Bill & Melinda Gates Foundation
440 5th Ave N.
Seattle, WA 98109

Dear Ms. Carolyn Stepnich,

The purpose of this report is to inform the Bill & Melinda Gates Foundation of a new toilet design that will address the inability to properly dispose of bodily waste in developing countries.

Due to a non-existent waste disposal system, the lives and well-being of citizens in developing countries are in jeopardy. At least 10% of the world's population is thought to consume food irrigated by wastewater. Around 2 billion people all over the world do not own a proper toilet. Poor sanitation is related to transmission of disease, impaired development, malnutrition, and death. However, these diseases and deaths can be prevented.

The overarching goal of our project is to create a toilet that is capable of being used on a single family level with minimal energy and cost. The toilet should be capable of rendering bodily wastes on single-day time scales into clean water, CO2, and mineral ash, at a per capita daily total cost not to exceed $0.07, in a safe, enduring, and environmentally satisfactory manner without any sewage connection. It is desirable for the toilet to be well-lit and free from insects, odors, stains, and unhygienic surfaces. In addition it is ideal for the operation to not require external utilities and convert water into potable-grade water.

In this report, we will discuss our whole design process starting from a client needs assessment and ending with the concept selection analysis. We will provide a physical model to illustrate our solution. Our concept's functionality, risks, and economics will be discussed in order to compare the advantages and disadvantages of our concept to currently existing concepts.

If you have any questions, comments, or concerns, please feel free to contact our research team at Team3@uw.edu

Sincerely,
Team Reinvent the Toilet
August 2019

Reinvent The Toilet

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Executive Summary

The objective of this project is to design a new waste disposal system that can be used on a single family level with minimal energy and cost. The toilet should be capable of: (1) rendering bodily wastes of an adult human into water, CO2, and mineral ash, (2) at a per capita daily total cost not to exceed $0.07, (3) in a safe, enduring, and environmentally satisfactory manner. However, the waste disposal system must have unqualified freedom from inputted water and output sewerage connections of any type and operate on single-day time scales. Secondary objectives include: sustained operation without any external utilities (i.e. grid power, natural gas pipeline), conversion of recovered water into potable-grade water, proper lighting, and freedom from insects, odors, stains, or unhygienic surfaces.

Our proposed solution is a urine diverting toilet that uses an electric furnace to turn solid waste into mineral ash and an electrochemical reactor to turn urine into clean water. A drain in the front of our toilet bowl will allow liquid waste to be diverted so that the solid and liquid waste can undergo their respective processes separately. The liquid waste will then undergo electrolysis to break down urea and eliminate bacteria. A secondary filter will be used after electrolysis to ensure potable water. Solid waste will be collected in a bowl that rotates to a downward position when closed, and rotates back to the upward position when the lid is open. This allows the solid waste to drop into the combustion chamber and also creates a more hygienic and odorless environment for the user. Once a night, the incineration chamber will be activated and the solid waste will be burned until it is converted to mineral ash. Water from the electrochemical process can be collected from an output container. Mineral ash will have to be collected and disposed of weekly.

The proposed solution has improved quality in the areas of potable-grade water recovery, odor, maintenance requirements, energy efficiency, and cost. Many other toilet designs simply pipeline the treated water back into the toilet system for grey water purposes such as flush water or faucet water. However our design features potable-grade water stored in such a way that the water can be recovered and used in any way someone chooses. In terms of odor, the rotating bowl with a hydrophobic Teflon coating ensures that no waste is stuck onto the surface, and that the odor from the incineration chamber is blocked off when the user is actively using the toilet. Additionally, the operational life of an electrochemical reactor is estimated to be every 2-3 years. Our design is more energy efficient than other designs, because we use two separate processes to deal with liquid and solid waste. The incineration chamber doesn't use more energy than necessary to produce mineral ash because the waste in the incineration chamber only contains the internal moisture it came with. The electrochemical reactor requires a very low voltage to clean the urine. Higher energy efficiency results in a lower per capita daily total cost.

Table of Contents

List of Figures and Tables

Introduction

The motivation behind this project is to provide a safe way to dispose of bodily waste for people living in rural areas of developing countries. According to the World Health Organization, two billion people do not have access to basic sanitation facilities, and an estimated 432,000 diarrhoeal deaths annually are associated with inadequate sanitation [1]. Figure 1 shows the areas most affected by lack of safe sanitation. As you can see, the highest areas of concern are sub-saharan Africa and India. Poor sanitation caused by a lack of proper lavatory facilities has been shown to reduce the overall well-being of those exposed, as well as hindering economic development and disrupting education [1]. It also cultivates an environment in which diseases such as cholera, dysentery, hepatitis A, typhoid and polio can spread easily [2].

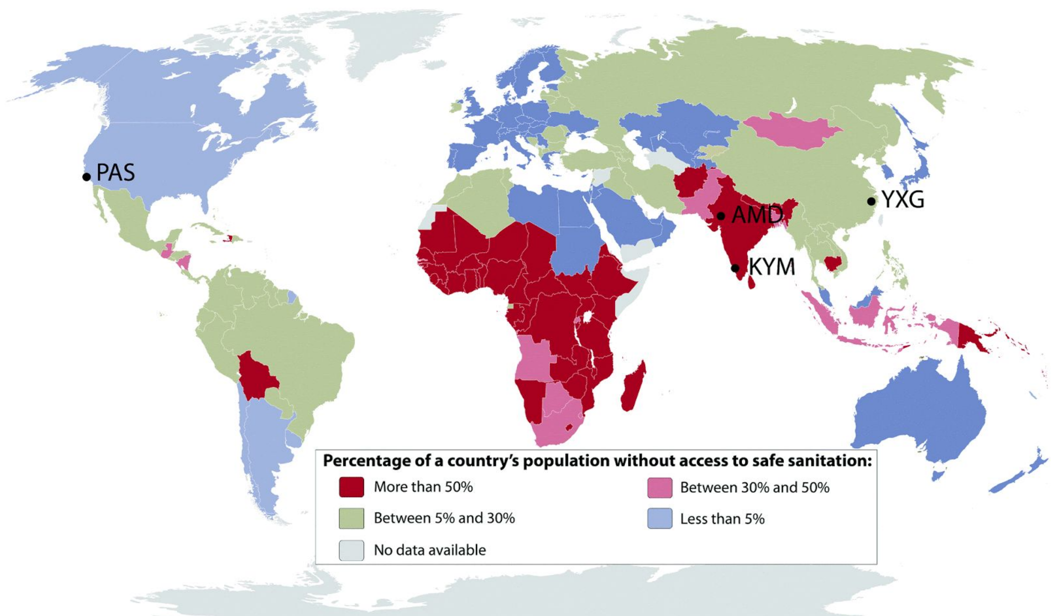


Figure 1: Percentage of Population Without Safe Sanitation [3]

The challenge of improving sanitation in these developing countries is not as simple as providing the facilities. There are cultural and social barriers that must be considered in order to achieve a successful integration of the lavatories. According to one study conducted in rural Eastern Zambia, there was a strong taboo associated with others knowing that you had just used the latrine. This was enough for the facility to not be used by some, despite strong feelings that it improved hygiene and lowered the risk of disease [4].

In response to this waste epidemic, The Bill & Melinda Gates Foundation has posed a design challenge to university researchers called “Reinvent the Toilet”. We have been tasked with designing a solution that fits the criteria outlined by the Reinvent the Toilet Challenge. This report will include our problem statement, project timeline, client needs assessment, concept generation, functional decomposition, and concept selection analysis. It will also include the functionality, model, risk, and economics of our final design.

Problem Statement

The problem statement given by the Bill and Melinda Gates Foundation is to design a new waste disposal system that can be used on a single family level with minimal energy and cost. The toilet should be capable of rendering bodily wastes of an adult human into water, CO_2, and mineral ash, at a per capita daily total cost not to exceed $0.07, in a safe, enduring, environmentally satisfactory manner that will be widely acceptable by the world's poorest people [5].

Key requirements include: acceptance of mixed-content (urine and feces), single-day time scales for rejecting rendered input wastes, and zero connections between inputted water and an output sewage system.

Key desires include: provision of a toilet that is well-lit, hygienic, and odor free, that is able to sustain operations without external utilities, and can convert recovered urine into potable-grade water.

Overall, the goal is to have a toilet that is used and culturally accepted in developing countries. Toilet usage will hopefully improve hygiene and reduce illnesses and deaths that are associated with improper sanitation facilities. This will lead to a better quality of life for those in developing countries.

Project Timeline & Client Needs Assessment

The project timeline was created in the form of Gantt Chart (Figure 2). We were given deadlines which allowed us to determine when each task should be completed. Additionally we made sure to extend our engineering research for an additional week because we knew that our project would require ongoing research. We also gave our group extra time to complete the tasks under progress report four because there was a large amount of work accompanying that progress report.

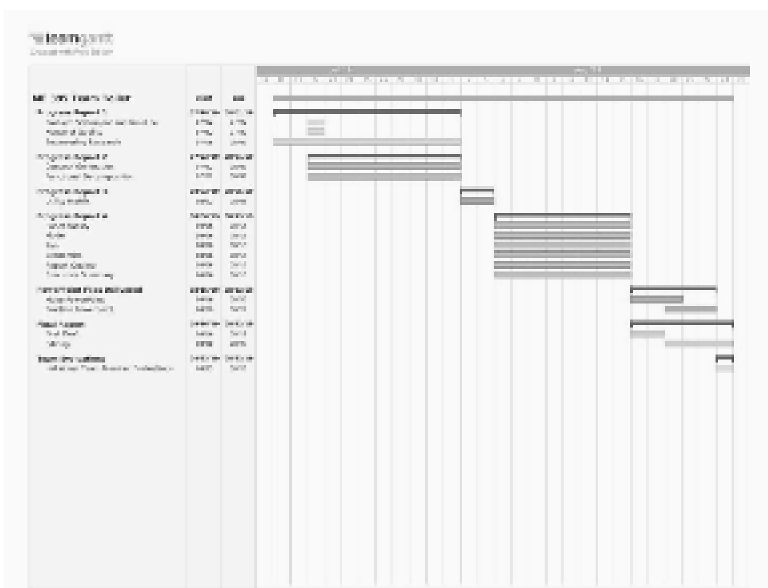


Figure 2: Gantt Chart of Our Project Timeline

Preliminary Engineering Research

For our preliminary engineering research, we focused on existing attempts at solving this design challenge. Existing toilet designs and a short description of their features is given below.

- *Cranfield Nanomembrane Toilet* [6] - Available features include a toilet hinge gear driver, a swipe blade to clean bowl, an archimedes screw to carry solid waste, a combustion chamber to burn solid waste, nanomembrane filters to clean water, and a heat exchanger to condense liquids.
- *Electrochemistry* [7] - Human waste contains a decent amount of salts. Therefore electricity breaks down the molecular bonds producing chlorine-containing oxidants - a powerful disinfectant.
- *Caltech Toilet* [8] - Solar panels power an electrochemical reactor, breaking down urine into water and hydrogen that is stored in fuel cells to power reactor on cloudy days. Waste is broken down through aerobic digestion.
- *Biofil Digester* [9] - Uses aerobic bacteria and red worms to aerate solids. Remains are treated through a reed bed.
- *Biodigester Toilet* [10] - Fermentation of waste takes place in a dark moist area creating gases that can be used to power gas stoves. Leftovers can be used as manure.
- *Parabolic Mirrors* [11] - Mirrors are used to concentrate sun rays to heat up waste collection chamber to 600°F. Chamber converts waste into mineral ash.
- *Hydrothermal carbonization* [12] - Converts wet biomass into “coal” and urine into a plant nutrient enhancer. Produces heat as a chemical byproduct.

Client Needs Assessment

The client needs assessment was carried out with a streamlined House of Quality (Table 1). As a team we utilized a house of quality to connect customer needs to quantifiable engineering characteristics. In terms of the customer requirements and their respective weight values, we incorporated both key requirements and key desires under customer requirements. Meanwhile, we gave an importance weight factor of 4 to 5 for our key requirements and an importance factor 2 to 3 for our key desires, both of which were dependent on our team’s opinions. Aside from the specific needs and requirements, our team ultimately decided to add “manageable initial cost” as one of our key desires. Although not listed in the project specifications, we believed that a lower initial cost is important for mass production, and widespread implementation.

For the various engineering characteristics, we brainstormed as many quantifiable characteristics that would fit our clients’ needs. After assigning the scores and calculating the relative weights, we noticed that most of our results varied about either 5% or 10%. The characteristics around 10% are “cost per day”, “energy required to convert”, “net energy”, “number of particulates in water/air”, “mass of mineral ash”, and “cost of maintenance”. On the other hand, characteristics around 5% are “volume of the tank”, “corrosive resistance”, “fracture toughness”, and “time for cycles”. Since the percentages hover about two percent, we disregarded the importance of rank. Rather, we viewed the engineering characteristics at around 10% as our primary design concerns, and the characteristics around 5% as our secondary design concerns. Clarifying the difference between “net energy” and “energy required to convert”, we defined “net energy” as the total amount of energy required for the toilet to function (incorporates both power sources and energy needed for processes), and “energy required to convert” as more specifically the amount of energy needed to convert human waste into mineral ash/potable grade water.

		Engineering Characteristics											
Improvement Direction		↑	↓	↓	↑	↑	↓	↓	↓	↓	↑	↑	↓
Units		m^3	J	dollars	n/a	Pa*(m^0.5)	J	days	PPM	PPM	Kg	m^3	dollars/year
Customer Requirements	Importance Weight Factor	Volume of Tank	Energy Required to Convert	Cost per day	Corrosive Resistance	Fracture Toughness	Net Energy	Time for cycles	Number of particulates in water	Number of particulates in air	Mass of Mineral Ash	Volume of Potable Water Generated	Cost of Maintenance
Turn waste into safe water, CO2, and mineral ash	5	3	9	9			9	9			9	9	
Per capita daily total cost doesn't exceed $0.07	4		9	9			9	3					9
Enduring	4			3	9	9	3						9
Culturally Acceptable	3		1						3	3			
Mixed-content acceptance	5	3			3								
Combat Odor	4	3							9	3			3
Hygienic	5	3							9	9	3	3	3
Self-maintaining	3	3	3	9	3		3		3	3	3		3
Single-day time scales for rejection of inputted waste	4		3	3			9	9					
Potable-grade water	3								9			9	
No power grid	4		9	9			9						
Freedom from insects and stains.	2												9
No input water	5			1									
No sewer system	5											3	
Environmentally satisfactory	5		1							9	9	9	1
Safety	5	1			9	9			9	9	9	9	9
Manageable initial cost	2	9											
	Raw Score	89	146	173	105	81	174	93	171	165	159	192	176
	Relative Weight %	5.2	8.5	10.0	6.1	4.7	10.1	5.4	9.9	9.6	9.2	11.1	10.2
	Rank	11	8	4	9	12	3	10	5	6	7	1	2

Table 1: House of Quality

Concept Generation

Our concept generation process took the form of a morphological chart (Table 2). Using our preliminary engineering research and further exploration into the concept, we divided the problem into subproblems. We then analyzed existing designs, and isolated their design elements that fulfilled the subproblems. We simplified previous morphological charts to come up with our final morphological chart.

Through the construction of the morphological chart, we observed that there were three basic processes that separated the existing toilet designs. These processes were used to convert the feces and urine into clean water and mineral ash. The processes were incineration (parabolic mirrors or a furnace), decomposition (worms and bacteria), and chemical processes (hydrothermal carbonization and hydrothermal oxidation). While these processes could theoretically be used in a single toilet design, it is not necessary because each process fills a niche in the toilet design - creating clean water and mineral ash given urine and feces. It is also important to note that some of the subproblem design solutions may or may not be compatible with subproblem solutions of a separate column. For example, the “Separate compartments / toilets for solid and liquid waste” subproblem solution would be compatible with the

“Worms (turns solids into soil)” solution. However, the “Incinerator evaporates urine” solution would not be compatible with the “Worms (turns solids into soil)” solution as it would not be feasible for a toilet to have both an incinerator and worm decomposition tank. These relationships were taken into account during the process of selecting our final toilet design.

Subproblem	**1**	**2**	**3**	**4**	**5**
Separate solid waste from liquid waste	Incinerator evaporates urine	Separate Compartments/ toilets for solid and liquid waste	Liquid waste filters through soil tank and is collected at the bottom to the filtration system	Solid waste is allowed to settle, liquid waste remains on top	Centrifuge dries out waste and separates liquid waste out
Turn solid waste into mineral ash	Parabolic mirrors heat up combustion chamber	Anaerobic Digestion by bacteria	Worms (turns solids into soil)	Incineration via furnace, solids are dried and flattened beforehand	Hydrothermal carbonization
Turn urine into potable-grade water	Urine evaporates and condenses	Electrochemical reactor cleans urine	Urine filters through soil, gravel, and filtration system at bottom of tank	Membrane distillation through heated urine	Sand filter, UV-ray disinfection chamber for pathogens
Transport waste to tank	Gravity, tank is directly beneath the toilet but access can be closed off to avoid smell	Urine passes through pipes, solid waste is in a rotating compartment that is scraped clean	Waste is mixed with bark as it is collected in a rotating chamber and then drops into main tank	Powered conveyor belt transports flattened solids	Assisted flush with created water
Power Source	Collected heat from solar radiation	Hydrogen from electrochemical reactor	Mechanical Power stored in batteries	Natural gas heats incineration chamber	Heat from hydrothermal carbonization, solar panels
Collect mineral ash/water	Incinerator and water tank are manually emptied every few days	Water pumped to top, fertilizer collected beneath toilet	Soil can stay in tank without needing collection, some amount of soil can be collected for fertilization, water is pumped back into the water tank to assist pump	Toilet is periodically serviced by an outside party and ash is collected	Water is pumped to the top, “coal” is collected beneath structure

Table 2: Morphological Chart

Functional Decomposition

We created a function structure (Figure 3), with the assistance of the morphological chart and references to the textbook. The key functions of the function structure were derived from the subproblems of the morphological chart. We initially connected the key functions with a material connection, as the material (i.e. urine and feces) best represents and connects the function flow. We then connected the functions with energy, and then the status signal.

We broadened our function structure to encompass different processes that could be used in the toilet, as we were unsure of the specific functions we would include in the final design. Therefore various connections do not exist in the final design of the toilet. For example, our toilet does not require water to flush the feces. Therefore, the connections relating the functions "Transfer clean water" and "Transport urine + feces into toilet" are not applicable for our final design.

Likewise, we also broadened the forms a single connection could take. For instance, clean water can be transferred via hydraulic, human, or gravitational energy in the functional decomposition. However the clean water is transferred only through gravitational energy in our design; the connections were included initially just so we did not limit ourselves for the final design.

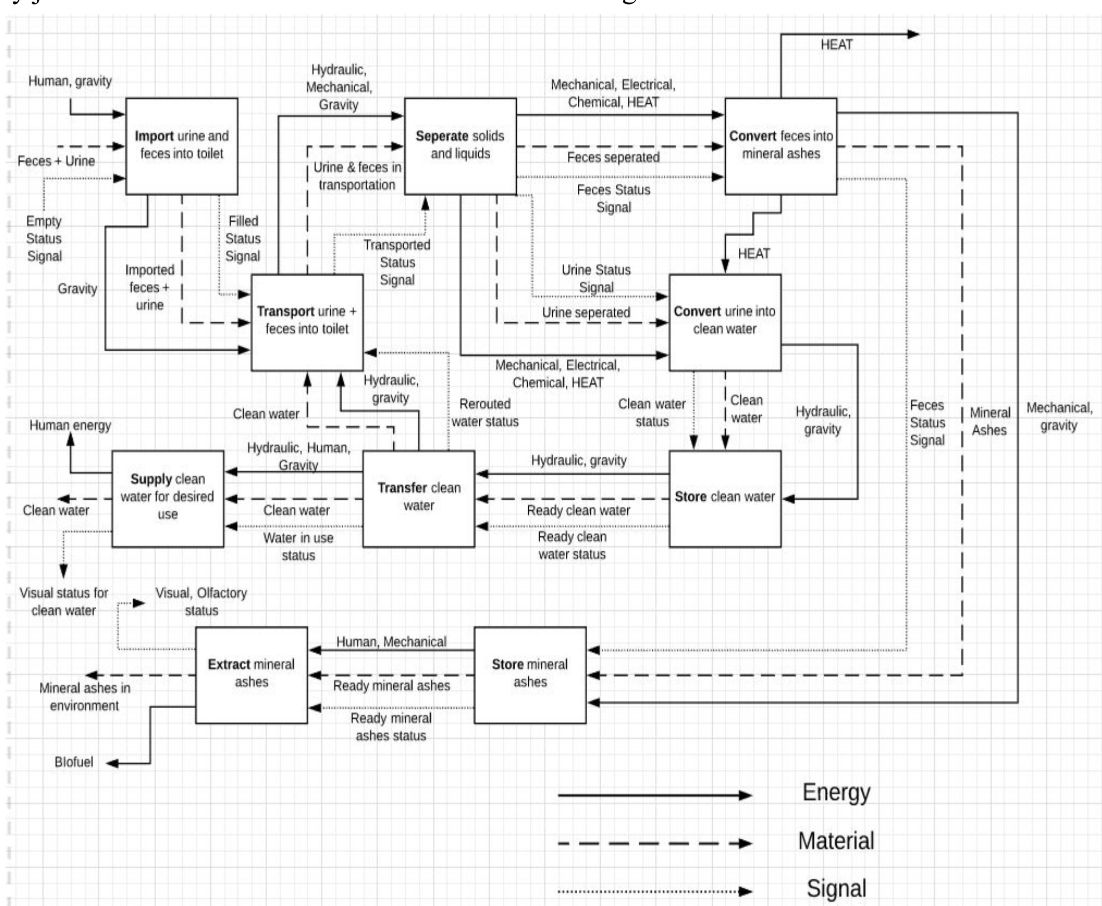


Figure 3: Functional Decomposition

Concept Selection Analysis

For the separation of solid waste from liquid waste, our group decided on separate compartments. In terms of the Pugh chart, the separate compartments idea performed well, ranked as the 2nd best design solution as shown in Table 5 and 6, located in the appendix. The most important factor in this decision was not captured in the Pugh chart: by having separate compartments, the feces will have a higher likelihood of being dry, which will make it easier to combust into mineral ash. Additionally, although allowing urine and feces to settle (feces sink toward bottom while urine floats) was the highest scoring option, we ultimately chose separate compartment option because it takes too long for the urine and feces to settle (worse time per cycle). With the project specifications, we placed a greater emphasis on disposing the waste on a single day time scale. This is because we don't want the urine and feces to fill up the toilet's volume and we don't want to the lingering feces and urine to create odor in the toilets.

For the transformation of feces into mineral ash, we decided that a furnace would be the best choice. The relative score of the furnace was not the highest in the Pugh charts (Table 7 & 8). However we decided the furnace better fit our given and assumed requirements and desires, specifically the time per cycle, and the ease of manufacturing / use. Much like how it took too long for feces and urine to settle, the anaerobic digestion by bacteria took too long to break down the feces, lasting an estimated 40 days to create usable fertilizer. The hydrothermal carbonization required pumps, pressurizers, supercritical water, etc. so the manufacturing of a toilet using this process would be difficult. Furthermore, a key requirement is to convert the feces into mineral ash; mineral ash is defined as possessing no organic material. Fertilizer created from anaerobic digestion contains organic material, so would not fit the problem statement. Lastly, we decided against using the parabolic mirrors because the manufacturing costs were too high, and maintenance could prove difficult.

For the process to turn urine into clean water, we decided on an electrochemical reactor. The electrochemical reactor had the highest score in the Pugh chart (Table 9 & 10). The most important factors we considered were the time per cycle and maintenance. The electrochemical reactor should be able to operate with only 0.37 volts of electricity that can easily be generated from a solar panel, and the maintenance should not occur often or be as costly as replacing nanomembrane filters, the other main contender. Moreover, the nanomembrane filters had a high initial cost according sources online, adding to our decision of using the electrochemical reactor.

For transporting the waste to the tank (Table 11 & 12), we decided on a rotating bowl with a non-stick surface coating. This solution is somewhat a combination of two solutions. It is a combination of simply using gravity to facilitate fecal transport, and using the rotating compartment design, but without the suggested scraper. The reason for this is because in our idea for the gravity assisted feces transport, we needed a mechanism to seal off any fumes, since the feces would be directly dropped into the tank below. We realized that the rotating compartment mechanism could be used to form the seal. The assisted flush concept also performed very well in our Pugh charts, but ultimately doesn't fit in well with other aspects of our design. We also desired a solution that did not require assisted flushing with water, because it would be ideal for the water to be used for other purposes such as drinking or agriculture.

There are a few problems we've run into with both of these solutions. If we had some sort of scraper for a rotating compartment, we are not sure the scraper will remove all of the feces in the compartment (i.e. the bottom of the toilet bowl). This would obviously be a source of unpleasant odor, and would not be hygienic. The rotating chamber would theoretically be more hygienic, as the feces would fall directly into the rotating chamber, and from there into the combustion chamber. However we are still considering the material the wet feces should be mixed with in the rotating chamber. We thought using mineral ash from previously dried feces would do well in drying the feces and neutralizing the odor. However we then have an extra subproblem of transporting mineral ash to the rotating chamber. We also considered using kitty litter or small clay balls to dry the feces in the rotating chamber.

For our power source (Table 13 & 14), we decided to use a series of solar panels. The solar panels are intended to power the electric furnace. Our biggest reason for choosing solar panels is because they are self sufficient. Also, energy gathered from solar panels can be stored in a battery; other power sources do not have this option. Aside from that, there were a few reasons that we did not choose other higher scoring options. For converting mechanical power into battery storage, we decided against it because we believe that this method either does not provide enough power, or demands too much out of the user. For using natural gas, we decided against it because we placed higher emphasis on self-sufficient options. Lastly, we decided against parabolic mirrors because the mirror usage is highly dependent on the time of day, and the assembly would be unsafe by nature. Our Pugh Charts for power source can be found in Tables 13 and 14.

Lastly, for our collection of water / mineral ash, the ranking outcomes of the design solutions were very interesting (Table 15 & 16). Based on the characteristics we were considering, all of the design solutions ranked equally overall. There were essentially two different groups for these solutions. The first was the mineral ash/fertilizer and water being collected underground, and the second was the mineral ash/fertilizer being collected underground and water pumped back to the bowl to assist with the flush. We ended up choosing an option that was not listed: the mineral ash/fertilizer being collected within or next to the toilet itself. We created a new design solution because we felt limited by those we had originally, and felt there was something better. We did not want to add a pump to the toilet because it would be more difficult to manufacture and install, would require more maintenance costs, and requires more moving parts.

Functionality

Our proposed design uses two technologies to transform human waste into clean water and mineral ash. A small electric furnace will turn solid waste into mineral ash once per night. Liquid waste will go through an electrochemical reactor to remove E. coli, Nitrogen, and phosphorous, as well as other harmful bacteria. Liquid and solid waste will be separated so that they can undergo these processes separately.

To separate the solid waste from liquid waste, we are utilizing a urine-diverting toilet design: a drain in the front of the toilet bowl collects urine while solid waste falls to the back of the bowl. The solid waste will be collected in a bowl that rotates every time the lid of the toilet is closed, allowing the solid waste to drop down into the incineration chamber. This feature also provides a seal against odor. The rotating bowl will have a hydrophobic teflon coating, allowing waste to slide into the incineration chamber. The urine collected will be routed directly through pipes to a tank containing the electrochemical reactor. The advantage of separating liquid and solid waste is that the furnace will operate more efficiently with dry solids. However, both the electrochemical reactor and the incinerator are capable of handling both solid and liquid waste, so it is not necessary to achieve perfect separation. That makes our urine diverting toilet design the best option because it is simple and there is no energy or regular maintenance required.

The electrochemical reactor uses a cathode and an anode to attract ions in the solution to the electrode of opposite charge. These anodes and cathodes are titanium dioxide and stainless steel plates respectively. This process is called electrolysis. Urea, the predominant compound in urine is broken down into hydrogen gas, nitrogen gas, and carbon dioxide during this process. Extra water is left behind in the tank.The advantage of using electrolysis to purify urine is that is takes a very low voltage, only about 0.37 Volts to power. The only disadvantage of the electrolysis process is that it will take roughly 4 hours to complete the process, but this can be done nightly and the toilet can still be used while this process is taking place. Treated water from the electrochemical reactor is considered potable. However the water is transferred via a carbon filter into the clean water storage tank as a further safeguard.

Solid waste (including toilet paper, vomit, and any other combustibles that make their way into the toilet) will be burned in a mineral ash collecting unit. The used mineral ash collector is heated by the electric furnace to 1100 degrees Fahrenheit for 15 minutes. After 15 minutes the feces will be converted completely into mineral ash. Fans within the toilet will then be activated to remove the heat due to the electric furnace; the outputted hot air will be exerted through a pipe in the back of the toilet. Additionally a heat sink is located behind the furnace to improve the efficiency of the incineration process and facilitate the heat transfer when the fans are cooling the system.   Mineral ash will have to be collected from the mineral ash collector once or twice per week, depending on the size of the family. This is somewhat of a hassle, but combustion was the only process that we came upon that truly turned solid waste into mineral ash, as opposed to some other form of organic material, such as fertilizer.

Additionally, both the incineration chamber and electrochemical reactor are turned on by an embedded system. The startup time can be controlled, but its default will be in late night / early morning; the toilet will be unusable while the incineration is in process.

Model

Rendered Views

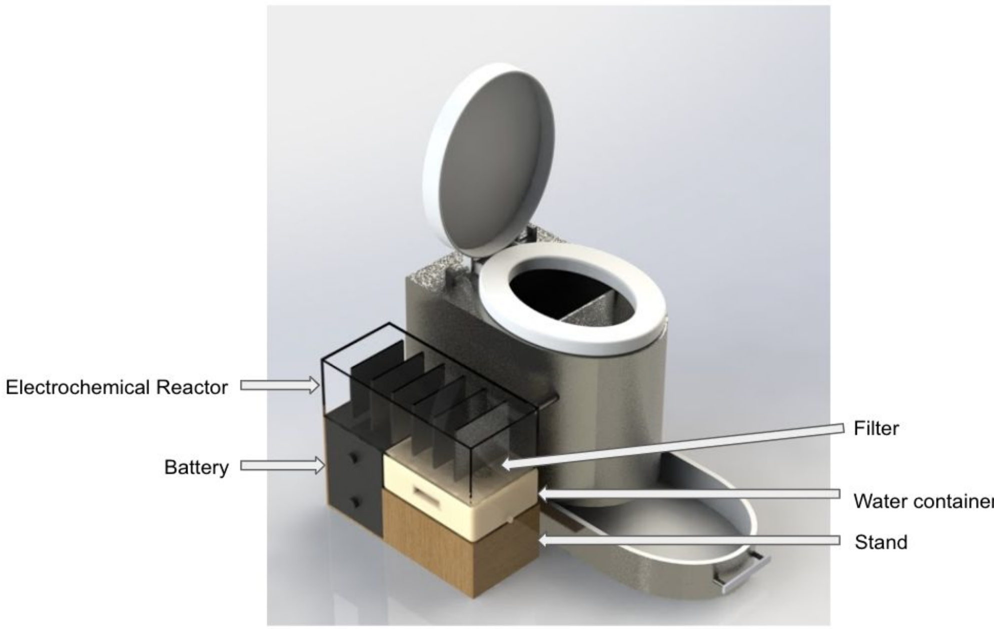


Figure 4: Labeled toilet

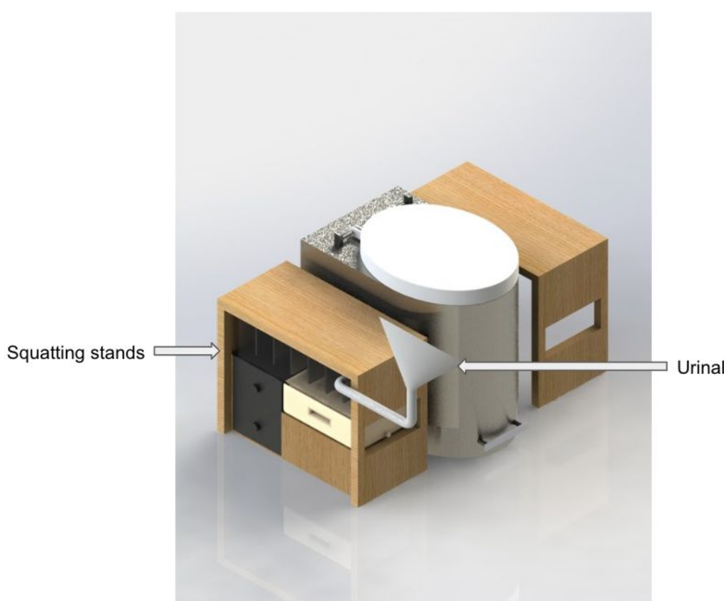


Figure 5: Culturally considered toilet

Figure 6: Optional housing structure

Scaled Views

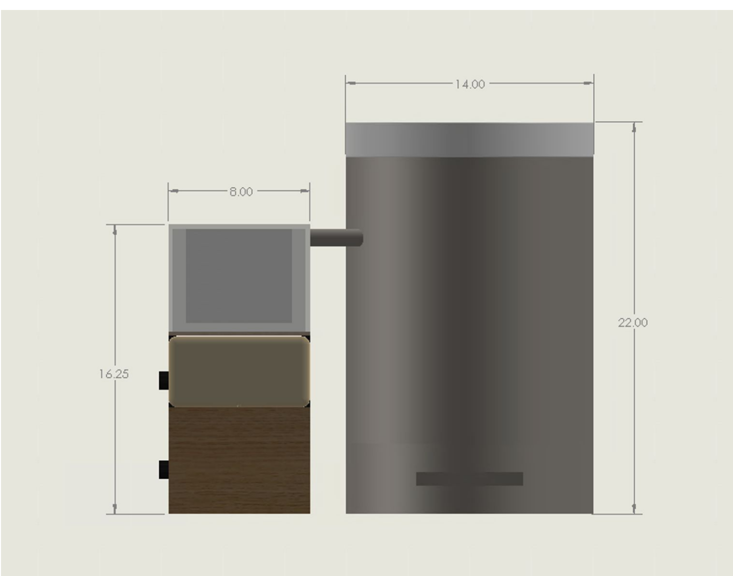


Figure 7: Front scaled view of toilet

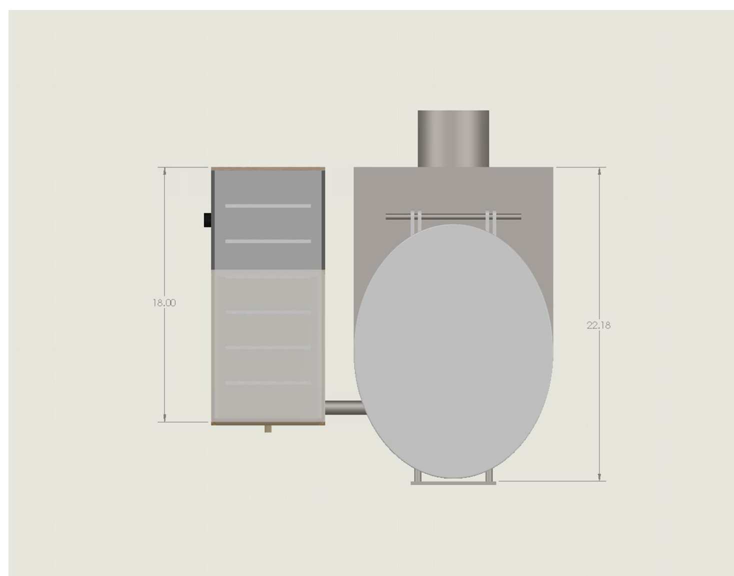
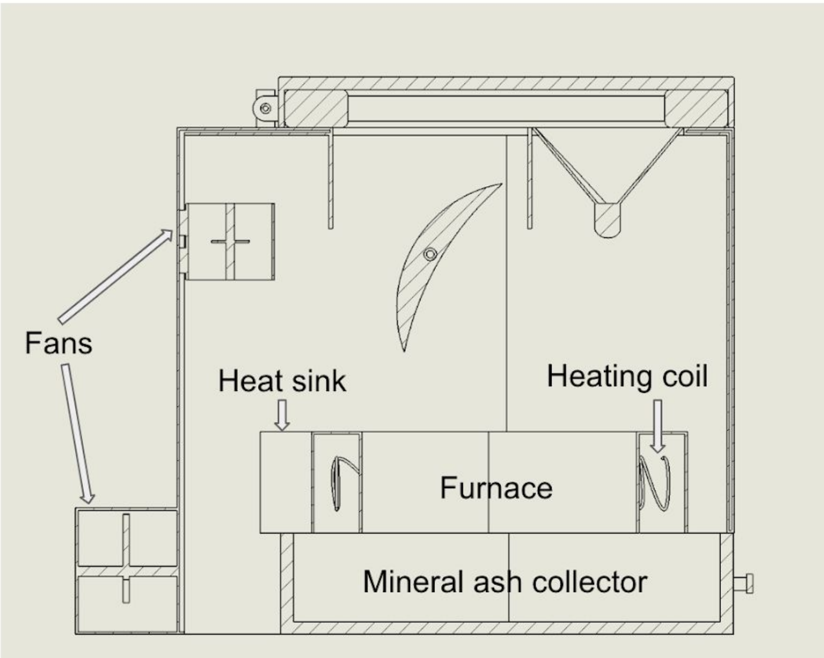


Figure 8: Top scaled view of toilet

Side Section Views



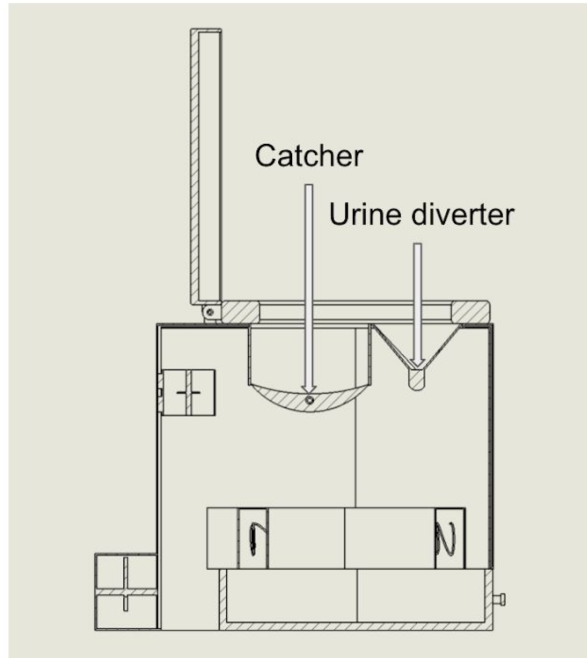


Figure 9: Side section view of toilet (down position)

Figure 10: Side section view of toilet
(up position)

Risks

Tolerable Risks

Reuse of Unhygienic Water

The data from the World Health Organization indicates that several developing countries have a substantially higher mortality rate due to unsafe sanitation, as can be seen in Figure 11. For example, countries, such as the Congo, Cameroon, and Ethiopia have about 40 to 60 deaths per 100,000 people due to unsafe sanitation in 2016. These values are much higher than the world average at 11.8 deaths per 100,000 and the U.S average at 0.2 deaths per 100,000. In terms of death per person per year, the values are around $4*10^{-4}$ to $6*10^{-4}$. At the order of 10^{-4}, we assume this is a tolerable risk because it is lower than our 10^{-3} threshold [13]. Although our design does not directly use water to transport urine and feces, we approached this risk pessimistically. We plan on using an electrochemical reactor to filter urine into potable grade water to ensure the water becomes usable. However, if the reactor fails due to lack of maintenance, then the risk of unsafe water becomes more prominent. For now, our solution is a properly maintained electrochemical reactor.

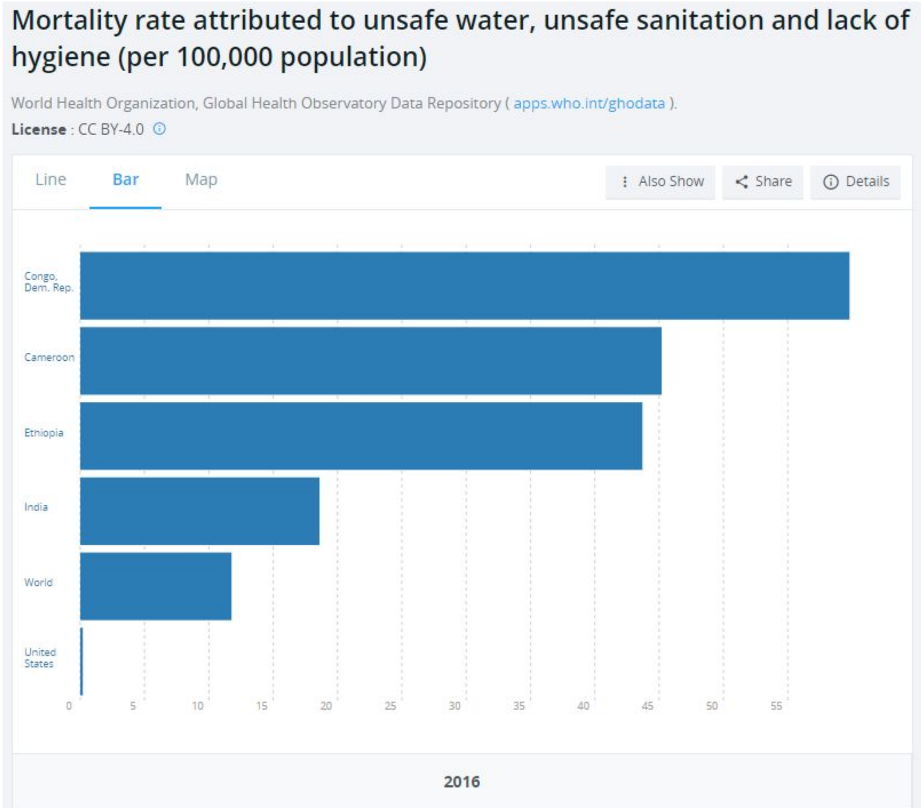


Figure 11: Mortality rate attributed to unsafe water [13]

Breathing in Mineral Ash/Smoke

In terms of the dangers of breathing in mineral ash, we treat it as a type of particulate matter. If one breath in particulate matters, then one faces increased risks of cardiovascular and respiratory mortality, especially if one has respiratory issues like asthma. In 2017, about 21 people out of 100,000 died from "household pollution from solid fuels", resulting in a tolerable but not acceptable annual death rate of about $2.1 * 10^{-4}$ [14]. For clarification, we treat burning human feces as a process of "burning solid fuel". Furthermore, increasing the concentration of $PM_{2.5}$ also increases the mortality rate. As a result, we have to limit the concentration of mineral ash that reaches the air; otherwise this could ultimately become an unacceptable risk. Currently, we have a designated area for storing mineral ash. This an adequate solution, but requires proper disposal and maintenance to prevent mineral ash particulate from entering the air. We are treating smoke exiting from the toilet furnace as a type of secondhand smoke. CDC statistics have indicated that second hand smoke kills approximately 41,000 people per year in the U.S. Assuming there are about 300 million people in the U.S, the mortality rate per person per year for second hand smoke is about $1.36*10^{-4}$ [15]. This is within our tolerable range of 10^{-3} and 10^{-5}. Although this is a tolerable risk, a method of reducing the damage from smoke should be researched and implemented in the future. The death rates from air pollution is illustrated in Figure 12.

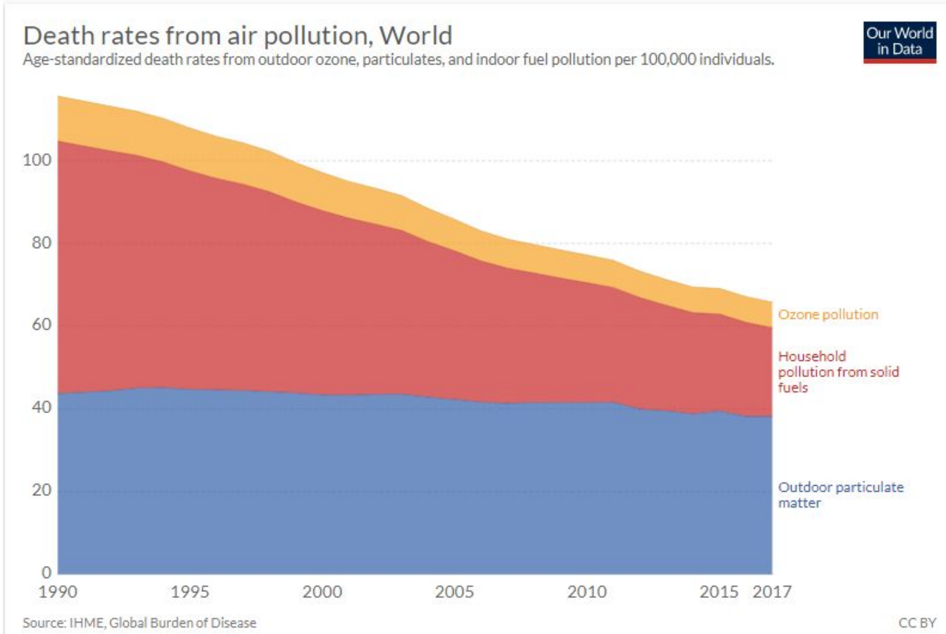


Figure 12: Death rates from air pollution with various sources [14]

Fire Hazards

Fire is another major concern of our design. We plan on burning feces in a safe region that won't burn the user. The materials that we use will have sufficient heat capacity to contain the flames. A potential problem lies in the situation when one accidentally inputs a highly combustible material in the toilet, such as a can of hair spray. Another hazard would occur if the toilet shell failed to contain the heat, due to a crack or faulty mechanical equipment. Lastly, we worry that our rotating waste catcher could potentially get too hot, which could lead to burn damage if a person comes in contact with it. Overall, we view these potential problems as part of the inherent risk of using fire. According to Figure 13, fire has a mortality rate of $4*10^{-5}$, which is in the tolerable range of 10^{-3} and 10^{-5} [16]. For now, we will add heat prevention methods, such as adding a heatsink and putting a ceramic coating around our furnace. Additionally, we added an embedded system that schedules our toilet incinerating during non-operational hours. The user will also be informed when the toilet is incinerating with an LED on the side of the toilet. A problem that could exist includes the system malfunctioning, causing the toilet to incinerate at an undesignated time. As can be seen, improvements in preventing deaths due to fire is something that could be further explored. On a side note, including external solutions such as having a fire extinguisher around would definitely help.

TABLE 14.3
Fatality Rate

Cause of Fatality	Fatality per Person per Year
Smoking (20 per day)	5×10^{-3}
Cancer, in general	3×10^{-3}
Race car driving	1×10^{-3}
Motor vehicle driving	3×10^{-4}
Fires	4×10^{-5}
Poison	2×10^{-5}
Industrial machinery	1×10^{-5}
Air travel	9×10^{-6}
Railway travel	4×10^{-6}
California earthquake	2×10^{-6}
Lightning	5×10^{-7}

Figure 13: Fatality rate of several causes [16]

Acceptable Risks

Solar Power, Electrical Shorts, and Battery

In terms of electricity from solar power, we discovered there are about 440 deaths per trillion kWh [17]. Comparing other popular methods like oil (36000 deaths per trillion kWh) and biofuel/biomass at (24000 deaths per trillion kWh), solar power is about two orders safer. Additionally, a large quantity of the deaths from rooftop solar power comes from maintenance and installation. Additionally, the mortality rate of electrical shorts and battery failures is around 400 deaths per year in the U.S according to NCBI [18]. Assuming there are about 300 million electricity users in the U.S, the mortality rate per person per year is about $1.33 * 10^{-6}$, which satisfies the acceptable threshold of 10^{-5}. As a result, developing extra measures to prevent electrical failures is unnecessary.

Falling and Other Toilet Injuries

Much like the traditional toilet, one is prone to falling, having one's hand stuck in the toilet, and the lid jamming body parts. For that, we decide to assume that the general risks for our toilet is the same as that of the traditional toilet. Luckily, most of the accidents that occur are non-fatal. Based on data collected by the CDC, there were about 3300 bathroom related ER injuries in 2008 [19]. The fatality rate should be much lower, especially since we are only looking at our toilet and not the entire bathroom. This should put our toilet mortality rates in the acceptable range.

Corrosion/Cracks

Corrosion will likely occur from the urine/feces traveling through while cracks will likely occur from forces applied on the material. These are natural degradations of the toilet that can be fixed through simple replacements.

Unacceptable Risks

Currently, we have not identified any sources of unacceptable risk.

Economics

One of the key requirements is for the per capita daily total cost to not exceed $0.07. We wanted a toilet design that is basic but durable, so the exterior toilet design is simplistic. Inside, as mentioned previously, is a urine-diverting toilet design which leads to the two different chambers of the toilet: electrochemical reactor and an incinerator/small electric furnace. We have used the current Incinolet toilet design as our basis to calculate the energy costs required and the cost for installing the incinerator. The solid waste bowl leads straight to the incinerator. Next, using the Caltech toilet as our inspiration for the electrochemical reactor, we researched the cost for installation. In the electrochemical reactor we have titanium dioxide as our anode and stainless steel as our cathode. The solar panel used for powering our toilet has the dimensions of 64.96 x 39.25 x 1.57 inch. We have two 300 W solar panels on top of the housing or the house. The following Table 3 shows the components required for the installation of the toilet, as well as their initial prices.

ROW	Components	Prices
1	Incinerator base [20]	$1800
2	Modification/Urine Diverting Bowl [21]	$70
3	Electrochemical Reactor [3]	$300
4	Solar Panels (300 W panel) [22]	$309 ea
5	Water container with filter [23]	$150
6	Housing [24]	$250
7	Surprise/Extra costs	$90
8	Urinal [25]	$35

Table 3: Cost of each major component

The cost of the replacements of the electrochemical reactor and the maintenance of the incinerator cost $125 per three years. There is an annual maintenance cost for the 3V batteries used in the reactor which cost $30 per year. The solar panels used have a 25 year warranty, so the panels will undergo maintenance or be replaced. With all the data acquired, we found that the initial cost for the entire toilet was approximately $3,500. We have the solid waste bowl covered with teflon which is also used on cooking pans. It needs to be changed every year and has a maintenance cost of $10. We also have an optional housing as shown in fig 6 which means that this toilet can be installed outside the house as well as inside. The cost of this optional housing is around $250.

Next to understand more of the economics of our toilet, we generated a Life Cycle Cost analysis (Table 4). We used the average electricity inflation rate of 2.7% in 2019 to calculate the electrical fees for the LCC and a maintenance rate of 2%. The LCC analysis was done for 50 years where the total worth of annual costs comes up to $12,243. The present worth of annual costs comes up to $8,559. After this, we calculated the cost per day per capita for this LCC and we get 7 cents per day per capita which satisfies our requirement.

discount rate - 2%								
Electric Rate - 2.7%								
Maintenance			2019 - 2069		2.0%			
(Begin) Year	First & Replace. Costs	Annual Maint. Costs	Annual Nat. Gas Costs	Annual Electric Costs	Total Annual Costs	Present Worth Factor	Present Worth of Annual Costs	Present Worth of Cumulative Costs
2,019	$3,500	$40	$0	$0	$40	(1+i)^-n		
2,019	$3,500	$40	--	$0	$3,500	1.00	$3,500	$3,500
2,020	0	41	0	0	41	0.98	40	3,540
2,021	0	42	0	0	42	0.96	40	3,580
2,022	133	42	0	0	175	0.94	165	3,745
2,023	0	43	0	0	43	0.92	40	3,785
2,024	83	44	0	0	127	0.91	115	3,900
2,025	141	45	0	0	186	0.89	165	4,065
2,026	0	46	0	0	46	0.87	40	4,105
2,027	0	47	0	0	47	0.85	40	4,145
2,028	149	48	0	0	197	0.84	165	4,310
2,029	91	49	0	0	140	0.82	115	4,425
2,030	0	50	0	0	50	0.80	40	4,465
2,031	159	51	0	0	209	0.79	165	4,630
2,032	0	52	0	0	52	0.77	40	4,670
2,033	0	53	0	0	53	0.76	40	4,710
2,034	269	54	0	0	323	0.74	240	4,950
2,035	0	55	0	0	55	0.73	40	4,990
2,036	0	56	0	0	56	0.71	40	5,030
2,037	179	57	0	0	236	0.70	165	5,195
2,038	0	58	0	0	58	0.69	40	5,235
2,039	111	59	0	0	171	0.67	115	5,350
2,040	189	61	0	0	250	0.66	165	5,515
2,041	0	62	0	0	62	0.65	40	5,555
2,042	0	63	0	0	63	0.63	40	5,595
2,043	201	64	0	0	265	0.62	165	5,760
2,044	630	66	0	0	696	0.61	424	6,184
2,045	0	67	0	0	67	0.60	40	6,224
2,046	213	68	0	0	282	0.59	165	6,389
2,047	0	70	0	0	70	0.57	40	6,429

2,048	0	71	0	0	71	0.56	40	6,469
2,049	362	72	0	0	435	0.55	240	6,709
2,050	0	74	0	0	74	0.54	40	6,749
2,051	0	75	0	0	75	0.53	40	6,789
2,052	240	77	0	0	317	0.52	165	6,954
2,053	0	78	0	0	78	0.51	40	6,994
2,054	150	80	0	0	230	0.50	115	7,109
2,055	255	82	0	0	337	0.49	165	7,274
2,056	0	83	0	0	83	0.48	40	7,314
2,057	0	85	0	0	85	0.47	40	7,354
2,058	271	87	0	0	357	0.46	165	7,519
2,059	166	88	0	0	254	0.45	115	7,634
2,060	0	90	0	0	90	0.44	40	7,674
2,061	287	92	0	0	379	0.44	165	7,839
2,062	0	94	0	0	94	0.43	40	7,879
2,063	0	96	0	0	96	0.42	40	7,919
2,064	488	98	0	0	585	0.41	240	8,159
2,065	0	99	0	0	99	0.40	40	8,199
2,066	0	101	0	0	101	0.39	40	8,239
2,067	323	103	0	0	427	0.39	165	8,404
2,068	0	106	0	0	106	0.38	40	8,444
2,069	202	108	0	0	310	0.37	115	8,559
	$8,792	$3,491	$0	$0	$12,243		**$8,559**	**=50-year LCC**
	1st+Repl	Maint	Fuel	Elec	Total Annual			

Table 4: Life Cycle Cost Analysis of Our Proposed Design

Conclusion

The main objective of this project was to design a toilet that operated on a single family level with minimal energy and cost. The toilet should be able to turn bodily waste into water, CO_2, and mineral ash; at a per capita daily total cost not to exceed \$0.07; in a safe, enduring, and environmentally satisfactory manner. The toilet must not require inputted water and an outputted sewerage connection, and must operate on a single-day time scale. It was desirable, but not necessary, for operation without any external utilities (i.e. grid power, natural gas pipeline), conversion of recovered water into drinkable water, and freedom from insects, odors, stains, or unhygienic surfaces.

Our toilet design has accomplished all of the above. Our proposed solution operates at \$0.07 per capita per day for an expected life cycle of 50 years. It uses an electric furnace to turn solid waste into mineral ash and an electrochemical reactor to turn urine into clean water. The toilet diverts the bodily waste into separate compartments located at the front and back ends of the toilet bowl. The liquid waste undergoes electrolysis to break down urea and eliminate bacteria, and then gets ran through a carbon filter. Solid waste will be collected in a bowl that rotates to a downward position when the toilet lid is closed, and rotates back to the upward position when the lid is open. In the downward position, the user is not using the toilet and is dumping the solid waste into the incinerator. In the upward position, while the user is actively defecating, the bowl forms a seal to block any odors from reaching the user and catches the excreted feces.The result is safe drinking water, and waste elimination where harmful and pungent fumes do not reach the user. The mineral ash resulting from the electric furnace will be converted daily, while the clean water resulting from the electrochemical reactor will be converted every 4 hours, so our solution meets single-day time scales. Our solution does not require any sewer connection. It does not require an external grid as it gets its power from solar panels and a car battery. Lastly, due to the nature of our rotating bowl design with a teflon coating, coupled with our housing for the toilet itself, we can say that our waste disposal system is well lit and free from insects, odors, and stains.

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Appendix

Calculation for solar panel power

We have 2 - 300 W solar panels attached on the housing or top of the house which cost about \$618. To power the incinerator we need about 1-2 kwh which is entirely powered by our solar panels. If we assume that it's sunny for at least 3 hours per day, the panels generate,

$$2 * (300 * 3) = 1800\ W$$

This is just the minimum power that can be generated through minimum solar exposure of 3 hours.

Calculation for 7 cents per day

To calculate the cost per day per capita we use the Life cycle cost analysis. After 50 years, the present worth of annual costs is \$8,559. So we use the present worth of 50 years reduce the initial cost from it and then divide the remaining cost by the number of years and days. This will give us the average cost for the toilet per day. Assuming having a 4 person family over the world, we further divide the cost per day by 4 to get cost per day per capita.

$$Annual\ Costs\ = Present\ Worth\ of\ annual\ costs\ -\ Initial\ costs$$

$$Annual\ Costs\ =\ \$8559 - \$3500$$

$$Annual\ Costs\ =\ \$5059$$

This is the total annual costs for the next 50 years. Next to get cost per day per capita,

$$Cost\ Per\ person\ per\ day\ =\ \frac{5059}{365*4} \approx \$0.07$$

So the cost per day per person is 7 cents which meets our requirements.

PUGH CHARTS

Table 5: Separate solid waste from liquid waste - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Incinerator evaporates urine	Separate Compartments/ toilets for solid and liquid waste	Liquid waste filters through soil tank and is collected at the bottom to the filtration system	Solid waste is allowed to settle, liquid waste remains on top	Centrifuge dries out waste and separates liquid waste out
Cycles Until Failure	DATUM	+	+	+	-
Volume of Waste Accepted		+	=	+	=
Volume of Structure		-	-	=	-
Energy Required		+	+	+	=
Time per Cycle		+	+	+	=
Initial Cost		+	+	+	=
Long-Term Cost		+	+	+	=
Ease Of Manufacturing		+	=	+	-
Ease of Use		-	=	=	=
Safety		+	+	+	=
Pluses		8	6	8	0
Minuses		2	1	0	3
Total		6	5	8	-3

Table 6: Separate solid waste from liquid waste - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Incinerator evaporates urine	Separate Compartments/ toilets for solid and liquid waste	Liquid waste filters through soil tank and is collected at the bottom to the filtration system	Solid waste is allowed to settle, liquid waste remains on top	Centrifuge dries out waste and separates liquid waste out
Cycles Until Failure	-	=	-	DATUM	-
Volume of Waste Accepted	-	+	-		-
Volume of Structure	=	-	-		-
Energy Required	-	=	=		-
Time per Cycle	-	+	+		-
Initial Cost	-	-	-		-
Long-Term Cost	-	=	-		-
Ease Of Manufacturing	-	-	-		-
Ease of Use	=	-	=		=
Safety	-	=	=		-
Pluses	0	2	1		0
Minuses	7	4	5		9
Total	-7	-2	-4		-9

Table 7: Turn solid waste into mineral ash - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Worms (turns solids into soil)	Anaerobic Digestion by bacteria	Parabolic mirrors heat up combustion chamber	Incineration via furnace, solids are dried and flattened beforehand	Hydrothermal carbonization
Cycles until failure	DATUM	+	-	+	-
Volume		-	-	-	-
Energy Required		=	-	-	-
Time per Cycle		-	+	+	+
Initial Cost		+	-	-	-
Long-Term Cost		+	+	+	+
Ease Of Manufacturing		-	-	-	-
Ease of Use		+	+	+	+
Corrosive resistance		+	+	+	+
Safety		=	-	-	-
Pluses		5	4	5	4
Minuses		3	6	5	6
Total		2	-2	0	-2

Table 8: Turn solid waste into mineral ash - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Incineration via furnace, solids are dried and flattened beforehand	Anaerobic Digestion by bacteria	Parabolic mirrors heat up combustion chamber	Worms (turns solids into soil)	Hydrothermal carbonization
Cycles until failure	DATUM	+	=	-	=
Volume		-	-	+	=
Energy Required		+	=	+	=
Time per Cycle		-	=	-	-
Initial Cost		+	-	+	=
Long-Term Cost		+	-	+	=
Ease Of Manufacturing		+	=	+	-
Ease of Use		-	=	-	=
Corrosive resistance		+	-	+	=
Safety		+	=	+	=
Pluses		7	0	7	0
Minuses		3	4	3	2
Total		4	-4	4	-2

Table 9: Turn urine into clean water - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Urine evaporates and condenses	Electrochemical reactor cleans urine	Urine filters through soil, gravel, and filtration system at bottom of tank	Membrane distillation through heated urine	Sand filter, UV-ray disinfection chamber for pathogens
Potable-Grade Water	=	=	-	DATUM	=
Energy Required	=	+	+		=
Time per Cycle	=	=	-		=
Initial Cost	=	+	+		+
Long-Term Cost	-	+	-		-
Ease Of Manufacturing	=	-	+		+
Maintenance	+	+	-		=
Automatic	=	=	=		-
Pluses	1	4	3		2
Minuses	1	1	4		2
Total	0	3	-1		0

Table 10: Turn urine into clean water - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Urine evaporates and condenses	Electrochemical reactor cleans urine	Urine filters through soil, gravel, and filtration system at bottom of tank	Membrane distillation through heated urine	Sand filter, UV-ray disinfection chamber for pathogens
Potable-Grade Water	=	=	=	=	DATUM
Energy Required	=	+	+	=	
Time per Cycle	=	=	-	=	
Initial Cost	=	=	+	-	
Long-Term Cost	-	=	-	+	
Ease Of Manufacturing	+	+	+	-	
Maintenance	=	+	-	=	
Automatic	-	+	+	=	
Pluses	1	4	4	2	
Minuses	2	0	3	2	
Total	-1	4	1	0	

Table 11: Transport waste to tank - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Gravity, tank is directly beneath toilet but access can be closed off to avoid smell	Urine passes through pipes, solid waste is in a rotating compartment that is scraped clean	Waste is mixed with bark as it is collected in a rotating chamber and then drops into main tank	Powered conveyor belt transports flattened solids	Assisted flush with potable water
Cycles until failure	DATUM	-	-	-	+
Volume Required		-	-	-	-
Energy Required		-	-	-	-
Smell		+	+	=	+
Hygiene		+	+	+	+
Maintenance/ Servicing Requirement		=	-	-	+
Initial Cost		-	-	-	-
Long-Term Cost		-	-	-	-
Ease Of Manufacturing		-	-	-	-
Pluses		2	2	1	3
Minuses		6	7	7	5
Total		-4	-5	-6	-2

Table 12: Transport waste to tank - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Urine passes through pipes, solid waste is in a rotating compartment that is scraped clean	Gravity, tank is directly beneath toilet but access can be closed off to avoid smell	Waste is mixed with bark as it is collected in a rotating chamber and then drops into main tank	Powered conveyor belt transports flattened solids	Assisted flush with potable water
Cycles until failure	DATUM	+	+	-	+
Volume Required		+	-	-	=
Energy Required		+	-	-	+
Smell		-	-	-	+
Hygiene		-	=	=	+
Maintenance/ Servicing Requirement		+	=	-	+
Initial Cost		+	-	-	=
Long-Term Cost		+	-	-	=
Ease Of Manufacturing		+	=	=	+
Pluses		7	1	0	6
Minuses		2	5	7	0
Total		5	-4	-7	6

Table 13: Power source - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Collected heat from solar radiation	Hydrogen from electrochemical reactor	Mechanical Power stored in batteries	Natural gas heats incineration chamber	Heat from hydrothermal carbonization, solar panels
Cycles until Failure	DATUM	=	-	=	=
Energy Produced		-	-	=	-
Efficiency		-	-	=	-
Initial Cost		=	+	=	-
Long-Term Cost		=	=	-	=
Ease Of Manufacturing		-	+	=	-
Ease of Use		+	+	+	+
Reliability		+	+	+	+
Amount of Storage of Energy		+	+	+	+
Pluses		3	5	3	3
Minuses		3	3	1	4
Total		0	2	2	-1

Table 14: Power source - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Collected heat from solar radiation	Hydrogen from electrochemical reactor	Mechanical Power stored in batteries	Natural gas heats incineration chamber	Heat from hydrothermal carbonization, solar panels
Cycles until Failure	=	=	-	DATUM	=
Energy Produced	=	-	-		-
Efficiency	=	-	-		-
Initial Cost	=	=	+		-
Long-Term Cost	+	+	+		+
Ease Of Manufacturing	=	-	+		-
Ease of Use	-	+	+		=
Reliability	-	=	=		=
Amount of Storage of Energy	-	-	=		-
Pluses	1	2	4		1
Minuses	3	4	3		5
Total	-2	-2	1		-4

Table 15: Collect mineral ash / water - Datum 1

	Subproblem Design Solutions				
Engineering Characteristics	Incinerator and water tank are manually emptied every few days	Water pumped to top, fertilizer collected beneath toilet	Soil can stay in tank without needing collection, some amount of soil can be collected for fertilization, water is pumped back into the water tank to assist pump	Toilet is periodically serviced by an outside party and ash is collected	Water is pumped to top, “coal” is collected beneath structure
Cycles Until Failure	DATUM	-	-	=	-
Volume of Water/Mineral Ash Accepted		=	=	=	=
Volume of Structure		+	=	=	+
Energy Required		-	-	=	-
Max time Until Collection		+	+	=	+
Initial Cost		-	-	=	-
Long-Term Cost		+	+	=	+
Ease Of Manufacturing		-	=	=	-
Ease of Collection		+	+	=	+
Pluses		4	3	0	4
Minuses		4	3	0	4
Total		0	0	0	0

Table 16: Collect mineral ash / water - Datum 2

	Subproblem Design Solutions				
Engineering Characteristics	Incinerator and water tank are manually emptied every few days	Water pumped to top, fertilizer collected beneath toilet	Soil can stay in tank without needing collection, some amount of soil can be collected for fertilization, water is pumped back into the water tank to assist pump	Toilet is periodically serviced by an outside party and ash is collected	Water is pumped to top, "coal" is collected beneath structure
Cycles Until Failure	+	DATUM	=	+	=
Volume of Water/Mineral Ash Accepted	=		=	=	=
Volume of Structure	-		-	-	=
Energy Required	+		=	+	=
Max time Until Collection	-		=	-	=
Initial Cost	+		=	+	=
Long-Term Cost	-		=	-	=
Ease Of Manufacturing	+		+	+	=
Ease of Collection	-		=	-	=
Pluses	4		1	4	0
Minuses	4		1	4	0
Total	0		0	0	0