Preliminary Design of a Mobile Toilet for Use by Muslim Refugees in Kenya

A final report presented to
Sanivation and the GT Capstone Faculty

by

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"To bring relief to Muslim refugees in Kenya by designing an inexpensive, mobile toilet that lowers fecal-oral contamination and reduces stress on the body while maintaining the cultural practices of squatting and anal cleansing."

Executive Summary

Sanivation, a Georgia Tech/Emory start-up that treats and transforms human waste into useful, non-pathogenic substances, commissioned Wonder Women to design a novel sanitation solution for developing countries. Currently, Sanivation works with several other organizations including the Centers for Disease Control and Prevention (CDC) to achieve its goals and it recently began work in Kenya in order to impact vulnerable, neglected populations. Specifically, Wonder Women collaborated with Sanivation to design an inexpensive and non-permanent toilet for Somali Muslims living in the Kakuma Refugee Camp in Kenya.

To define the project's objectives, Wonder Women conducted interviews with key stakeholders, studied the Kakuma Refugee Camp annual reports, and performed an in-depth background analysis of the global precedents of sanitation technology, the geographical and climate constraints, and the specific cultural and religious practices of the Somali Muslim refugees. Wonder Women then synthesized its findings to develop specific design constraints, begin component design, and iterate through prototypes.

Wonder Women identified detailed objectives and pertinent constraints for its proposed design through its comprehensive ethnographic research. Expressly, the conclusions drawn from interviews with specialists and the wide-ranging analyses of the population, technology, and environment elucidated the need for a toilet that incorporated both the explicit and implicit cultural, religious, and technological needs. These constraints were identified as being inexpensive, non-permanent, conducive to squatting and anal cleansing, and separating waste products for collection. The scope of the project narrowed as the specific design and engineering constraints were further developed during the prototyping phase. Specifically, the prototyping process focused the design plans and confirmed the product concept that, at its minimum, was a mobile household toilet that separated waste and maintained cultural practices.

Wonder Women iterated through various prototypes via analytical modeling and experimental testing. Through this process, Wonder Women successfully designed, built, and tested its solution: the Safi Choo toilet. Unlike traditional pit latrines, the Safi Choo toilet ("good toilet" in Swahili) offers a more hygienic and ergonomic experience through the separation and collection of waste by a four-part drawer and filtration system and a human-centric design that reduces stress on the body when squatting or anal cleansing. A working prototype of the Safi Choo toilet was presented to Sanivation in December 2013. Pending funding, the Safi Choo toilet will undergo field-testing in Kenya by Wonder Women and Sanivation in Summer 2014.

Key Words: Sanitation; Anal Cleansing; Squatting; Ergonomics; Filtration; Refugee Camps

Table of Contents

I. Introduction

According to UNICEF, 2.6 billion people—one in three people—live without access to basic sanitation. As a result, more than 3.4 million people die each year from water, sanitation, and hygiene (WASH)-related diseases in the developing world. [1] Sanivation is a Georgia Tech/Emory startup that treats and transforms human waste into useful, non-pathogenic substances in developing countries. Specifically, Sanivation facilitates waste collection and transport by trained employees from community homes to local treatment centers for processing and reuse of human waste via its novel solar concentrators. [2] Recently, Sanivation expanded its innovative sanitation initiative to Kenya after identifying the need for an improved sanitation solution for Muslim refugees who squat and anal cleanse. Thus, this project aimed to design an inexpensive, non-permanent toilet for Somali Muslims temporarily living in the Kakuma Refugee Camp in Kenya (Figure 0) that also separates waste products in preparation of a centrally processed solar dehydration stage to generate energy from feces.

Kakuma is currently home to more than 140,000 refugees; however, the temporary camp was originally built in 1992 for only 20,000 people, leaving it overcrowded and with rampant sanitation and health issues. [3] Particularly, given the expansive, overcrowded conditions, eliminating diseases from fecal-oral contamination and decreasing the camp's subsequent high fatality rate from WASH-related diseases, is a paramount health concern. [4] In order to prevent this issue, Sanivation actively works in the refugee camp to design and install sustainable, mobile household toilets. Prior to Sanivation's involvement, all of the sanitation solutions in Kakuma focused on the South Sudanese refugee population of the camp, which is predominantly Christian. [5] However, since Muslims have very different practices when it comes to defecating and cleansing, it was determined that a toilet designed to fit the cultural and religious needs of the Muslim population was needed. [6] Thus, due to the specificity of the Muslims' sanitation needs and current widespread practice of open defecation due to the lack of clean toilets that support this practice, Wonder Women's proposed sanitation solution, the Safi Choo toilet, expressly targeted this Muslim Somali refugee population.

The Safi Choo toilet is an innovative toilet system that offers a more hygienic and ergonomic experience for Muslim refugees who currently squat while defecating and practice anal cleansing. Unlike traditional pit latrines, the Safi Choo toilet offers a non-permanent, above ground solution to counter the lack of space in refugee camps and, as demonstrated by other improved sanitation solutions, is expected to reduce diarrhea morbidity in the refugee camp by 37.5% via the separation and collection of waste by a four-part drawer and filtration system. With Safi Choo's ergonomic, human-centric design, users of all ages and abilities can sit or squat comfortably to maintain the cultural practice of squatting and anal cleansing, while also reducing stress on the body.

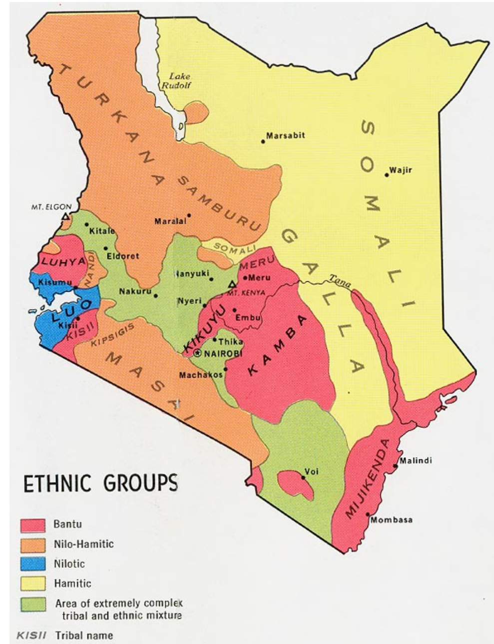


Figure 0. Map of Kakuma Refugee Camp

Stakeholders

Stakeholders were identified based on perceived importance and influence to the project, whether during the initial background research, design, prototyping, testing, or implementation phases (Figure 1). Next, stakeholders were separated into four broad categories: least important, show consideration, meet their needs, and key players. The size of the circle correlated with the extent of consideration required when developing design constraints, as well as the frequency of contact that occurred during ideation and prototyping to maintain positive professional relationships to achieve the project goals.

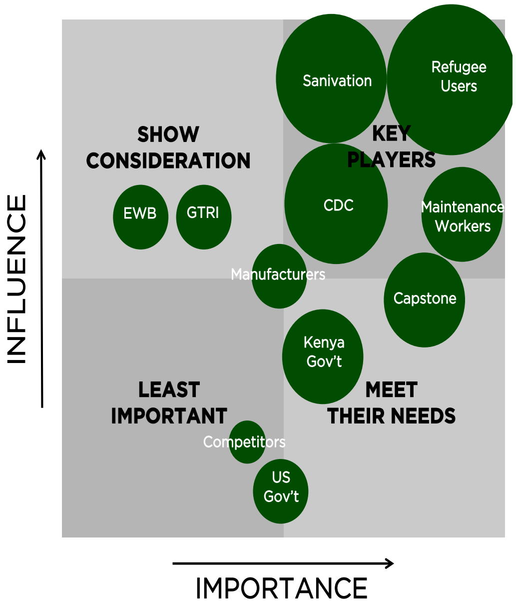


Figure 1. Stakeholder Analysis

As seen in Figure 1, the most influential and important stakeholders were Sanivation, the Muslim refugees, CDC, and the maintenance worker (Stephen) who transports the waste products to the central treatment facility. Of these, Sanivation was considered the most influential and important stakeholder since it is Wonder Women's sponsoring organization. The refugee users and maintenance workers were also considered pertinent stakeholders since they will actually interact with the proposed product daily. The CDC was deemed influential and important because it represents the project's main financial support. Moreover, the design met the needs of the capstone course and the Kenyan government since, otherwise, the final design would not be approved. Wonder Women also showed consideration to Engineers Without Borders (EWB) and the Georgia Tech Research Institute (GTRI) during the design and prototype phases, given their strong basis for technological support and close relationship with Sanivation. Additionally, Wonder Women considered the interests of those who will manufacture the final product in Kenya. The United States government and any prospective competitors were identified as the least influential and least important stakeholders, given the specialized niche of the project objective, but the final design still needed to consider their opinions. Key conclusions extrapolated from interviews with these stakeholders can be found in the interview section of this report (Page 10).

Market Environment

Understanding the market environment was pertinent to generating a successful, desirable design. If Wonder Women could not effectively market the toilet to the Muslim refugees, the refugees would continue to use less sanitary options such as the unclean and overflowing pit latrines or openly defecate.

A Green's Analysis (Appendix IV) provided insight into the prospective market environment for the Safi Choo toilet. Using this analysis tool, it was determined that the Safi Choo toilet has a specialized niche because there exists such a precise user demographic (Somali Muslims in the Kakuma Refugee Camp). Moreover, a competitive analysis of Safi Choo's competitors (Appendix VI) explored similar designs that are currently being implemented elsewhere in the world; however, due to the strong humanitarian design focus of the Safi Choo toilet, this tool helped Wonder Women realize that natural competitors were actually collaborators during the design process. In particular, Wonder Women quickly realized the benefit of collaborating instead of competing with other designs since the ultimate objective of the both the Safi Choo toilet and competing products is to improve sanitation in developing countries and not necessarily to produce large profits.

Furthermore, the market analysis also revealed that the existing, "competing" toilet designs were not created with the same goals and constraints as Wonder Women's Safi Choo toilet. Expressly, none of the existing sanitation products were explicitly designed for Muslim users or a refugee camp environment. Ultimately, Wonder Women determined that the Safi Choo toilet would mainly compete against pre-existing pit latrines and open defecation. Thus, in order to persuade users to use the Safi Choo instead of its alternatives, these market analysis tools developed the additional design constraints that the Safi Choo toilet also needed to be intuitive, easy to use, and have clear benefits for the user over using alternative options.

Target

- is a **household toilet**

-**separates** waste

-is an **above ground structure**

-maintains the **cultural practices** of the refugee camp

-is a **working built** prototype

Ideal

-includes **privacy**

-**dehydrates** waste

-is made of **locally sourced** materials

-eliminates **waste handling**

-incorporates a **bidet**

-includes a **removable skin** for the disabled and children

-integrates **sanitation education**

-utilizes a **sand filter**

Figure 2. Target and Ideal Goals

Project Goals

Wonder Women divided the project into target and ideal goals to ensure the creation of a viable product (Figure 2). The target goals were considered the realistic aspects of the design that must be incorporated in the final product, while the ideal goals were considered additional aspects that might not appear in this preliminary Safi Choo product. Wonder Women incorporated multiple realistic constraints into developing its target goals. Thus, the final product concept was determined to be, at its minimum, a mobile household toilet that separated waste and maintained cultural practices. This was demonstrated by the following target sub-goals:

- •Develop a mobile, above ground household toilet
- •Enhance waste separation via a urine-diverting design and a secondary filtration system
- •Maintain cultural practices by allowing for squatting and anal cleansing

Additionally, several design components were determined to be outside of the scope of this initial design phase to produce a viable product. As a result, Wonder Woman also identified ideal goals, which could be achieved during future design phases of the Safi Choo toilet, some of which were explored after achieving the project's target goals. These ideal goals included enhancing privacy and security for female users, using locally sourced materials, eliminating direct waste handling by both the users and maintenance workers, improving the anal cleansing process, adapting the design for the disabled/elderly/children, and minimizing toilet odors. Future design phases of the Safi Choo toilet will continue to

Proposed Solution

The Safi Choo toilet is an innovative toilet system that offers a more hygienic and ergonomic experience that can be implemented as a mobile sanitation solution for any refugee camp. Unlike traditional pit latrines, Safi Choo offers an above ground solution to counter the lack of space in refugee camps and reduces direct waste handling via the separation and collection of waste by a four-part removable drawer and filtration system. With Safi Choo's human-centric design, users of all ages and abilities will be able to sit or squat comfortably to maintain the cultural practice of anal cleansing, while also reducing stress on the body.

Additionally, Wonder Women incorporated the option of using a hand-operated bidet in lieu of traditional anal cleansing techniques. The team also designed for children, the elderly, and the disabled by creating handles and an enhanced ergonomic form to make defecating an easier experience for these neglected populations. Finally, Wonder Women designed a cover that forms a barrier between the human waste containers and the outside environment in order to minimize odors.

All design components were iterated through various prototypes via analytical modeling and experimental testing. Through the design process described in this report, Wonder Women successfully designed, prototyped, and tested its sanitation solution. The final product was a full-scale, working prototype of the Safi Choo toilet.

II. Project Intention

The objective of this project was to make an inexpensive mobile toilet for Muslim refugees, who squat and use anal cleansing, that then separates the waste products so that the feces can be used in an energy generation process at a central location. The primary goals for the design included the separation of waste, the design of an above ground household toilet, and the maintaining of Muslim cultural and religious practices. Once these target goals were achieved, Wonder Women focused on designing solutions for its previously identified ideal goals including safety, portability, minimizing direct contact with the waste, designing an attachment for the disabled and children, and improving the anal cleansing practice to decrease oral-fecal contamination. The final product was a working, life-size prototype of the Safi Choo toilet.

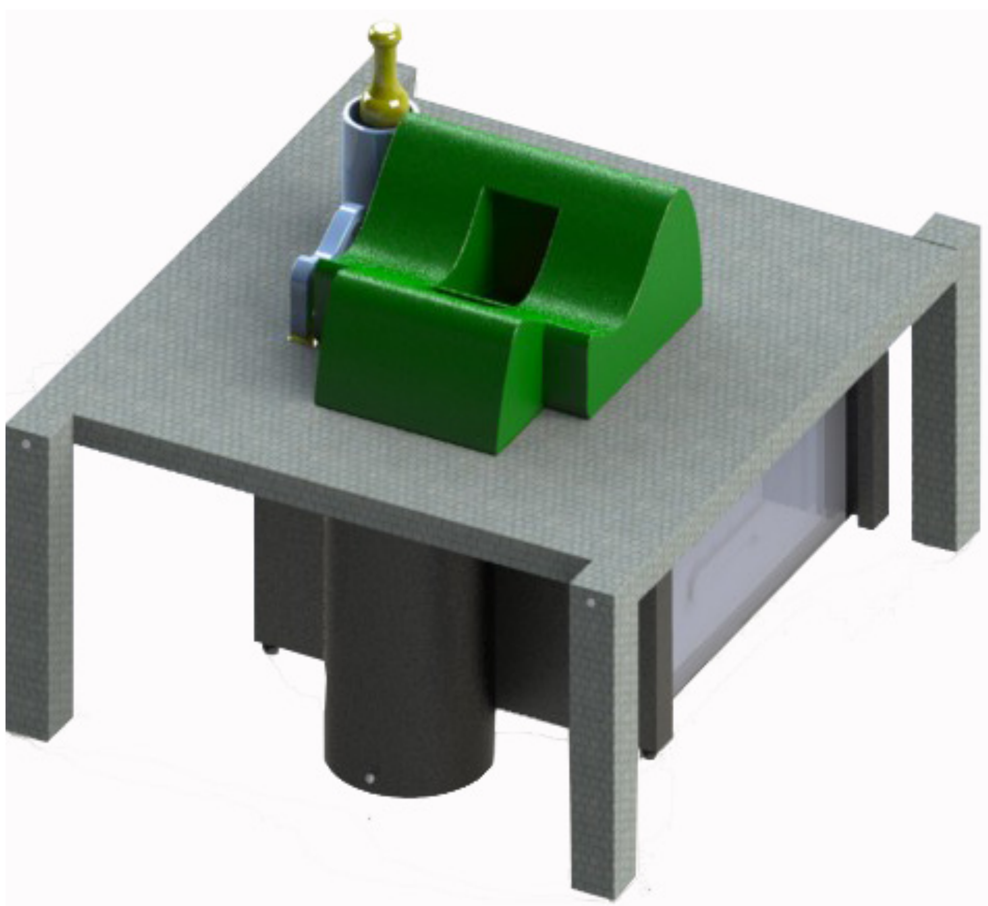


Figure 2.5 Complete SafiChoo System

III. Ethnographic Research

Wonder Women completed a lengthy research process during its need finding phase of the project. Specifically, Wonder Woman conducted fifteen interviews with relevant experts, investigated thirteen different areas of additional research, and examined a 40-page annual report on the Kakuma refugee camp by the Norwegian Refugee Council (NRC). This research process generated an in-depth background analysis of the global precedents of sanitation technology, the geographical and climate constraints, and the specific cultural and religious practices of the Somali Muslim refugees. These comprehensive ethnographic findings were then synthesized to identify the project objectives and, subsequently, were used to develop specific design constraints and begin component ideation. The conclusions drawn from interviews with specialists and the wide-ranging analyses of the population, technology, and environment elucidated the need for a toilet that incorporated both the explicit and implicit cultural, religious, and technological needs. The various research methods used and the initial needs and constraints identified by these processes are discussed below..

Interviews

Wonder Women identified and interviewed fifteen experts in their field including Chrissy Bracewell (Global Growers Network) [7], Kevin Carvati (GTRI) [8], Lily Ponitz (EWB) [9], Susan Davis (Improve International) [10], Douglas Cox (former resident of Middle East) [11], Mariam Ishraq (a Kenyan Muslim) [12], Moreed Khosravanipour (American Muslim) [13], Brandie Banner (former Kenya resident) [14], Tess Byler (Professional Geologist and Hydrogeologist) [15], Charlie Crawford (Coaches Across Continents: Kenya) [16], Erin Johnson (Alliance for Human Needs and Human Rights:

Kenya) [17] , Mona Mijthab (MoSan toilet creator) [18], Sarah Rehman Morabu (Kenyan Georgia Tech Student) [19], Louis Woofenden (Engineering Director at Net Zero Solar) [20], Andrew Foote (Sanivation Co-founder) [21], and Emily Woods (Sanivation Co-founder) [22, 23, 24]. Questions were compiled for all interviewees to gain broad insight into the day in the life of a Muslim refugee, review current toilet designs, and discuss potential ideas for sanitation solutions. Wonder Women also inquired about how children, the elderly, and the disabled currently use the existing toilets, as well as discussed current hand washing and anal cleansing practices. Due to the high number of interviews conducted, Wonder Women organized the interview results into three main, recurring themes:

- The need to design a toilet that maintains Islamic practices
- The lack of space in the Kakuma refugee camp
- The importance of aesthetics in toilet designs

These three themes directly contributed to the creation of Wonder Women's project objectives and ideal project goals since the interviews elucidated the fervent need for a final product that considered Islamic practices, the lack of space, and aesthetics.

Maintaining Islamic Practices

All stakeholders highlighted the need for Wonder Women's sanitation solution to be designed to maintain Islamic practices. In particular, there were many different aspects of the Muslim faith that needed to be considered including the importance of having separate restroom facilities for men and women, the inherent high aversion to waste, and the importance of anal cleansing.

The principal piece of information that Mariam Ishraq shared with Wonder Women was that men and women need to have completely separate facilities or the women will not use the toilet. [12] This was important during the ideation phase since, originally, Wonder Women thought about designing a unisex toilet that could be adapted to either gender. However, given the importance of gender separation exposed by this interview, this idea was quickly discarded.

Next, due to the importance of cleanliness to the Islamic faith, there is a high cultural aversion to waste among the Somali Muslim refugees. As Sanivation's Emily Woods stated, "Somali is much more difficult for a lot of reasons. First, there is an extreme high aversion to waste... Shit and Muslims do not go hand in hand." [22] The high cultural aversion to waste dictated several different design constraints. First, it demonstrated the need for a solution that minimized or eliminated contact with waste products, including contact by both the Muslim refugee users and the maintenance worker who collects and cleans the toilets. Second, this knowledge dictated what Wonder Women could do with the processed waste products. For example, Wonder Women initially explored the idea of purifying and reusing the anal washing water collected in its toilet; however, this idea was discarded after Ishraq expressed that the Muslim refugees would not re-use water that had previously been used for anal cleansing.

Additionally, there are specific cleansing procedures in the Islamic culture that Muslims must perform before considered clean for prayer, such as anal cleansing. Anal cleansing is the hygienic practice of cleaning the anus with water following defecation and involves pouring water across the anus and wiping with the left hand. Given that refugee camps are generally associated with limited resources, including a potential shortage of water, Wonder Women also questioned its Muslim interviewees about the cleansing process if a Muslim refugee cannot anal cleanse with water. In response, Moreed Khosravanipour said, “the desire is to be clean... If you are in an instance where [something other than what is ideal] is your only option, then God will forgive you.” [13] Khosravanipour then explained that it is acceptable to use ash or dust if water is unavailable since Islam focuses on the intention behind the action of an individual.

Space Restrictions in the Camp

Kakuma was originally designed as a temporary haven in 1992 for 20,000 refugees but now contains more than 140,000 refugees. Since the refugee camp was created to be a temporary solution, Emily Woods of Sanivation stressed the importance of designing a toilet that according to Kenyan law is not “too permanent”. Woods further elaborated that, “Pit latrines aren’t sustainable... They’ve used up all the space in their backyards with old pits, so they have like 2 or 3 old pits that are covered now. There’s currently no other place to dig a pit.” [23] As a result, Wonder Women determined that its proposed toilet must be completely above ground not just for easy removal, but also because there is no space below ground for Wonder Women to use.

Furthermore, Woods stated that Sanivation supports the NRC’s goal of eliminating communal toilets in the next five years and promoting only household toilets. Currently, only 77.2% of households in Kakuma have their own toilet. [3] Thus, the design and implementation of household toilets quickly emerged as an important constraint for the design of Wonder Women’s sanitation solution. Since a household toilet produces less waste than a communal latrine, it was determined that Wonder Women’s final design would be constrained by the

the amount of waste generated weekly by a family of five. Additionally, the process for weekly waste collection quickly emerged as an important system consideration.

Toilet Aesthetics

Given the volatile nature of refugee camps, many interviewees discussed the association of refugee camps with with high crime and assault rates. Kakuma's high crime rate presented a unique challenge for Wonder Women since it revealed the need for the design to be both aesthetically pleasing to persuade the refugees to use the toilet, but not pleasing enough to get stolen or sold. Woods explained that, "one of the main things you have to think about are other uses for various materials because people will use [your material] for whatever is more valuable to them". [23] For example, Woods explained that the NRC experienced difficulty getting the refugees to use hand soap in the latrines because they saw the soap bottle as having more value than the soap itself.

Nevertheless, as Wonder Women conducted interviews with more experts, it became apparent that aesthetics was still crucial to the design. Particularly, Mona Mijthab, who designed the MoSan toilet, stated that since refugees often have few belongings, they take pride in the items that they do own: "People sometimes live in one room houses, so each product they own is visible. If people come to your house they see everything, so people care a lot about what they have and how their house looks even though they are very poor." [18] Brandie Banner shared similar experiences while she was in Kenya. [14] In particular, Banner found that Kenyans were proud to show her everything they owned, which highlighted the fact that form and aesthetics are important to help satisfy higher level needs, such as esteem, in Maslow's Hierarchy of Needs.

Thus, in order to bridge the gap between lessening the motivation to steal and the need for an attractive design, Mijthab explained that “you need to explain how this toilet changes or improves your livelihood. And then I think that once people understand… the motivation to steal, to get the money, or to destroy will be much less.” [18] Thus, Wonder Women concluded that its design needed to convince the refugees that a sanitary toilet has more value than any other unintended use.

Kakuma Refugee Camp WASH Report

Wonder Women gained an in-depth understanding of the Kakuma Refugee Camp’s population, environment, and current sanitation situation by reading the most recent Kakuma Refugee Camp Water, Sanitation, and Hygiene (WASH) Report [3]. The NRC gathered the information for the report in March 2012 in one of the three primary sectors of the Kakuma Refugee Camp in Naivasha, Kenya. In particular, the NRC surveyed 403 Somali (Muslim) and South Sudanese (Christian) refugees via phone.

The WASH report gave Wonder Women valuable insight into the specific needs of the Kakuma refugee community. For example, although Wonder Women initially thought that there would be limited water access in the refugee camp, the report discussed that access to water in the refugee camp is actually high (99.8%) because of nearby Lake Naivasha. However, the report further described the camp as having a shortage of containers to transport the water, which has caused containers to be of high value to the refugees. Thus, given the value of containers for water transport, Wonder Women realized that its solution must minimize the number of removable containers from its design to ensure it functions as designed.

Additionally, the WASH report revealed that sanitation is a widespread problem in the camp, especially with regards to the pit latrines currently in use. The report stated that pit latrines are often not clean and that many refugees noted feces and urine overflowing and surrounding the pit. Additionally, nearly half of the refugees surveyed reported that they do not have access to materials to clean their latrines.

The WASH report also focused on the fact that the Kakuma Refugee Camp is running out of space for pit latrines, supporting Emily Wood's interview that future sanitation solutions must be above ground. The impact on sanitation due to flooding during the Monsoon season was also discussed. Specifically, the pooling of water around latrines during the heavy rain months causes the pit latrines to overflow and deposit feces in the surrounding areas. Since this also describes a general issue with drainage, and stagnant waste water is a breeding site for mosquitoes, it was reported that mosquito-borne illnesses are ubiquitous in the camp during these months. Given the rampant drainage issues and lack of space below ground, an above ground sanitation solution quickly became a target project goal.

The WASH report also gave insight into the need for targeted sanitation solutions for children, pregnant women, and the disabled. For example, approximately 4% of people in Kakuma have an illness or are missing limb(s) that impair them from using a typical pit latrine. As a result, it is common for this group to openly defecate due to difficulty accessing the communal latrines. Additionally, the report stated that open defecation is not limited to the disabled or children. In fact, other refugees cited openly defecating since they found the communal latrines to be unclean, locked at night, overflowing, dark, and not user friendly. Moreover, refugees also described other barriers to communal latrine use including superstitions associated with ghosts living in latrines and public embarrassment if the user is female. As a result, it became clear that Wonder Women's Safi Choo toilet is ultimately competing against the unsanitary pit latrines and the practice of open defecation in the refugee camp.

Technological Precedents

A matrix of different patents (Appendix II) as they relate to the various identified project aims was developed in order to conduct a background analysis of current innovative technologies. The patent search was aided the ideation process since it identified potential technologies that were not yet fully developed or that were unavailable on the consumer market. The patent search was conducted using a myriad of similar key words derived from the functions listed on the morphological chart. The search was then narrowed by researching specific patent categories for related patents. In particular, relevant patents were identified for the following potential aims:

- Separation of solid and liquid waste
- Separation of pathogenic material
- Reuse of urine and feces
- Elimination of waste handling
- Reduction of oral-fecal contamination

Patents regarding urine diversion technologies (EP 2568885A1, US 6640355 B1, US 7846143 B1) were identified to help with developing a form that naturally and immediately separated urine and feces. However, since Wonder Women's research revealed that many of these urine-diverting technologies (UDTs) do not yield 100% separation, additional technologies (US 200020193517 A1, EP 1135561 B1, WO 2007042764 A3) were identified to achieve secondary filtration of pathogenic material. Although these technologies included high-tech filters, chemical treatments, and secondary urine diversion devices, ultimately a basic sieve system was selected given its relative ease of use and understanding.

Furthermore, technologies aimed at reusing urine (US 7135116 B2, EP 1795211 A3, WO 2008126793) and reusing feces (WO 2007055011 A1, WO 2010045696 A1) were researched; however, as the stakeholder interviews determined that Wonder Women's design must be a household not communal toilet, which generates a reduced volume of waste, it was determined that Wonder Women cannot incorporate any effective reuse processes unless each household's waste products are first transported to a central processing area. As a result, this aim was outside of the project's scope.

Finally, Wonder Women explored several different precedent technologies surround the goal of eliminating contact with waste and waste handling. For example, Wonder Women explored the idea of force-activated trays (WO 2010133089 A1), self-contained systems (WO 2008044806), and removable waste bags that can be composted (DE 202008003712 U1). After comparing basic prototypes of these different technologies, Wonder Women decided to integrate several different components and create a self-contained drawer system for the feces that is fully removed weekly and a spigot-tube system for removing urine on site.

Overall, this extensive patent search proved crucial during the ideation phase when identifying potential solutions to address the project needs and constraints since it elucidated potential innovative uses of basic technology as applied to separation, filtration, sanitation, and hygiene. Moreover, the patent search helped Wonder Women identify potential materials for the different components of the Safi Choo toilet by identifying the materials used in current toilets. Nevertheless, the most important outcome of Wonder Women's patent search was that there is no patent for a toilet that specifically targets users who squat and practice anal cleansing. Moreover, it was found that patents for ergonomic toilet forms were uncommon, while those for technological components were widespread. Thus, the patent search elucidated the unfulfilled technological niche that could be filled by the Safi Choo toilet.

Additional Research

Additional market and user research was conducted in thirteen different research areas to gain in-depth knowledge about the project's background and needs. This research primarily focused on current global sanitation solutions, different waste treatment methods, the geography and climate of Naivasha, the composition of urine and feces, the Somali diet and clothing, and the evolution of using the bathroom. A full list can be found in the Appendix. The exploration of the various research areas helped the team gain a better perspective of the global precedents, user mindset, and potential constraints regarding toilet placement and technology limitations. For example, the geographical and weather analysis of the area surrounding the Kakuma Refugee Camp revealed that there was not enough annual rainfall for a supplementary rainwater catchment system to adequately support the collection of water needed for anal washing. This helped Wonder Women eliminate this potential design component from the final Safi Choo toilet system. Moreover, this research also revealed that the Somali diet alters the final composition of waste by increasing the final fiber content and that there is a significantly decreased volume of feces and urine generated by those in developing countries, such as Kenya, when compared to the volume produced by those in developed countries such as the United States. This information was used to generate the theoretical weekly yield of feces and urine for a household in Kakuma, which helped Wonder Women calculate the potential energy yield of each household and to develop its final Safi Choo drawer dimensions. [25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]patent search was that there is no patent for a toilet that

IV. Market & User Analysis Tools

House of Quality

House of Quality (HoQ), aptly named for its house-like shape, is an interdisciplinary analysis tool used to define the relationship between customer needs and consumer constraints and capabilities. [47] Given this broad ability, Wonder Women's HoQ bridged marketing, engineering, and manufacturing perspectives in order to identify key areas of product design focus. In particular, the HoQ utilized a multifaceted matrix structure that directly correlated user needs and design plans to address these needs: the body of the house compared customer needs with product functions, the roof indicated the degree of interaction between specific functions, and mock windows ranked the product's achievement of its constraints as compared to competitors. This allowed Wonder Women to identify similar functional needs of consumers and to determine broader aims that encompassed these similar functional requirements. For example, there was a high correlation between the consumer's explicit requirement to limit contact with waste products and the potential functional requirements to separate feces/urine/diarrhea/vomit and indicate a non-pathogenic output. Moreover, all of these functional requirements fell under the broader aim of increased hygiene and safety.

Most importantly, quantitative rankings were used to determine design priorities, allowing for a more focused design phase in otherwise complicated projects with multiple areas of potential focus. This proved invaluable to Wonder Women, given its initial large project scope, since it highlighted the importance of certain design aspects to the primary stakeholders while diminishing the importance of other prospective aims.

For example, the HoQ illustrated the importance of a design that maintained cultural and religious practices, while incorporating energy generation was not considered to be an important project constraint for this design phase. Thus, the developed HoQ (Appendix III) helped narrowed the project focus by quantitatively sorting specific functional constraints into target and ideal goals, as well as requirements that were outside of the project's scope. By narrowing the project focus, the resulting project aims, based on the set of refined target goals, became more manageable, increasing the likelihood of Wonder Women's success. Table 1 lists the weighted results of the HoQ analysis.

Requirements (Target)	Future Aims (Ideal)	Irrelevant (Unnecessary)
Cultural and Religious Practices Maintained	Adaptable for the disabled and children	Water Reclamation
Separation of Urine and Feces	Separation of Vomit and Diarrhea	Energy Generation
Enhanced Ergonomic Form	Non-pathogenic Indicator	Hand Washing Component
More Hygienic	Elimination of Waste Handling	
Inexpensive	Enhanced privacy	
Durable	Enhanced safety	
Non permanent		

Table 1. Refined project aims list as determined by the House of Quality analysis

Green's Contextual Needs Analysis

Green's Contextual Needs Analysis (CNA) is a systematic needs analysis process that helped answer the "How", "Where", and "Who" of the project background in order to better understand the usage application, surrounding environment, and customer characteristics. [47] Green's CNA (Appendix IV) helped Wonder Women better understand how consumer-oriented need finding research correlated with developing an engineering perspective within environment, user, and daily usage contexts. Specifically, this method highlighted the importance of understanding the number of unique visits to the latrine. This allowed Wonder Women to determine the theoretical daily yield urine and feces so that the information can be used to calculate the amount of waste generated and water used for anal cleansing per week.

However, Green's method addressed, but minimized the importance of cultural factors on the sanitation redesign as well as overlooked important takeaways from global and local precedents. Particularly, Green's CNA diminished the importance of maintaining the cultural practice of squatting and anal cleansing, which was previously determined to be a primary target goal during background research and stakeholder interviews. Thus, the results were used in conjunction with other analytical tools to develop holistic background knowledge for future toilet ideation and design constraints. Overall, Green's CNA proved to be most helpful to Wonder Women when analyzing the materials process and flow of the finalized system since it highlighted the dynamic nature of the final system and identified potential changes to the maintenance process, including changes to the frequency of visits and cart size, with the new Safi Choo toilet.

Morphological Chart

A morphological chart (Appendix V) was generated via function analysis. [47] Specifically, the left side listed the required functions of the proposed sanitation solution, while the right side described the different mechanisms and technologies that could perform the listed function. This tool proved helpful during the ideation phase, since it necessitated that Wonder

Women think of several feasible designs using different mechanisms for each function, many of which might not have been recognized as having similar functions otherwise. For example, following its patent search, Wonder Women immediately selected a sieve, or a surface filter, to address the functional requirement of “filtration”. However, the morphological chart identified several other technologies that could also achieve “filtration” including centrifugation, depth filters, wind powers, and weight-based mechanical cranks. Ultimately, however, a basic sieve filter remained as the primary selection due to its simplicity, ease of use, and ability to be sourced and fixed locally.

Competitive Analysis Matrix

An analysis of Wonder Women’s competitors (Appendix VI) was conducted in order to assess the strengths and weaknesses of current and potential toilet designs that address a similar niche as this project scope. [47] Using this analysis, Wonder Women developed both offensive and defensive strategies in relation to the design and manufacturing of the Safi Choo toilet. In particular, the analysis identified current gaps in competing parallel markets with regards to system functions that were identified as target goals. For example, since no competitor specifically targets Muslim users, including this function was determined to be an asset to Wonder Women.

Additionally, by comparing other designs and researching competitors, prospective materials were identified and potential issues were avoided. For example, the MoSan toilet provided the precedent for developing a wood-colored polypropylene toilet since it was found to be both durable and asethestically pleasing by its users during field-testing in developing countries. Moreover, given that the MoSan design is currently being used in developing, rural environments, potential issues such as stealing, people vomiting in the toilet, and women disposing of sanitary napkins in the toilet were identified. This revealed that Wonder Women's proposed design also had to take into account other valid uses of toilets, such as vomiting and diarrhea, that might impact the quality of the collected feces and urine. This is important since Sanivation's primary goal is to convert the collected feces into energy via a solar dehydration process.

Thus, this analysis method assisted in developing cost constraints for the final Safi Choo product and in selecting materials for mass manufacturing via setting a baseline precedent. This baseline precedent revealed that nearly all current and potential toilet designs were made from injection or rotational molded plastic. Further exploration into manufacturing plastics revealed that the most common plastic used is polypropylene.

V. Ethnographic Design & Function Criteria

Market Environment

Understanding the market environment was pertinent to generating a successful, desirable design. If Wonder Women could not effectively market the toilet to the Muslim refugees, the refugees would continue to use less sanitary options such as the unclean and overflowing pit latrines or openly defecate.

The Green's Analysis (Appendix IV) provided insight into the prospective market environment for the Safi Choo toilet. Using this analysis tool, it was determined that the Safi Choo toilet has a specialized niche because there exists such a precise user demographic (Somali Muslims in the Kakuma Refugee Camp). Moreover, a competitive analysis of Safi Choo's competitors (Appendix VI) explored similar designs that are currently being implemented elsewhere in the world; however, due to the strong humanitarian design focus of the Safi Choo toilet, this tool helped Wonder Women realize that natural competitors were actually collaborators during the design process. In particular, Wonder Women quickly realized the benefit of collaborating instead of competing with other designs since the ultimate objective of the both the Safi Choo toilet and competing products is to improve sanitation in developing countries and not necessarily to produce large profits.

Furthermore, the market analysis also revealed that the existing, "competing" toilet designs were not created with the same goals and constraints as Wonder Women's Safi Choo toilet. Expressly, none of the existing sanitation products were explicitly designed for Muslim users or a refugee camp environment. Ultimately, Wonder Women determined that the Safi Choo toilet would mainly compete against pre-existing pit latrines and open defecation. Thus, in order to persuade users to use the Safi Choo instead of its alternatives, these market analysis tools developed the additional design constraints that the Safi Choo toilet also needed to be intuitive, easy to use, and have clear benefits for the user over using alternative options.

Environmental and Sustainability

Sustainability was a primary area of concern during the design phase of the SafiChoo toilet since it was determined that the Kakuma Refugee camp needed a long-term sanitation solution that was better than the existing pit latrine technology. As described previously, Kakuma refugees currently use communal pit latrines that overflow every four years; as such, a new pit latrine must be dug with the same frequency. This continual process of filling and replacing pit latrines demonstrated that there was no sustainable sanitation precedent in the refugee camp. Subsequently, the development of a sustainable sanitation solution was identified as a primary need.

In order to address this deficit, Sanivation initiated a pilot waste collection program during which a maintenance worker, Stephen, removes the waste and cleans the toilets twice a week. Given that this collection system is highly valued by Sanivation, since it allows for integration into its solar concentrator for feces hydration and energy generation, Wonder Women aimed to not just support this waste management program but also improve the process to yield more effective waste collection. A collection system conducted by a third-party was also identified as being important since Muslims have a high aversion to waste and because Wonder Women aimed to eliminate any contact with waste products to reduce disease transmission. Thus, it was determined that a maintenance worker would remove all pathogenic waste materials from the household and that Sanivation will centrally process all waste. This collection process is described further in Systems Integration (page 34).

Additionally, Wonder Women created systems to recycle the collected feces, urine, and anal cleansing water for enhanced sustainability. Principally, Sanivation will dehydrate the feces in its solar concentrator to render it non-pathogenic and create briquettes for energy generation. The collected urine will be diluted in a 1:4 ratio to create a high nitrogen fertilizer for the local tulip industry in Kenya [3]. The water used for this dilution process will be derived from the collected anal washing water, which will undergo a centrally processed gravity sand filtration process. These waste recycling systems will directly decrease the volume of waste in the camp, eliminating potential aquifer contamination and reducing the incidence of WASH-related diseases.

Users

Sanivation specified the user group as Somali Muslims living in the Kakuma Refugee Camp near Naivasha, Kenya. [22] However, although this is a relatively small demographic, SafiChoo can actually be implemented in Muslim refugee camps worldwide. Through extensive ethnographic research, it was found that the following areas were important to the typical Somali Muslim user: privacy, safety, cleanliness, low cost, compact, and being aesthetically pleasing. Privacy and safety were determined to be of paramount concern due to rampant crime and high sexual assault rates in Kakuma. Moreover, it was determined that SafiChoo must be easily cleaned and allow the Muslim users to squat and use anal cleansing. Since the targeted users are refugees, with limited financial resources, Sanivation decided to financially support the purchase and implementation of Wonder Women's proposed design. However, in order for the toilet to be feasibly implemented, Sanivation required that it cost less than $100. [24] Additionally, given severe overcrowding in Kakuma and the need for a household not communal design, the SafiChoo toilet was designed to occupy less than 1 m3. [3] Finally, the design had to be somewhat intuitive and aesthetically pleasing so that the refugees actually use the toilet for its intended purpose. Also, given the large percentage of disabled refugees and children (4% and 27%, respectively), the SafiChoo design also takes these two users into consideration. [3] In the future, Wonder Women aims to adjust the capacity of its design for families of different sizes by modifying the volume of the toilet's urine, feces, and wastewater containers.

Ergonomics

Given that the SafiChoo toilet specifically targets Muslim users, one of its primary components is a more ergonomic form that maintains the cultural practice of squatting and reduces impact on the body. Thus, an important goal of the design was to make it user friendly, meaning that the form was intuitive and comfortable for the user to use. Moreover, since Muslim refugees currently squat while defecating [6], the SafiChoo toilet was designed to better facilitate this process. This was achieved by promote designing a form that promotes squatting positions associated with less stress on the user's knee and hip joints, two areas particularly impacted by stress/strain when squatting. [49] Specific quantitative calculations of the reduced impact on the body are discussed in Section VIII. Design Performance.

Functional

The functional characteristics of the design dictated that it be sanitary, safe, non-permanent, and compact.

The toilet needed to allow for the continued cultural and religious practice of anal cleansing. The design also needed to be safe for users to use structurally. Due to the limited space in the overcrowded Kakuma Refugee Camp, design height and area restrictions must be considered. Specifically, it was determined that the toilet base can have a maximum height of 2 feet, while the area of the base should be equal or less than the current UNICEF standard of 1 m3 [3]. Additionally, since Sanivation specifically requested a system that separates urine and feces for later processing, Wonder Women designed a primary urine diversion system to initially separate urine and feces and a secondary filtration system to separate solid feces from diarrhea, vomiting, and anal cleansing water. This secondary filtration system, with two sieves of different sizes, also functioned as method for enhanced dehydration before processing in Sanivation's central solar concentrator. The secondary filtration system's set of drawers also functioned as portable storage containers to eliminate direct waste handling by maintenance personnel. The inclusion of a lock on the final structure's door allows the users to maintain privacy and enhance safety, particularly at night. The addition of a toilet hole cover functioned as a means to minimize the release of undesired odors from inside the toilet's drawers.

Aesthetic/Emotive

The form of the SafiChoo toilet was built to be intuitive so that the refugees will use it correctly. In particular, it was determined that there needs to be a balance between having an aesthetically pleasing toilet such that people will want to use the product and an overly aesthetic toilet such that people will be incentivized to steal it. Refguees take pride in everything they own, including something as simple as a toilet. [10,17] Thus, the design was developed to show the refugees the value in having a sanitary toilet over the value of selling its parts for money. [18]

Jurisdictional

Kenyan law states that nothing in a refugee camp can be “too permanent”. [1, 3] Thus, this mandated that the final design be completely above ground, non-permanent, and able to be moved (whether disassembled or moved as one piece) by 2-6 men.

VI. System Design Considerations & Specifications

Before beginning any in-depth technological research, technology selection, or testing, the prospective design needs of the proposed toilet were determined. Specifically, the average amount of waste products (urine and feces) produced weekly and the calculated energy yield of feces, given a perfect combustion reaction of the available products, were calculated. Additionally, the average volume of water used daily for anal cleansing was determined. This quantitative analysis helped to narrow specific functional system metrics and design constraints and to determine if Wonder Women's proposed design could be successfully implemented.

Waste Generation

Waste products generated by the Muslim refugee users were determined to be feces, urine, and used anal cleansing water. Based on average use and the number of users, the average weekly volumes of these waste products were quantitatively determined. The results of these calculations are discussed in the subsequent sections; however, an overview can be found in Table 2.

Waste Product	Volume per Visit	Visits per Week	Volume of Container
Urine	300 mL	21 (105 total)	20 L
Feces	130-520 g	3 (15 total)	30 L
Used Anal Cleansing Water	1.5 L	3 (15 total)	40 L

Table 2. Average Volume of waste products per household in the Kakuma Refugee Camp.

Urine

Given that the toilet was designed for a single household (~5 people in Kakuma) and each person urinates an average of 1 L per day, it can be determined that approximately 5 L of urine will be collected each day per household (35 L per week). [6] However, given the high prevalence of dehydration in the camp, it was assumed that the refugees actually produce the smaller volume of urine. [3] This assumption was confirmed by Sanivation's current collection system, which collects less than 15 L of urine per household weekly. This difference between theoretical and actual use resulted not just from the decreased urine volume per person due to dehydration, but also the fact that Muslim men do not normally urinate in toilets and, instead, urinate outside, which further decreased the number of unique visits weekly. [22] Thus, it was determined that the container designed to hold urine must have a volume of at least 20 L (1.83 ft3).

Feces

Given that the toilet was designed for a single household (~5 people in Kakuma) and each person defecates an average of three times per week, there are fifteen unique visits per week. Moreover, the average daily weight of feces in developing countries was determined to be 130-520 grams since the diet is higher in fiber than in developed countries. [48] Thus, it was determined that approximately 1,950-7,800 grams of waste will be generated per week. Since water content is 75-90% of the content of fresh feces, this means that the composition of the waste generated weekly from one family toilet will be 1,463-7,020 grams (1.5-7.0 L) water and 195-1,755 grams of feces. Given that the density of feces is 1.01 g/cm3, 0.95-1.76 L of solid feces is generated weekly. [6] However, due to the feces piling phenomena, which can cause feces to be half as tall as wide, the container needed to be developed in order to not pile and obstruct the filtration system entrance. Thus, the container was designed to contain a minimum volume of 30 L of feces (2.12 ft3).

Water Consumption

Background research revealed that an individual uses an average of 1.5 L of water for anal cleansing each time they defecate. Since a typical individual visits the bathroom defecates an average of three times per week, it was calculated that there were 15 unique visits per week. Thus, it was calculated that each individual needed approximately 4.5 L of water per week. [23] Given that there are an average of five members per household, the total amount of water needed weekly for anal cleansing was calculated to be 22.5 L. Thus, the container designed to hold used anal cleansing water needed to have a volume of at least 40 L (3.01 ft3).

Energy Conservation

Since carbon is only 44-55% of dry feces, 200-2502 grams of carbon will be generated on a daily basis for combustion. [6] Additionally, given that this combustion reaction is exothermic, free energy is generated. In particular, it was reported that human feces has an energy content per gram weight of 6-8 kJ/g. Consequently, a household toilet in Kakuma can only produce 1,200-20,020 kJ when functioning optimally. [6] Since an average light bulb in Kenya is between 50-100 kW, and 1 kW is equivalent to 1 kJ per second, a single family can only generate enough power to illuminate a light bulb for 12-400 seconds (0.3-6.67 minutes). [50] Since this is clearly a relatively insignificant amount of power, Wonder Women concluded that the energy generation portion of the proposed system must take place at a centralized facility. In particular, Wonder Women determined that a significant amount of energy can only be produced by combining the waste products from multiple households. Thus, Wonder Women maintained Sanivation's current model for centralized waste processing. The collected waste will be dehydrated via Sanivation's solar concentrator to form briquettes that can be used for energy production. This conclusion was important since it mandated that the SafiChoo toilet function within the constraints of the pre-existing system.

VI. Design Summary

System Overview

Wonder Women's SafiChoo toilet provides a more hygienic and ergonomic experience for Muslim refugees who currently squat while defecating and practice anal cleansing, as well as efficiently separates and collects waste products for subsequent reuse. In order to achieve these design functions, several different design specifications were implemented. A full list of the components and their functions are listed in Table 3.

Wonder Women's SafiChoo toilet integrated engineering and industrial design via concept design and prototyping of the toilet's ergonomics and waste filtration system. SafiChoo incorporates both engineering by separating waste and design by inducing better form for squatting. In particular, after quantitatively calculating the optimal angle of the body to minimize the stress and strain on the patellofemoral joint, the knowledge was then used to design an aesthetically pleasing and more comfortable form that incorporated this optimized angle. This integrated process benefits the user because it produces an aesthetically pleasing product that induces the most comfortable and healthy position to squat. Additionally, the two stage filtration components of the proposed toilet allowed for faster, more effective secondary waste separation.

Design Specification	Function	Aim
Urine Diversion	Separation of Waste; Waste Reuse	Target
Secondary Filtration	Separation of Waste; Waste Reuse	Target
Enhanced Ergonomic Form	Enhanced User Experience; Maintaining Cultural and Religious Practices	Target
Improved Anal Cleansing Process	Improved Hygiene; Enhanced User Experience	Ideal
Odor Minimization	Improved Hygiene; Enhanced User Experience	Ideal

Table 3. Functional Design Specifications

Urine Diversion

The SafiChoo toilet includes an initial urine diversion process utilizing simple urine diversion technology (UDT). Specifically, there are two holes that naturally funnel urine and feces into separate storage containers, allowing for initial waste separation. The front hole processes urine, while the back hole processes feces and used anal cleansing water, mimicking the natural location of these two orifices while squatting. The front hole, designed for urine collection, funnels the liquid into a hole of approximately 3 centimeters in diameter; as such, the funnel minimizes potential splashing and restricts the accidental inclusion of any solid waste. [28] The back hole, designed for collecting feces and used anal cleansing water, which has a diameter of 20 centimeters, processes used anal cleansing water and all solid waste products including solid feces, diarrhea, and vomit.

Secondary Filtration

A secondary filter system was developed for the enhanced separation of solid feces, diarrhea, vomit, and anal cleansing water. In particular, a removable, three-drawer filtration system was developed under the back hole of the urine diversion system. The first drawer contains a metal sieve filter at a 5° relief angle with holes of 10 mm in diameter; the filter catches the solid feces waste and is replaced weekly by Sanivation's collection and maintenance system. Given that it is metal, the filter can be sterilized via heating at high temperatures. [60] Additionally, the solid contents of this top drawer will be transported to Sanivation for further dehydration in its solar concentrator to render it non-pathogenic and create briquettes for energy generation.

The second drawer, located below the solid feces drawer, includes a cheesecloth mesh filter at a 5° relief angle with holes of 1 mm in diameter. This second filter sieves smaller particles of waste including diarrhea and vomit, which freely passed through the larger 10 mm metal filter. Since diarrhea and vomit often contain parasites, bacteria, and microbes, the cheesecloth filter and contents of this drawer will be burned weekly by Sanivation given its lengthy contact with highly pathogenic and potentially acidic materials. Burning and replacing this filter will also prevent pathogens from getting into the water supply. [60]

The last drawer catches the remaining liquid waste, which is comprised of used anal cleansing water, water from solid feces and diarrhea, and small particles (<50 Qm) from the disintegration of the feces. As such, it was determined that this liquid must be filtered and purified to remove pathogens before being reused. Although Wonder Women did not prototype and test potential purification methods, given that it was outside of the project scope, Wonder Women identified this water purification system as being an important future aim for the next capstone team. Regardless, Wonder Women identified intermittently operated slow sand filtration for point-of-use water treatment. [61] This purified water would then be mixed with the collected urine in a 4:1 dilution to create a nitrogen-rich fertilizer for the local flower industry surrounding the refugee camp.

Enhanced Ergonomic Form

SafiChoo's final form encourages the user to both squat and sit. Its natural curvature, which features a curved seat with a back support, causes the user to sit in a squatting position, reducing stress and strain on the body. Particularly, by better supporting the load on the patellofemoral and acetabulofemoral joints, potential harm to the body that could arise as the result of excessive stress and strain on these joints was minimized. Furthermore, the novel ergonomic form can be used by both abled and disabled refugees given that the user can sit instead of squat if needed and there is a handle for support when attempting to stand after using the toilet. Finally, since the ergonomic form closes direct access to the waste collection area below, children can also use SafiChoo without incident since there is no way for small children to fall into the pit below. Validation of these claims are discussed in VIII. Design Performance.

Improved Anal Cleansing Process

Wonder Women incorporated a bidet-like system into its SafiChoo toilet to improve the existing anal cleansing process by making it more sanitary. Currently, the Somali Muslim refugees pour water down the intergluteal cleft while wiping their anus with their left hand. However, this process leads to a high incidence of fecal-oral contamination due to the lack of soap in the refugee camp and the low personal value associated with washing ones hands.

SafiChoo's bidet was modeled after a hand-pump bidet, much like a pump in a blood pressure cuff, and it pumps water for anal cleansing through a short tubing system that is directed by the user at the anus. Specifically, a downward force onto the plunger generates a pressure difference in the system and creates a low-pressure area. This low-pressure area directly causes the pressure gradient needed for water to pressurize, flow through the plastic tubing system, and clean feces from the anus.

The bidet was designed to have a capacity of 1.5 liters of water, the amount currently used by the Muslim refugees, but it was experimentally determined that less water was required to remove the fecal matter via the pressurized bidet system (≤ 500 mL). In particular, the nozzle of the bidet concentrates the water spray to one area, allowing for faster removal and, as a result, less water. Thus, SafiChoo's bidet system decreases the need for wiping their anus with their left hand, which will minimize fecal-oral contamination in the camp and improve the camp's long-term sanitation.

Odor Minimization

In order to eliminate the presence of flies surrounding the toilet and minimize the smell of the waste, Wonder Women incorporated a manual flap to cover both the solid and liquid waste holes of the urine diversion component of the toilet. Specifically, the system was designed to remain closed when not in use; as such, a user must pull a handle, located on the right side of the toilet, to uncover the hole prior to use and recover the hole after use. Given that the flap physically covers the system's openings, it limits the odors released into the environment. Additionally, by covering the system opening, it was found to also facilitate improved intended use of the system since users were less likely to throw trash into the system.

System Integration

The integration of system components must function seamlessly together in order for the entire system to function as designed. Thus, Wonder Women conducted a user-centric design process, during which the needs of the user were placed at the forefront of the design, while also following a logical, quantitative-based engineering approach towards validation. For example, Wonder Women selected a drawer system for its secondary filtration system because it incorporates both engineering and design. In particular, since filtration is more effective when filters are periodically maintained and replaced, WonderWomen quickly realized that the maintenance worker who replaces the filters and his interaction with the system are pertinent.

Moreover, the process of using the SafiChoo toilet,, collecting the waste products generated by the system, and reusing the waste products required systems-integrated design. This was especially crucial since the material flow and process was altered from the existing process due to the new product design. As such, material flow and specific component integration of the SafiChoo toilet were analyzed. Figures 3 and 4 describe the specific process flow of both the existing system and the new SafiChoo system, highlighting key differences between the two processes and the amount of interaction different stakeholders have with the different waste products.

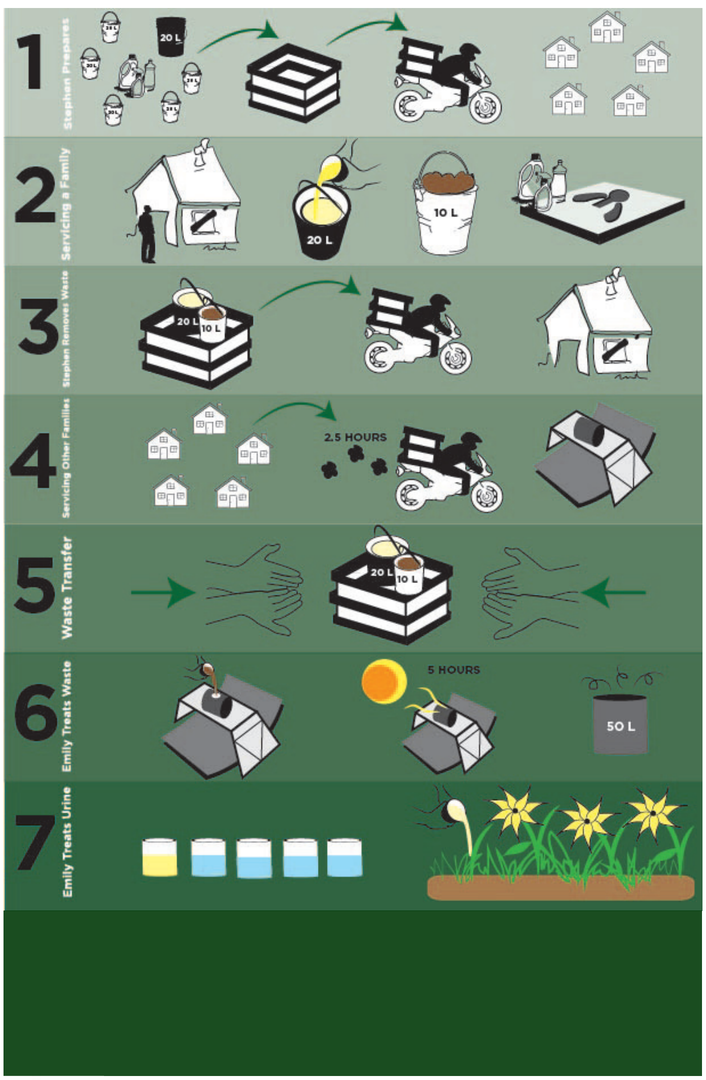


Figure 3. Current Sanitation Maintenance System

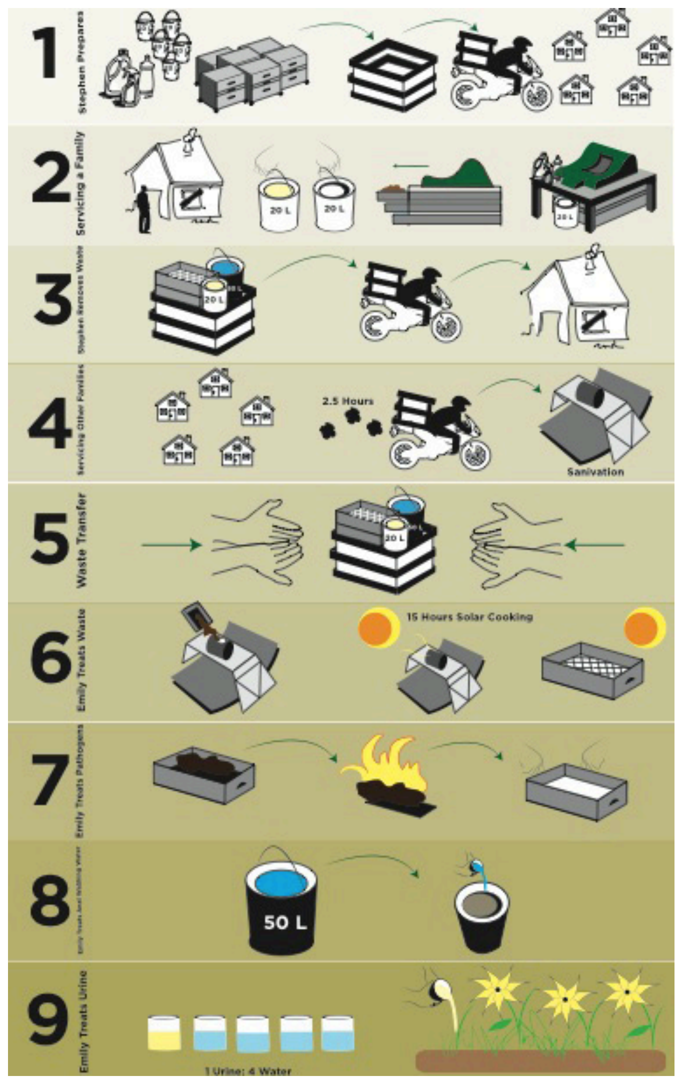


Figure 4. SafiChoo Sanitation Maintenance System

VII. Design Summary

Urine Diversion

Initial Urine Diversion Prototypes

To test the initial separation of waste, Wonder Women prototyped several variations of a urine diverting toilet. The first design that was considered, modeled by a metal mixing bowl, foam board, and a paper cup, had two holes (Figure 4). The first hole, for urine, had a diameter of 8 centimeters. The second hole, about 6 centimeters away from the first hole, was semi-circle shaped with a diameter of 30 centimeters; a divider separated the two holes from each other. Although the design was able to conceptually separate urine from feces, the dimensions of the holes did not correspond to average body dimensions and needed to be altered using the correct distance between the anus and urethra. Additionally, the liquid waste hole was determined to have too large of a surface area since some solid waste entered the urine hole.

The next prototype considered was a three-hole urine diversion toilet: one hole for urine, one for solid waste, and one for used anal cleansing water. However, in order for this to be effective, the user has to shift their body position to be over the anal cleansing hole after defecating. From an industrial design perspective, this was determined to not be intuitive not be user-friendly; from an engineering perspective, the more complicated form required more extensive manufacturing analyses and no added ergonomic benefit on the body. Since one of the design constraints was horizontal space (1 m3), this idea was quickly discarded due to the added length of the toilet to accommodate the additional hole. Additionally, through a functional analysis, it was determined that a similar function could be achieved by introducing a secondary filtration system underneath the toilet form, since the project was not constrained vertically. Since the function of a three-hole system could be achieved by different designs, Wonder Women discarded the design and a two-hole system was selected.

Urine Diversion Design Validation

The selected design closely followed the form of the first prototype considered for urine diversion, but had adjustments in dimensions (Figure 5). Principally, it was determined that the average distance between the anus and urethra in women is 4.8 cm (3.5-7.0 cm). [65] As a result, the final prototype has two holes that, based on this biologically-derived distance, naturally funnel urine and feces into separate containers, allowing for initial waste separation. The concept was validated experimentally using mimicked urine and feces dropped from the correct height and distance from each other using biological-derived values of this anal-urethral distance for females (mimicked urination and defecation) and males (mimicked defecation only). Thus, the urine diversion design was validated for front hole collection of urine and back hole collection of feces and used anal cleansing water.

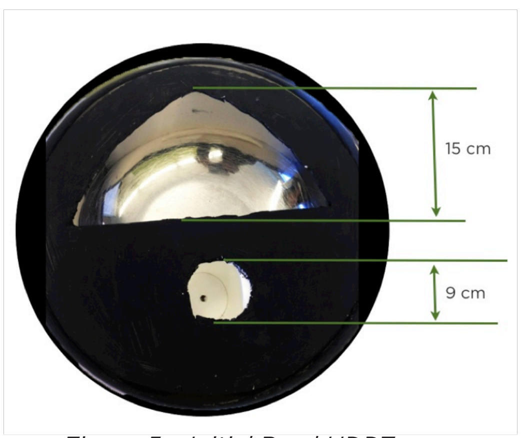


Figure 5a. Initial Bowl UDDT

The front hole funnels the liquid into a hole of approximately 3 centimeters in diameter; the back hole, which has a diameter of 20 centimeters, processes used anal cleansing water and all solid waste products including solid feces, diarrhea, and vomit. This increased back hole radius was found to better accommodate to all body sizes and shapes. Additionally, the wider radius allowed for potentially non-linear trajectories of feces as it exits the anus due to the presence of an initial horizontal velocity from contracting the anal, rather than a widespread problem in the camp, especially with just falling due to gravity, which does not influence the horizontal motion of the feces. However, if an individual were to voluntarily forcefully expel the stool downwards by increasing the pressure in the abdominal cavity through the Valsalva maneuver, it is possible that the exiting stool will have a horizontal velocity component. Thus, the maximum horizontal change was calculated to be 3.8 cm using the projectile motion of falling feces with a pressure of 19 mmHg.

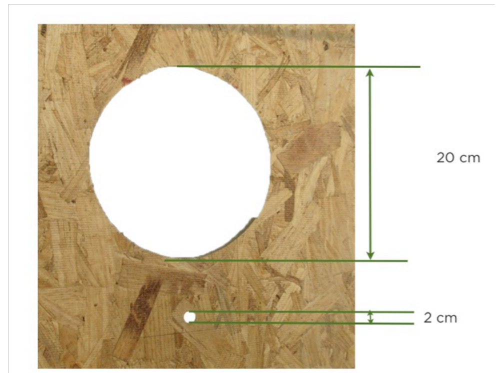


Figure 5b. Secondary Prototype

Secondary Filtration

Initial Secondary Filtration Prototypes

The first prototype generated for the goal of secondary filtration of feces from diarrhea, vomiting and anal cleansing water was a three drawer, not-to-scale system (Figure 6). The drawers were fabricated similar to common dresser drawers. The first drawer had linear acrylic slots 2 centimeters apart, designed to catch the solid waste. The second drawer had linear acrylic slots 1 centimeter apart, designed to catch the diarrhea and vomit. The bottom drawer was designed to catch the liquid waste. Wonder Women tested this conceptual model using simulated feces (a mixture of oatmeal, peanut butter, and apple juice). It was found that the drawer concept successfully minimized the amount of waste-handling needed during maintenance (Figure 7). However, the slot dimensions of this proof-of-concept filtration system were not ideal as large, solid particles were contained in the bottom drawer, which should have only contain liquid if functioning as designed.


Figure 6. Initial Drawer Model

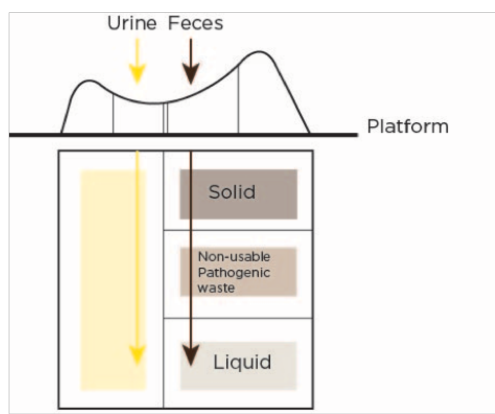


Figure 7. Initial Drawer Model

In an effort to better select filter sizes and filter materials, analytical analyses and experiments were conducted. Specifically, the various types of bowel movements (Figure 8) were identified and analyzed to determine the smallest particle that could be generated at each filtration level. In general, it was found that the solid stool types (I-IV) would remain at sizes above 10 mm, while the softer stool types (V-VII) would be broken down into particle sizes of 0.001-1 mm. [51] Using this information, Wonder Women consulted a Particle Size vs. Filtration table (Figure 9) to determine the type of filtration system to use. Given that Wonder Women works primarily with large particles, it was concluded that simple, conventional filtration methods could be used to separate solid and liquid waste. [52] Next, using a theoretical Filter Efficiency vs Particle Size graph (Figure 10), Wonder Women selected sieving as the method of conventional filtration for its secondary filtration system. Sieves were selected as the filtration method for both drawers; however, the diameter of the holes in the top filter was selected to be greater than the diameter of the holes in the second filter in order to allow for a two-stage sieving process. [53] This allowed for maximized filtration and separation of the waste products into solid feces (top drawer), diarrhea and vomit (middle drawer), and liquid waste (bottom drawer).

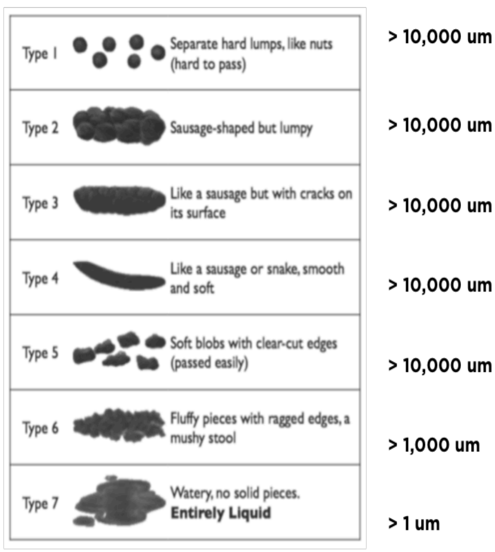


Figure 8. Types of Poop

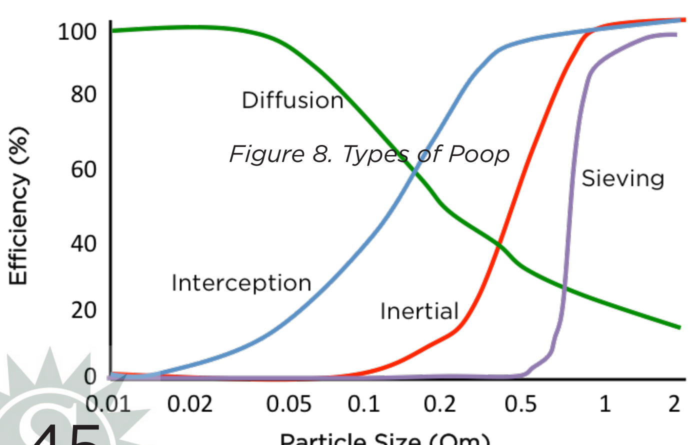


Figure 9. Filter Efficiency & Particle Size

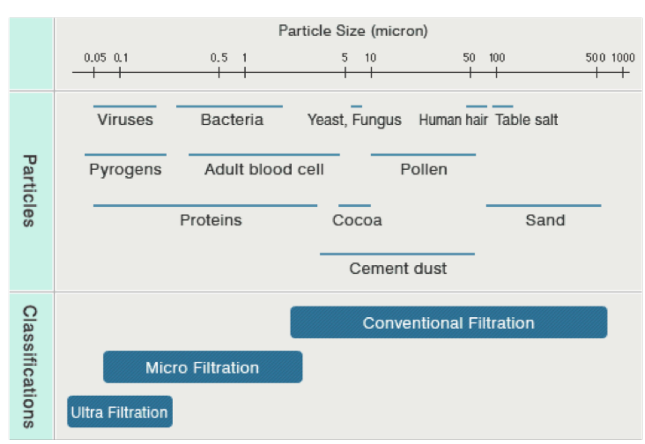


Figure 10. Particle Size vs. Filtration

As a result, Wonder Women tested three different materials to act as filters: metal, plastic, and cheesecloth (Figure 11). The metal filter had 10 mm holes and cost $2.00 per 3 ft3 of material. The plastic filter had 10 mm holes and cost $1.00 per 3 ft3 of the material. However, despite having the same diameter, an analysis of the differences between plastic and metal revealed that the metal filter was preferred for the filter in the first drawer because it was easily sanitized and reused via heat treatment. The cheesecloth filter has 1 mm holes and cost $0.30 per 3 ft3 of material. Given that the cheesecloth was found to be inexpensive enough to replace and burn weekly, it was determined to be the preferred material for the filter in the second drawer.

In order to validate the two filters' sieve diameters, Wonder Women filtered a mimicked defecation sample with the 1 mm cheesecloth and 10 mm metal filter touching. However, although the sample was effectively filtered, and little to no solid waste remained after passing through both filters, the combined filter was easily clogged during "repeated defecation" experiments that sought to determine the propensity and upper limit of each filter towards clogging. Given that Sanivation wanted to replace filters weekly, this close placement was not considered to be an ideal design.

Next, Wonder Women tested the scenario of the 10 mm metal filter being placed 10 mm-150 inches above the 1 mm cheesecloth filter. Using this experimental testing, it was determined that from 10-50 mm, the sample was effectively filtered but that again, the bottom filter quickly clogged. However, it was determined that from 50-150 mm of distance between the two filters, successful filtration and separation occurred. Additionally, even after several "repeated defecation" experiments, the filters remained unclogged if placed between 50-150 mm apart (Figure 12). This was important, since it allowed

Wonder Women to develop the needed volume of the drawers without worrying about the potential for clogging, since the minimum calculated height for the smallest drawer was 50 mm. Specifically from 50-150 mm, the top 10 mm metal filter caught the vast majority of the solid waste (the feces), while the 1 mm cheese cloth filter caught all remaining particles (vomit and diarrhea). Through these findings, Wonder Women decided to use the 10 mm metal filter used in conjunction with the 1 mm cheesecloth filter since it provided the minimum ideal results.

Secondary Filtration Design Validation

After initial validation via experimental testing, additional analytical models were used to both validate and combat potential issues that could arise with the design. Specifically, flow rates through the different filters were mathematically derived using the Carman-Kozeny form of Poiseuille's Equation:

$$\frac{\Delta p}{L} = \frac{180\bar{V}_0\mu}{\Phi_s^2 D_p^2}\frac{(1-\epsilon)^2}{\epsilon^3}$$

Specifically, the Carman-Kozeny form gives the mean velocity of the flow through a filter in terms of its thickness and porosity. Using this equation, it was determined that the flow rate through the 10 mm filter was 74.3 L/min while the flow rate through the 1 mm filter was 4.1 L/min. Intuitively, this makes sense given the difference in diameter and was confirmed experimentally by noting that at high volumes there was no lag for filtration through the 10 mm metal filter while, given the same volume, there was a notable filtration lag with the 1 mm cheesecloth filter.

However, the Carman-Kozeny equation cannot dynamically calculate the new flow rate when portions of the filter become clogged. As such, "repeated defecation" experimental tests that mimicked the weekly use of the proposed system (15 bowl movements with 1 L of anal washing water each) were conducted to determine the percent of the filter that becomes clogged each week. During this experimental testing, the feces was dropped into the same location, to mimic field conditions if the drawer system were static beneath the ergonomic toilet form, and the percent of clogged mesh was recorded after each bowel movement. The results of these tests can be found in Table 4.

Number of Simulated Defecations	Percent of Clogged 10 mm Metal Filter	Percent of Clogged 1 mm Cheesecloth Filter
1	10%	10%
2	10%	10%
3	10%	10%
4	10%	10%
5	10%	10%
6	15%	10%
7	15%	10%
8	15%	15%
9	15%	15%
10	20%	15%
11	20%	15%
12	20%	15%
13	25%	15%
14	25%	15%
15	25%	15%

Table 4. Experimental Filter Clogging Results

Using these results, Wonder Women experimentally determined that the maximum clogged area in the 10 mm metal filter was 25% while the maximum clogged area in the 1 mm cheesecloth filter was 15%, resulting in a 25% reduction of the flow rate through the top filter and a 15% reduction of the flow rate through the bottom filter. It was observed that the majority of this clogging and subsequent flow reduction was due to the immediate piling of the feces that blocked the next feces/water sample obtaining the same percent of unclogged area. As a result, Wonder Women placed each filter at a 5° tilt angle to combat the “poop pyramid” phenomena. [53]

According to literature, effective tilt angles range from 3°-13° and serve to increase flow capacity by decreasing debris occlusion. Thus, the drawer filtration system was re-tested using a 5° tilt angle, which resulted in decreased clogging. In particular, it was determined that the maximum clogged area in both the 10 mm metal filter and 1 mm cheesecloth filter was 10%, resulting in a 10% reduction of the flow rate through both filters. However, given that the system still function as designed despite some clogging and debris occlusion, this degree of clogging was not determined to be an issue due to the weekly maintenance of the filter screens. In particular, with consistent weekly collection and replacement of the filters, it was determined that the filters would never become critically clogged to the point where no liquid could flow through the filters.

Figure 11. Wire Mesh

Ergonomic Form Validation

Initial Ergonomic Form Protoypes

Ergonomic considerations were of utmost importance to Wonder Women’s design process when considering SafiChoo’s form and its varied potential impact on the human body given different forms. Since squatting and anal cleansing are integral parts of Muslim culture [12,13,19], maintaining these traditional cultural and religious practices was quantitatively determined to be a top design priority by the HoQ and Green’s CNA. However, given that traditional squatting is difficult for elderly and disabled people, Wonder Women sought to identify solutions that would promote improved squatting posture for the general population as well as better support children, the elderly, and the disabled in defecating with decreased impact on their bodies.


Figure 12. Poop Separation

Figure 13 shows several ergonomic designs that were initially considered since their form directly encouraged users to squat and better supported the body, shielding it from stress/strain, during the process. Sketches A and B model a “motorcycle” like toilet which features the user straddling toilet and leaning with their arms for support. Sketch C features a typical squatting toilet that is now above ground and has handrails for support. Finally, sketch B shows an initial toilet form with a ledge that forces the user squat instead of sit.

To further integrate ergonomic considerations into its final design, Wonder Women continued to explore other prototypes. Working from initial concepts highlighting the effectiveness of squatting when defecating, the team modeled a toilet encouraging users to squat with the aid of a contoured form. The laser cut cardboard model (Figure 17) profile pulled dimensions simply by using the natural shape of the human body while squatting. For example, the curved back of the form design correctly mimics the normal curvature of the spine and back when squatting. Moreover, to consider targeting for a diverse audience, the model implemented a rotating upper component that allows the user to choose either a sitting or squatting position based on their abilities. After analyzing the feasibility of the design in full scale, the team discovered that a flipping mechanism would not be effective in the 1 m2 space constraint. This initial prototype not also helped to inspire SafiChoo’s final form, but it also highlighted critical constraints before moving into the next round of ideation. In particular, it highlighted the need to identify the particular physiological angles for improved ergonomic form and reduced long-term impact on the body.

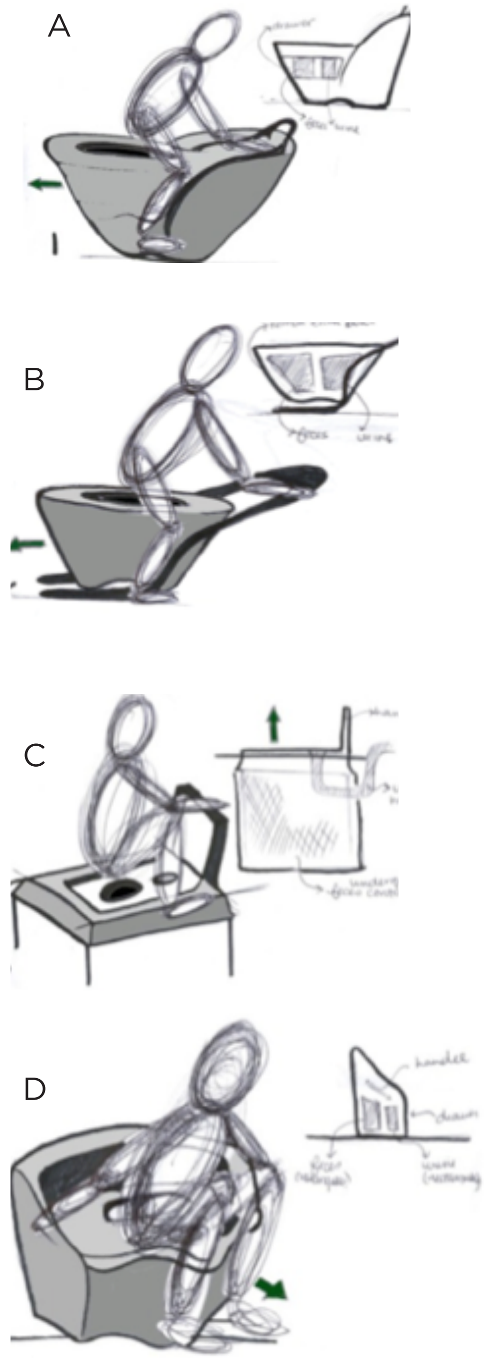


Figure 13. Initial Ideation of Improved Ergonomic Form

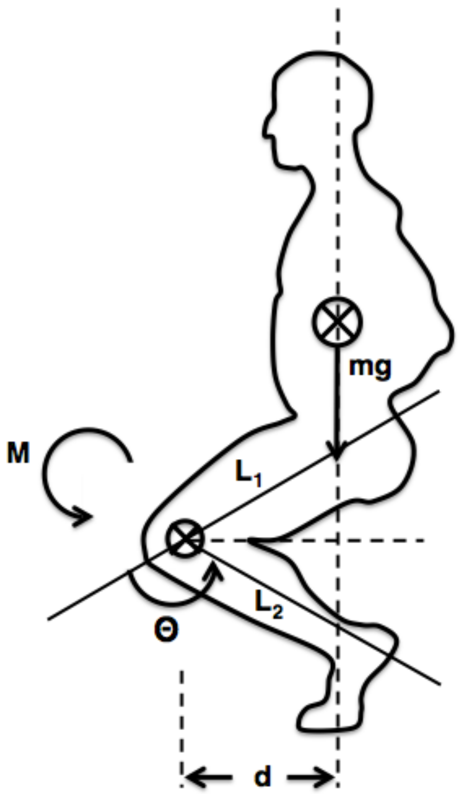


Figure 13. Free Body Diagram of Squatting

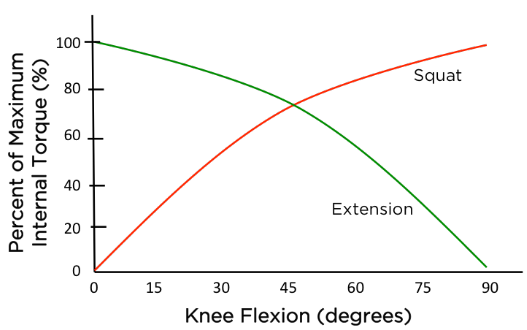


Figure 14. Torque-Angle Relation of Knee

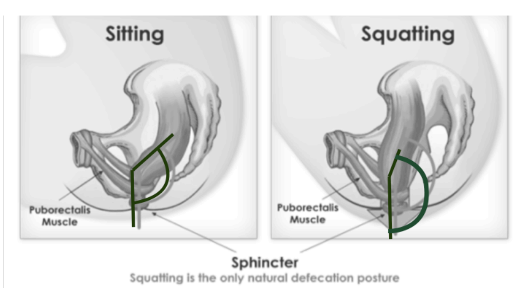


Figure 15. Anorectal Angle

Ergonomic Form Design Validation

Physiologically, squatting causes increased stress and strain on both the patellofemoral and acetabulofemoral joints. [49] In particular, by looking at the moments of force at the hip and knee (Figure 14), and analyzing the resultant torque as a relation of angle, Wonder Women calculated the knee angles that resulted in decreased force at the patellofemoral joint, which is felt by the user in the form of increased comfort and reduced muscle and joint fatigue. These angles, shown in Figure 15, were found to be optimized at angles <45° and >135°. [55] Given this, it was determined that the best physiological position for squatting and defecating occurs when the knee is almost completely bent (angle of <45°) or almost completely vertical (angle of >135°).

However, a second factor was used in conjunction with knee angle to mimimize stress and strain on the patellofemoral and acetabulofemoral joints and to determine the optimal physiological angle of squatting. Specifically, Wonder Women considered the internal angle of the bowels in order to ensure the optimal release of feces from the anus. Thus, it was demonstrated that the anorectal angle (Figure 16) is crucial to determining the release capability of the sphincter; in particular, sitting or standing hinders the feces from fully leaving the large intestines, leaving some residue inside the colon and rectum, while squatting allows for complete elimination of feces from the large intestines. [56] Moreover, the puborectalis muscle hinders the rectum to maintain continence, while squatting relaxes the puborectalis muscle allowing for easier elimination of feces. Thus, it was determined that the sphincter muscle is the most relaxed at anorectal angles between 25° and 45° and, therefore, is healthiest within that range. Using this combined

combined knowledge, Wonder Women designed its ergonomic toilet form to best support its average users by creating a design that facilitates both sitting and squatting at a healthy 35° angle.

In an effort to more accurately design a full-scale prototype and validate that the design addresses all potential user needs, Wonder Women conducted experimental and comparative ergonomic research. In particular, male and female volunteers of various physical capabilities ranging in size from 5'2" to 6'5" were asked to squat and each individual's desired squatting angle was recorded. The results highlighted a variance in squatting angles among users of different heights (Figure 18) and experimentally differentiated the comfortable squatting angles of disabled users as compared to those of abled users. Expressly, taller volunteers had larger squatting angles (35°-45°), while shorter volunteers had smaller squatting angles (25°-35°). No difference in squatting angles between males and females of the same height were determined in the experiment. Moreover, while able volunteers had squatting angles of <45°, which correlates to being able to squat, disabled volunteers had squatting angles of >135°, which revealed that they cannot and, principally, do not squat while defecating. Thus, although SafiChoo's design supports active elderly users, via a form that allows the user to squat while sitting and, thus, mimics the physiological health benefits and cultural desire to squat without actually causing any forces to negatively impact the body's various joints and muscles, the basic SafiChoo design does not support disabled users. In fact, despite the inclusion of an ergonomic handle for balance and standing up after squatting, additional component systems must be attached to be base design in order to more effectively target this population. For example, handrails for enhanced support and a plastic "skin" or attachment that allows for a disabled person

person to urinate and defecate with a squatting angle of >135° would need to be designed prior to widespread use by disabled users.

Additionally, the distance between the user's feet and the distance from the floor to the user's back while squatting were measured to define other dimensional form constraints including width and height of the final form. For example, it was determined that most users squat with their feet in line with their shoulder width; thus, although this distance also varied among tested users, the average distance was experimentally calculated to be 12 inches. Built in full-scale from sin foam, the final ergonomic prototype (Figure 19) assists a wide range of users in maintaining the cultural and religious practice of squatting while effectively minimizing stress on the patellofemoral and acetabulofemoral joints. SafiChoo's final form and its comfortability were assessed via user feedback.


Figure 17. Ergonomic Sketch Model

Expressly, Wonder Women validated its ergonomic form by conducting interviews with mimicked refugee users. In particular, given the importance of adhering to the traditional cultural and religious practices of squatting and anal cleansing, Wonder Women targeted Muslim male and female volunteers in order to ensure that it received feedback from the actual demographic of SafiChoo's intended users. These Muslim volunteers ranged in size from 5'1" to 6'3" and they were asked to squat on SafiChoo and review their experience. Specifically, Wonder Women tested the intuitiveness of the SafiChoo design by not initially telling the Muslim volunteers how to squat on the toilet; in all test cases the experimental users correctly identified the proper way to use the design. Additionally, users were asked to both squat and sit on the form and compare the two experiences. Interestingly, Wonder Women found that consistently, across both gender demographics, there was no preferred method (squat or sit). In fact, two females mentioned that they enjoyed the duality of being able to both squat and sit simultaneously since she felt like she was in the correct form but didn't have to work as hard to maintain that squatting posture. This feedback validated the previously described analytical calculations that discussed how the form minimized the impact on the body's joints and muscles due to additional support. to urinate and defecate with a squatting angle of >135° would need to be designed prior to widespread use by disabled users.

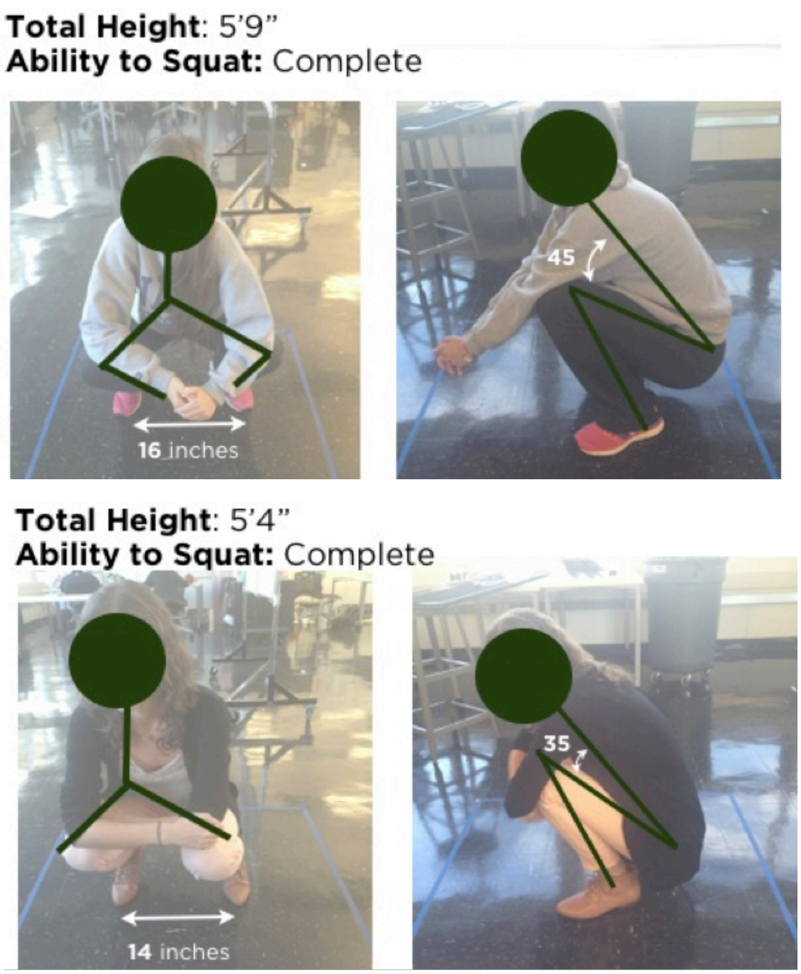


Figure 18. Analysis of Squatting Positions


Figure 19. Second Ergonomic Prototype

Improved Anal Cleansing

Initial Bidet Prototypes

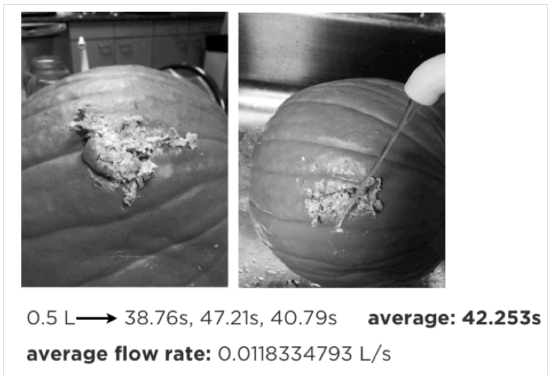


Figure 20a. Hygienna Flow Rate

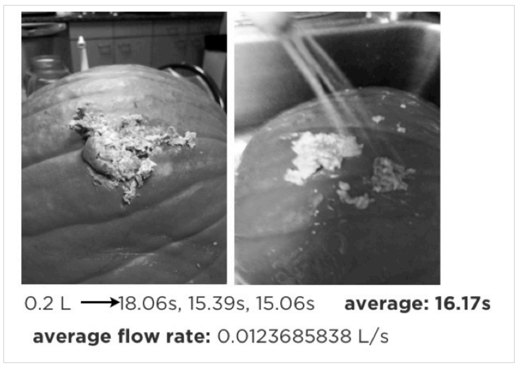


Figure 20b. Blue Bidet Flow Rate

Given that the Muslim refugees currently splash water on their anus and wipe with their left hand [12,13,19,22], Wonder Women sought to design a component that eliminated the need for the user to directly interact with feces. Thus, initial prototypes to achieve this function attempted to use pressure to generate a jet of water for anal cleansing. To demonstrate this concept, a basketball pump was connected to plastic piping and a valve and pumped in order to create a pressure difference; the valve was released to mimic the release of water from the pressurized cylinder (Figure 20). However, despite achieving its needed function and successfully eliminating the need for Muslim users to wipe with their left hand, this initial prototype was not considered ideal since the pump took two hands to operate and did not effectively clean the anus due to difficulty aiming the stream of water. Wonder Women also considered a bidet system that was activated by an accordion foot pump to free the hands. However, Wonder Women quickly realized this was improbable since, once the Muslim user moves into his squatting position for defecation, it is physically impossible for him to lift his toes and power the pump without falling.

Wonder Women's second iteration of bidet prototypes utilized existing technology for mobile bidets. Specifically, three different types of bidets were explored: Hygennia, Blue Bidet, and Pure Clean Bidet. Wonder Women experimentally tested the efficacy of the three bidets at 45° and 90° by using a pumpkin to model the anus and a mixture of oatmeal, peanut butter, and apple juice to mimic human feces. In particular, Wonder Women experimentally calculated the time and amount of water needed to completely remove a tablespoon of "feces" from the "anus".

The first bidet tested was the Hygienna hand-held bidet that screws into a standard plastic water bottle and has a nozzle that releases a singular, concentrated flow. [57] In particular, the Hygennia bidet required 11.65 seconds and 0.5 L of water to remove the "feces" from the "anus". The second bidet tested was the Blue Bidet that features a refillable, flexible water bottle and a nozzle that releases a dispersed water flow. [58] Specifically, the Blue Bidet required 14.28 seconds and 0.2 L of water to remove the "feces" from the "anus". Finally, the last bidet tested was the Pure Clean Bidet. [59] However, because it must be screwed into a traditional flush toilet, it was not tested because it did not fall within Wonder Women's design constraints. Given that the efficacy of each bidet was tested at two different angles (Figure 21), the optimal angle for maximum removal of feces from the anus with minimal water waste was experimentally determined to be 45. This was validated by the percentage of surface area reached by the bidet, the time until waste removal, and the volume of water used to remove the "feces" from the "anus". A comparison of the different bidets at both can be found in Table 6.

Figure 21a. Hygienna Bidet at 45 and 90 degrees

Bidet Model	Percent of Surface Area	Time (s) for removal	Volume (L) of water needed
Hygiennia (45°)	20%	11.65	0.5
Hygiennia (90°)	30%	12.01	0.5
Blue Bidet (45°)	50%	14.28	0.2
Blue Bidet (90°)	60%	15.61	0.4

Table 6. Analysis of Bidet Models for Identification of Optimal Angle for Waste Removal

Using these experimental results, it was concluded that Hygennia was the most effect bidet tested since required the least amount of time for feces removal and, due to its single, concentrated stream, also reduced the amount of water needed for anal cleansing. However, for the purposes of the finalized SafiChoo

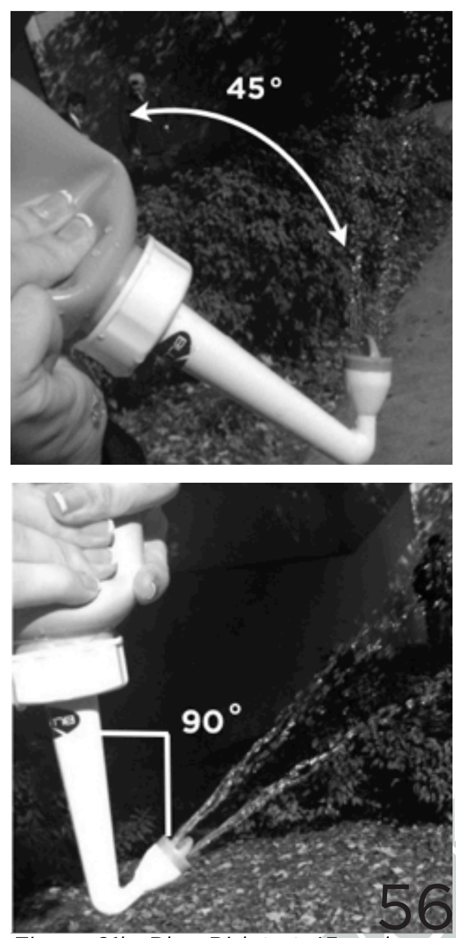


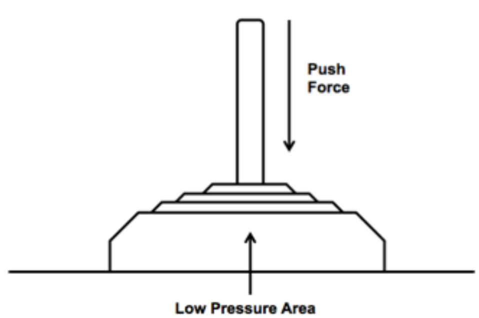
Figure 21b. Blue Bidet at 45 and 90 degrees

prototype, a bottle bidet was determined to not be ideal due to the limited number of containers in Naivasha to transport water. [3] Thus, the bottle would have greater value as a drinking water bottle rather than as a bidet to decrease oral-fecal contamination and improve sanitation. As a result, Wonder Women integrated the idea of a hand operated, pressure-driven system with the nozzles of the commercial bidets in order to develop its final solution.

Bidet Design Validation

In order to reduce the high incidence of fecal-oral contamination in the Kakuma refugee camp, a bidet system was incorporated into Wonder Women's SafiChoo toilet to improve the existing anal cleansing process by making it more sanitary. As such, the final bidet system utilizes a 4" diameter PVC pipe, a plunger, and 10" of tubing with a diameter of 0.2". Specifically, a downward force onto the plunger generates a pressure difference in the bidet system and creates a low-pressure area. This low-pressure area directly causes the pressure gradient needed for water to pressurize, flow through the plastic tubing system, and clean feces from the anus. The tubing was connected to the ergonomic form at a 45° angle to optimize waste removal, with open access for additional manual manipulation of this angle by the user if necessary.

FEA Calculated Pressure Loss:
0.146 psi



Needed Pressure:
0.158 psi

Available Pressure:
8.5 psi

Simplified Bernoulli Equation:

$$P_1/\Upsilon + \alpha(V_1^2/2g) + z_1 = P_2/\Upsilon + \alpha(V_2^2/2g) + z_1 + h_L$$

Figure 22. Bidet Overview

The bidet was designed to have a capacity of 1.5 liters of water, the amount currently used by the Muslim refugees, but it was experimentally determined that less water was required to remove the fecal matter via the pressurized bidet system (≤ 0.5 L). In particular, the nozzle of the bidet concentrates the water spray to one area, allowing for faster removal and, as a result, a reduced volume of water. Thus, SafiChoo's bidet system decreased the need for Muslim refugees to wipe their anus with their left hand, which will minimize fecal-oral contamination in the camp and improve the camp's long-term sanitation.

First, the placement of the bidet on the back right corner of the SafiChoo toilet was validated by calculating the ease of force generation and the minimum force generated at various heights and angles to the user. In particular, the placement of the bidet was validated using an analysis of the minimum force that can be generated by the physiologic range of the arm and muscle strength in the x, y, and z directions. First, a general free body analysis determined that force generation was optimized between 60°-180° in the x direction, 0°-90° y direction, and 0°-90° z direction. Since the final bidet was placed at 60° in the x direction, 30° in the y direction, 90° in the z direction, it was found to fall within an ergonomically comfortable range that allows for force generation with minimal effort.

Several different theoretical users were used in order to determine the force that can be generated by a specific user in order to expel water from the bidet. In particular, a representative child, female, and male user from the 50th percentile of their respective demographic was used. Given the normal strength range of these three user groups and the specific angle at which the bidet was placed in relation to the user squatting on the toilet (60° in the x direction, 30° in the y direction, 90° in

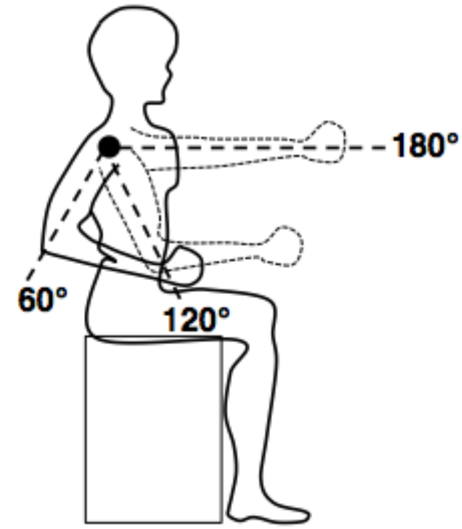


Figure 23a. Side View X

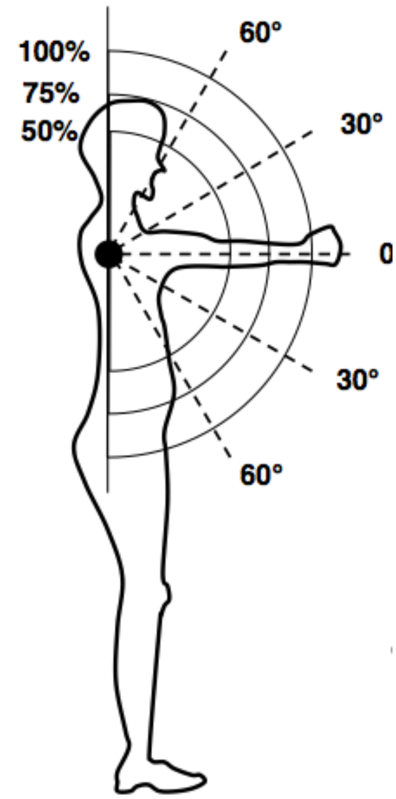


Figure 23b. Side View Y

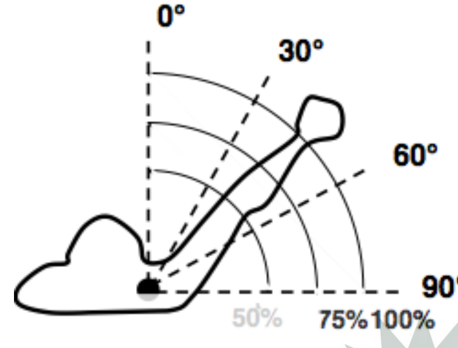


Figure 23c. Side View Z

in the z direction), it was determined that an average child could produce 34 lbs of force, an average female could produce 56 lbs of force, and an average male could produce 92 lbs of force. In order to ensure that the bidet system can be universally used by all demographics, it was determined that the minimum push force on the bidet was 34 lbs (8.5 psi). This was then compared to the minimum pressure required to expel any water from the bidet in order to ensure that it not only functioned as designed but also that it also targeted children. Targeting children was important to Wonder Women since the children in Kakuma represent the largest demographic that openly defecates, predominately because it has been reported that children frequently fall into pit latrines. [22]

The bidet design was further validated by calculating the minimum pressure needed for the bidet to function and comparing it to the minimum pressure available from pushing down the plunger. In particular, the minimum pressure needed for the bidet system was calculated using a simplified Bernoulli equation:

$$P1/ \quad + \quad (V12/\ 2g) + z1 = P2/ \quad + \quad (V22/\ 2g) + z1 + hL$$

First, a finite element analysis (FEA) was used to calculate a pressure loss of 0.146 psi in the rubber tube portion of the bidet system. Additionally, the velocity of the inlet and outlet of the bidet were calculated using the known cross sectional areas and flow rates of the input and output, in conjunction with the equation V = Q/ A.

Thus, it was determined that the minimum pressure required for a person to expel water from the bidet is 0.158 psi. Given that the minimum push force at a 60 angle and height of 10” was determined to be 8.5 psi, the system will clearly function. Using this minimum physiological push force to generate a pressure difference of 8.5 psi via the PVC-plunger system, it was further calculated that the pressure exiting the bidet would be about 8.654 psi, or 0.425 pounds of force. This was subsequently experimentally validated to be sufficient to remove one tablespoon of mimicked feces from a pumpkin.

An additional flow analysis of the full bidet system was completed in Solidworks (Figure 24) that further validated the ability of the water to flow out of the bidet system at a pressure high enough to remove feces from the anus.

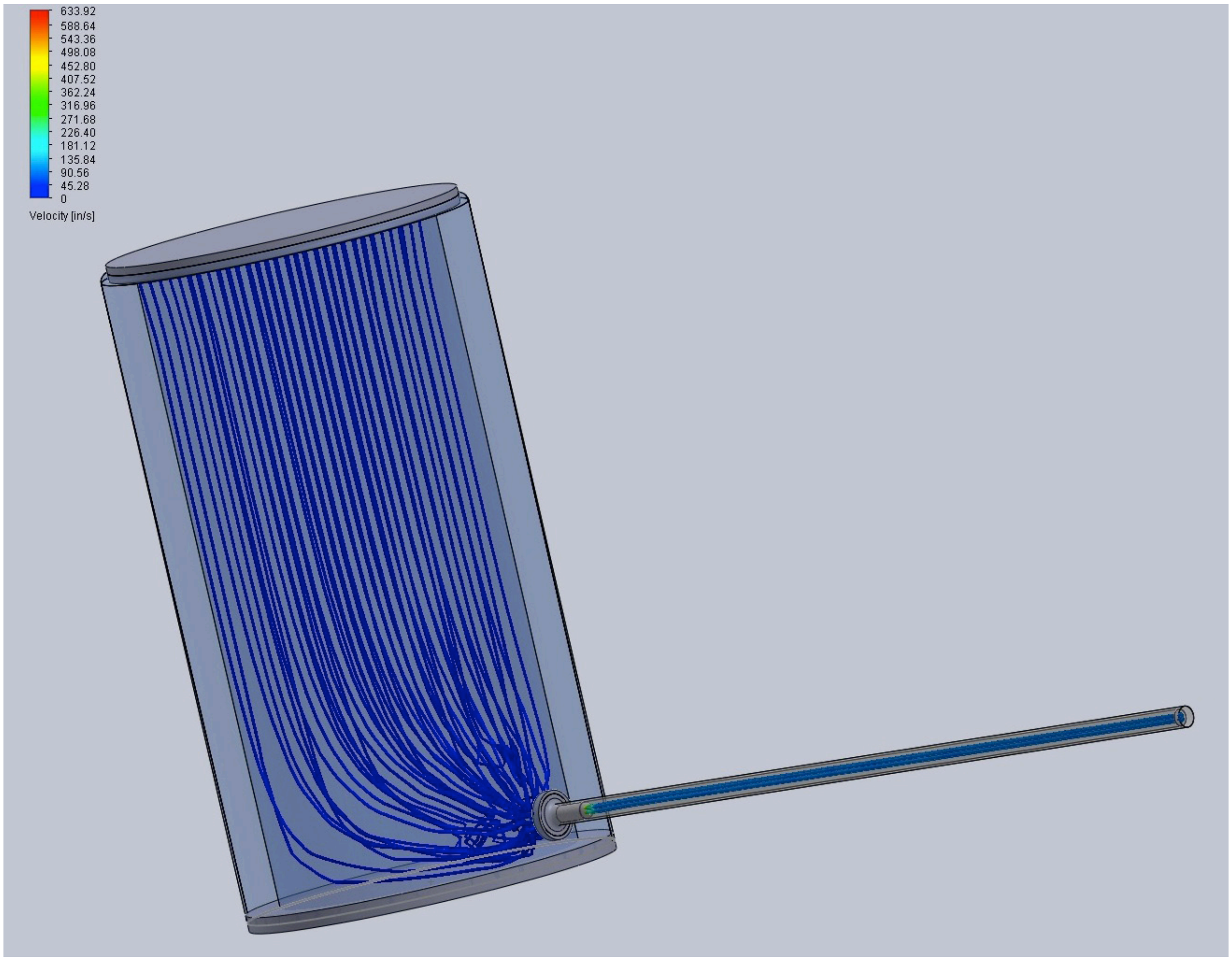


Figure 24. FEA of the Bidet

IX. SafiChoo Toilet Manufacturing

Given that there are 16,827 Somali Muslim households in the Kakuma Refugee Camp, ultimately there are 16,827 SafiChoo toilets that need to be produced in order to adequately address the sanitation needs of this neglected population. [3] However, before large-scale manufacturing can begin, SafiChoo must first undergo field-testing similar to the small pilot program Sanivation is currently conducting in Naivasha with the MoSan toilet. [22] Specifically, the initial pilot testing of Wonder Women's SafiChoo toilet will involve five Muslim households in the Kakuma Refugee Camp. If the design is well received by the Muslim refugee users, SafiChoo will expand its design to a larger sector of the refugee camp and enhance manufacturing.

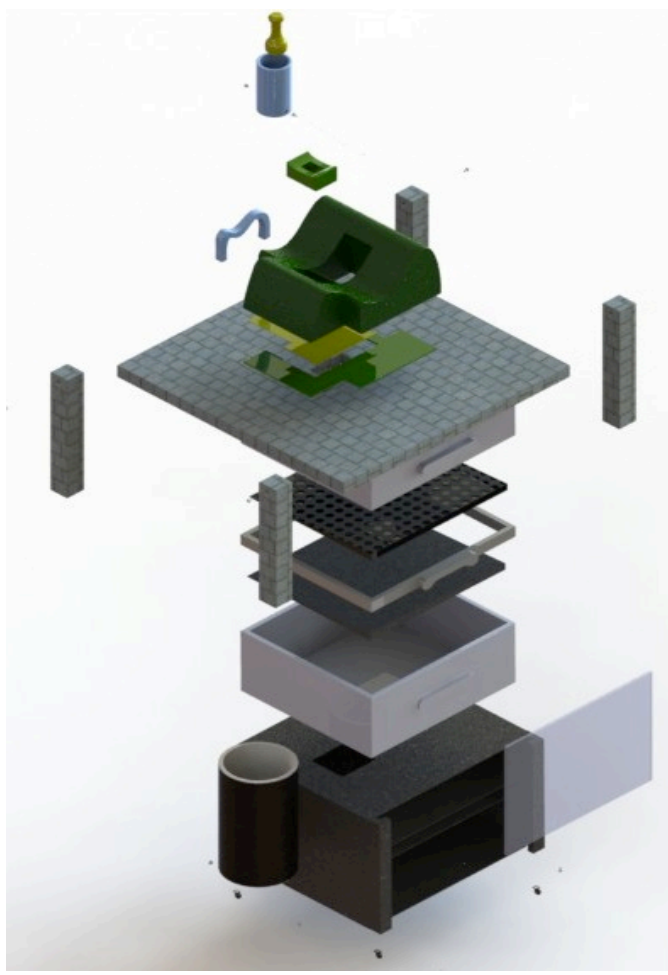


Figure 25. Exploded SafiChoo Design

Materials and Costs

When considering manufacturing and cost projections for the industralized SafiChoo toilet system, it is most effective to sort SafiChoo's components by material choice. Principally, Wonder Women ensured that all materials for the SafiChoo toilet were locally available either in the Kakuma Refugee Camp or in nearby Kenyan cities such as Naivasha and Nairobi. This allows for the toilet to be locally created, with minimized transportation costs, as well as locally fixed if a component were to break. A break down of the SafiChoo toilet system materials and costs are in Table 7.

SafiChoo Component	Selected Material	Price
Stairs or Ramp	PEP	$5.00
Bucket	PEP	$3.00
First Filter	Chicken Wire	$3.00
Second Filter	Cheesecloth	$2.00
Wardrobe	HDPE	$15.00
Bidet System	PVC	$12.00
Ergonomic Toilet Seat	Clay	$15.00
Drawer System	PEP	$35.00
Miscellaneous Items	N/A	$10.00
	TOTAL	$102.00

Table 7. Needed Materials & Expected Costs

Given that the majority of these materials can be purchased from hardware stores and do not require additional manufacturing, only the polyethylene plastic (PEP) drawer system and clay ergonomic toilet seat are discussed below since they are the only components that require actual, extensive manufacturing processes.

Clay Ergonomic Toilet Seat

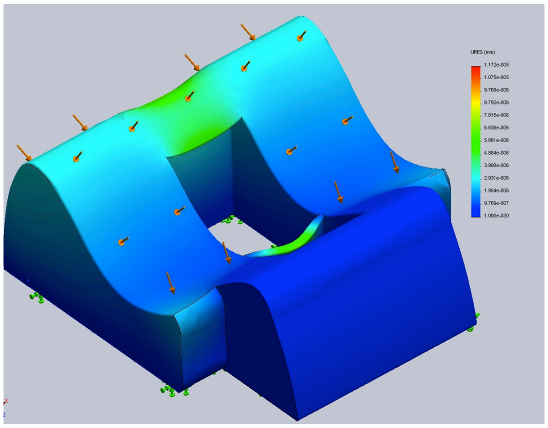


Figure 26a. FEA of Clay seat

Moreover, in an effort to continue investment in local Kenyan industry, the ergonomic toilet seat will be molded from clay found commonly in Kenyan soil. To begin manufacturing, acrylic sheeting is stretched over the existing sin foam part at high temperatures in a process known as vacuforming. After cooling, the acrylic material holds the existing shape design, serving as a cavity to create the two-sided mold necessary for repeat production. After the initial mold has been created, local Kenyans can be employed within the Kakuma camp for a relatively simple following process. Soft clay is compressed by hand within the molded acrylic cavity and is then leveled off to create consistency between parts. The molded cavity is then screwed into another acrylic plate to maintain balance as the clay goes through the drying process. Over a three day time period, the water will evaporate from the clay material as it enters a stage commonly called greenware. At this point, the piece has lost all flexibility and is able to be transported without the help of a mold structure. The mold is then heated, or fired, in a kiln for another 3 days before being deemed usable. During the drying and firing process, clay may lose 4% to 15% of its total volume. Commonly called shrinking, this loss of material varies based on the porosity and initial qualities of the clay used in production. Before defining final measurements, the Sanivation team must test the quality of Kenyan clay being used and adjust the dimensions of the mold design accordingly. Though a relatively labor-intensive manufacturing process, clay offers impressive material strength, natural water resistance, and possible economic returns for the end user group. The cost of both the clay material and manufacturing for the toilet seat is only 15 dollars per unit.

Polyethylene Plastic Drawer System

As seen in the part material breakdown in Table 7, high density polyethylene plastic constitutes a vast majority of part selections including the UDT Funnel, handle, and drawer system. Chosen predominantly for its strength, low cost, and impact resistance, HPDE offers versatility for varying parts. While many plastic manufacturing options currently exist, injection and rotational molding were found most beneficial for the team from financial and feasibility standpoints. Figure 26b highlights cost analyses for various plastic manufacturing processes at varying values. Though rotational molding offers cost advantages for a 17,000 unit output value, the process is not readily available in Kenya and thus would require additional importing expenses. As a result, with a focus on investing in local Kenyan industry, the Sanivation team selected injection molding to manufacture its PEP drawer filtration system.

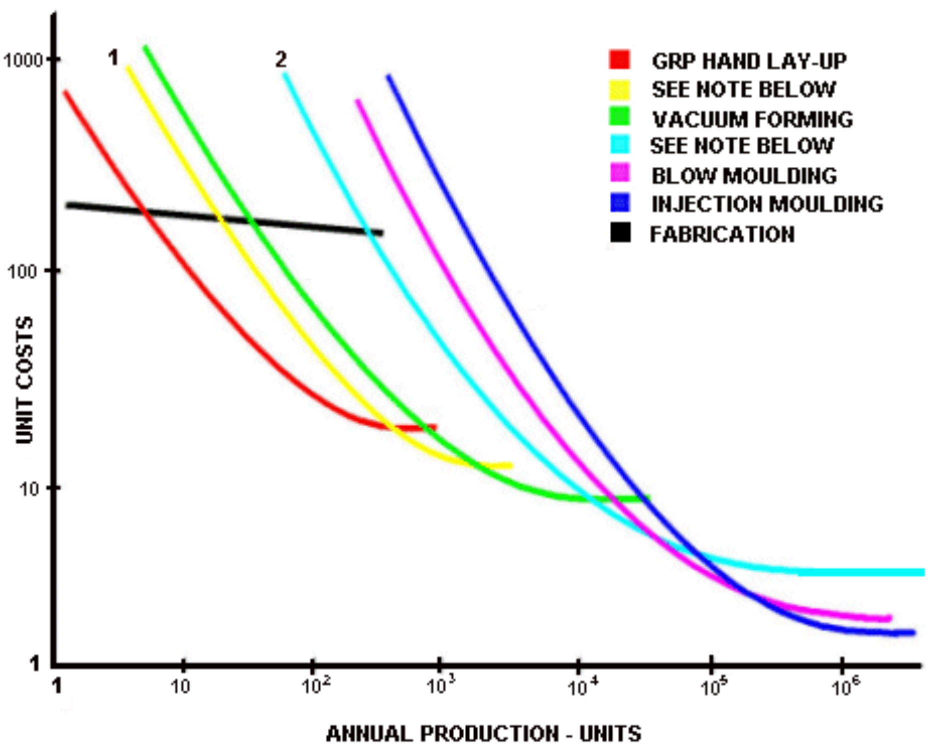


Figure 26b. Types and Costs of Large Scale Plastic Manufacturing

X. Realization and Deployment

Wonder Women, although making significant progress towards developing an improved sanitation solution for Muslim refugees, did not have adequate time to fully develop some of its ideal goals. As such, future teams should explore and build on these unfinished ideal goals. These goals include enhancing privacy, adapting the design for the disabled/children, integrating sanitation education, decreasing the number of weekly waste collections, improving the energy yield from the collected feces, and designing a toilet that costs less than $100. Future teams, particularly one with an industrial engineer, could also scale up and optimize the material collection and flow processes for energy generation in the entire Kakuma Refugee Camp (140,000 refugees). Additionally, Wonder Women plans to deploy and test the SafiChoo toilet in Kenya next summer. Some anticipated challenges include setting up the toilet system, training the sanitation workers (Stephen) in the new collection process, teaching the refugees how to use the design, and scaling up the collection and flow processes for future implementation in more than just a small pilot sector of households. Thus, Wonder Women imagines small design changes could arise in the field, such as with materials or drawer removal and replacement, and aims to be ready to combat these issues before they even begin.

XI. Conclusion

Wonder Women completed its initial design and prototyping phases and will begin testing and building its final working prototype over the next month. As the team's Gantt Chart (Appendix VII) shows, Wonder Women adhered to its project timeline. In particular, Wonder Women finished all initialization, background research, ideation, initial prototyping phases, and built a finalized working prototype. Each component of the final prototype was experimentally tested and analytically validated before all individual components were integrated into a final working system that mimics a potential testable field model.

As a result, Wonder Women presented both engineering designs plans and a working toilet prototype (Safi Choo) to Sanivation and CDC in December. The Safi Choo toilet will be a household toilet that is entirely above ground, separates waste through urine diversion and secondary filtration, and maintains all cultural practices associated with anal cleansing. The specific design of these elements can be seen in the following figures. By iterating through pertinent component prototypes based on extensive user and market research, Wonder Women achieved its stated target goals. Wonder Women's final product was shown to be a working prototype that is ready for field-testing in the Kakuma Refugee Camp in Kenya. Sanivation will build on Wonder Women's proposed design in subsequent semesters.

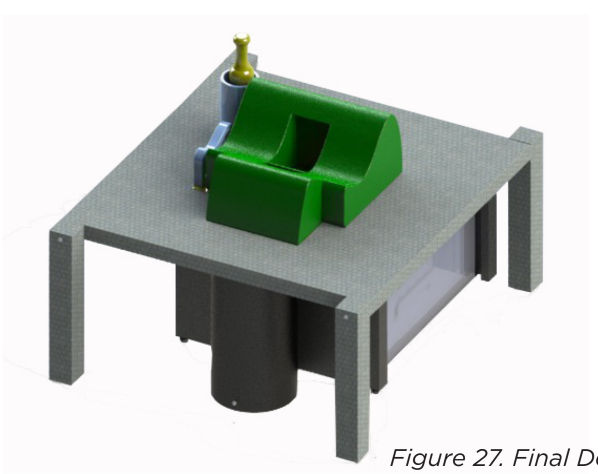


Figure 27. Final Design

XI. References

1. UNICEF. Water, Sanitation, and Hygiene Statistics. <http://www.unicef.org/wash/index_statistics.html>. September 2013.
2. Sanivation. Designing, Testing, and Implementing Novel Solutions for the Sanitation Crisis. <http://sanivation.com>. August 2013.
3. Norwegian Refugee Council. Kakuma Refugee Camp Water, Sanitation, and Hygiene (WASH) Report. March 2013.
4. World Health Organization. Simple Pit Latrines. <http://www.who.int/water_sanitation_health/hygiene/emergencies/fs3_4.pdf>. September 2013.
5. The UN Refugee Agency. "2013 UNHCR country operations profile - Kenya." N.p.. Web. 10 Sept 2013. <http://www.unhcr.org/pages/49e483a16.html>.
6. McMahon, S and Caruso, B. Anal Cleansing Practices and Faecal Contamination: A Preliminary Investigation of Behaviors and Conditions in Schools in Rural Nyanza Province, Kenya. Journal of Tropical Medicine and International Health. 16(12):1536-1540. 2011.
7. "Interview with Chrissy Bracewell from Global Growers Network." Personal interview. 6 Sept. 2013.
8. "Interview with Kevin Caravati from Georgia Tech Research Institute." Personal interview. 3 Sept. 2013.
9. "Interview with Lily Ponitz from Engineers Without Borders." Personal interview. 8 Sept. 2013.
10. "Interview with Susan Davis from Improve International." Telephone interview. 10 Sept. 2013.
11. "Interview with Douglas Cox." Telephone interview. 2 Sept. 2013.
12. "Interview with Mariam Ishraq." Personal interview. 3 Sept. 2013.
13. "Interview with Moreed Khosravanipour." Personal interview. 2 Sept. 2013.
14. "Interview with Brandie Banner." Personal interview. 30 Aug. 2013.
15. "Interview with Professional Hydrologist Tess Byler." Personal interview. 10 Sept. 2013.
16. "Interview with Charlie Crawford from Coaches Across Continents" Personal interview. 15 Sept. 2013.
17. "Interview with Erin Johnson from Human Needs and Human Rights." Personal interview. 15 Sept. 2013.
18. "Interview with Mona Mijthab." Telephone. 10 Sept. 2013.
19. "Interview with Sarah Rehman Morabu." Personal interview. 3 Sept. 2013

20. “Interview with solar expert Louis Woofenden.” Personal interview. 10 Sept. 2013.
21. “Interview with Andrew Foote from Sanivation.” Personal interview. 4 Oct. 2013.
22. “Industrial designers’ interview with Emily Woods from Sanivation.” Telephone interview. 13 Sept. 2013.
23. “Engineers’ interview with Emily Woods from Sanivation.” Telephone interview. 18 Sept. 2013.
24. “General Communication with Emily Woods.” E-mail interview. 21 Sept. 2013.
25. “Reliance Luggable Loo.” REI. N.p.. Web. 10 Sept 2013. <.rei.com/product/679029/reliance-luggable-loo>.
26. “Human waste Anaerobic digestion = Biogas Fertilizer.”LooWatt. N.p., n.d. Web. 10 Sept 2013. <http://www.loowatt.com/digestion/>.
27. “Sanergy.” . N.p., n.d. Web. 15 Sept 2013. <http://saner.gy/>.
28. Vinneras, Bjorn. Faecal Separation and Urine Diversion for Nutrient Management of Household Biodegradable Waste and Wastewater. Rep. Sveriges Lantbruks Universitiet, n.d. Web. 22 Oct. 2013.
29. “Cleanwaste PETT Portable Environmental Toilet.” REI. N.p.. Web. 10 Sept 2013. <http://www.rei.com/product/662980/cleanwaste-pett-portable-environmental-toilet>.
30. “Quick Set Portable Toilet.” CampigWorld. N.p.. Web. 10 Sept 2013. <http://www.campingworld.com/shopping/item/quick-set-portable-toilet/65906>.
31. Reinvent the Toilet Challenge Winner: Bill and Melinda Gates Foundation. N.d. Video. n.p. Web. 1 Sept 2013. <http://www.youtube.com/watch?v=z7PQMqGuWlU>.
32. “How waterless toilets work.” WooWoo: Waterless and composting toilets. N.p., n.d. Web. 15 Sept 2013. <http://www.waterlesstoilets.co.uk/content/how-waterless-toilets-work-0>.
33. “Functional Diagram of the System.”Stone BioTech. N.p., n.d. Web. 1 Oct 2013. <http://stonebiotech.co.in/manufacturing-facilities.php
34. “PeePoo.” PeePoople. N.p.. Web. 10 Sept 2013. <http://www.peepoople.com/peepoo/start-thinking-peepoo/>.
35. “The Crapper.” Toilets for People. N.p., n.d. Web. 13 Sept 2013. <http://www.toiletsforpeople.org/the-crapper/>.
36. “Sustainable Organic Integrated Livelihoods.” Models. N.p.. Web. 11 Sept 2013. <http://www.oursoil.org/what-we-do/toilets/models/>.

37. “EcoLove.” Toil-O-Preneurs. N.p., n.d. Web. 12 Sept 2013. < http://www.ecoloove.com/index.html>.

38. “How No-Flush Toilets Can Help Make a Healthier World.” Environment 360. N.p., n.d. Web. 25 Oct 2013. <http://e360.yale.edu/feature/how_no-flush_toilets_can_help_make_a_healthier_world/2581/>.

37. “EcoLove.” Toil-O-Preneurs. N.p., n.d. Web. 12 Sept 2013. < http://www.ecoloove.com/index.html>.

38. “How No-Flush Toilets Can Help Make a Healthier World.” Environment 360. N.p., n.d. Web. 25 Oct 2013. <http://e360.yale.edu/feature/how_no-flush_toilets_can_help_make_a_healthier_world/2581/>.

39. “Borgen.” 5 Innovative Toilets for Developing Countries. N.p., n.d. Web. 16 Sept 2013. <http://www.borgenmagazine.com/5-innovative-toilets-for-developing-countries/>

40. “DEHYDRATING TOILET.” Backcountry Energy Environmental Solutions. N.p., n.d. Web. 9 Sept. 2013. <http://www.beeshive.org/?page_id=90>

41. “Six of the Most Innovative Ways to Process Your Poo.” Wired UK. N.p., n.d. Web. 4 Sept. 2013. <http://www.wired.co.uk/news/archive/2011-07/21/waterless-toilets>

42. “How Does It Work?” Kazuba. N.p., n.d. Web. 2 Sept. 2013. <http://www.kazuba.eu/index.php/en/how-does-it-work/8-how-does-it-work?start=6>

43. “Poo Powder® Waste Treatment!” Poo Powder® Waste Treatment. N.p., n.d. Web. 4 Sept. 2013. <http://www.cleanwaste.com/poo-powder-waste-treatment>

44. “Wastewater Technology.” Environmental Protection Agency. N.p., n.d. Web. 2 Oct. 2013. <http://water.epa.gov/scitech/wastetech/>

45. Goodier, Rob. “Ten Ways to Put Human Waste to Use.” Engineering for Change. N.p., n.d. Web. 10 Sept. 2013. <https://www.engineeringforchange.org/news/2012/11/21/ten_ways_to_put_human_waste_to_use.html>

46. Dixon, Robyn, and Nicholas Soi. “In Nairobi, Kenya, Biogas from Human Waste Wins over Few Cooks.” Los Angeles Times. Los Angeles Times, 16 Nov. 2012. Web. 5 Sept. 2013. <http://articles.latimes.com/2012/nov/16/world/la-fg-kenya-biogas-toilets-20121116

47. Linsey, J and Li, W. “Senior Design Lectures”. Georgia Institute of Technology. Fall 2013.

48. Gates Foundation. Sustainable Sanitation for Developing Countries: Current Research Needs and Priorities. 2009.

49. Mason, J. J., F. Leszko, T. Johnson, and R. D. Komistek. “Patellofemoral Joint Forces.”Science Direct. N.p., n.d. Web. 9 Oct. 2013. <http://www.sciencedirect.com/science/article/pii/S0021929008002340>.

50. Murphy, JL, SA Wootton, SA Bond, and AA Jackson. “Energy content of stools in normal healthy controls and patients with cystic fibrosis.”Archives of Disease in Childhood. n. page. Print. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1793018/>.

51. Bristol Stool Chart. Digital image. GP Notebook. N.p., n.d. Web. 20 Oct. 2013. <http://www.gpnotebook.co.uk/Bristol_Stool_Chart.png>.

52. Vigneswaran, Balasubramaniam. “Effect of Particle Size in Depth Filtration: Measurements and Modeling.” Scholarworks. University of Massachusetts, n.d. Web. 15 Oct. 2013.

53. Rep. N.p.: n.p., n.d. High Efficiency Particulate Air: HEPA Filtration Facts. Donaldson Filtration Systems. Web. 18 Oct. 2013.

54. Orion, Doreen. “The Pyramid of Poop or Why I’ll Never RV Without My Husband.” Queen of the Road. N.p., n.d. Web. 22 Oct. 2013. <http://blog.seattlepi.com/queenoftheroad/2008/12/29/the-pyramid-of-poop-or-why-ill-never-rv-without-my-husband/>.

55. Schoenfield, Brad. Issue brief. N.p.: n.p., n.d. Squatting Kinematics and Kinetics and Their Application to Exercise Performance. Denton Independent School District. Web. 14 Oct. 2013.

56. “Japanese vs. Western-style Toilets.” RocketNews24 RSS. N.p., n.d. Web. 5 Oct. 2013. <http:// en.rocketnews24.com/2013/08/28/japanese-vs-western-style-toilets-squatty-potty-stool-gives-us-the-best-of-both/>.

57. “Introducing the Hygienna Solo.” Introducing the Hygienna Solo. N.p., n.d. Web. 7 Oct. 2013. <http://hygienna.myshopify.com/>.

58. “Blue Bidet.” Blue Bidet. N.p., n.d. Web. 5 Oct. 2013. <http://www.bluebidet.com/>.

59. “Pure Clean Fresh Water Spray Non-Electric Mechanical Bidet Toilet Seat Attachment.”Amazon.com. N.p., n.d. Web. 7 Oct. 2013. <http://www.amazon.com/Pure-Clean-Non-Electric-Mechanical-Attachment/dp/B008R54IQM>.

60. Cleaning, Sterilization, & Maintenance of Surgical Instraments. Rep. N.p., n.d. Web. 20 Oct. 2013. <http://www.roboz.com/catalog%20pdfs/Sterilization_and_Maintenance.pdf>.

61. “Slow Sand Filtration.” Centers for Disease Control and Prevention. Centers for Disease Control and Prevention, 21 Mar. 2012. Web. 10 Oct. 2013. <http://www.cdc.gov/safewater/sand-filtration.html>.

62. Dannenberg, Andrew L., Howard Frumkin, and Richard Jackson. Making Healthy Places: Designing and Building for Health, Well-being, and Sustainability. Washington, D.C.: Island, 2011. Print.

63. Barry, Mohamed B. Planning for Drinking Water Supply and Sanitation in Developing Countries. Thesis. Atlanta: Georgia Institute of Technology, 1982. Print.

64. Lupton, Ellen, and J. Abbott. Miller. The Bathroom, the Kitchen and the Aesthetics of Waste: A Process of Elimination. Cambridge, MA: MIT List Visual Arts Center, 1992. Print.

65. Hooton, T. Perineal Anatomy and Urine-Voiding Characteristics of Women with and without Recurrent Urinary Tract Infections. Clinical Infectious Diseases. 29:1600-1. 1999.