speed replaced the 43cc 2-cycle gasoline engine for lab testing to observe the effect of the rotational speed on the pressure head and flow rates produced. A metal stand was constructed to hold the motor vertical and was hinged to make switching between bentonite mixtures easier. The stand also facilitated adjusting the height to allow for different lift heights of the Extraction Auger from the surface of the bentonite mixtures. Due to spatial constraints in the lab a 5 foot section of the HDPE auger was used translating to a 5-ft total lift. A 2-inch flexible PVC hose connected to the sanitary tee fitting with cam-lock fittings to recycle the flow back into the drum. An air vent was added at the outlet of the sanitary tee fitting to prevent suction from occurring. A

hole was drilled in the fabricated attachment piece to enable a laser tachometer to measure the rotational speed from a piece of reflective tape placed on the shaft. To evaluate the capabilities of the Extraction Auger, the flow rates and pressure head throughout the lift were measured for varying rotational speed, choke length, and lift height. Choke lengths of 2 and 4 inches were chosen in addition to lift heights of 105 and 120 cm (before running the auger) which were driven by the spatial constraints within the drum. The pressure head produced throughout the lift was measured by manometer tubes at designated heights (schematic in Figure 3.1) with elbows tapped into the pipe and clear 3/8 in hose. Flow rates were measured with by filling a 5-gallon bucket to a designated volume and timing with a stopwatch.

The laboratory testing procedure went as follows:

- 1) Assemble Extraction Auger on the metal stand.
- 2) Place Extraction Auger into 5% bentonite mixture drum and adjust the stand to the deep submergence setting.
- 3) Turn on electric motor and adjust to approximately 100 rpm. The rheostat was sensitive so getting rotational speeds to exact numbers proved difficult. The goal was to obtain measurements at five speeds between 100 and 500 rpm, which cover the range speeds of most any mechanical or hydraulic drive motors that would be used in the field.
- 4) Measure the rotational speed using the laser tachometer through the hole drilled in the fabricated attachment piece.

- 5) After steady state is reached (usually a few seconds after the speed is set), measure the height of the bentonite clay in the drum in addition to the height in each of the manometer tubes from the center of the respective elbow.
- 6) Use a stopwatch to measure the time that is taken to reach an indicated mark in a 5-gallon bucket. Empty the bucket back into the drum and wash out remnants.
- 7) Repeat steps 4 – 6 for duplicate measurements.
- 8) Adjust rheostat to next speed setting and repeat steps 4 – 6.
- 9) Repeat steps 4 – 8 until measurements have been taken for all five speed settings.
- 10) Adjust stand to shallow submergence setting and repeat steps 3 -9.
- 11) Repeat steps 2 – 10 for 6 and 7% bentonite mixtures.
- 12) Complete steps 2 – 11 for 2 and 4-inch choke lengths.



Figure B.5 Bentonite clay mixture being lifted with the Extraction Auger and recycled into a 210 L drum. Notice the material exiting the hose is less viscous than the material that is stationary in the drum due to the bentonite clay's thixotropic properties.

The effectiveness of using a double helix inlet tip was also tested in the lab (Figure B.6). An 8-inch section of metal double helix bit was attached to the bottom of the HDPE auger but the total auger length of 5 feet was maintained. This setup was tested with a 2 and 4-inch choke length but only at the deep submergence and with no pressure readings. The purpose of the test was to determine if the double helix would bring more material into the pipe, increasing the flow rate. This setup was tested in the same 5, 6, and 7% bentonite drums used in previous laboratory testing. Actual measured bentonite concentrations for this series of tests were 4.96, 5.92, and 6.98% respectively.

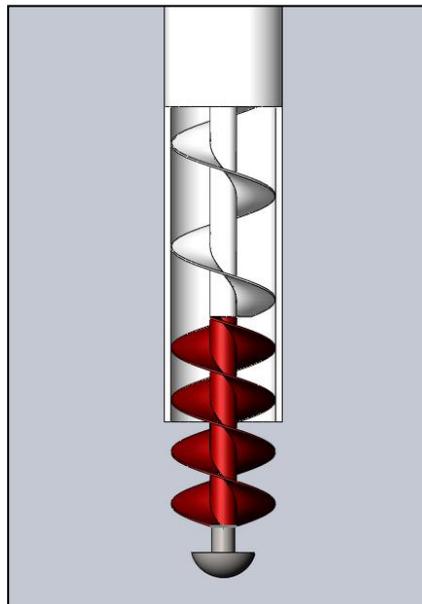


Figure B.6 Schematic of the inlet of the Extraction Auger with the metal double helix bit.

B.4 Results

Of the parameters tested, rotational speed and the viscosity of the material had the greatest effects on the pressure head generated and the flow produced. For the 5% and 6% bentonite mixtures, a threshold of at least 200 rpm was required to produce any flow and speeds of over 300 rpm were needed to produce flows significant enough to be used in the field. The more viscous 7% bentonite mixture produced significant flows of over 20 lpm for every parameter tested. This rotational speed threshold can be explained by Roberts (2001) theoretical output for screw conveyors (Equations 1.1 – 1.3). For any flow to occur, a positive effective helix angle, λ_e , needs to be obtained to achieve a vortex efficiency greater than zero. The derivation of flow based on Roberts's equations predicts negative flows for low coefficient of friction values due to the resulting negative effective helix angles. As negative flows are impossible, it can be assumed that negative approximations of flow are zero flow. Roberts's theoretical approximation for flow through a screw conveyor and the observed flows in laboratory testing indicate that the more viscous wastes would be lifted at higher flow rates as long as there is enough power available from the drive unit due to higher coefficients of friction. This data would also suggest that the Extraction Auger would lift fresh human feces (mentioned in section B.1) and the dense bottom sludge described in most latrines at significantly high flow rates.

Positive correlations were also found between the pressure generated throughout the lift and increasing rotational speeds and viscosity. However, the greatest pressure head produced at the outlet was only 14 cm. Figures B.7 and B.8 show the minimal amount of the pressure head produced at the outlet and throughout the lift. These findings suggest that the

Extraction Auger is capable of lifting waste at a high rate, but once it reaches the outlet it must flow by gravity through the outlet hose. Therefore, transport containers must be within a few meters of the outlet and at a height lower than outlet.

The double helix test resulted in flow rates that followed similar patterns to initial testing. However, significantly less flow was produced when compared to the single flighted auger (Figure B.9). At the maximum rotational speed and viscosity, a 50% reduction was noticed between the single and double flighted augers. This would suggest that the double helix actually disturbed the movement of the material into the pipe instead of bringing more material into the pipe.

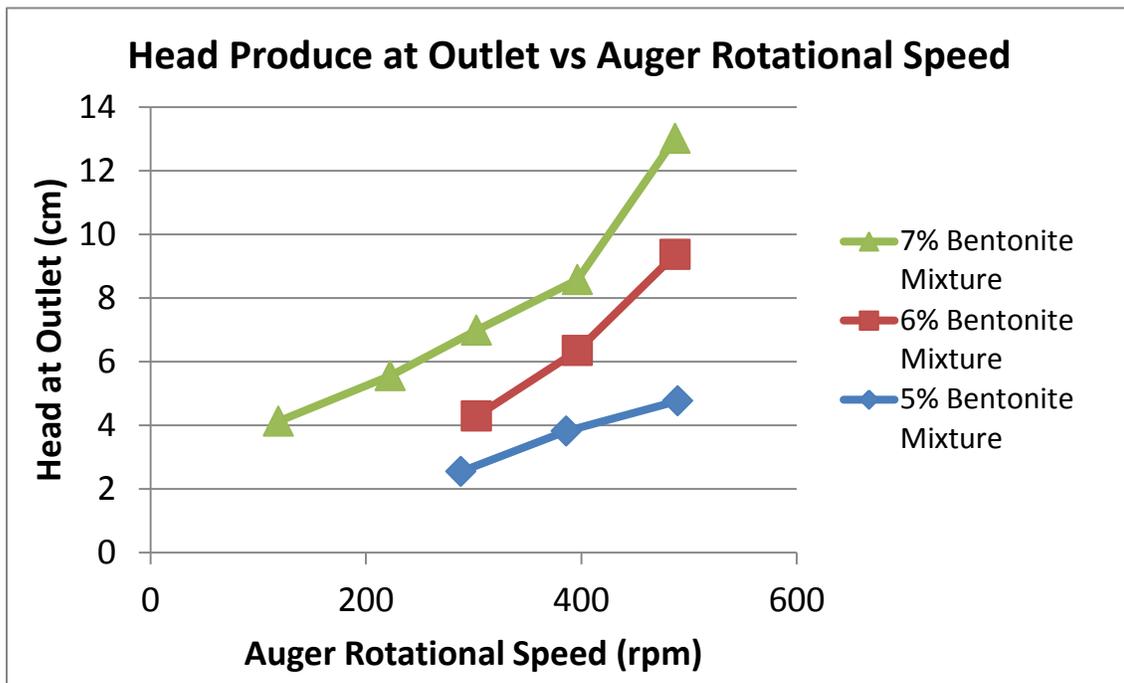


Figure B.7 The head produced at the outlet (port 4) for varying bentonite concentrations at the deep setting (105 cm lift height) and with a 5.1 cm choke length.

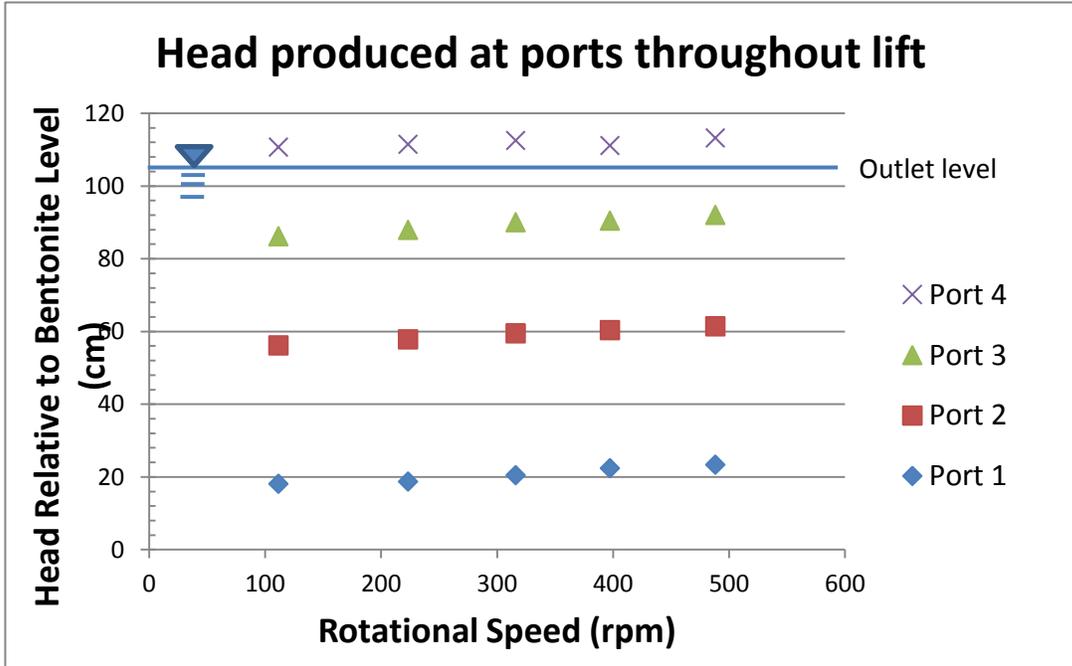


Figure B.8 Head produced at each port for the 7% bentonite mixture, deep setting (105 cm lift height), and 10.2 cm choke length.

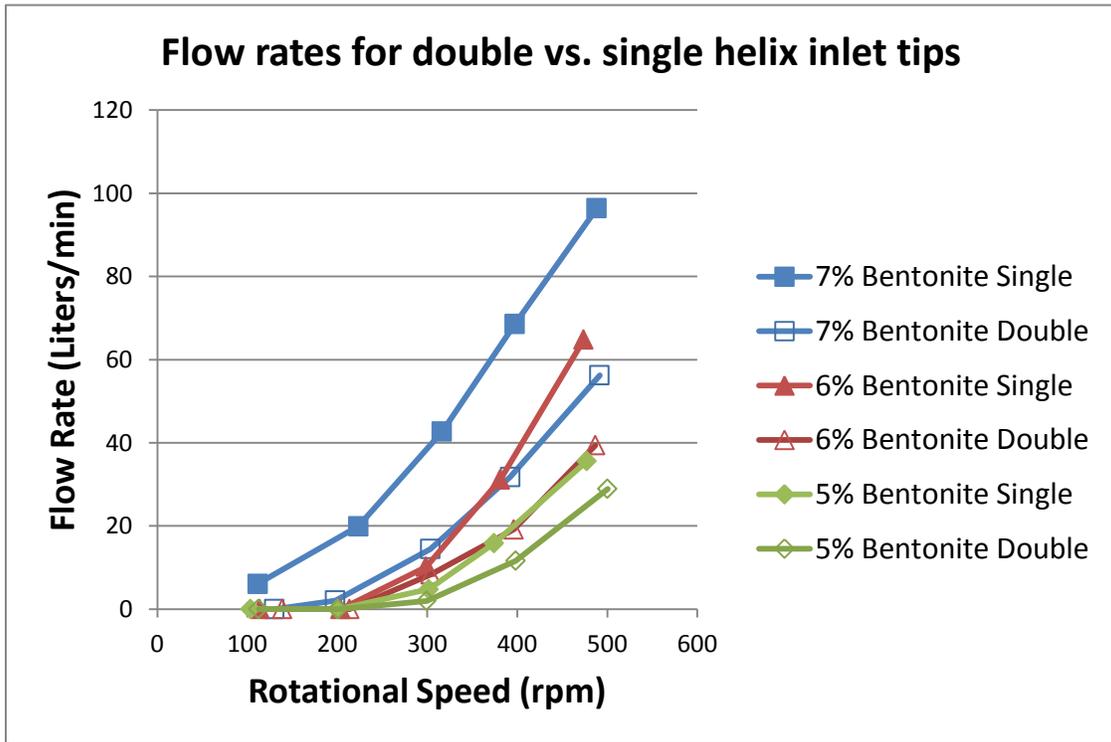


Figure B.9 Flow rates produced for single versus double helix metal inlet tips at the deep setting (105 cm lift height) with a 10.2 cm choke length.

APPENDIX C – Field-testing

C.1 One man 43 cc 2 HP Mechanical Drive Engine

C.1.1 Description

Engine:

- Viper 2 HP Engine
- Maximum 300 rpm
- 45.5 ft. * lbs. output shaft torque
- Weight: 32 lbs. (77 lbs. fully assembled with a 2.7 m auger length)

This setup was identical to the lab testing setup with the exception of replacing the electric motor with a 43 cc 2-cycle gasoline engine. A 4-inch x 4-inch x 2-inch sanitary PVC tee was used for the outlet at the top of the PVC pipe and had a 6-inch piece of pipe glued into the top of the tee. Two rubber O-rings were placed around the top 6-inch section of pipe so that upon placing the tee into the fabricated attachment piece, a seal was created to prevent leaking. The HDPE auger and bottom portion of PVC pipe were cut according to the intended length and choke length desired for the specific pumping situation described below. A 1-inch steel ball was welded to a shaft that protruded approximately 2-inch below the auger to prevent the auger from digging into the subsoil or being damaged from a cement-bottomed pit.

C.1.2 Rogers Farm Testing

Once the Extraction Auger was proven in laboratory testing, the functionality of the machine was evaluated in a field setting on a local North Carolina farm. Two simulated pits were constructed from 5-ft sections of 18-inch PVC pipe buried in the ground at a vertical orientation. Cement was added to the bottom of these pits to keep water from draining out through the bottom of the pit. Another simulated pit was constructed from two 210 L drums fastened together with a total height of 5-ft. The Extraction Auger was tested in three different mixtures: a 10% bentonite mixture, a 7% bentonite mixture, and a 7% bentonite mixture with the addition of horse manure. To create these mixtures in the pits:

- 1) The pits were filled to approximately 90% with water.
- 2) High yield bentonite clay was added to reach the desired concentrations
- 3) The pits were filled to the top with water.



Figure C.1 10% bentonite mixture being mixed in a simulated pit.

- 4) The contents of the pits were mixed with an electric drill and paint mixer until a homogenous mixture was obtained (Figure C.1).
- 5) Two wheelbarrow loads of horse manure were added to the 7% bentonite mixture after testing was complete on the pure 7% bentonite mixture.
 - a. The horse manure was mixed in with the bentonite using a shovel until the manure was mixed throughout the pit (Figure C.2).



Figure C.2 7% bentonite mixture with the addition of horse manure.

To facilitate emptying directly into a drum, the Extraction Auger was cut for an 8-ft length from the bottom of the auger to the outlet. This length would allow the auger to rest on the bottom of the pit and be high enough out of the pit to be above the 3-ft tall drum for where the material was to be emptied. The exterior pipe was cut to have a 2-inch choke length since there were no materials with the pit that would be able to clog up the inlet.

The 7% bentonite pure and with horse manure mixtures produced very similar flow rates that were observed in the lab with flows up to 49 lpm at a lift height of 3 – 4-ft. However, when testing in the 10% bentonite mixture, the 43cc engine lifted the material through the pipe and out through the hose but stopped rotating after only a few seconds. The higher viscosity material appeared to put too great of a strain on the motor, causing it to stop rotating. This indicated that a more powerful engine was needed to lift highly viscous materials over greater lengths. Removing the Extraction Auger from the pit proved difficult, as the pipe would still have a large amount of waste within the pipe, which greatly increased the weight. This also made cleaning very difficult, as it proved difficult to clean and disassemble the mechanism without coming in contact with the waste. For these reasons, future designs incorporated a reverse mechanism that would not only allow most of the material to be emptied from the pipe upon completion but also allow for easy unjamming of solid waste materials.

C.1.3 Dairy Farm Testing

The setup with the 43cc engine was also tested at the NC State Dairy Farm. A mixture of cow manure and wood shavings used for cow bedding were settled in a 29-inch cement basin. The mixture was completely saturated by standing water present in the basin. The water level in the basin was at 18 in from the bottom. Using an auger length of 6 feet allowed at least three feet above the edge of the basin for emptying into a 210 L drum. This version of the Extraction Auger was operated at maximum speed for several minutes but did not produce any flow from the outlet. The engine would also stop rotating frequently from the load of the material within the pipe. Upon removing the exterior pipe, it was observed

that the material had been lifted but instead of moving out through the 2-inch tee, it became compacted in the fabricated attachment piece. This occurrence can most likely be attributed to the high solids content of the material. As the material is lifted, most of the water is drained through leakage around the periphery of the pipe causing the lifted material to lose most of its flow properties. The material will therefore not flow freely out of the tee like the bentonite mixtures. Therefore, a solution was necessary to force the material out through the tee fitting. This issue was resolved by the installation of a 4-inch wye fitting coupled with a



Figure C.3 The Extraction Auger prototype with the 43cc 2 HP engine recycling dairy waste from the settling basin after the addition of the section of reverse flights.

short section of reverse flights above the outlet to force the material out of the pipe (Figure C.4) (Still and O’Riordan 2012). After these modifications were made, this version of the Extraction Auger performed well and produced significant flow (Figure C.3). These modifications were also utilized in the later versions of the Extraction Auger. Although the 43cc engine performed well in this setting, it was obvious that a more robust engine would be needed for a mechanism that would be used for several hours on a day-to-day basis.



Figure C.4 Schematic of the reverse flights within the wye fitting (left) Metal double helix reverse flighted section before pipe is attached (right).

C.2 Hydraulic Drive Motor with Gasoline Engine

C.2.1 Engine and Hydraulic Motor

- 10.7 HP gasoline engine
- 110 ft-lbs. torque
- Maximum of 2000 psi
- Weight of hydraulic motor and mounting: 60 lbs. (106 lbs. fully assembled with 2.7 m auger length)

C.2.2 Dairy Farm Testing

The most promising of the Extraction Auger designs utilized a hydraulic motor powered by a 10.7 HP gasoline engine. This setup was able to produce high rotational speeds with the required torque to lift the highly viscous waste. The hydraulic motor also allowed for easy reversing for unjamming and cleaning. The hydraulic motor was attached to the fabricated attachment piece. Both of these were fastened to a fabricated mounting that included wrap-around handlebars for easy maneuvering (Figure C.5). The rest of the Extraction Auger mechanism incorporated the new modifications including the section of reverse flights, the 4-inch wye fitting at the outlet, and the single flighted metal auger inlet tip. A 6-inch choke length was used for all tests with the hydraulic unit to allow adequate material to flow into the pipe. The hydraulic motor was also equipped with a pressure relief valve that stopped the motor from turning if a certain pressure in the hydraulic lines was reached.

To better simulate the conditions that would be encountered when testing on actual pit latrines, a simulated pit was constructed. The simulated pit consisted of a 1-m³ container that was 3-ft wide x 4-ft long x 4-ft high. The container was filled with the waste from the dairy settling basin using a tractor equipped with a front-end loader. The material in the settling basin consisted of cow manure, water, and a small amount of sand that was used as

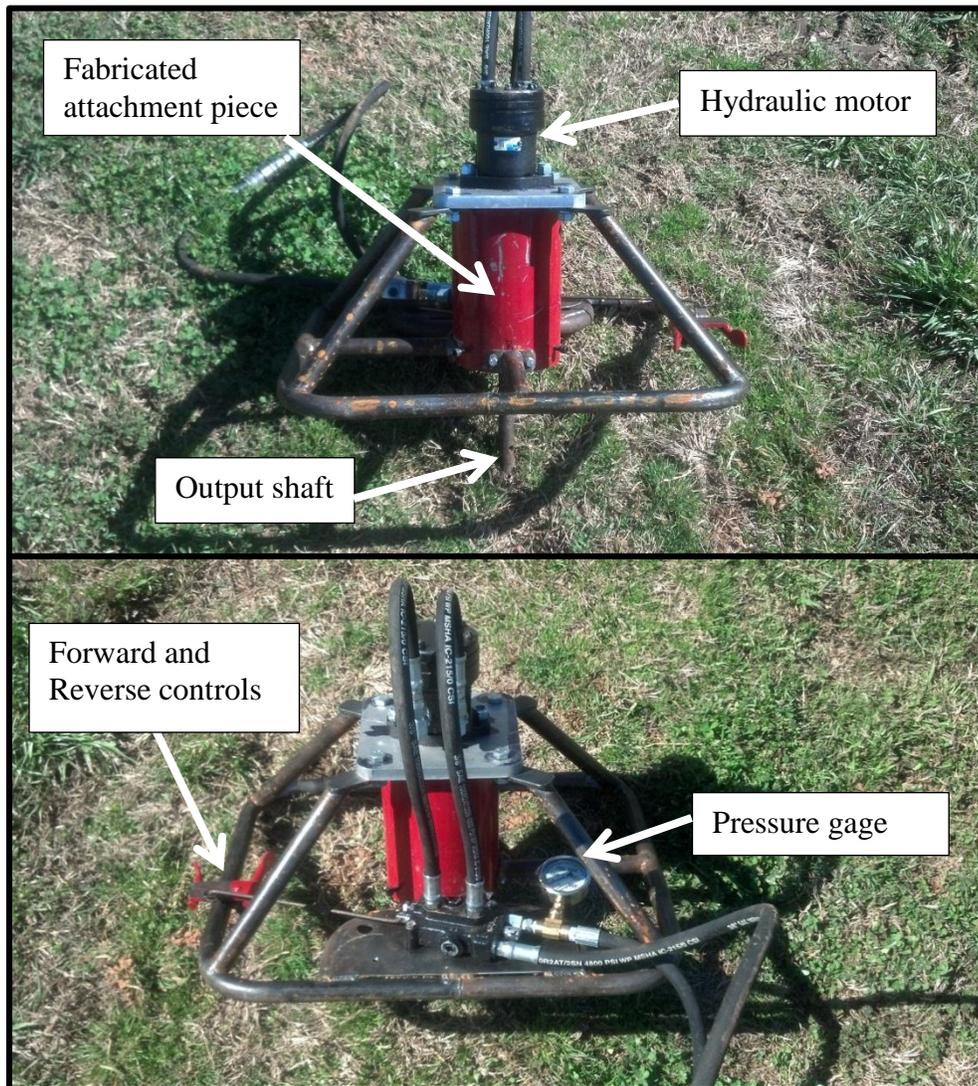


Figure C.5 Hydraulic unit mounting front (top) and back views (bottom).

an alternate to wood shavings for cow bedding. A lift equipped with a cage was used to lift the operators to a height that allowed the auger to be positioned at the bottom of the container (Figure C.6). An auger length of 8.8-ft (2.7 m) was used for testing which corresponds emptying into a 1 m high container from a 1.8 m pit in a field setting. Typical pit depths of 1.5 m to 2 m were reported by a personal correspondence in Pietermaritzburg, South Africa where field-testing of the Extraction Auger is scheduled for Spring 2013.

The hydraulic motor version of the Extraction Auger was capable of a maximum rotational speed of 450 rpm when assembled and operated in no material. The pressure relief



Figure C.6 Dairy farm setup to simulate emptying from a 1.8 m deep pit.

point was set at 1500 psi for initial testing. This setting proved to be too low as the friction caused from the material moving between the edge of the flights and pipe quickly raised the pressure above 1500 psi. Running the motor in reverse for only a few seconds would unjam the auger and allow it to run in the forward direction again. However, the pressure relief point would be reached again between 10 seconds and 1 minute later. This frequent occurrence would cause the loss of a significant amount of time and would be impractical in a real field application. To address this issue, two options were considered: Increasing the pressure relief point and increasing the clearance (distance between the edge of the auger flights and the pipe).

First, the pressure relief point was adjusted to its maximum setting without increasing the size of the hydraulic motor of 2000 psi. The auger clearance was left the same at a negligible distance as the auger made contact with the inside of the pipe. The unit performed well after this change with a steady state operation of approximately 1800 psi. However, the auger would still occasionally jam causing the hydraulic pressure to jump over 2000 psi and stop the auger from turning. This occurred less frequently as the reverse was only needed for unjamming every 1 to 5 minutes. Two inlet pipe formations were tested at this setting: a bare auger and a half pipe formation that was positioned on the bottom side of the auger during operation. The half pipe formation is similar to the common screw conveyor as the auger is gravity fed from the top and the half pipe does not allow material to fall through the bottom of the auger before it is lifted into the main pipe. The container was emptied to a designated mark that indicated 29% of the total auger length was submerged in the dairy waste which corresponds to a 2 m lift height. Rotational speeds of approximately 380 rpm were recorded

during operation. This is a reduction from the maximum recorded speed of 450 rpm due to the load on the auger and friction within the pipe from the material being pumped. Flow rates were then measured for each setup by timing the filling a 5 gallon bucket to a designated volume of 3.72 gallons (14.1 L) in triplicate. The bare auger produced the highest flow rates with an average of 127 lpm while the half pipe formation produced flows of 108 lpm. It is important to note that the half pipe formation had rotated slightly during the test so it was not directly on the bottom of the auger. The time for both setups to remove a volume of 91 gallons from a lift height of 2.0 m to 2.34 m was also observed. The bare and half pipe formations took 3.9 and 4.7 minutes corresponding to average flow rates of 88 and 73 lpm respectively. This would suggest that flow rates decrease as the pit is emptied and the lift height increases. It was also observed that flow decreased dramatically when the waste reached a level below the end of the pipe. At this point, it may be required to use a long shovel or tool to move the waste to the inlet. Smaller choke lengths may also be used to remove more waste from the bottom of pits; however, problems might be encountered if solid waste is present. Upon removing the pipe from the auger, significant marking or scoring of the interior of the pipe was noticed (Figure C.7). However, no cracking was observed throughout the pipe during testing with the exception of a very short piece at the inlet that was broken off (Figure C.8). It is assumed this was caused by an object being wedged between the edge of the auger and end of the pipe. Future testing could incorporate a short section of metal pipe at the inlet to prevent this occurrence in addition to possibly helping shear some of the larger materials entering the auger.



Figure C.7 Deterioration of a section of pipe after testing with the hydraulic motor in dairy waste.



Figure C.8 The inlet of the auger after a piece was snapped off when using the hydraulic motor in the dairy waste.

Secondly, the HDPE auger was shaved down to facilitate a clearance of $\frac{1}{8}$ -inch (3.2 mm). However, the metal section of auger at the inlet was not altered. A drop in steady state pressure was noticed to approximately 1200 psi when operating this setup. This drop in pressure would imply that a significant reduction in friction within the pipe was occurring due to the increased clearance. It should be noted that this setup recorded at steady state pressure of approximately 1600 psi on another testing date. The dairy waste used on this day appeared to be drier because the water from the settling basin had been drained upon arrival to the farm. The reduced friction also allowed a higher rotational speed of 410 rpm when compared to the smaller clearance. However, a smaller flow rate of 94 lpm was observed at the same 2 m lift height. This is most likely due to leakage at the periphery of the auger due to the increased clearance. The loss in flow would be expected to be more significant with less viscous or more free-flowing materials (Roberts 1964). Therefore, there is a tradeoff between the flow rate and operating hydraulic pressure. A larger clearance will allow for lower operating pressures meaning less deterioration of the auger and pipe and less power consumption. However, a larger clearance will reduce the flow rate (especially with more free-flowing materials) which will increase the emptying time. Studies of field operation on actual latrines over an extended period will be needed to assess the optimal operating setup of the Extraction Auger. However, both setups provide significant flows in addition to meeting many of the requirements of an adequate pit emptying device.

Both setups were also tested with the auger and pipe assembled in 4-ft sections, which allow for increased modularity in the field when encountering pits of different depths and/or only interior pit access. No noticeable changes in flow or functionality were observed

when using the sections of auger and pipe as compared to the full length used in previous tests.

The entire hydraulic unit prototype cost approximately \$3,000 - \$3,500 to build. This price would decrease dramatically if it were produced on a mass scale. Field-testing with the hydraulic unit on actual pit latrines with various waste makeups will be performed in Pietermaritzburg, South Africa in March 2013.

C.3 Two man 160 cc 5.5 HP Mechanical Drive Engine

C.3.1 Engine Description

- Honda GCV160 OHV
- Weight of engine and gearing mechanism: 117 lbs. (162 lbs. fully assembled with 2.7 m auger length)
- 5.5 HP
- Auger speed 120
- Torque 228 ft. * lbs.

C.3.2 Dairy Farm Testing

An alternative direct mechanical drive version of the Extraction Auger was also developed as a more powerful version of the original design that used the 43cc 2 HP engine. This prototype only cost approximately \$1,000 to build. This version of the Extraction Auger required several modifications to reach the necessary rotational speeds for significant flow rates and to equip the engine with a reverse mechanism. A gearing system including the

gearbox, an input shaft and output shaft sprocket were purchased through an online auction site from several sources. Aluminum housing was fabricated to hold the gearbox and input shaft in a vertical orientation. Toothed sprockets were machined to use $\frac{1}{2}$ -inch pitch toothed "timing" belts to increase the speed from 120 rpm to approximately 480 rpm measured at the auger and provide a reverse. The belts were tensioned by sliding the carrier on a mounting frame.

The reverse was added by using a standard "GY6 reversing gearbox". The "GY6" is a common 150cc engine-transmission combination that is used on many scooters and ATVs. The reversing gearbox is added externally on these engines for ATVs so that they may be reversed. The GY6 reversing gearbox is a planetary gear set. During forward operation, the input shaft is locked to the gear carrier so the output shaft turns at the same speed and direction as the input shaft. To engage reverse, a lever on the handle operates against a spring to unlock the input shaft from the carrier. This allows the planetary gears to function, reversing both the direction and speed of the output shaft relative to the input shaft. Releasing the lever on the handle then re-locks the carrier and rotation resumes in a forward direction. This system was mounted to the bottom of the 160cc Honda engine with aluminum framing (Figures C.9 and C.10). The mechanism was tested with the same setup as the hydraulic unit including the auger, pipe, and pipe fittings. A 2.7 m auger length with a 6-inch choke was tested in the same container and conditions as the hydraulic motor testing. The material in the settling basin consisted of cow manure, water, and a small amount of sand that is used for cow bedding.

After only a few seconds of operating this version of the Extraction Auger in the dairy waste, the ribbed belts began to slip and tear apart dramatically. The torque created from lifting the waste through the pipe appeared to put too much strain on the belts. This indicated the need to replace the rubber belts with roller chain and sprockets to withstand the strain applied during operation. Another issue noticed with this version is the weight of the engine and gearing mechanism (117 lbs.) which is cumbersome and requires at least two men to handle. Testing of this version of the Extraction Auger is still ongoing.

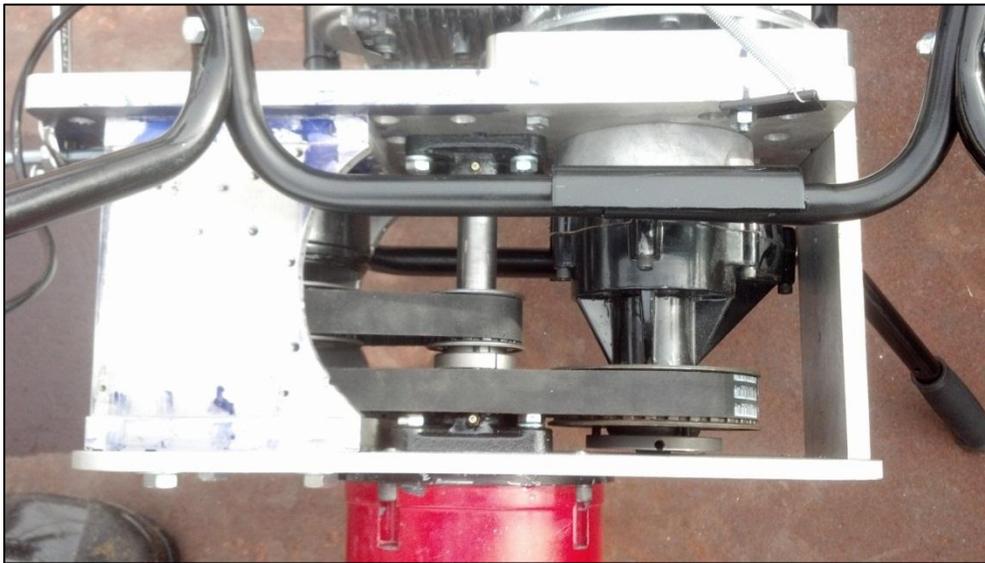


Figure C.9 Gearing and reverse mechanisms for 160cc engine setup.

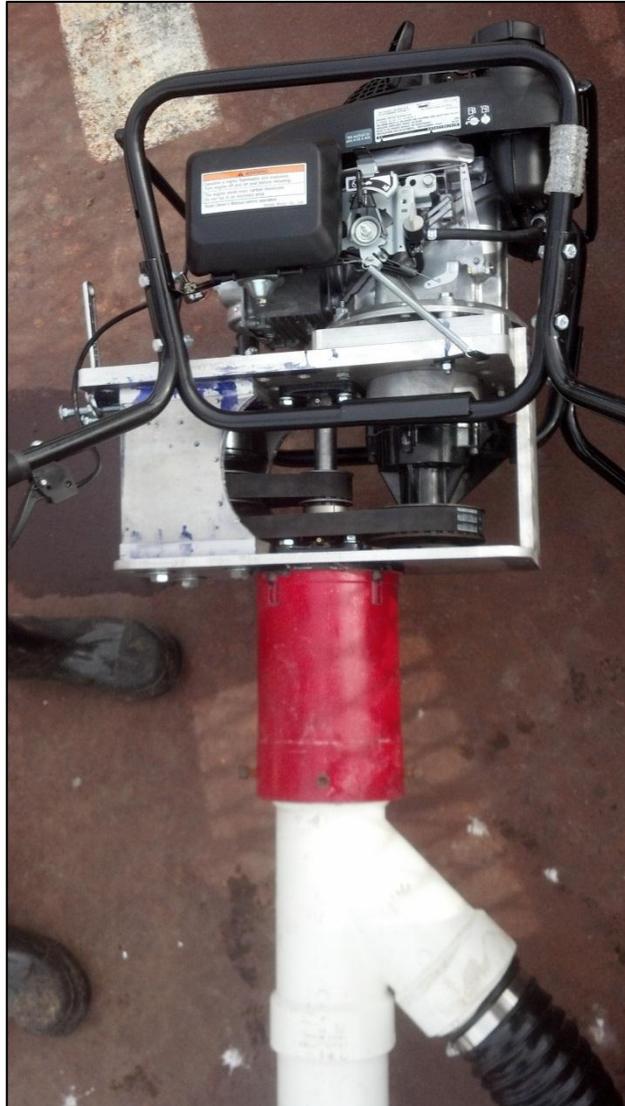


Figure C.10 Extraction Auger setup with the 160cc mechanical drive engine.

C.4 Moisture, Organic, and Inorganic Content of Dairy Farm Waste Procedure

To quantify the dairy waste tested at the NC State Dairy Farm a moisture content test was completed based on the following procedure:

1. The waste was collected directly from the 1-m³ container that was filled with dairy waste. The collection was completed based on the NCDA&CS Agronomic Division's Plant/Waste/Solution Section (Casteel 2005) suggestion for collecting from a liquid slurry which uses the following procedure:

“Premixing the slurry in a pit or storage basin prior to sampling is ideal. An eight to ten foot section [five foot section was used] of one-half- to three-quarter-inch PVC pipe can be used to collect samples. Insert the pipe into the pit, and then press a thumb over the end to create an air lock. Remove the pipe from the waste, place it over a container (i.e., clean, plastic bucket) and release the air lock. Do not rinse the sample into the container because dilution will distort results. However, if you plan to add water to the waste prior to application, then adding a proportionate amount of water to the sample is appropriate. Waste should be collected from several areas of the pit and mixed thoroughly. Transfer the thoroughly mixed slurry to a sample container (i.e., clean, beverage container) suitable for shipping. The container should be no more than two-thirds to three-fourths full to allow for expansion due to gas pressure.”

2. Four subsamples were taken and weighed in crucibles.
3. Crucibles were placed in 105°C oven for at least 24 hours.
4. Crucibles were removed from oven, weighed, and returned to 105°C oven for at least 24 hours.
5. Step 4 is repeated until the weight stabilized (less than a .05% difference from last weighing).

Crucibles are placed in 550°C oven for 24 hours, then removed and weighed.