April 2015

Redesign of the Sol-Char Toilet

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Redesign of the Sol-Char Toilet

APRIL 30, 2015

A Major Qualifying Project
Submitted to Faculty
of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

By Sandra Garcia-Fine

Approved by Professor Jeanine Plummer, MQP Advisor

Abstract

There is currently a worldwide sanitation crisis. Nearly 2.5 billion people do not have access to basic sanitation, and 1 billion people practice open defecation. Lack of sanitation causes diarrheal diseases, which were estimated to cause 1.5 million deaths in 2012. In response to the lack of basic sanitation in the world, the Bill & Melinda Gates Foundation initiated the Reinvent the Toilet Challenge (RTTC) in 2011. The challenge aims to engineer a completely unique toilet that follows criterion set by the Foundation. In September 2011, The University of Colorado (CU) Boulder was one of sixteen teams to receive a grant from the Bill & Melinda Gates Foundation. CU Boulder's research team developed a waterless, self-contained toilet that can function completely off the grid through the utilization of concentrated solar power. While the mechanical processes of the Sol-Char Toilet are functional, there is room for improvement. The current design is not economically feasible. This Major Qualifying Project looked at the pros and cons of the current design, developed alternative designs, and made a design recommendation from researching successful implemented toilet designs and speaking with professionals in the sanitation technology field.

Executive Summary

There is currently a worldwide sanitation crisis. Nearly 2.5 billion people do not have access to basic sanitation, and 1 billion people practice open defecation. Lack of sanitation causes diarrheal diseases, which were estimated to cause 1.5 million deaths in 2012. In 2000, the United Nations developed eight Millennium Development Goals (MDGs). One of these eight MDGs included the objective to halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation. Progress has been relatively limited. Since 1990, 98 million people have gained access to improved sanitation. Now in 2015, the sanitation MDG has not been met. For the MDG to have been met, 1.6 billion more people would have needed to gain access to improved sanitation.

In response to the lack of basic sanitation in the world, international efforts across all borders have been sparked. Organizations like the Bill & Melinda Gates Foundation have come together to help create a solution to the sanitation crisis. In 2011, the Bill & Melinda Gates Foundation initiated the Reinvent the Toilet Challenge (RTTC). The challenge aims to engineer a completely unique toilet that follows criterion set by the Foundation. It must remove harmful pathogens from human waste and recover valuable resources; operate "off the grid" without connection to water, sewer, or electricity; cost less than US $0.05 per user per day; and promote sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings.

Since the Challenge's inception, sixteen research teams around the world have been awarded grants. In September 2011, The University of Colorado (CU) Boulder was one of the sixteen teams to receive a grant. CU Boulder's research team developed a waterless, self-contained toilet that can function completely off the grid through the utilization of concentrated solar power. Eight parabolic concentrators focus sunlight through fiber optic cable bundles and transmit the solar power to an outer lid positioned over a waste collection container. The solar power illuminates the inner collection container and disinfects the waste through pyrolysis, a thermochemical decomposition process of organic material at high temperatures in the absence of oxygen. Through pyrolysis, the solid waste is transformed into biological charcoal and can be used as a soil amendment or alternative fuel. This unique toilet system is called the Sol-Char Toilet.

While the mechanical processes of the Sol-Char Toilet are functional, there is room for improvement. The current design is not economically feasible. The solar capture and solar transmission components comprise 80% of the total expense. The main objective of this Major Qualifying Project was to redesign the Sol-Char Toilet to mitigate the overall high cost of its production and develop a new design. The areas of focus for the new design included the overall cost, life expectancy, ease of use, aesthetics, maintenance, reactor efficiency, and safety. This novel sanitation technology has not been field tested to assess its feasibility in real life scenarios. In order to understand the success of new technologies in developing communities, case studies were researched. Also, people involved in sanitation development were interviewed to better understand design constraints of a solar powered toilet in developing communities.

Through research and interviews, four top designs were developed and then evaluated during a peer group discussion. All four designs were also weighted in a decision design matrix. The final recommendation for the next design phase of the Sol-Char Toilet was an above ground auger system. This design was the least expensive because of the shortened fiber optic cables. It also promotes financially profitable sanitation services and businesses, a criterion for the Reinvent the Toilet Challenge. The future of the Sol-Char Toilet relies heavily on the reduction of its production cost. Therefore, the design recommendations are intended to advance the unique Sol-Char Toilet project into the new phase of implementation.

Acknowledgements

I would like to thank my two project advisors, Professor Jeanine Plummer of WPI and Professor Karl Linden of CU Boulder, tremendously. I did not know what I was getting myself into when I decided to individually complete a MQP, but you both went out on a limb to support me and I could not have finished without your guidance and encouragement.

Thank you to Blake McKinlay of iDE for taking interest in my project and gathering helpful sanitation technology information from his colleagues at iDE. Thank you to Joseph DiMasi of BrightSpace Technologies for providing information on his company's novel solar technology and for being enthusiastic about my project and the future of the Sol-Char Toilet.

Thank you also to all those who helped me while I was in Boulder; whether it was sitting down with me to discuss my project in-depth or treating me to delicious C4C, you all made my transition to living in Boulder comfortable and my individual project less overwhelming. Thank you so much BJ Ward, TesfaYacob, Wyatt Champion, Laura Kohler, Lauren Hafford, and Alex Hyde-Wright.

Lastly, I'd like to thank my mother and Kristen Schleier for their never-ending love and support.

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"All the participants [of the Reinvent the Toilet Challenge] are united by a common desire to create a better world – a world where no child dies needlessly from a lack of safe sanitation and where all people can live healthy, dignified lives."

-Bill Gates (Gates Foundation, 2015)

Chapter 1: Introduction

There is currently a worldwide sanitation problem. Nearly 2.5 billion people do not have access to basic sanitation and 1 billion people practice open defecation. These poor conditions cause diarrhoeal diseases, which were estimated to cause 1.5 million deaths in the year 2012 (Prüss-Ustün *et al*., 2014). In response to these statistics, the Bill & Melinda Gates Foundation launched the Reinvent the Toilet Challenge in 2011. Sixteen research teams have been awarded grants to develop innovative toilet designs to combat the lack of sanitation in developing communities. The University of Colorado Boulder was one of the sixteen teams granted research funding to design their unique Sol-Char toilet.

1.1 Sanitation Issues around the World

In 2010, the UN General Assembly recognized access to safe and clean drinking water and sanitation as a human right. This sparked international efforts to help countries provide safe, clean, accessible and affordable drinking water and sanitation. In 2013, the UN Deputy Secretary General issued a call to action on sanitation that included the elimination of open defecation by 2025 (WHO, 2015).

The goal of universal access to basic drinking water is within reach with almost a quarter (24%) of the current world population having gained access to an improved drinking water source since 2000 (WHO and UNICEF, 2014). The Millennium Development Goal (MDG) drinking water target that was developed by the United Nations in 2000, to halve the proportion of the population without sustainable access to safe drinking water between 1990 and 2015, was met in 2010 (United Nations, 2015). However, the MDG sanitation target is likely not to be met in 2015. There are currently 46 countries where less than half of the population has access to an improved sanitation facility. A map illustrating this is shown in Figure 1.

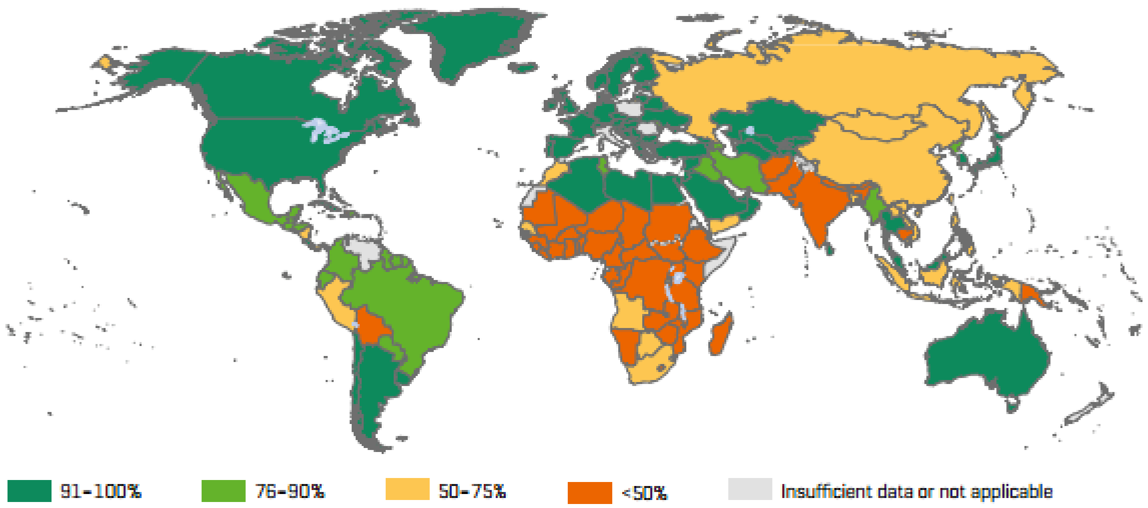

Figure 1: Proportion of the population using improved sanitation in 2012 (WHO and UNICEF, 2014)

There is still a need to improve sanitation. Poor sanitation conditions in countries around the world lead to diarrhoeal deaths and other health concerns. One third of the entire global population- some 2.5 billion people- do not use an improved sanitation facility. One billion of those people practice open defecation (WHO and UNICEF, 2014). Open defecation perpetuates a cycle of disease and poverty. Nine out of ten people that defecate in the open live in rural areas. More than 840,000 people in low- and middle-income countries die as a result of diarrhoeal deaths from inadequate sanitation and hygiene each year (WHO, 2015). Poor sanitation is also linked to the transmission of diseases such as cholera, dysentery, hepatitis A, typhoid and polio. It also contributes to malnutrition.

According to the UN Deputy Secretary-General, Jan Eliasson, “If you do sanitation right, you actually help five MDGs. Child mortality goes down, maternal health improves, and girls stay in school past puberty, so education rates improve.” (WHO, 2015). The need to better sanitation conditions is a pressing issue. Even though there has been improvement within the past twenty years, there is much to still improve. For post-2015 development goals, when MDGs will have been realized and theoretically ended, Sustainable Development Goals (SDGs) have informally been established. The United Nations is in the process of defining a post-2015 development agenda that will be launched at a Summit in September 2015. Currently there are seventeen goals, and goal six is to ensure availabilty and sustainable management of water and sanitation for all (United Nations Department of Economic and Social Affairs, 2015).

1.2 The Reinvent the Toilet Challenge

In response to the lack of basic sanitation in the world, the Bill & Melinda Gates Foundation initiated the Reinvent the Toilet Challenge (RTTC) in 2011. The Challenge aims to create a toilet with the following criteria: removes harmful pathogens from human waste and recovers valuable resources; operates "off the grid" without connections to water, sewer, or electrical lines; costs less than US $0.05 per user per day; and promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings (Bill & Melinda Gates Foundation, 2015). Since inception of the RTTC, grants have been awarded to sixteen research groups around the world who are creating innovative approaches based on fundamental engineering processes for the safe and sustainable management of human waste.

There have been two Reinvent the Toilet Fairs since 2011. The first was held in Seattle, Washington in August 2012 that brought together participants from 29 countries including researchers, investors, and representatives from the communities who could ultimately adopt these innovative approaches to sanitation. In March 2014, a second fair was held in New Delhi, India co-hosted by the Government of India's Department of Biotechnology and the Bill & Melinda Gates Foundation. India is uniquely positioned to become a global leader in the development of new sanitation technologies. Globally, India is the country with the highest number of people (597 million people) practicing open defecation (WHO and UNICEF, 2014). This is shown in Figure 2, which provides data on countries with the highest number of people practicing open defecations.

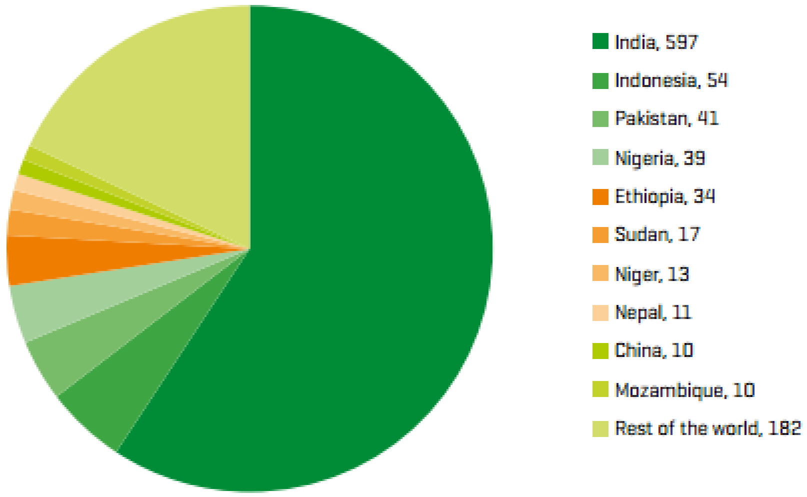

Figure 2: Top 10 countries with the highest numbers of people (in millions) practicing open defecation (WHO and UNICEF, 2014)

The Reinvent the Toilet Fair: India aimed to stimulate discussion and spur partnerships to bring safe, affordable sanitation to the 597 million people in India who lack access. The fair was also a part of a broader partnership between the Bill & Melinda Gates Foundation and India's Biotechnology Industry Research Assistance Council (BIRAC) that aims to reduce maternal and child mortality, provide scientific and technical solutions for infectious diseases, strengthen India's scientific translation capacity, make scientific and technical advances related to agriculture, and increase scientific advancement in food and nutrition (Bill & Melinda Gates Foundation, 2015).

1.3 Key RTTC Toilet Designs

As mentioned before, sixteen research teams have been awarded grants from the Bill & Melinda Gates Foundation as part of the RTTC to create innovative toilets. The varying designs include toilets powered by solar, hydrothermal carbonization, and ultra-violet light that produce several kinds of products including electricity, hydrogen, and biological charcoal. After the RTTC Fair in Seattle, Bill Gates announced "winners" of the challenge. These teams were recognized because their designs most closely matched the criteria presented in the challenge. First prize went to the California Institute of Technology solar-powered toilet that generates hydrogen and electricity. Second prize went to the Loughborough University toilet that produces biological charcoal, minerals, and clean water. Third prize went to the University of Toronto toilet that sanitizes feces and urine and recovers resources and clean water. Special recognition went to

Eawag (Swiss Federal Institute of Aquatic Science and Technology) and EOOS for their excellent design of a toilet user interface. Other notable designs since the RTTC Fair in Seattle in 2012 include the RTI International toilet that disinfects liquid waste and turns solid waste into fuel or electricity through a biomass energy conversion unit, and the University of Colorado Boulder toilet (which this Major Qualifying Project revolves around) that uses concentrated sunlight to disinfect liquid-solid waste and produce biological charcoal.

A table with all the teams funded by the Gates Foundation as part of this Reinvent the Toilet Challenge is shown in Table 1.

Table 1: RTTC Grantees

Research Team	Award Date	Award Amount	Design Proposal	Status
California Institute of Technology	Summer 2011	$400,000	Solar-powered toilet that generates hydrogen and electricity	Still in development
Delft University of Technology	Summer 2011	$400,000	A toilet that converts human waste to fuel gas	Still in development
Eawag and EOOS	Summer 2011	$400,000	Diversion for safe sanitation	Completed two field tests and in process of being implemented
Loughborough University	Summer 2011	$400,000	Hydrothermal carbonization toilet produces biochar, minerals, and clean water	Still in development
National University of Singapore	Summer 2011	$400,000	A urine-diverting combustion toilet	Still in development
Stanford University and the Climate Foundation	Summer 2011	$400,000	A sanitation system that converts human waste into biochar	Field tested in Nairobi, Kenya
University of Kwazulu-Natal	Summer 2011	$400,000	A community bathroom block that recovers clean water, nutrients, and energy	Still in development
University of Toronto	Summer 2011	$400,000	A toilet that sanitizes feces and urine to recover resources and energy	Still in development
Cranfield University	Sept. 2012	$810,000	A toilet that removes water from human waste and vaporizes is using a hand-operated vacuum pump and unique membrane system	Still in development
Eram Scientific Solutions Private Limited	Sept. 2012	$450,000	Public toilets made accessible via the eco-friendly and hygienic “eToilet”	Currently deploying eToilets across India

RTI International	Sept. 2012	$1.3 million	Self-contatined toilet system that turns solid waste into fuel or electricity through a biomass energy conversion unit	Still in development
University of Colorado Boulder	Sept. 2012	$780,000	Solar toilet that disinfects liquid-solid waste and produces biochar	Entering second phase of design
Unilever PLC	May 2013	$1.1 million	To advance the application of pyrolysis technology at communal toilet sites	Still in development
Duke University	April 2013	$1.8 million	Treat fecal sludge using supercritical water oxidation	Nearing completion and getting ready for field testing
Santec LLC	Sept. 2013	$619,000	Electric toilet powered by solar power stored in batteries that separates liquids and solids and dewaters and produces biochar	Still in development
The Asian Institute of Technology (AIT)	Sept. 2011 & Sept. 2014	$5.8 million	Develop and commercialize improved sanitation systems in poor, particularly urban areas	Still in development

1.3.1 Caltech Solar Toilet

The Caltech solar-powered toilet is self-contained and includes a wastewater treatment system. A solar panel produces enough power for an electrochemical reactor to break down water and human waste into hydrogen gas. The gas can be stored in hydrogen fuel cells for use as a backup energy source during nighttime operation or low-sunlight conditions during the day. A pump sends treated water to a reservoir on the top of the toilet, where it can be used for irrigation or other purposes (Woo, 2015). An image of Caltech's toilet is shown in Figure 3.

Figure 3: CalTech's RTTC Toilet (Gates, 2015)

1.3.2 Loughborough University HTC Toilet

The toilet designed by researchers at Loughborough University transforms feces into a biological charcoal through hydrothermal carbonization (HTC), or decomposition at high temperatures without oxygen and in water. The system generates heat from combusting the produced biological charcoal and recovers water and salts from feces and urine. The toilet's configuration eliminates the need to separate urine and feces, and may also take in other organic waste, such as sanitary napkins and food products (Reinvent the Toilet Fair: India, 2014).

1.3.3 University of Toronto Smoldering Toilet

The toilet created at University of Toronto treats solid waste through mechanical dehydration and smoldering. Smoldering is a flameless combustion process at a low-temperature that sanitizes feces. For this design, the sanitation is done within 24 hours. Before solid waste is incinerated in the smoldering chamber, it is flattened and dried in a roller/belt assembly. Urine is diverted and passed through a sand filter to be disinfected (University of Toronto, 2015). The novelty of this design is in its simplicity.

1.3.4 Eawag Water Cycle Toilet

Eawag (Swiss Federal Institute of Aquatic Science and Technology) and a renowned Austrian design studio developed a noteworthy toilet design in 2011. It has its own water cycle, which means there is water available to keep the toilet bowl clean, for hand washing and also for anal hygiene at all times. Pathogens are removed from the water by a gravity-driven passage through a membrane (Eawag: Aquatic Research, 2015). An image of this toilet, that Eawag and EOOS call the Blue Diversion Toilet, is shown in Figure 4. This toilet design has been successfully field tested in Uganda and Kenya, which is discussed in Section 4.1.1. It is only one of two designs from the RTTC that have been successfully field-tested.

Figure 4: Eawag RTTC toilet design (Gates, 2015)

1.3.5 RTI International Combustion Toilet

RTI International has partnered with Colorado State University, Duke University, and Advanced Diamond Technologies, Inc. to develop a toilet that disinfects liquid waste, dries and burns solid waste, and converts the resulting combustion energy into stored electricity. The liquid and solid wastes are separated through a mechanical screw-like device. Liquid waste is disinfected through electrochemical processes using carbon electrodes and can be used as rinse water for the toilet or as a fertilizer supplement. The solid waste is dried through a combination of mechanical, solar, and thermal energy. As it travels through the screw-like device it is broken down into uniform-sized pellets, and then burned in a combustion unit. This self-powered unit captures some of the heat produced and converts it into electricity (RTI, 2015). A schematic of this toilet is shown in Figure 5.

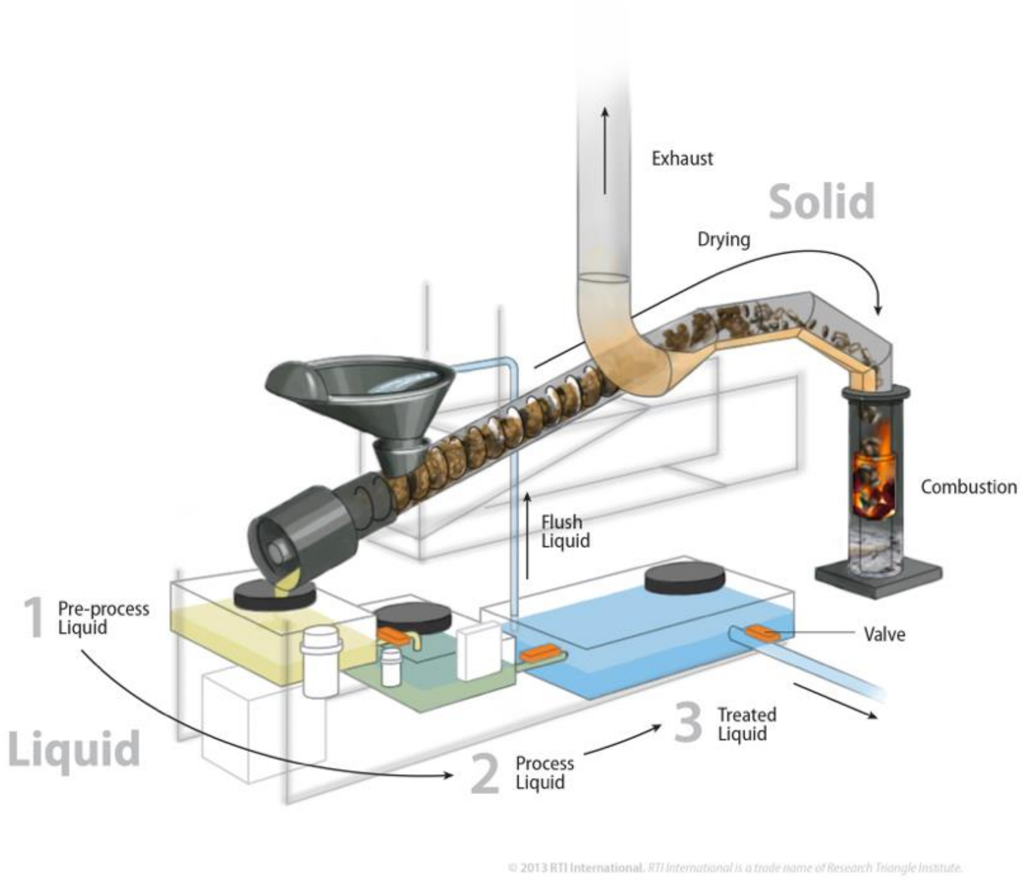

Figure 5: RTI International Toilet Design (RTI, 2015)

1.3.6 University of Colorado Boulder Sol-Char Toilet

The Sol-Char Toilet developed by a multi-talented team at the University of Colorado Boulder is a waterless, self-contained toilet that can function completely off grid through the utilization of concentrated solar power. Eight parabolic concentrators focus sunlight through fiber optic bundles and transmit the solar power to an outer lid positioned over a waste collection container. The solar power illuminates the inner collection container and disinfects the waste through pyrolysis, or the thermochemical decomposition of organic material at high temperatures in the absence of oxygen. After pyrolysis, the solid waste is transformed into biological charcoal (University of Colorado Boulder, 2015). The design outlined above is the first phase of the Sol-Char toilet. A more detailed explanation of the mechanics and the research findings from this toilet are provided in Chapter 2. The Major Qualifying Project centered on the redesign of this toilet.

1.4 Major Qualifying Project Objectives

The first phase design of the Sol-Char Toilet has been successful. All of the mechanics work and valuable end products of biological charcoal and disinfected urine are created. However, there is room for improvement. The economic feasibility of the current design needs to be reevaluated and the overall look can be changed to advance the project into the future. The work done for this Major Qualifying Project centered on the pros and cons of the current design of the Sol-Char toilet while looking for new ways to advance the design into another phase. Areas of focus while creating a new design included the overall cost, life expectancy, ease of use, aesthetics, maintenance, reactor efficiency, and safety.

The major objective of this Major Qualifying Project was to redesign the Sol-Char toilet to mitigate the overall cons of the current design and develop a new design. In order to do so, people involved in sanitation development were interviewed to better understand design constraints of a solar powered toilet in developing communities. Members of the Sol-Char Sanitation team were also interviewed for their ideas on how the first phase could be improved. Sketches were then drawn of the new possible designs. Based on the established criteria, four top designs were chosen and then evaluated during a peer group discussion. Finally, recommendations for the next design of the Sol-Char toilet were given.

Chapter 2: Sol-Char Toilet Phase I and Research Results

A grant of $780,000 from the Bill & Melinda Gates Foundation was awarded to the University of Colorado (CU) Boulder in September 2012. An interdisciplinary team of CU environmental and chemical engineers, solar energy specialists, and community development experts was formed to create the Sol-Char toilet. This toilet uses solar energy to thermally disinfect human waste and create biological charcoal (biochar). Pyrolysis, or the thermal decomposition of organic matter in the absence of oxygen, is used within the toilet's reactor.

The Sol-Char toilet has been through many stages of research since its inception in 2012. Creating the optimal design is ongoing, dependent on funding, and the Sol-Char team strives to make a toilet that will improve sanitation options in the developing world while fulfilling all the requirements set in the Reinvent the Toilet Challenge. These requirements include making the design affordable and desirable to use, rendering fecal waste harmless within a short time span, being self-contained without the need for flush water or electricity, and producing valuable end products.

When the project first began at CU Boulder in 2012, design teams were assigned to different aspects of the toilet that were necessary to be developed. The four teams were the Solar Team, Reactor Team, Biochar Team, and Integration Team. The Integration team focused on collaborating all research efforts from the other three teams and optimizing the overall design process. A concept sketch of the original design is shown in Figure 6.

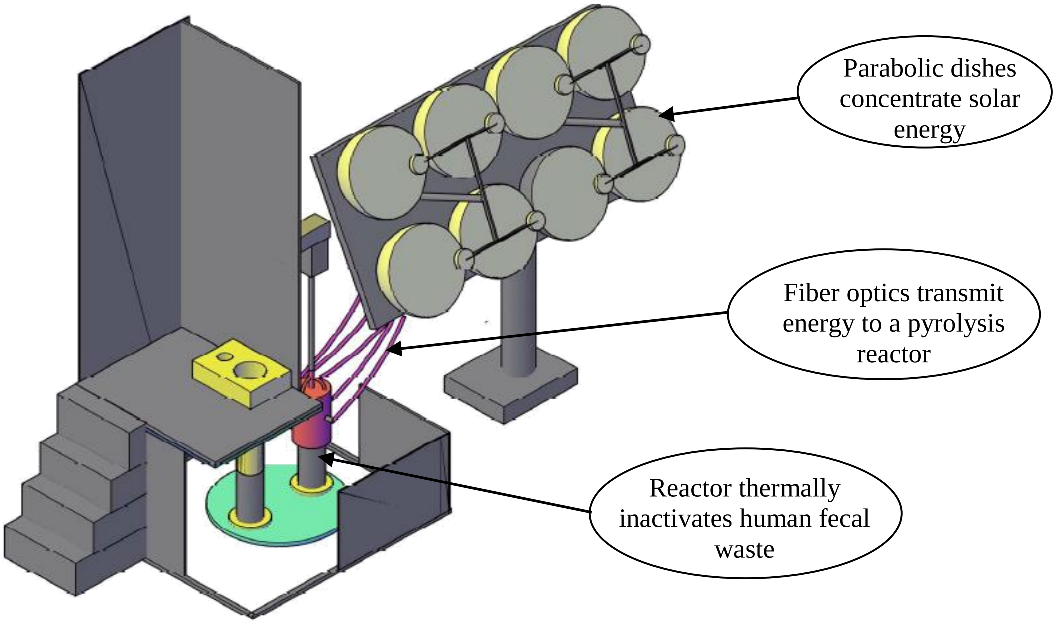

Figure 6: Concept Sketch of Sol-Char Toilet (Sol-Char Sanitation Research Group, 2013)

The overall energy flow of the Sol-Char system starts with solar tracking. Solar energy is concentrated and then transmitted through the fiber optic cables. From there, solid waste is reacted and liquid waste is disinfected. The end results are disinfected urine and biochar. A diagram of the energy flow of the system is shown in Figure 8. The energy efficiency, η, is shown for each process.

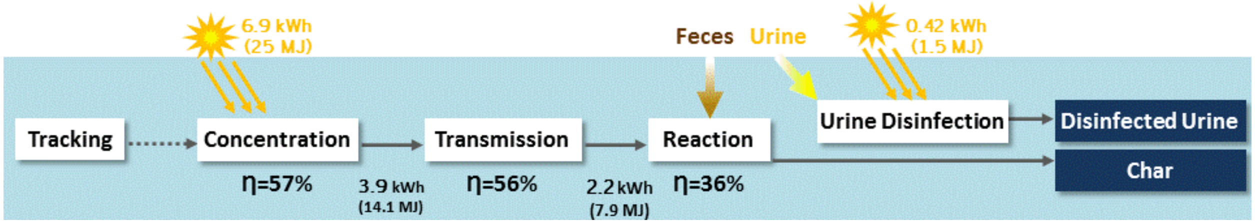

Figure 7: Sol-Char Energy Balance- A Diagram of Energy Flows (University of Colorado Boulder, 2015)

2.1 Solar Research Results

The design of the Sol-Char toilet consists of eight parabolic solar concentrators that track the sun throughout the day transmitting the sun's energy through fiber optic bundles to a reactor chamber where human waste is collected. A simple sun sensor detects changes with the sun's position and signals the drive motors to move with the sun. The tracker updates every 10-40 seconds, depending on the location, time of day, and time of year (University of Colorado Boulder, 2015). This tracking is a necessary part of the design to consistently achieve a high concentration of solar energy and high reactor temperatures. The solar concentrators are assumed to receive 800 W/m^2 of sunlight intensity within at least a four-hour period throughout the day. The 0.6 meter in diameter discs are assumed to have 46% overall efficiency. Each disc delivers around 130 watts (Weimer, 2013). The design of the parabolic discs is relatively simple. In Figure 8, a side view of a disc is shown.

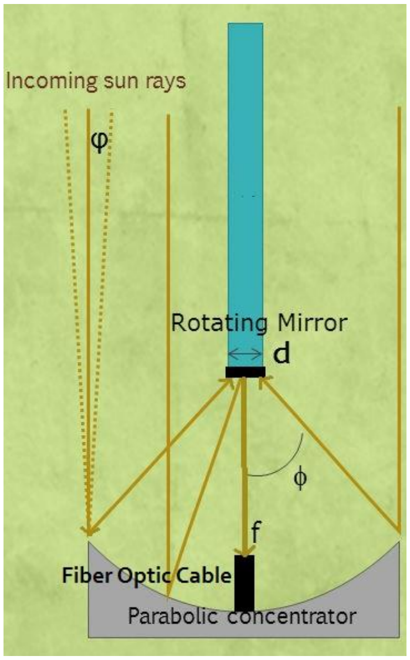

Figure 8: Solar Concentrator Side View Design (Weimer, 2013)

Incoming sunrays hit the concentrator and are reflected towards a rotating mirror that directs the light to a fiber optic cable. A quartz rod is placed in between the redirected focal point and fiber optic cable to homogenize a peaked input flux distribution so the potential for heating of the fiber bundle is reduced (Weimer, 2013). Each bundle has a fused end, which minimizes interstitial space between fibers that causes a decrease in the amount of solar energy collected. The rotating mirror is a key design aspect because it allows fiber optics to be attached at the back of the concentrator, significantly shortening the required length of the cable. Fiber optics allow for delivery to a specific, fixed reactor location and for high temperatures to be achieved in an insulated reactor. Without fiber optics, complicated mechanical systems would be required to locate the reactor at the focal point.

Results of the solar concentration technology have been promising. The performance characteristics of the solar concentrator have been measured, including, the like flux distribution and power delivery from reflective surfaces to fiber input. The power delivery and durability of the existing fiber optic bundles have also been evaluated. The CSP (Concentrated Solar Power) of the designed system provides 500W-1000W from the 8 total concentrators. Each concentrator is coated with a silver-polymer reflective film which aides in increasing the amount of sunlight reflected (Fisher *et al*., 2013). An area that was brought up that could be incorporated to drastically reduce the energy burden on the CSP system is a pre-drying/de-watering process upstream of the feed to the reactor system.

2.2 Reactor Research Results

The Sol-Char Toilet reactor processes solid human waste through pyrolysis. The reactor reaches high temperatures in order to achieve effective pyrolysis. The end result is a biological charcoal. The Sol-Char Toilet reactor is on a carousel that rotates between two containers. One container is used to collect waste, while the other container is under the reactor hood being pyrolyzed. The carousel is electrically operated from solar energy; however, there is a mechanical back up.

2.2.1 Solid Waste Reactor Research

In the reactor chamber of the Sol-Char toilet design, pyrolysis is achieved to create a biological charcoal from the collected waste. Pyrolysis thermo-chemically decomposes organic material and forms a product rich in carbon. The Sol-Char toilet pyrolysis process reaches temperatures of 300°C to 700°C. A sketch of the reactor design is shown in Figure 9. Human waste subjected to pyrolysis, which creates biochar rich in not only carbon but also other nutrients, such as nitrogen, which make it a valuable soil amendment. Research done on this valuable end product is discussed in Section 2.3 of this report.

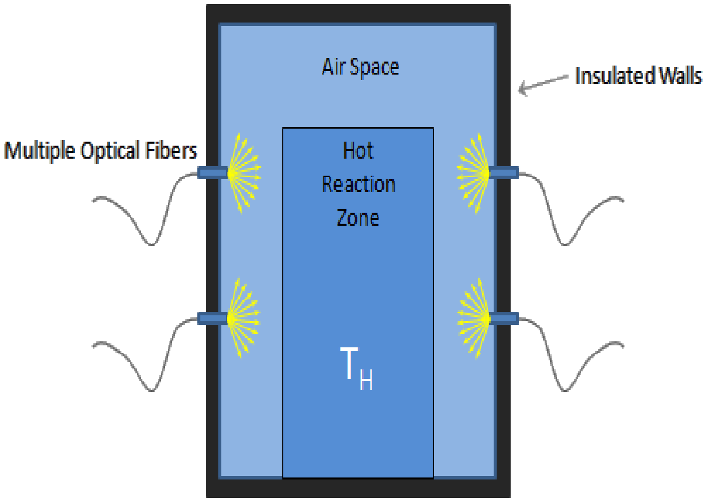

Figure 9: Sol-Char Reactor Detail (Sol-Char Sanitation Research Group, 2012)

The hot reaction zone of the chamber is a 4-liter sized, 20-cm diameter stainless steel container. The waste is collected in this container throughout a 20-hour period, after which the container is rotated on a carousel operated electronically, although there is a mechanical back up. A rendered image of the containers on the carousel of the toilet design is shown in Figure 10.

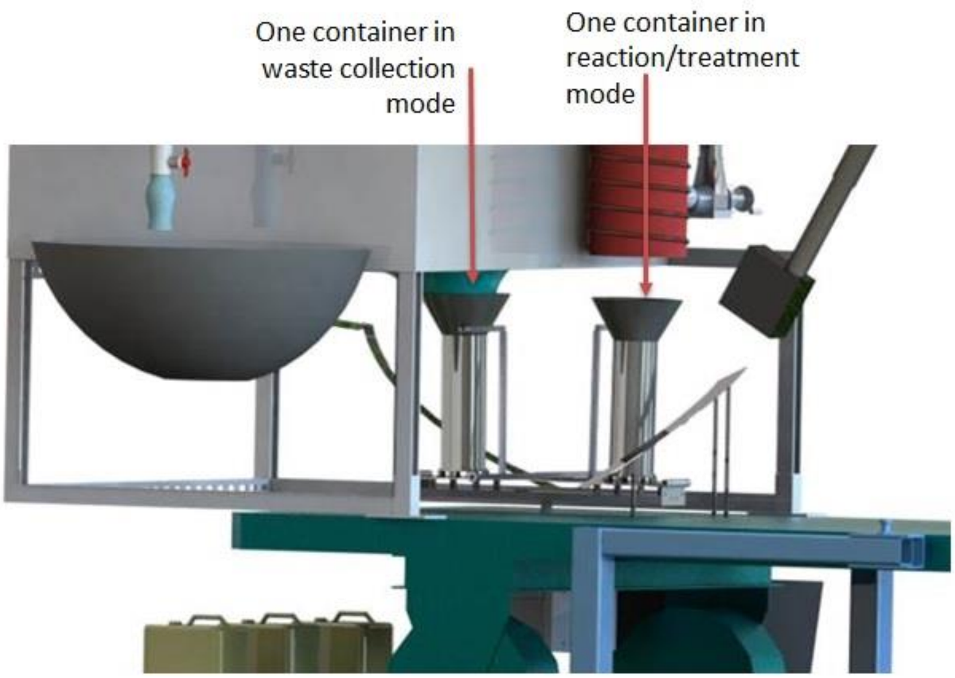

Figure 10: Detailed Carousel Sketch (Weimer, 2013)

The container on the right in Figure 10 does not have the reactor hood enveloping the container yet. This involves another mechanical process that lowers the reactor hood down over the container. The reactor hood is connected to the eight solar concentrators by fiber optic cables. The system requires at least four hours of sunlight to properly collect enough solar energy to convert the waste into biochar. To help with the process, inside the reactor the walls are coated with a reflective surface and the outside has high infrared visible light absorbing material. Shown in Figure 11 are the exhaust, insulation, and waste included in the reactor design. The reactor's exterior surfaces are painted with PyroMark 2500 paint and from experimental testing was found to reach a maximum temperature of 1100 ˚C. CSP is delivered from the fiber optic cables, and because temperatures are hot (reaching 300˚C and above), insulation is provided to protect the fibers from overheating and to keep heat in the reactor. The seal shown in Figure 11 prevents soot, smoke, and tar from depositing on the inner wall of the solar hood.

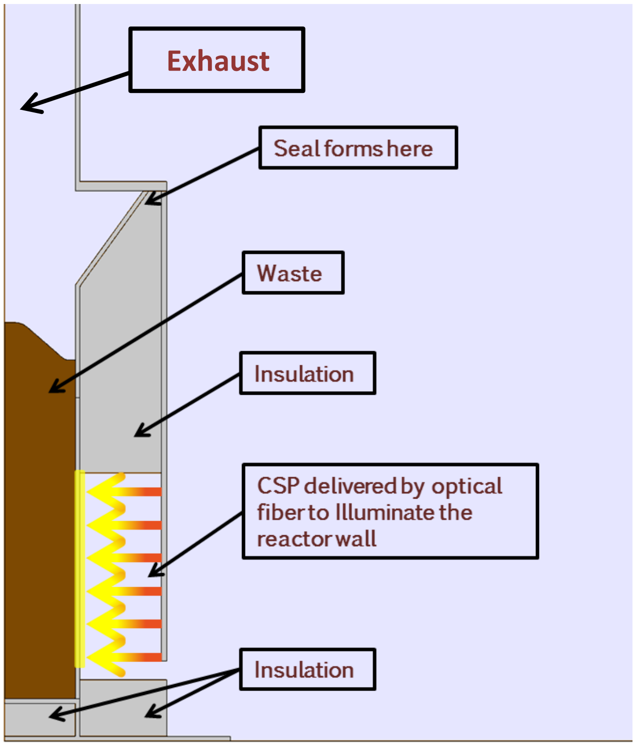

Figure 11: Reactor Chamber Side-View Detail (University of Colorado Boulder, 2013)

The reactor has 88% emissivity and 95% absorptivity of the solar spectrum (Fisher *et al.*, 2013). Simulations account for various solar irradiance conditions. Different insulation configurations were experimentally tested to compare to simulated results. Figure 12 demonstrates the comparison between simulated and experimental tests of an insulation configuration. The simulated tests were done in a temperature-controlled oven where the reactor and waste were monitored with two thermocouples. The experimental tests were done with the reactor on the Sol-Char Toilet on a sunny day in January 2014. It can be seen in this figure that in this particular experimental test, the waste did not reach a high enough temperature. This can be explained by the efficiency of the reactor or inefficient sunlight on this particular day.

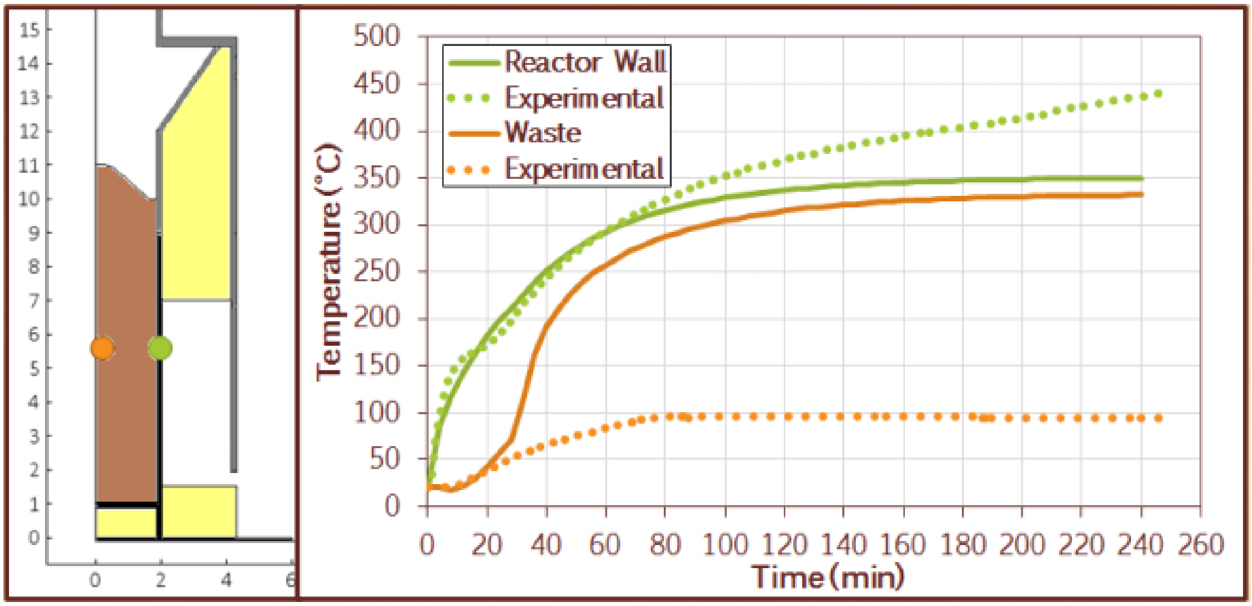

Figure 12: Comparison of Experimental and Simulated Insulation Configurations (Fisher *et al.*, 2013)

The pyrolysis of feces and fecal sludge depends on the rate of temperature increase, flow of gas, and particle size. Thermogravimetric analysis (TGA) coupled with Mass Spectrometry (MS) has been conducted on dried and ground feces powder in order to investigate the kinetics of the reaction, as well as quantitatively characterize the pyrolysis gases produced. Experiments were carried out at five different heating rates, and quantitative analysis using calibration gases generated a standard curve of ion current vs. gas concentrations. The gas concentrations of each heating rate were determined for carbon dioxide, carbon monoxide, ethane, methane, and hydrogen. In addition, the char, tar/liquid, and gas yield of the feces pyrolysis were determined. Multiple kinetic modeling approaches were used to determine the activation energy of the pyrolysis reaction (University of Colorado Boulder, 2015).

2.2.2 Liquid Disinfection Research

Liquid and solid wastes are initially separated with a urine-diverting squat plate in the Sol-Char Toilet. Urine pumps through a coil welded to the reactor hood and is pasteurized by excess heat from the reactor. Simulated laboratory disinfection experiments at 60 ˚C showed complete disinfection of *Escherichia coli (E. coli*) and virus surrogate (MS2 bacteriophage) in 30 minutes (Weimer, 2013). In Figure 13, the coil that is welded onto the reactor hood is shown. The prototype for this module is still under development and can be completely redesigned in the second phase.

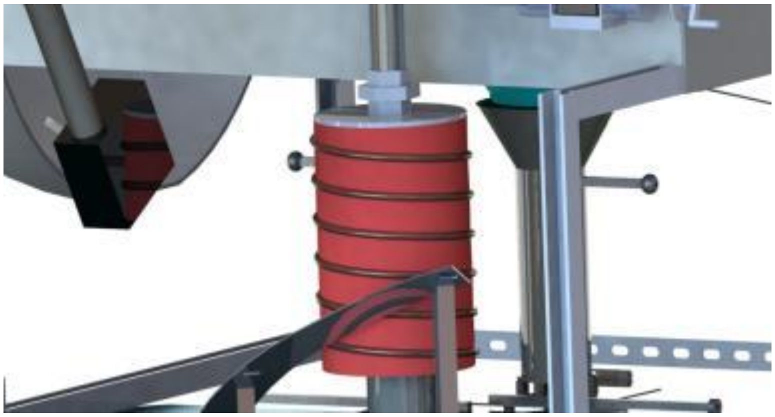

Figure 13: Urine Disinfection Coil on Reactor Hood (Weimer, 2013)

2.3 Biochar Research Results

After five hours of pyrolysis, the reactor hood is raised, and the carousel is rotated again dumping the pyrolyzed material out in the process. The resulting product is a biological charcoal, or biochar. This valuable end product can be used for a number of things such as a soil amendment and an alternative fuel. An image of the biochar produced is shown in Figure 14.

Figure 14: Biochar Product (Weimer, 2013)

2.3.1 Biochar as a Soil Amendment

Experiments were conducted by the CU Boulder team on the water holding capacity of soil after the addition of biochar. When mixed with sandy soil, it was found that biochar makes a significant impact on water holding capacity (WHC). Even at 10% biochar addition, WHC increases by 50% (Weimer, 2013). In can be seen in Figure 16, the percent increase of WHC from an increase of biochar ratio.

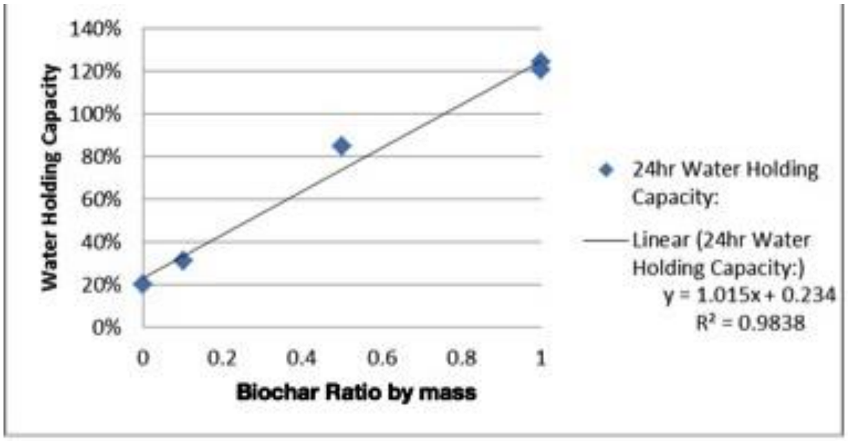

Figure 15: Water Holding Capacity of Soil with Biochar (Weimer, 2013)

2.3.2 Biochar as an Alternative Fuel

Biological charcoal has the potential to be used as an alternative fuel. Biochar was made into briquettes that could then be burned using two different types of binders. The binding ratios were selected based on their performance in published data (Ward, 2014). The first binder type was molasses and lime with a binder ratio by weight of 10% and 3.5% or 20% and 7%, respectively. The second binder type was cornstarch and wheat gluten with a binder ratio by weight of 3% and 7% respectively (Ward *et al.*, 2014). The chars were first pulverized and homogenized before briquetting and analyzing. Char briquettes were manufactured using a 1.25-inch diameter stainless steel die and a Carver Model C pneumatic laboratory press. An image of finalized biochar briquettes is shown in Figure 16.

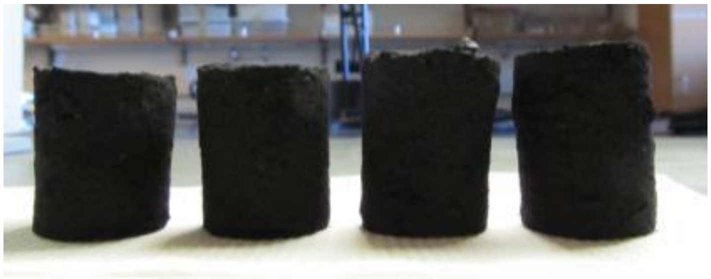

Figure 16: Biochar Briquettes (Weimer, 2013)

Fecal char briquettes were analyzed for energy content at different temperatures and for different binders. The higher heating value (HHV) of the briquettes were found using the following equation:

$$HHV_{briquette} = x_{char}HHV_{char} + x_{binder}HHV_{binder}$$

Where $HHV_{briquette}$ is the higher heating value of the briquette, x_{char} is the weight fraction of char in the briquette, HHV_{char} is the higher heating value of the char, x_{binder} is the weight fraction of binder in the briquette, and HHV_{binder} is the higher heating value of the binder.

Briquettes bound with starch were determined to have higher energy contents than those bound with molasses and lime. The briquettes made with starch at 350˚C had an estimated HHV of 25.1 MJ/kg. On the other hand, the briquettes made with molasses and lime had an estimated HHV of 23.4 MJ/kg at 10% molasses and 3.5% lime and an estimated HHV of 21.3 MJ/kg at 20% molasses and 7% lime. These results compared to average HHVs of common fuels such as commercial charcoal briquettes and wood are shown in Figure 17. The solid black vertical line indicates the minimum Food and Agriculture Organization (FAO) charcoal briquette HHV standard.

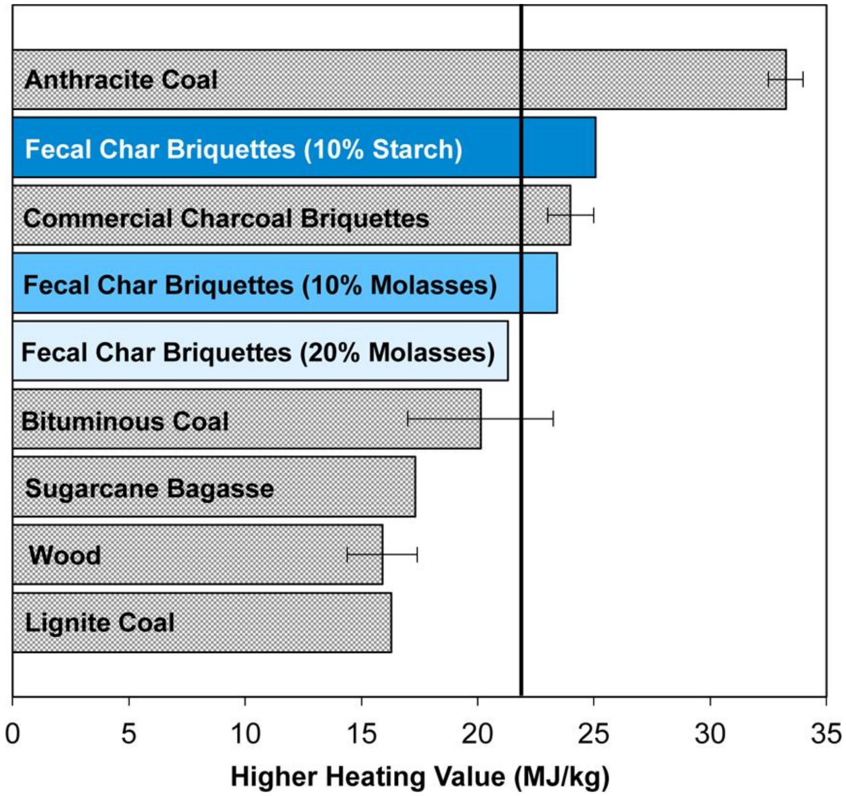

Figure 17: Higher Heating Values of Briquettes Compared to Common Fuels (Ward *et al.*, 2014)

This research was significant in determining the value of fecal char briquettes. These briquettes have the potential to be used as a supplementary, renewable energy source in the developing world. One of the criterions in the RTTC is to "recover valuable resources." By producing biochar from human waste and assessing its feasibility as alternative fuel, the Sol-Char toilet meets this criterion.

2.4 The Future of the Sol-Char Toilet

The research performed on the various aspects of the first phase design of the Sol-Char toilet has enabled the team at CU Boulder to successfully locate the shortcomings and strengths of the design. The solar capture and transmission has been effective. The reactor has been able to partially pyrolyze waste and create a valuable end product. Tests have shown the value in the biochar created. Areas of shortcoming in the first phase design are small but have a large need for improvement. The high cost of the fiber optic cables needs to be reduced and the reactor efficiency needs to be improved. Goals of the next phase of the Sol-Char Toilet include improving the economic viability, designing a modular treatment system that generates valuable end products, and conducting market analysis for application of technology and end products.

Chapter 3: Methods

The objective of this project was to redesign the Sol-Char toilet to mitigate the shortcomings of the current design and move it forward into the next design phase. Currently the design of the Sol-Char toilet operates successfully mechanically, however the high cost of solar capture and solar transmission make it economically infeasible. Also, the overall aesthetics and acceptability of the toilet into a community have not been fully researched. To meet the objective of this project, data were gathered via case study analyses and interviews. Then, a location for implementation of the Sol-Char toilet was researched. Lastly, design options were evaluated. The following sections detail these methods.

3.1 Toilet Case Study Analysis

To better understand the difficulties of implementing a new technology in developing communities, case studies were researched on current organizations implementing improved sanitation systems. The objective was to find commonalities and differences in successful implementation of toilets from the selected case studies. There are many different toilet designs currently being developed and implemented in different regions of the world. The toilets mentioned in Chapter 1 are solely related to the Reinvent the Toilet Challenge. They are highly technologically advanced and only two have been able to launch field tests in communities. One of these, the Blue Diversion Toilet created by Eawag and EOOS, was researched further. This toilet was chosen because of the availability of information of its field tests.

Non-profit organizations and government agencies in various countries have invested resources into projects building toilets and improving sanitation for the poor in communities. Several of these kinds of projects were researched via Google Scholar with the keywords, “improved sanitation,” “developing communities,” and “sanitation technology implementation.” The case studies that were researched are shown in Table 2.

Table 2: Toilet Implementation Case Studies

Case Study	Organization(s)	Location(s)	Toilet Technology	Implementation Date
The Blue Diversion Toilet	Eawag and EOOS	Kampala, Uganda Nairobi, Kenya	Toilet part of the RTTC Continuous water cycle	Uganda- 2013 Kenya-2014
Clean Team	IDEO, Unilever, WSUP	Kumasi, Ghana	Business model of how to implement toilets in a community	2010- ongoing
Student Led Research Team	WPI	Southern Namibia	The Otji-Toilet	2011
Community-Led Total Sanitation (CLTS)	WSP of the World Bank, National Governments, and many more	Several countries around the world, Began in Bangladesh	Methodology for mobilizing communities to completely eliminate open defecation	2000- ongoing

These case studies were chosen because they successfully show how involving the community while implementing new technology led to the design ultimately being accepted and effective.

3.2 Interviews

Interviews were a large part of the methods. To avoid bias while conducting interviews, how to properly conduct an interview was researched through Google Scholar. Interviews can be structured, semi-structured, or unstructured. One of the interviews done in this project was informal and semi-structured. The other interviews were informal and unstructured. A semi-structured interview is a verbal exchange between two people where the interviewer has a list of predetermined questions. However, semi-structured interviews unfold in a conversational manner offering the participants the chance to explore topics they feel are important (Longhurst, 2010). Unstructured interviews have no prerequisite questions. They follow more of an intimate conversation than the other types of interviews. In unstructured interviews, which are sometimes referred to as open-ended or narrative interviews, participants are given considerable control over the course of the interview (Corbin, 2003). Some of the main findings of how to conduct a proper interview included keeping questions focused on the research topic, recording the interview transcript, and avoiding distractions while interviewing (Roulston, 2003). There are many other recommendations for conducting a successful interview, but these main findings were sufficient to conduct the interviews in this project.

3.2.1 IDEO Human Centered Design (HCD)

Human Centered Design (HCD) is a research and design methodology developed by IDEO (Innovation, Design, and Engineering Organization, San Francisco, CA) and adapted for the developing world context through a partnership with iDE (International Development Enterprises, Denver, CO). Blake McKinlay, Global WASH Knowledge Manager at iDE, was emailed and then interviewed on the phone in February 2015.

The three questions asked in this informal, semi-structured interview were:

1. What are the first things considered when thinking of implementing new technology like the Sol-Char toilet in a developing community?
2. What are common constraints of designs?
3. What makes HCD successful?

Mr. McKinlay provided insightful answers to all questions. He also provided a table of the common constraints iDE teams have encountered over the years and the top user preferences of toilets in projects from various countries from iDE teams.

In addition to the interview, the basics of the HCD process were also researched by examining its use in design implementations performed by world renowned companies such as Acumen Fund (New York, NY), AyurVAID (Bangalore, India), and Heifer International (Little Rock, AR). These organizations are successfully making a difference in communities around the world. For example, the process has led to innovations such as the HeartStart defibrillator, Cleanwell natural antibacterial products, and the Blood Donor System for the Red Cross (IDEO, 2015). The objective of researching the HCD process was to comprehend the correlation between its use and the success of implementing new designs in a community.

3.2.2 BrightSpace Solar Technology

BrightSpace Technologies (Boulder, CO) formally known as Creative Light Source, Inc., is a solar energy startup. They recently received a Phase II SBIR (Small Business Innovation Research) grant in 2014 from the Department of Energy to develop a novel new solar energy product. This new technology is key to the next generation of an off-the-grid sanitation solution, and a partnership between the Sol-Char Sanitation team and BrightSpace Technologies has been created. Joseph DiMasi, CEO of BrightSpace, was emailed and an unstructured interview was conducted in his Boulder office in February 2015. The topics discussed were the novel technology, the benefits of using this technology, and the future of the partnership between BrightSpace and the Sol-Char team. A SolidWorks file of their technology was also obtained to help visually imagine the use of the technology with the next phase of the Sol-Char toilet.

3.2.3 Sol-Char Sanitation Team

In order to understand how the current design could be rethought to become more economical, members of the original Sol-Char team were emailed and interviewed in unstructured interviews. These were conducted over a two-month period in January and February 2015. A total of four people were contacted. Topics of discussion were the current state of the toilet design, areas of the design where the overall cost of the toilet could be mitigated, and the future of the toilet design.

3.3 Choosing the Optimal Location for Sol-Char Toilet Implementation

The final design of the Sol-Char toilet relies heavily on the location of implementation. To find the optimal location, DNI (Direct Normal Isolation) and countries lacking adequate sanitation were researched. Global DNI was found using the website, GeoSUN (GeoSUN, 2015). Only the countries that had sufficient DNI were considered for the Sol-Char toilet implementation. Among these countries, only the ones that had a need for improved sanitation were considered. This need was based on data from the WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation. Each country in the world has estimates on the use of water sources and sanitation facilities from 1980-2012 (JMP, 2015). Qualitative data such as the types of communities, the current methods of sanitation, and partnership possibilities with existing industries and/or governments were also researched via informal emails with members of the Sol-Char sanitation team and reading scholarly articles to arrive at the final possible location for the Sol-Char toilet.

3.4 Decision Design Matrix

To come to a final decision on the best design, a decision design matrix was created. A decision design matrix evaluates and prioritizes a list of possible design options. For this project, each design aspect was weighted and then ranked for each design alternative. This allowed every alternative design to have an overall weighted score to assist in determining the best option. Within a decision matrix, the designs are not compared to one another, but only to the criteria of evaluation. These criteria provide a constant “yardstick” against which meaningful comparisons can be made (Burge, 2009). Weighting each criteria is an important aspect of the design matrix. Required features are of the greatest importance, so they have the highest weight. There are many different scales that can be used for assigning weights, but very few hard and fast rules exist for which scale is optimal. Generally, the scale is as simple as possible.

For this project, seven criteria were included: overall cost, life expectancy, ease of use, maintenance, aesthetics, reactor efficiency, and safety. Each criterion was given a weight ranging from 1 to 10: 1 being low importance and 10 being high importance. Zero was excluded because it was assumed that all criteria were important. Criterion can be weighted on a different scale, but 1 to 10 was chosen because it is simple. The two most important design aspects were determined to be overall cost and safety based on engineering knowledge. The two least important design aspects were determined to be ease of use and aesthetics. The results of how each design alternative was scored are discussed in the next chapter.

Chapter 4: Results

This chapter presents the findings used to develop recommendations for improved design alternatives for the next phase of the Sol-Char Toilet. First, key factors for successful technology implementation were researched by interviewing people working in the field and reviewing case studies of successful sanitation technology implementation. To mitigate the economic shortcomings of the current Sol-Char toilet design, a partnership with BrightSpace Technologies was discussed. The location of the Sol-Char Toilet was determined using a global Direct Normal Irradiance (DNI) map and data of the current sanitation situation in countries from the Joint Monitoring Programme (JMP) 2014 Report. Finally, the design alternatives were detailed and scored in a decision design matrix. Recommendations are given in Chapter 5.

4.1 Toilet Implementation Case Studies in the Developing World

Sanitation throughout the world varies from region to region. Off-site sanitation systems are used in developed areas, where water resources are plentiful and reliably delivered to household connections. The toilets in off-site sanitation systems are flush toilets connected to conventional piped sewer systems and septic tanks. They are considered improved sanitation facilities. Facilities that hygienically separate human excreta from human contact are considered improved (WHO, 2015). Table 3 shows an array of on-site toilet types and whether each is considered an improved toilet type, where that specific toilet is commonly used, and problems associated with that specific toilet.

Table 3: On-Site Toilet Types

Toilet Type		Improved?	Location	Problems
Pit Latrines	Open Pit	No	Sub-Saharan Africa	Attracts flies, falling in, smells
	Seated	Yes*	Most developing communities	Seat lid needs replacement
	Squat Plate	Yes*	Most developing communities	Attracts flies, falling in
	Ventilated Improved	Yes	Developing communities with assistance	Waste disposal
Bucket		No	Africa, Latin America, and Asia	Potential for human contact and contamination
Composting Toilet		Yes	Non-arid developing communities	Waste disposal, cost
Pour-Flush Toilet		Yes	Southern Asia, communities where anal cleansing is common	Requires a water supply, fitting seal
Urine-Diverting Dry Toilet		Yes	Developing communities in arid countries	Requires training to be used correctly, more expensive

*Seated and Squat Plate Pit Latrines are only considered improved if they have a slab or platform

The most commonly used toilet in developing communities is a pit latrine toilet. Pit latrines are improved because they limit contact between human waste and humans (excluding open pit latrines). However, the problem with this type of toilet is the need for proper management. Without management the latrines become filled with human waste and then become undesirable to use. They also attract insects, such as flies and mosquitoes, and emit foul odors adding to their undesirability. However, one type of pit latrine that is improved is a ventilated improved pit (VIP) toilet. This toilet is considered improved because of the addition of a ventilation pipe with a fly screen at the top that reduces the odor and keeps insects out (Franceys, 1992).

There are two types of composting toilets: double vault and continuous. Double vault composting latrines use anaerobic bacteria, and continuous composting latrines make use of aerobic bacteria. Both latrines biologically break down solid organic matter and produce a humic substance, or compost. Farmers and gardeners throughout the world have used composting toilets for many centuries (Franceys, 1992). Composting toilets are not desirable to use in arid regions because moisture is important for composting effectiveness. Urine-diverting dry toilets are toilets that operate without water and have a divider so that the user, with little effort, can divert urine away from feces. The only toilet listed in Table 3 that requires water is the pour-flush toilet. This type of toilet has the same design as a pit latrine; however, it is fitted with a trap providing a water seal.

The type of toilet used in a community is largely based on social and cultural factors. The introduction of on-site sanitation systems is much more than the application of simple engineering techniques- it is an intervention that entails considerable social change. The following sections outline case studies of on-site sanitation system implementation in developing communities. The types of improved toilets vary, but the approach for implementing the new technology was similar for all four case studies researched.

4.1.1 Blue Diversion Toilet Field Test in Uganda and Kenya

One of only two RTTC designs to be deployed in field tests is the Blue Diversion Toilet created by Eawag (Swiss Federal Institute of Aquatic Science and Technology) and EOOS. The Blue Diversion Toilet provides water for hand washing, anal and menstrual hygiene and toilet flushing, and has an automatically closing lid. Because it is part of the RTTC, its design is much more complicated than the commonly used pit latrine. It utilizes a squat pan to separate used wash water, urine and dry feces. The used wash water is recycled. Before being reused, the water is treated in a biologically activated membrane bioreactor and an on-site electrolytic chlorination unit. These processes require some electricity, which is provided by a solar panel (Eawag, 2015).

In April 2013 to June 2013, a working model toilet was installed in two informal settlements in Kampala, Uganda for the Blue Diversion Toilet’s first field test. Kampala’s population is around 2 million, and it is estimated that there are only 4 toilets for every 2000 people (Global Trader, 2015). An image of the prototype being transported for this field test is shown in Figure 18.

Figure 18: Blue Diversion Toilet during field test in Uganda (Bill & Melinda Gates Foundation, 2015)

This first field test was conducted in the informal settlement of Kifumbira. Kifumbira is one of the biggest slums in Kampala. An estimated 5000 people live in the Kifumbira slum, an area occupying less than a square kilometer. The existing sanitation in this area was poor consisting of non-private holes overflowing with feces. During this field test, the toilet was used around 1200 times. More than 400 one-time users (both men and women of all ages) and 22 people who used it during a 2-week “family test” period gave their feedback on it. A child testing the Blue Diversion Toilet can be seen in Figure 19.

Figure 19: Child testing the Blue Diversion Toilet during field test in Kampala, Uganda (Eawag, 2015)

This initial two-month field test was instrumental in improving the functionality of the Blue Diversion Toilet and identified some of the weak points that still needed redesigning. The feedback and critical issues gathered from a full-scale social acceptance survey can be summarized in the following three points:

- Improve functionality of the feces lid to better conceal previous users' droppings
- Reduce the height of the wall to ensure it fits to existing toilet superstructures, and
- Redesign the foot pump, which is considered too strenuous for children and the elderly (Lüthi and Larsen, 2015).

The Blue Diversion Toilet went through another field test in Nairobi, Kenya from February 2014 to April 2014. This fieldwork was conducted in collaboration with Sanergy (Nairobi, Kenya), a company building sustainable sanitation in urban slums. Sanergy has been building a network of urine diverting toilets in Nairobi since the company's inception in 2011. Currently, they have built a network of 372 toilets in and around Mukuru, an informal settlement in the industrial area of Nairobi. A service team collects waste from every toilet on a daily basis and delivers the waste to a semi-centralized treatment site outside of Nairobi. This collaboration between Eawag and Sanergy was chosen because Sanergy's sanitation approach is similar to what Eawag envisions for the Blue Diversion Toilet.

From the feedback of the first field test, the Blue Diversion toilet was redesigned to be smaller in size and its foot pump was simplified. The goal of the second field test of the Blue Diversion toilet was to validate the success of improvements made to the working model. This field test was also accompanied by a social science study funded by Eawag to gather information on the current sanitation situation in two informal settlements, Mukuru and Kibera (Eawag, 2015). Over 300 interviews of one-time users and 60 interviews with regular users of the toilet were collected. The results were overwhelmingly positive: 100% of the people interviewed liked the look of the toilet, 95% thought the toilet was easy to use, and 94% would also recommend the toilet to their friends and family (Künzle *et al.*, 2015).

4.1.2 Clean Team in Kumasi, Ghana

In November 2010, IDEO (San Francisco, CA), Unilever (London, United Kingdom) and WSUP (Water and Sanitation for the Urban Poor) partnered together and led a six week long exploratory research assignment in Kumasi, Ghana to develop an innovative business model and services for private sector delivery of improved household sanitation for the urban poor. While in Ghana, the team utilized IDEO's Human Centered Design (HCD) approach. Details of this design approach are discussed in Section 4.2 of this chapter.

Prior to 1990, the majority of Kumasi residents used bucket latrines as their means of sanitation. Bucket latrines were either metal or plastic buckets built in a common area of a multi-family compound. In 1990, this type of latrine was outlawed because the service collectors were often dumping the contents of the buckets into the street illegally and not in designated collection locations. Since the outlaw of bucket latrines, public toilet latrines have become the only legal sanitation system available to Kumasi residents. Public toilets are generally blocks of 15-20 squatting stalls with minimal privacy and cost between US $0.03-0.20 per use charged by the city government. For many families, public toilets can be a significant financial burden to use every day. The average daily income of a family in Kumasi is around US $1.64. This leads to families resorting to open defecation and "flying toilets." Flying toilets are bags that people empty their waste in after collecting it in a chamber pot. These bags are tossed in roadside ditches, garbage piles, and waterways (IDEO, 2011).

To purchase an in-home latrine in Kumasi, it costs around US $700 from a local vendor. Thus, there is no middle ground between public toilets and an in-home latrine. IDEO, Unilever, and

WSUP created the Clean Team of Ghana during their exploratory research assignment. Issues that the Clean Team addressed while working to come up with a sustainable sanitation business plan included awareness, purchasing, cleanliness, community infrastructure, treatment, women’s needs, and services. Through in-depth analysis of the needs and aspirations of the urban poor residents in Kumasi, and the markets in which they exist, they created a model for a profitable social business.

The Clean Team found key design principles while in Ghana. They found convenience to be the major driver for people’s waste management approaches. If it didn’t make their life easier, people likely wouldn’t use it. Convenience is the benefit that customers most value and should be prioritized over other messages (IDEO, 2011). Next, they found that small payments over the life of a product are easier than larger upfront payments. People in Kumasi were used to the idea of spending small amounts toward sanitation services. The Clean Team also found that it was necessary for sanitation to be approached as an interconnected system. In order to create effective sanitation solutions, a design needs to include every part of the sanitation journey, from awareness to treatment. This includes incentivizing private sectors to become involved.

The business model that the Clean Team developed includes renting households portable toilets and collecting the waste 2-3 times per week. This waste is transported to a municipal treatment site where it is converted to organic fertilizer and sold to commercial farms in the region. An image of Ghanian schoolchildren with one of the portable toilets is shown in Figure 20.

Figure 20: Clean Team Toilet (WSUP, 2015)

Overall, the efforts in Kumasi, Ghana have been a success. The Clean Team was able to effectively enter a poor community with sanitation problems, gather information necessary to improve the current situation, and create a completely new market for household sanitation. Today, they have 690 toilets installed and approximately 4800 people benefit from them (Clean Team Toilets, 2015).

4.1.3 Worcester Polytechnic Institute Student Team in Rural Namibia

The next case study researched was an Interactive Qualifying Project (IQP) done by four university students at Worcester Polytechnic Institute (Worcester, MA) on the water quality and sanitation on Odendaal farms in southern Namibia. The students spent seven weeks interviewing farmers, meeting with local experts, and conducting water tests to organize an approach to improve water and sanitation and piloting a dry sanitation system.

Odendaal farms exist in the Hardap region of Namibia. They were formed around boreholes that the Namibian government installed as water points in the 1960s. Fifty years of poor sanitation practices and livestock activity around these boreholes have contaminated the local ground water. In fact, from water samples taken from eight different farms, only two tested as having acceptable water, four tested as having water of low health risk, and two tested as having water unfit for human consumption based on the level of nitrate in the water samples (Boutin *et al.*, 2011). The communities believed that the water was suitable to use, and people claimed to use no sanitation system instead relying on “bush” or “bucket” waste systems.

The students focused on creating a baseline assessment of the water quality and developing specific solutions for improving water quality and sanitation issues. They recommended nitrate ion exchange filters, chlorination treatment, and routine water tests to help improve water quality. To help improve sanitation issues, they recommended the installation of dry sanitation systems. In May of 2011, in their last week in Namibia, with the help of several members from surrounding communities, the students constructed an Otji-Toilet. Their objective was to develop a sense of ownership and pride among the community through the construction of this new sanitation system, which is key in forming acceptance.

The Otji-Toilet is single-family dry sanitation system that collects human waste in a large perforated bucket in a chamber beneath the toilet. An illustration of the system is shown in Figure 21. Eighty percent of urine is diverted into a soak pit in the ground and seeps into soil. The solid waste stays in the chamber; and after approximately six months, the chamber reaches full capacity. At this time, the full chamber is replaced by an empty one and moved to the rear part of the chamber to dry out the remaining solids. It is dried out through the heat created under the metal cover of the tank and ventilated through a pipe above the chamber. This process is repeated six months later, and the dry waste can be lifted out and safely disposed of or used as a fertilizer (The Network for an Economical and Ecological Habitat, 2015).

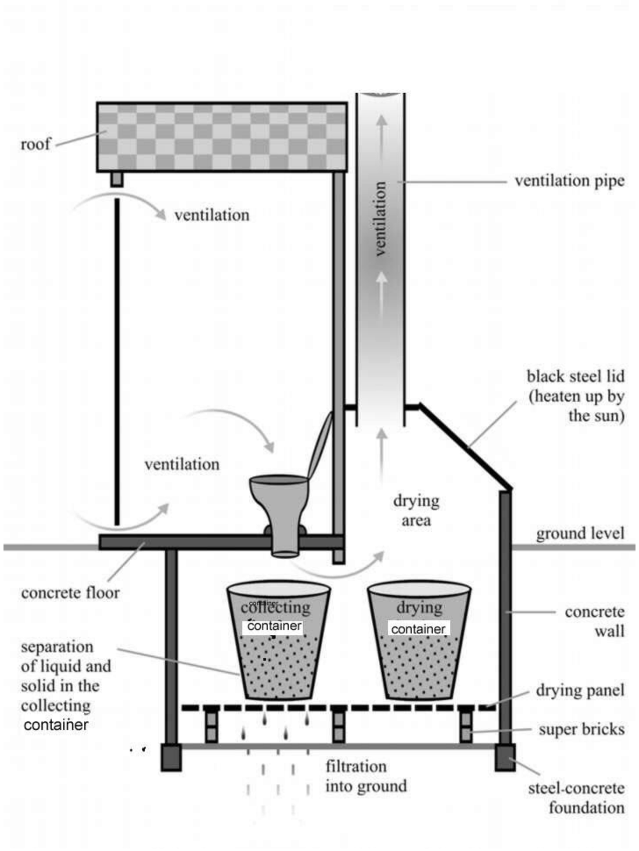

Figure 21: Otji Toilet System (The Network for an Economical and Ecological Habitat, 2015)

This type of toilet is best utilized in hot, arid regions, which is why it was an ideal toilet to install in Namibia. The last recommendation from this IQP was to have community members present and involved in all steps of implementing new systems that would improve their water quality and sanitation. The students concluded “involvement in all steps of the process will ensure that community members are dedicated to maintaining and supporting all efforts” (Boutin *et al*., 2011).

4.1.4 iDE and the Easy Latrine in Cambodia

In Cambodia, almost 11,000 people die of diarrhea every year; most of those deaths are children. Despite numerous NGO and Government initiated projects, latrine take-up has been minimal (Sandiko, 2014). iDE partnered with IDEO and a concrete engineer to develop the Easy Latrine in 2009. It was the first packaged latrine product in Cambodia. Up until then, most of the conventional approaches to sanitation improvement usually encompassed donating toilets while overlooking the market as a driving force to sustainable sanitation (Sandiko, 2014).

Using the Human-Centered Design approach, iDE identified the unique needs, desires, and barriers of users and produced a product that households wanted to buy and businesses wanted to sell, creating a sustainable solution that can be scaled across the country. In 2009, a group from iDE spent two weeks in Cambodia talking with villagers, latrine retailers, and masons to understand the behaviors and desires regarding latrines. Key design principles were established after this initial user research phase. Some of these design principles included the desire of villagers for pour-flush latrines over dry pits, making the design upgradable, reducing the complexity of installation, and reducing the complexity of the purchasing process (Wei, 2014).

During a sixteen-month implementation phase in 2009 of the pilot Easy Latrine project, households purchased 10,621 Easy Latrines without subsidy. The Easy Latrine served as a catalyst in the project to stimulate interest of businesses to join the market by seeing "proof of concept" from other businesses making a consistent profit from selling latrines. Given the success of the pilot project, iDE secured funding from the Bill & Melinda Gates Foundation, the Stone Family Foundation, and the Water and Sanitation Program of the World Bank (WSP) to further scale up the Easy Latrine implementation. As a result, in just over two and a half years, over 100,000 latrines by over 100 local businesses were sold (Wei, 2014).

The key takeaways of the successful implementation of Easy Latrines in Cambodia are that the user includes not only the end-user, but all stakeholders who affect the user experience; true innovation doesn't lie in the product alone but also in the business model that serves the needs of both producers and consumers; and lastly engagement with users at every step of the design process is key to effective prototyping.

4.1.5 Case Study Analysis Summary

In summary, the four case studies detailed above all have a similar approach to the implementation of sanitation technologies. They begin with the end users in mind. The difference between the case studies is the toilet type implemented. The Blue Diversion Toilet is the most technical of the toilets due to its involvement in the RTTC. The Clean Team developed a business model with a simple seated toilet. The WPI student-led team utilized a composting toilet suitable for dry, arid regions. The researchers at Eawag and the students from WPI may not have known about Human Centered Design (HCD) while field testing the Blue Diversion Toilet and implementing the Otji-toilet, but they followed the same principles of the HCD process which centers on the users' needs. These principles are detailed in Section 4.2.1 of this chapter. The Clean Team did utilize the HCD process developed by IDEO, and they were able to create a successful business that can continue to profit and improve sanitation in Ghana for years to come. Involving the community and their desires leads to successful implementation of new technology. This is also supported by Community-Led Total Sanitation (CLTS). CLTS is an innovative methodology pioneered by Kamal Kar, a development consultant in India, in 2000. The CLTS method mobilizes communities to completely eliminate open defecation. It moves away from the promotion of sanitation through individual rewards at a household level and focuses on promoting the outcomes of better sanitation by triggering collective behavior for the community as a whole (Community-Led Total Sanitation, 2015).

If the Sol-Char Toilet is to be successfully implemented, it will be necessary for the Sol-Char Sanitation Team to approach the implementation in a similar way as the case studies outlined in the above sections did.

4.2 Interviews

Several interviews were conducted during this project's duration. The interview with Blake McKinlay was informal and semi-structured. The other interviews including the ones conducted with Joseph DiMasi and members of the Sol-Char Sanitation Team were informal and unstructured. Valuable information was obtained from these interviews that assisted in the final recommendations for the second phase design of the Sol-Char Toilet.

4.2.1 IDEO Human Centered Design (HCD)

An informal, semi-structured phone interview was held with Blake McKinlay of iDE on February 4, 2015. The questions asked were outlined in Section 3.2.1 of the Methods Chapter. The purpose of this interview was to get an understanding of the HCD process and gather data on the sanitation needs of developing communities from iDE employees working in the field. The HCD process was developed by IDEO, in collaboration with nonprofit groups to help international staff and volunteers understand a community's needs in new ways, find innovate solutions to meet those needs, and deliver solutions with financial sustainability in mind (IDEO, 2015). It is not unlike the approach of Community-Led Total Sanitation mentioned in Section 4.1.5 in this chapter.

The HCD process was made into a toolkit and is available for purchase in a hardcopy or as a free download online (Design Kit, 2015). This toolkit is utilized by companies all over the world, including Acumen Fund (New York, NY), AyurVAID (Bangalore, India) Heifer International (Little Rock, AR), and VisionSpring (New York, NY) (IDEO, 2015). The toolkit walks users through the HCD process and supports them in activities such as building listening skills, running workshops, and implementing ideas. The process consists of three phases; and ways to successfully do all three phases for varying timelines are included in the toolkit. This process was recommended for the Sol-Char Sanitation team to utilize by Blake McKinlay.

The first phase is the Inspiration Phase where the needs of the people the design will be benefiting are deeply understood. This is done by becoming fully immersed in the lives of the people in the community. The second phase, or the Ideation Phase, identifies the opportunities for a design and prototypes any possible solutions. The final phase, or the Implementation Phase, is where the solution is brought to life, and eventually, to market. The final design is more likely to be successful than another design that did not use the HCD process because the people who will use the new design were at the heart of the design process.

iDE utilizes HCD with their projects and has been successful at implementing new technology in developing communities, such as the Easy Latrine in Cambodia that was discussed in Section 4.1.4 of this chapter.

In his interview, Mr. McKinlay was asked the following questions:

1. What are the first things considered when thinking of implementing new technology like the Sol-Char toilet in a developing community?
2. What are common constraints of designs?
3. What are the top user sanitation preferences in developing communities?

The first thing Mr. McKinlay said that should be considered when implementing new technology is the location and what kind of community the new technology will be used in. The HCD process starts with the people the design is for by examining their needs, dreams, and behaviors. Two of the case studies that were mentioned in Section 4.1 of this chapter utilized the HCD process. The other two did not have a HCD toolkit to follow but their approach was similar.

The Sol-Char Toilet has a general location of implementation established, which will be addressed in Section 4.4 of this chapter, but a specific community has not been selected. This made creating an alternative design for the Sol-Char Toilet challenging, but not impossible. Engineering decisions are data driven. The information obtained from the case studies show that involving communities is key to success. Other aspects, such as the material costs, were considered in creating a new design.

iDE has over 30 years of experience implementing new technologies in developing communities. Mr. McKinlay was able to email several iDE teams in various countries to inquire about what the top user preferences and common constraints in toilet designs are. The responses are shown in Table 4.

Table 4: iDE Field Workers' Responses for User Preferences and Common Constraints when considering toilet designs

Country	User Preferences	Common Constraints
Vietnam	• Be a "wet" toilet • Have a commode • Have a water tap • Have ceramic tile for the floor and wall • Have underground tanks that are as big as possible • New latrine installation is more preferred to an upgraded one	• Toilets are not a purchase priority • Lack of awareness of affordable toilet options
Cambodia	• Wet toilets • Strong preference for concrete • Durability • Purchase as a complete package (delivery and installation included)	• Sourcing imported products is difficult and unreliable • People want the "taj mahal" toilet
Bangladesh	• Falling into pits is a big fear • Sharing is only acceptable with family • Water access • Space • Ceramics are preferred over plastic • Design with women's needs in mind	• Quality control • Latrine businesses cut corners when possible • Household income is seasonal • Improving a latrine is not a priority
Ethiopia	• Strong preference for concrete • Desire to be modern • Convenient with minimal smell • Cleanliness • Only share with family	• Transportation is a major barrier and expensive • Pit collapse • Reusing human waste is not acceptable
Nepal	• People don't want to empty pits • Sell toilet as a package	• Income is seasonal • People are price sensitive and think nice latrines are too expensive • Limited space to build • Little acceptance of human waste as fertilizer
Zambia	• Function over luxury • Desire to be modern • Reusing waste is not desirable • Sharing is not preferred • Durability and longevity • Sitting toilets	• Transportation is difficult • Water access is poor • Pit collapse • High cost of goods

Some of the user preference commonalities between the different regions were the desire for the toilet to come as a complete package and to be durable. Users are more likely to purchase a new toilet if its delivery and installation is included. The case studies of the Blue Diversion Toilet, the Clean Team, and the Easy Latrine all exemplify this outlook on people's willingness to purchase a new toilet. The longevity of the toilet is an important design factor to consider. People do not want to purchase something that will break soon after installation. User preferences that may vary from region to region is the desire for water in the toilet, whether the toilet uses a seat or squat plate, and whether sharing toilets are accepted within the community.

Common constraints that the iDE teams came across were the lack of sanitation knowledge, difficulty transporting toilets, and the high cost of toilets. The lack of sanitation knowledge can be resolved when utilizing the HCD process. As part of the Inspiration Phase, communities can be educated about the need for safe sanitation and shown the possible solutions to poor sanitation. The difficulty of toilet transportation and high cost of toilets may vary regionally, where the quality of access roads and availability of materials vary. However, both of these constraints can be addressed with the creation of a sanitation business model. The case study of the Clean Team in Ghana demonstrates the success of a sanitation business model. Toilets are transported to individual homes and installed, and waste is collected twice a week for a small fee. There are benefits for both the consumers and producers in this system; consumers have a safe, affordable toilet to use and producers gain profit from the weekly fee.

The country specific and regional preferences in Table 4 are important when addressing issues for the next phase of the Sol-Char Toilet. Regardless of which country the Sol-Char Toilet may be implemented in, many of the same issues will likely arise.

4.2.2 BrightSpace Solar Technology

BrightSpace Technologies is a small, start-up solar company in Boulder, CO. They are currently in the process of designing and developing a novel solar technology that has been largely funded by a Phase II SBIR (Small Business Innovation Research) grant from the Department of Energy. An informal, unstructured interview with the company's CEO, Joseph DiMasi, was conducted on January 29, 2015. BrightSpace Technologies is positioned to be a valuable partner in the next phase of the Sol-Char Toilet design. One of the largest challenges with the first phase of the Sol-Char toilet is the high cost of solar transmission and solar capture. Shown in Figure 22 is the breakdown of the production cost of the first phase Sol-Char toilet design. These numbers were derived from a cost analysis performed by the Sol-Char Sanitation team in 2014.

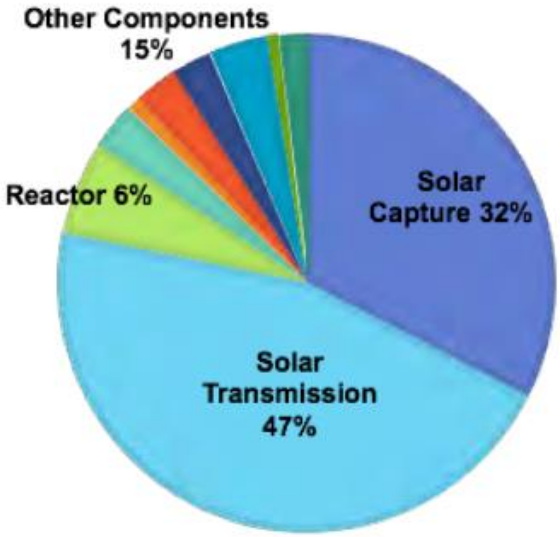

Figure 22: Cost Breakdown for Phase I Design at Production Scale (Linden, 2015)

The Phase I Sol-Char Toilet prototype cost $49,000 to make, and an estimate for a large-scale production model is around $11,900 (Linden, 2015). The most expensive components of the design are the fiber optics and solar concentrators. Fiber optics are shown in Figure 22 as solar transmission; and solar concentrators are represented by solar capture. The technology from BrightSpace enables the fiber optic technology cost to be reduced by tenfold (DiMasi, 2015). This is a considerable amount of savings and could advance the development of the Sol-Char Toilet by allowing it to be produced at a lower cost.

The BrightSpace technology is proprietary so detailed specifications cannot be disclosed. Rather, the rest of this section focuses on the positive outcomes of said partnership, such as the increase in number of people able to be served, the amount of electricity produced, and the decreased cost estimates. The BrightSpace technology utilizes photovoltaic cells in its solar capture design. The Sol-Char Toilet's current solar capture design uses parabolic discs to direct sunlight through fiber optic cables to its reactor chamber. The BrightSpace technology is more efficient (DiMasi, 2015), and this increased efficiency leads to better pyrolysis within the reactor chamber of the Sol-Char toilet and allows more waste to be processed. In other words, the solar technology from

BrightSpace allows more users to benefit from the technology and a better product to be made from the Sol-Char waste reactor. The current Sol-Char design allows 4-6 people to use the toilet. It is designed for single-family use. In the next phase, to help reduce the cost per user per day, the design should be able to accommodate more users.

The BrightSpace technology would allow the Sol-Char Toilet to be scalable. The number of solar collectors can be changed to make either a small system or large system scenario. The small system scenario includes 24 solar collectors that can potentially generate 3-7.5 kWhr/day depending on DNI. The less DNI, the less people are served and less electricity is generated. The large system scenario includes 48 solar collectors that can generate 6-15 kWhr/day. The overall cost of use per person per day decreases as DNI increases. The more intense the sunlight, the greater the energy emitted into the system is, therefore, allowing more waste to be processed. The more people that use the toilet, the less the overall cost is per person.

Table 5 shows the effect DNI has on the number of people served, the cost of use, and the electricity generated. These data were obtained from calculations done by Joseph DiMasi, CEO of BrightSpace Technologies, and Karl Linden, Professor at CU Boulder and principal investigator for the Sol-Char Toilet.

Table 5: Design Size Scenarios with varying DNI Values (DiMasi and Linden, 2015)

	DNI	People Served (#)	Cost of Use/Person/Day ($)	Electricity Generated (kWhr/day)
Small Scale System 24 Solar Collectors	3.0	23	0.034	3.2
	4.0	31	0.025	4.2
	5.0	38	0.020	5.3
	6.0	46	0.017	6.4
	7.0	54	0.014	7.4
Large Scale System 48 Solar Collectors	3.0	46	0.032	6.4
	4.0	62	0.024	8.5
	5.0	76	0.019	10.6
	6.0	92	0.016	12.7
	7.0	108	0.014	14.8

The photovoltaic cells of the BrightSpace technology would allow the Sol-Char Toilet to generate electricity, something that it is unable to do currently. This addresses the inability of the current design to process waste on cloudy days. The electrical ‘co-generation’ provides up to 15kW-hrs of electricity with battery backup for offline (cloudy) operation (DiMasi, 2015). The infrared light not only generates electricity to the toilet system, but also provides auxiliary heat, which can improve the solid waste processing efficiency.

The partnership between BrightSpace and the Sol-Char Sanitation team will prove to be important as both parties further their prototypes. BrightSpace will hopefully have a working prototype by the summer of 2015. As soon as their prototype has been tested and improved, it can be implemented for Phase II of the Sol-Char toilet.

4.2.3 Sol-Char Sanitation Team

Members of the Sol-Char Sanitation team were interviewed in intermittent, unstructured interviews during a two-month period beginning in January 2015. The various topics of discussion were the current state of the Sol-Char Toilet design, areas where the design could be improved and what the future holds for the Sol-Char Toilet. Current successful research findings of the current design include the success of the reactor system and the success of biochar production. It has been shown through testing of the solar discs that enough energy is transmitted to convert waste to biochar. However, the efficiency can be improved. The reactor uses a lot of its energy to dry the human waste, essentially ridding the waste of water. Members of the team noted a preliminary drying step as something to add to the next design.

All members interviewed agreed that the future of the Sol-Char Toilet relies heavily on the ability to obtain grants to help further develop its research. In order to receive another grant from the Bill & Melinda Gates Foundation, the Sol-Char Toilet has to become economically efficient. A modular design that allows the toilet to service more individuals with improved reactor efficiency will reduce production costs. Also, field-testing of the toilet will greatly increase its chances of receiving more grants by effectively demonstrating that it can be successful.

4.4 Possible Locations for the Sol-Char Toilet Implementation

The Sol-Char toilet technology cannot operate without enough sunlight. This is the first criteria for the implementation location of the Sol-Char Toilet. Research done in 2013 found that the least amount of energy the Sol-Char Toilet needed in order to pyrolyze waste was 3.2 kWhrs/m^2/day (Linden, 2015). The sunlight requirement is quantified as DNI (Direct Normal

Irradiation). A map illustrating the DNI values for different regions of the world is shown in Figure 23.

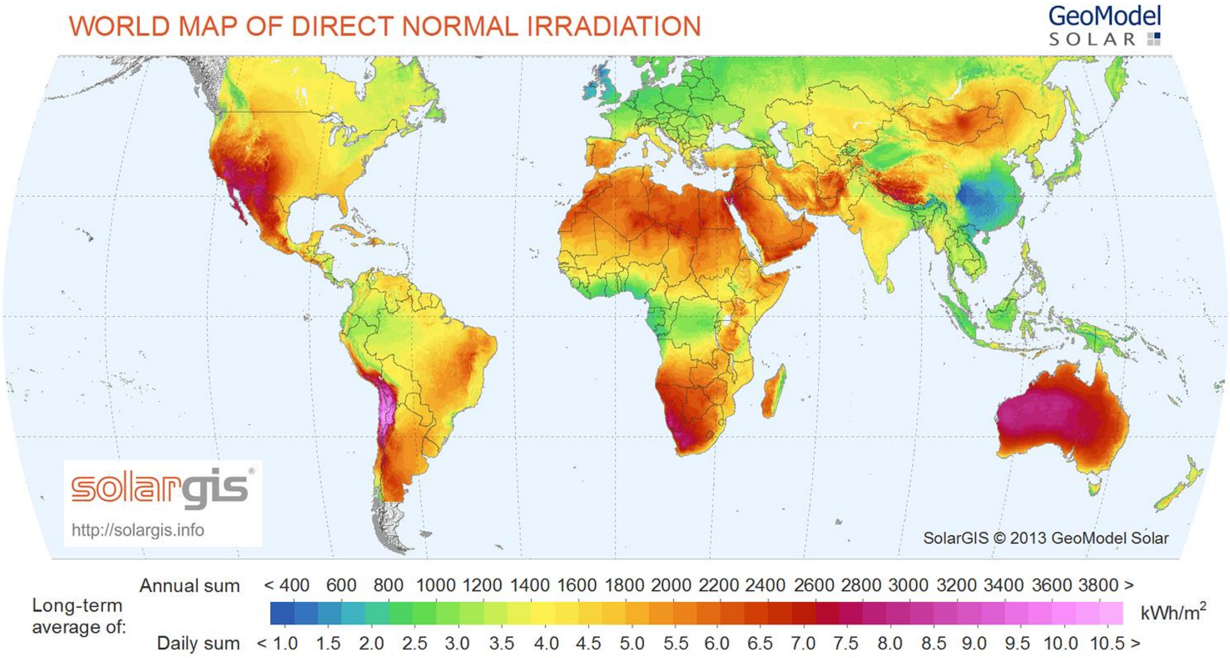

Figure 23: World Map of DNI (GeoSUN, 2015)

Many areas of the world have DNI values that are above the minimum for the Sol-Char toilet. However, only areas that are in need of sanitation improvement were considered for implementation of the Sol-Char toilet. Therefore, data on sanitation conditions in areas with sufficient sunlight were obtained. According to data from the Joint Monitoring Programme in collaboration with the World Health Organization and UNICEF, areas that had less than fifty percent of their population using improved sanitation facilities were Sub-Saharan Africa, Central Africa, and Southern Asia (WHO and UNICEF, 2014). A map that highlights areas in need of sanitation improvement is shown in Figure 25.

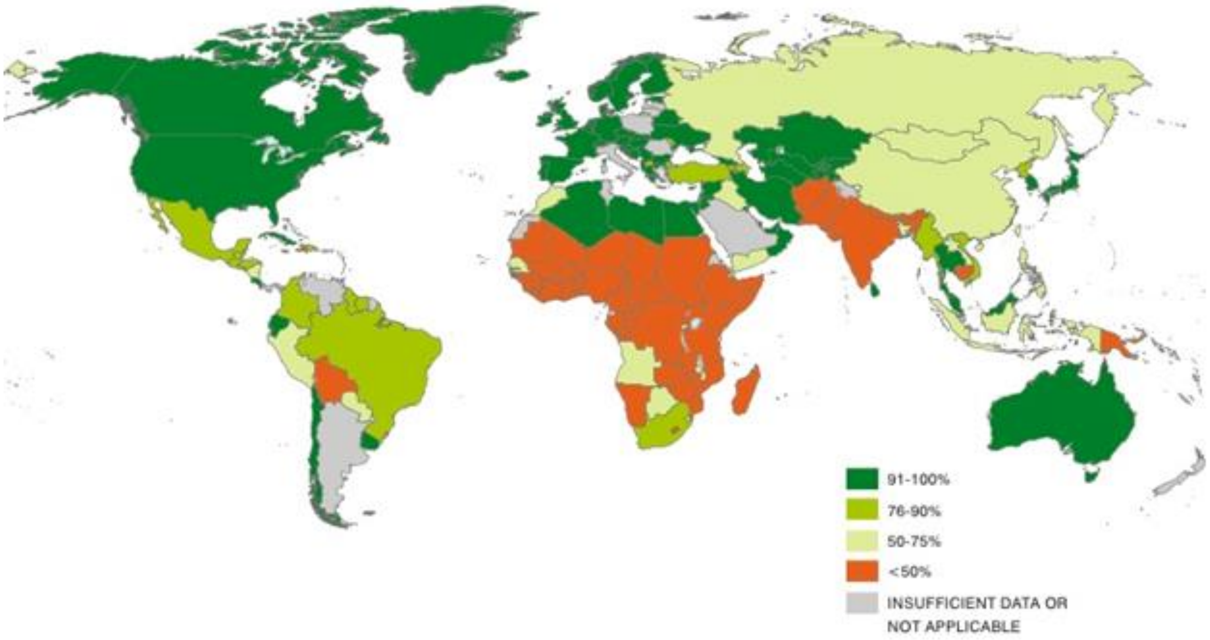

Figure 24: Proportion of the world population using improved sanitation in 2010 (WHO and UNICEF, 2014)

The next deciding factor for finding the optimal location for the Sol-Char toilet was the potential of partnering with other organizations and government agencies. This is vital to the success of the Sol-Char Toilet because a partnership with an existing Non-Government Organization (NGO), for example, would help in prioritizing communities with significant sanitation need. Also, receiving additional funding from an organization would assist with the costs associated with the Sol-Char Toilet's field tests and cost of redesigning/reengineering the system. A table of possible countries with a need for sanitation improvement and with existing organizations working in the sanitation sector is shown in Table 6.

Table 6: Possible Countries for the Sol-Char Toilet Implementation based on DNI, lack of sanitation, and potential partners

Country	Solar irradiance (kwh/m^2/d)	Access to improved sanitation (% of population) (WHO, 2010)	Potential partners
Burkina Faso	5.9	17%	WaterAid
Ethiopia	4.99	21%	Water.org, WaterAid
Ghana	4.49	14%	WaterAid
Mali	5.66	22%	WaterAid
Nigeria	5.45	31%	WaterAid
Tanzania	5.79	10%	WaterAid
Uganda	5.14	34%	Water for People, Water.org, WaterAid
Bangladesh	4.65	56%	Water.org, WaterAid
India	5.22	34%	Water for People, WaterAid
Rwanda	4.88	55%	Water for People
Peru	5.43	71%	Water for People
Kenya	5.01	32%	Sanergy, Sanivation

The countries that had the overall highest need for sanitation need included Burkina Fuso, Ghana, and Tanzania. The countries with the highest DNI values included Burkina Fuso, Tanzania, and Mali. These countries all have WaterAid as a possible partner. These are all possible locations for the Sol-Char Toilet. One country that does not comparatively show as much of a need for sanitation improvement from the table but should still be considered as a possible location for implementation is India. India held the second RTTC Fair in 2014. The Biotechnology Industry Research Assistance Council (BIRAC) of India has since partnered with the Bill & Melinda Gates Foundation to support sanitation research and development projects. India has also recently taken initiative to tackle its sanitation problem. In October 2014, Prime Minster Narendra Modi announced the Swachh Bharat (Clean India) Mission to ensure India is litter free and that every home has access to a toilet by 2019 (India Newsletter, 2015).

The countries listed in Table 6 all have a need for sanitation improvement in their communities. India meets the required DNI minimum, and although it might not have as much of a need for improved sanitation as Tanzania does (its proportion of population with access to improved sanitation was 34% while Tanzania's was 10%), India is still a greater desired location. Due to India's current government action to improve sanitation, India is the preferred location for the implementation of the Sol-Char Toilet.

4.5 The Design Alternatives for the Phase II of the Sol-Char

Data were obtained by performing interviews of the Sol-Char team members; researching case studies of toilets currently deployed in developing communities; and interviewing people currently in the field. Based on these data, alternative designs of the Sol-Char Toilet were created.

The following sections highlight four alternative designs, one having a conveyor belt system and three having an auger system. Each design was evaluated for key design aspects, which were overall cost, life expectancy, ease of use, aesthetics, maintenance, reactor efficiency, and safety. Each design is assumed to have a 40 ft. long shipping container as its shell. The shipping container was agreed upon by all members of the Sol-Char team to be the least expensive and easiest way to create a modular toilet design in Phase II of the Sol-Char Toilet (Linden, 2015).

4.5.1 Phase I Design Pros and Cons

The Phase I design of the Sol-Char Toilet is shown in Figure 25. As described previously, this design incorporates eight parabolic discs that concentrate sunlight and transmit the solar energy to a reactor chamber where human waste is pyrolyzed.

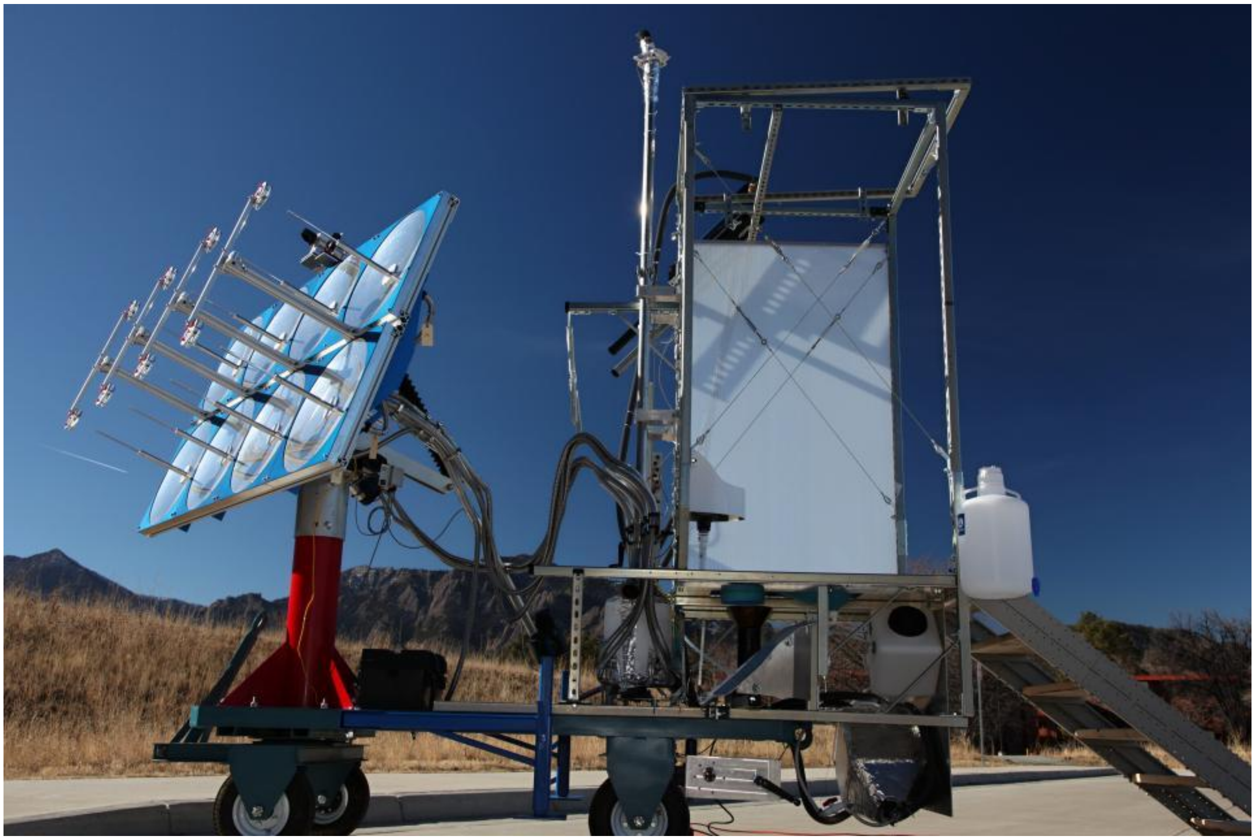

Figure 25: Sol-Char Toilet Phase I Design (University of Colorado Boulder, 2015)

In its Phase I design, the Sol-Char Toilet successfully collects sunlight (without interruption on a clear day), treats feces and urine, and includes exhaust to control odor. The mechanical parts are functional. For example, the mechanical system of dumping the treated waste out and changing the collection container to the treatment position work. However, there are improvements that could be employed in a second phase design. As determined from interviews with the Sol-Char Team and Karl Linden (Linden, 2015), the main improvement needed is increasing the efficiency of the reactor in order to dry and char more waste with the current amount of energy collected. As mentioned in Section 2.2.1 and as shown specifically in Figure 12, the Sol-Char reactor reached high temperatures of around 450°C, while the waste only reached around 100°C. Another improvement is on lowering the cost of the parts that make up the toilet, especially the fiber optic cables. As mentioned in Section 4.2.2 and specifically shown in Figure 22, the solar capture composes 32% of the overall cost of the Sol-Char Toilet. Another improvement is including a way to either store energy, or store waste for days when the weather doesn't permit use of the toilet. The designs outlined in the following sections show possible alternative designs to the Phase I design addressing different pros and cons.

4.5.2 Alternative Design with Conveyor Belt System

The first alternative design utilizes a conveyor belt system. This conveyor belt system is a new addition to the Sol-Char Toilet and is used as a pre-drying step. This design addresses the reactor efficiency issue. By pre-drying the waste, excess water is removed and the reactor requires less energy to pyrolyze the waste. The conveyor belt system concept can be seen in Figure 26. The conveyor belt flattens waste as it simultaneously dries the waste. The University of Toronto used this system in their first toilet design for the Reinvent the Toilet Challenge in 2012 (Gates Foundation, 2015). However, since 2012 the University of Toronto has moved away from the conveyor belt system and moved towards an auger system (Sauder, 2015). An advantage of the conveyor belt design is the removal of excess moisture from waste. A possible disadvantage of the conveyor belt design is the likelihood of mechanical failure. The conveyor belts need frequent maintenance and knowledge of how conveyors work mechanically must be known by those who maintain it.

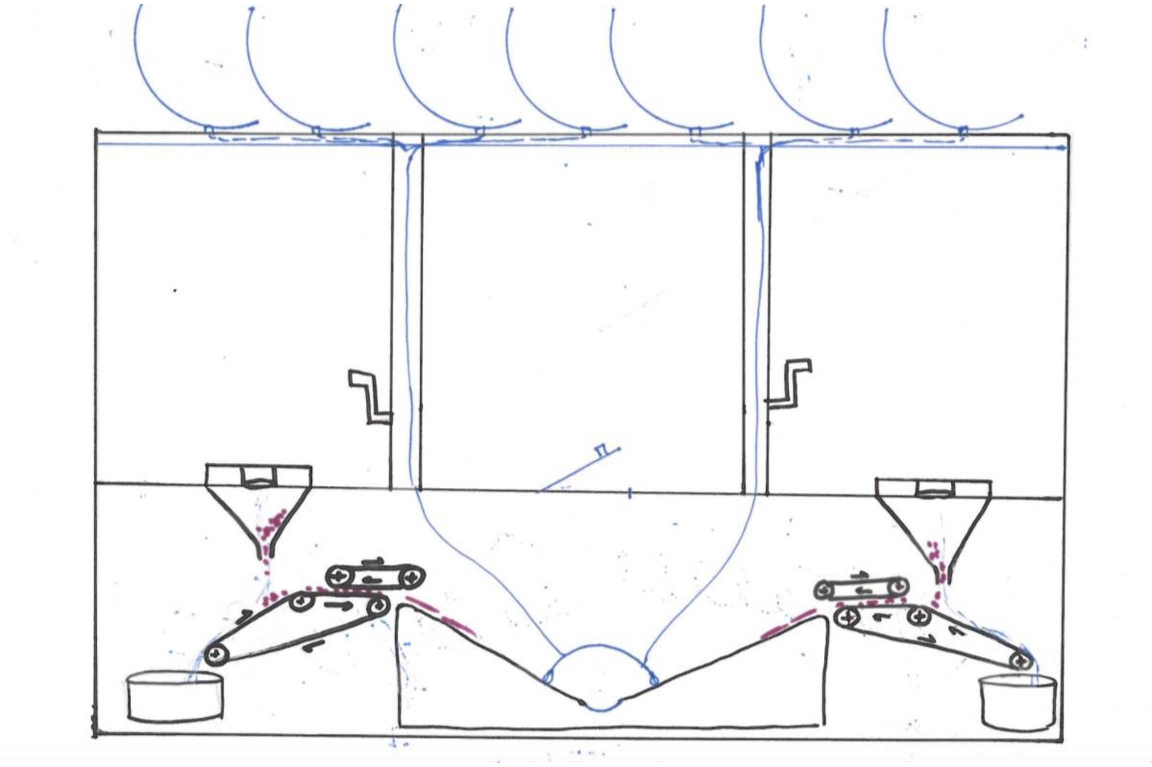

Figure 26: Alternative Design with Conveyor Belt Design

Another possible disadvantage of this design is the length of the fiber optic cables. The reactor is below ground so the cables have to be at least 8 feet, according to the typical height of shipping containers.

4.5.3 Alternative Designs with Auger System

Three alternative designs that utilize an auger system were created. As with the conveyor belt system, the auger system is used as pre-drying step. Figure 27 shows the first alternative design with an auger system with the reactor chamber below ground.

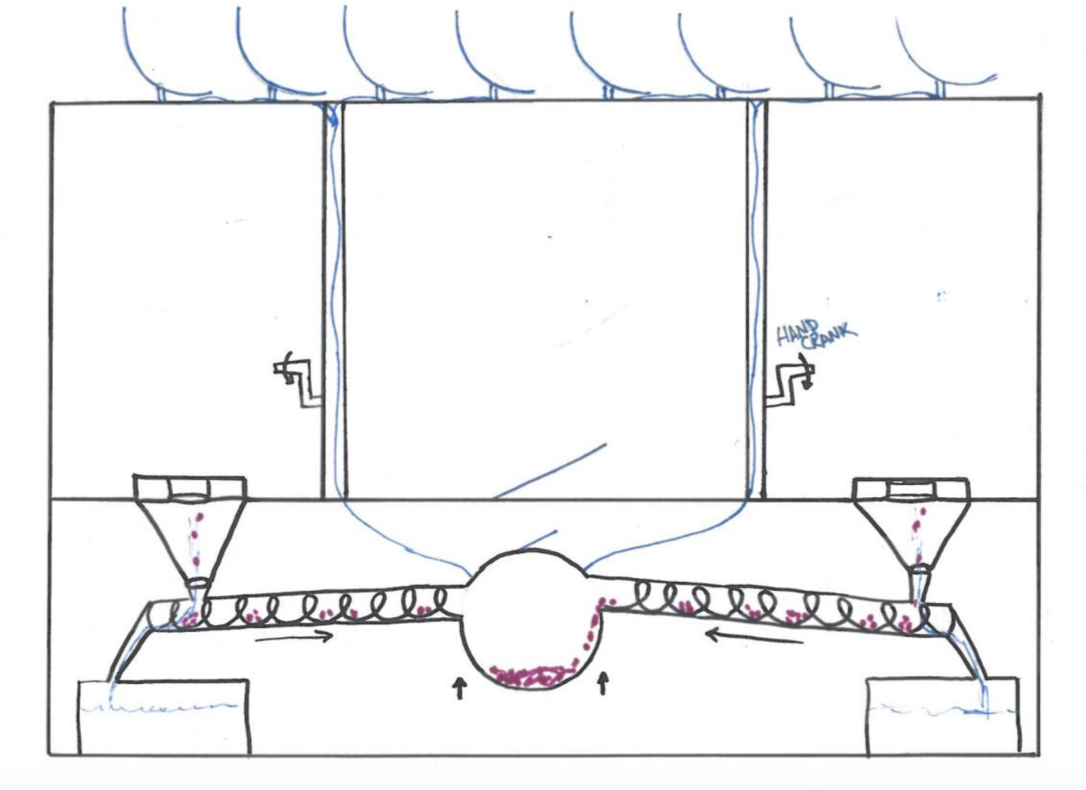

Figure 27: Alternative Design with Auger System and Reactor Chamber Below Ground

An advantage of this design is the heat produced from the reactor chamber. This excess heat may be used to assist in the pre-drying of the waste within the auger. This design does not include a urine-diverting squat plate. Liquid and solid wastes collect together in the auger; however, it is designed so that the auger has a slope to allow for liquid waste to flow down towards a collection tank where it will be treated separately. However, it is possible for this design to utilize a urine-diverting squat plate to separate liquid and solid wastes. The liquid waste could be collected in a container or in another way that the next design will demonstrate. Waste is collected from the middle compartment of the shipping container. Again, knowledge of how augers function must be known by those who maintain this toilet.

Another alternative design that utilizes an auger system and has the reactor below ground is shown in Figure 28. The difference between this design and the one shown in Figure 27 is urine diversion. This design uses a urine-diverting squat plate that channels liquid waste into a steel tube that is wrapped around the auger. The excess heat from the reactor chamber flows throughout the auger and heats up the liquid waste in the tube. Testing would need to be performed to analyze whether this design can effectively heat urine to a high enough temperature to rid the liquid of pathogens.

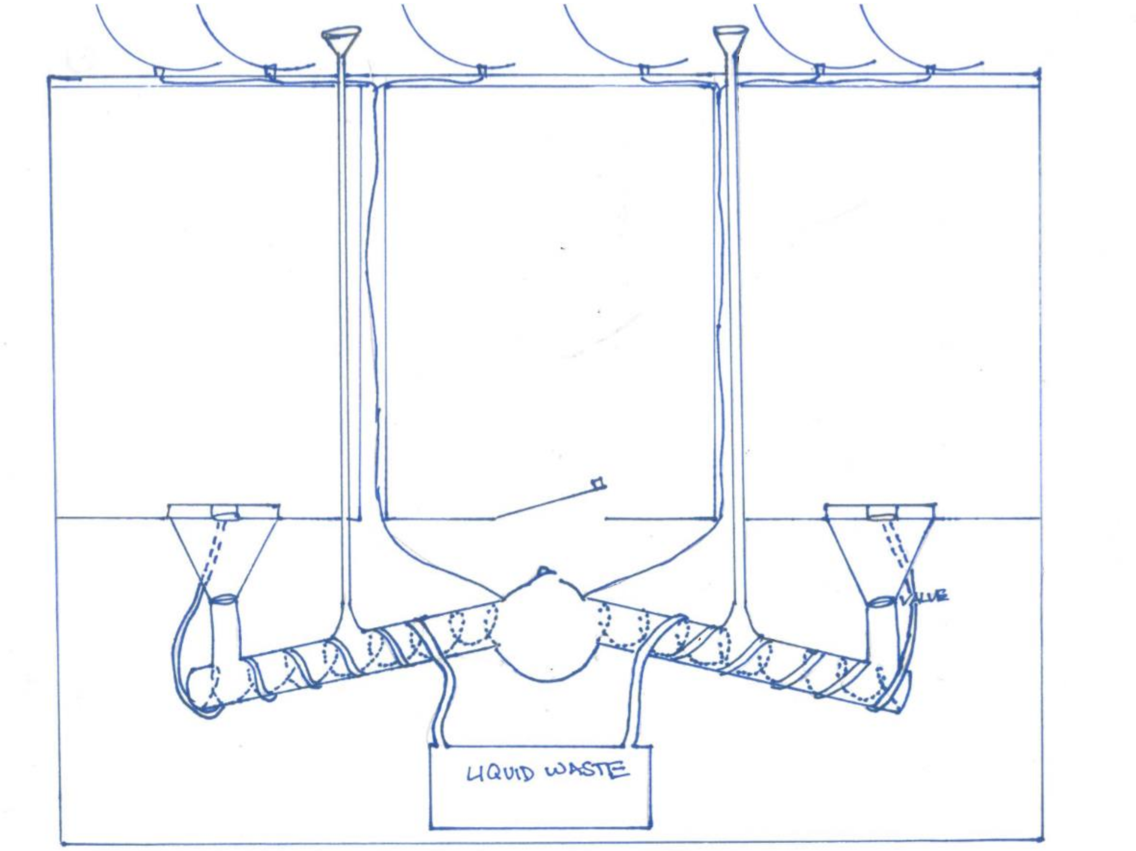

Figure 28: Alternative Design with Auger System Below Ground and Wrapped Liquid Waste Coil

A disadvantage of both auger designs thus far is the length of fiber optic cables. Fiber optic cables are one of the most expensive design components. The fiber optic cables currently used for the Sol-Char Toilet are $1500 per 4 meters (Fisher, 2015). Having to channel the fiber optic cables into the ground to reach the reactor will not resolve the current design's economic infeasibility (Linden, 2015).

To mitigate the potentially high cost of fiber optic cables, the next design has reactor chambers above ground. They are positioned in the middle compartment, or "utility room," of the shipping container shell. Figure 29 outlines this design concept. Two reactor chambers are positioned on the sidewalls of the utility room.

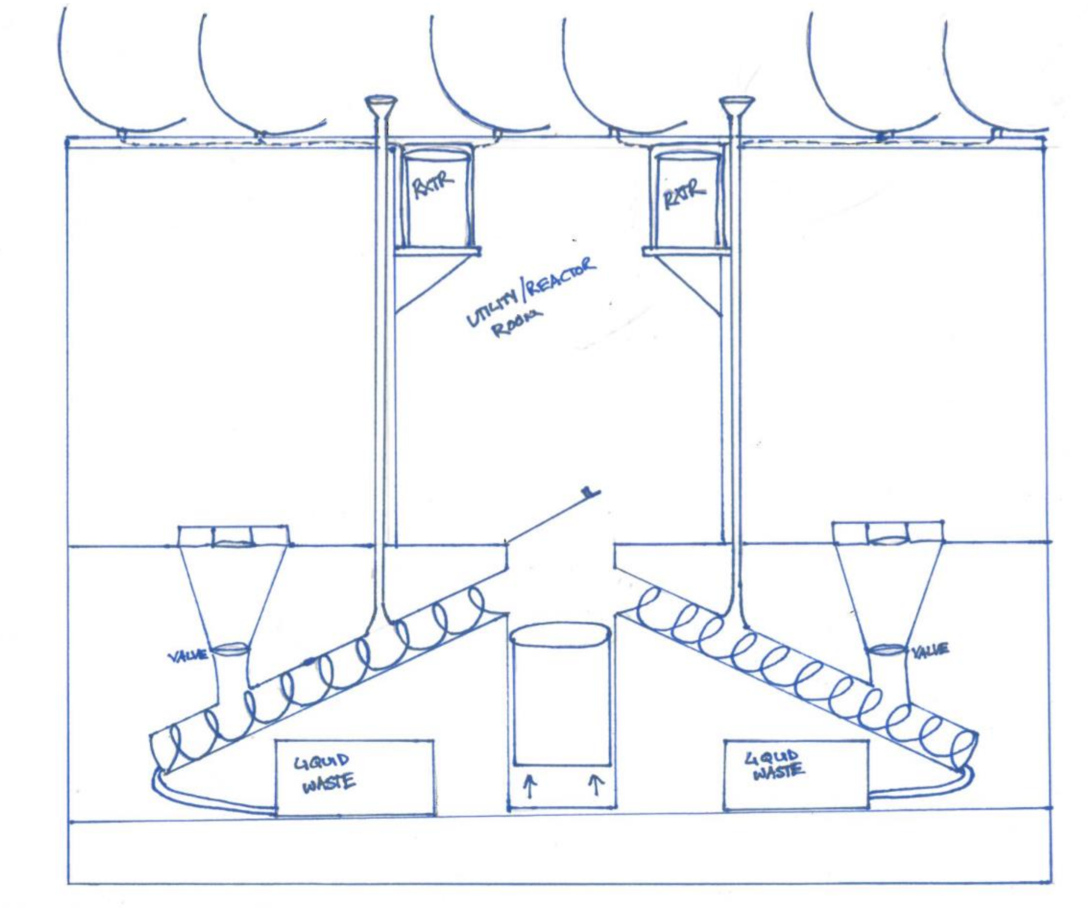

Figure 29: Alternative Design with Auger System and Reactor Above Ground

The advantage of this design is the decreased length of fiber optic cables. However, to appropriately upkeep this design a person must be trained how to properly transport waste from the collection tank underground to the reactors. This may not be culturally accepted. Still, this design alternative can be compared to the case study of the Clean Team in Ghana. They developed an innovative business model and services for private sector delivery of improved household sanitation (IDEO, 2011). Collection of waste was included within this business model. Ghanaians paid an initial fee to have a toilet installed in their homes and then a weekly fee for collection of waste. This type of business model could be adapted for the Sol-Char Toilet.

4.5.4 Design Decision Matrix of Alternative Sol-Char Toilet Designs

A decision design matrix evaluates and prioritizes a list of possible design options. For this project, each design constraint was weighted and then ranked for each design alternative. This allowed every alternative design to have an overall weighted score to assist in determining the best option. The seven design constraints identified for this project's decision matrix were the following: overall cost, life expectancy, ease of use, maintenance, aesthetics, reactor efficiency, and safety. To begin, each individual constraint was compared to each other in a rank order chart based on a combination of personal judgment, interviews with Sol-Char team members, and the interview conducted with Blake McKinlay. This chart is shown in Table 7. A value of 1.0 in the horizontal row denotes that factor to be of higher importance than the corresponding column's factor. A value of 0.0 denotes that factor to be of lesser importance, and a value of 0.5 denotes equal importance. The values assigned to each design constraint in the horizontal rows were then totaled. This method is called the Pairwise Comparison method (Temesi, 2006).

Table 7: Rank Order Chart

Design Constraints	*Overall Cost*	*Life Expectancy*	*Ease of Use*	*Maintenance*	*Aesthetics*	*Reactor Efficiency*	*Safety*	**TOTAL**	**Weighting Factor**
Overall Cost	-	1.0	1.0	0.5	1	0.5	0.5	4.5	75
Life Expectancy	0.0	-	1.0	0.0	1	0.5	0.5	3.0	60
Ease of Use	0.0	0.0	-	0.0	1	0	0.0	1.0	40
Maintenance	0.5	1.0	1.0	-	1	0.5	0.5	4.5	75
Aesthetics	0.0	0.0	0.5	0.0	-	0	0.0	0.5	35
Reactor Efficiency	0.5	1.0	1.0	1.0	1	-	0.5	5.0	80
Safety	0.5	0.5	1.0	0.5	1	0.5	-	4.0	70

To find the weighting factor of each design constraint shown in Table 1, Equation 1 was used. Each design constraint was weighted between 0-30 for “optional,” 31-70 for “moderate importance,” and 71-100 for “high importance” items. It was then assumed that all constraints were not optional, so each design constraint was weighted on a scale of 35-100 using Equation 1. The highest design constraint total possible in Table 1 would be 7.0 because there are seven design constraints total. If a constraint had this total than weighting factor (WF) derived from Equation 1 would be 100, the highest it possibly could be.

$$WF = \left[\left(\frac{Design\ Constraint\ Total}{10}\right) * 100\right] + 30 \qquad \text{(Equation 1)}$$

Based on the pairwise comparison method and Equation 1, the most important design constraint was found to be reactor efficiency. Tied for the second most important design constraints were overall cost and maintenance. These weighting values correlate to the improvements discussed with Sol-Char team members (Linden, 2015) dealing with the high cost of solar capture and solar transmission, and the interview with Blake McKinlay (McKinlay, 2015) dealing with human acceptance of the toilet design.

Each design alternative was then ranked from 0-10 on how well it met each of the design constraints, with 0 signifying it did not meet the design constraint and 10 signifying it met the design constraint extremely well. Values were determined based on knowledge gained fin the data-collection phase of the project. The design decision matrix is shown in Table 8. For example it can be seen in the table that the conveyor belt system was ranked 3 for overall cost because it is assumed that the conveyor belts are more costly than the auger systems. Also, the length of the fiber optic cables compared to the auger with the above ground reactor will be longer. Hence, the auger with above ground reactor was ranked 10 for overall cost because the potential fiber optic cost is much lower than the other designs. Other key rankings to note are reactor efficiency and aesthetics. The reactor efficiency for the conveyor belt, the auger system with below ground reactor, and the auger system with the wrapped urine coil were given low rankings because it is assumed that there will be significant energy loss from the longer length of the fiber optic cables compared to the auger system with the above ground reactor. The aesthetics of each design were ranked the same because each utilizes a shipping container as its shell. The inside or out of view parts of the designs are what changed in each design.

A total score was then calculated by multiplying the weighting factors of each design constraint by the values (0-10) assigned to each design alternative, as demonstrated in Table 8.

Based on the decision design matrix, the alternative design that uses the auger system with above ground reactor chambers is the best recommendation for Phase II of the Sol-Char Toilet. This design alternative will most likely be the least expensive option of the four designs due to the short length of the fiber optic cables. The maintenance will require education of proper waste transfer, but this downfall can be integrated into a long-term business plan of the Sol-Char Toilet.

Table 8: Design Decision Matrix

	Design Constraints							
	Overall Cost	*Life Expectancy*	*Ease of Use*	*Maintenance*	*Aesthetics*	*Reactor Efficiency*	*Safety*	
	Weighing Factors							
Design Alternatives	**75**	**60**	**40**	**75**	**35**	**80**	**70**	**TOTAL**
Conveyor Belt	3	1	9	1	10	1	7	**1640**
Auger with below ground reactor	5	6	9	4	10	2	9	**2535**
Auger with above ground reactor	10	5	9	2	10	10	3	**2920**
Auger with wrapped urine coil	5	6	9	4	10	2	8	**2465**

Chapter 5: Conclusions and Future Recommendations

In conclusion, based on the design constraints formulated in this report and from interviewing members of the Sol-Char Sanitation Team and Blake McKinlay, the final Phase II design should include an above ground reactor system and employ an auger pre-drying step. This is the best alternative design to the current Phase I design of the Sol-Char Toilet because it addresses the high cost of fiber optic cables and the efficiency of the reactor. A partnership with BrightSpace Technologies also addresses the high cost of the current design. BrightSpace has technology that greatly decreases the cost of each fiber optic cable. It is recommended that the Sol-Char team work closely with BrightSpace Technologies as they further finalize their solar capture prototype.

The reactor efficiency of the design will need to be tested as a second phase prototype of the Sol-Char Toilet is developed. However, with the addition of an auger system it can be theoretically estimated that the energy required for the reactor to pyrolyze collected waste will be less due to the decrease in moisture content of the waste. Less energy required for the reactor to effectively pyrolyze waste means theoretically more waste can be processed. Therefore, more users can benefit from the Sol-Char Toilet and the cost per user per day will be less.

One area that will need to be researched further is the cultural preferences in the implementation location. It was recommended that the Sol-Char Toilet be implemented in India because of the required DNI values and the possible NGO partners. However, a specific community will have to be determined. When this happens, it is recommended that the Sol-Char Team utilize the HCD process. A further recommendation is to have a member of iDE accompany members of the Sol-Char team to India to help successfully implement the toilet with the HCD process. This process will also help with the next recommendation, which is to employ a business model surrounding the production, transportation, and maintenance of the Sol-Char Toilet. This model will need to be developed in accordance to existing businesses within the community.

The Sol-Char Toilet has the potential to help alleviate sanitation problems in developing communities. With further research and help from NGOs, such as the Bill & Melinda Gates Foundation and iDE, and other organizations interested in helping with this unique project, such as BrightSpace Technologies, people in communities in need of improved sanitation may have the opportunity to live a more dignified and healthy life.

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