Decentralized Toilet for Municipal Nitrogen Recovery

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17.4 – Decentralized Toilet for Municipal Nitrogen Recovery
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Final Design Report

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Executive Summary

The City of Golden, Colorado tasked Mines Senior Design Team 17.4 with designing a decentralized, urine-diverting toilet for potential future implementation in the Golden Community Garden. In addition to providing restroom facilities desired by garden users, this project would allow for the collection and pasteurization of urine for onsite use as an environmentally friendly fertilizer product. This project would also help the City to achieve sustainability goals relating to closing the nitrogen cycle in the area by 2030, reduce vehicle miles travelled associated with fertilizer transportation, and support locally grown food.

The team's solution to this challenge is a modified portable toilet unit that features a urine-diverting seat, solar-powered hydraulics and pasteurization, and 110 gallons of storage for treated urine with secondary containment. This design was selected through an iterative process utilizing research and stakeholder input alongside weighted decision matrices to make the most appropriate design selections that met needs defined by the client. In particular, this project was unique to existing urine-diverting toilet models because it required the use of decentralized power, could not be connected to running water, and could not utilize underground storage of wastes or stored urine. Although the proposed design is conceptual in nature, the team has developed a complete set of design drawings, 3D models, and a full bill of materials for potential future construction. Additionally, the team conducted literature reviews on a variety of topics related to urine diversion (such as nutrient fate and transport, pathogen removal, trace organics removal, and land application of biosolids) to validate anticipated performance of this system. The team also developed a monitoring plan for assessing pathogen removal and determining appropriate land application volumes and dilution factors with the goal of mitigating human health risks and the potential for nitrogen burn. Altogether, these materials will allow for the client to pursue a urine diversion pilot program in the Golden Community Garden if desired in the future based on further investigation of user interest, funding, and support for this program.

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1. Introduction

The overall goal of this project was to design a urine-diverting toilet for the City of Golden (the City) for potential future construction in the Golden Community Garden. Urine diverting toilets allow for urine to be separated from solid wastes at the source; this diverted urine can then be pasteurized and used as fertilizer. Users of the community garden have expressed interest in the implementation of restroom facilities at the site, so a urine-diverting decentralized toilet will not only fulfill the desires of the gardeners but will also provide them with an environmentally friendly fertilizer resource. This project will be a part of achieving the City's sustainability goals to make efforts towards closing the nitrogen cycle in the area by 2030. Additionally, the City hopes to reduce vehicle miles travelled (VMT) associated with fertilizer delivery and to support the production of local food with this project.

The proposed design is a modified portable toilet that features a urine-diverting seat, solar powered hydraulics and pasteurization, and 110 gallons of storage for treated urine with secondary containment. The selection of this design was guided by existing research and design components that have been found to be the most effective with certain optimizations based on site-specific constraints. Unique considerations for this project relative to existing designs are that the system had to be waterless (with the exception of water used for dilution), could only utilize decentralized power sources, and could not feature underground urine storage. The selection of project components was based upon a series of factors including financial viability, feasibility, durability, environmental sustainability, effectiveness, and user experience utilizing weighted decision matrices. The goal of this report is to provide an overview of the design process and methodology used for this project, justify the design selection through engineering analysis, and to both reflect upon progress made over the course of senior design and to provide the client with a suggested path forward in the case that they choose to pursue construction of a decentralized toilet in the Golden Community Garden in the future.

2. Project Review

2.1 Historical Review

In the preliminary phases of the project, the team was tasked with developing a design for eventual implementation of a urine-diversion pilot program in the Golden Community Garden. To accomplish this, the first semester was intended to be focused on design while the second semester would involve construction and onsite construction and pilot program implementation. The team focused on constraints and criteria defined and discussed with the client, shown in **Table 1** below.

Along with the diversion and treatment of the urine, the team had to work with specific site constraints such as proximity to drinking water supply ponds, a decentralized location, and user accessibility considerations. While initial discussions centered around a design that included underground storage for the urine and using conventionally powered mechanical systems, further discussions led to an understanding of the full scope of constraints and allowed the team to realize that these would not be feasible at the site. The project is therefore unique relative to existing applications because the urine is could not be transported to another location for treatment or storage and there were not onsite sewer or electrical connections. Complications associated with these constraints were further compounded by budget and regulatory restrictions to which the team designed in the first semester.

Table 1. Project Constraints and Criteria

Constraint / Criteria	Description
Physical Urine Diversion	Solid and urine wastes are diverted at the source and stored separately for reuse (urine) and disposal (solid wastes)
Waterless Design	The system will not be able to be connected to an existing water source; a waterless design is required
Decentralized Electricity	Onsite electrical connections will not be available, so use of decentralized power (such as solar) is required
No Underground Storage	Although many urine-diverting systems rely upon underground storage to allow for a gravity-fed diversion system, all design components must be installed at the ground surface for this site (necessitates the use of pumps)
Urine Storage Capacity	The capacity for urine storage should be able to accommodate the use of approximately 200 visitors per week during a 6-month period, although not all urine must be stored for treatment and reuse (should only store the amount of urine that could feasibly be used as fertilizer during a growing season to prevent the wasting of stored urine)
Storage Overflow Prevention	Stored urine may be harmful to both human and environmental health, so precautionary measures must be taken to ensure that overflow does not occur
Pathogen Reduction	Although there are not binding regulations relating to pathogen reduction for the reuse of human urine, WHO guidelines and recommendations should be utilized to guide treatment and application [1]
Device Footprint	The footprint of the system must fit within a region of the Golden Community Garden that is not occupied by existing gardening plots or other manmade infrastructure and should not reduce accessibility to plots, sheds, or other areas
Ease of Maintenance	The system should be able to be easily maintained; in particular, solid wastes should be able to easily be pumped out without the interference of pumping systems and other design elements
Ease of Use	The system should be able to be used by all people; avoid designs that are not accessible to some individuals or are difficult to use
Urine Precipitation Prevention	Measures should be taken to prevent conditions that encourage precipitation, which can clog pipes and pumps (minimum slope for pipes should be at least 5% and minimize joint usage to promote higher flow velocities; for flexible tubing, the Rich Earth Institute recommends a minimum tubing diameter of 3/8 inches) [2]
Use of Corrosion-Resistant Materials	All pumps, pipes, storage containers, and other design components should be corrosion-resistant to prevent material breakdown and related system failures associated with urine contact

For the preliminary design, the team explored a series of different design options related categorized by subsystems (urine diversion technologies, treatment, hydraulics, and storage). Weighted decision matrices were used to make decision decisions as described in **Section 3 – Application of Design Methodology** for the urine diversion, treatment, and hydraulics subsystems. Ultimately, a design was created that used both a urinal and a urine-diverting insert paired with a peristaltic pumping system and long-term storage for pathogen removal, as shown in **Table 2**.

Table 2. Initial Decision Matrices (Preliminary Design Review)

Solution	Financial Viability (2x)	Feasibility (1.5x)	Durability (1.5x)	Environmental Sustainability (1x)	Effectiveness (2x)	User Experience (1x)	Overall Score
				Urine Diversion			
Flush Toilet	2	0	0	3	4	-	18.5
Conveyor Belt	2	1	2	0	2	-	14.5
Urinal	**4**	**3**	**4**	**0**	**1**	**-**	**22**
Diverting Insert	**3**	**4**	**4**	**4**	**3**	**-**	**31.5**
				Treatment			
Slaked Lime	3	3	4	3	4	-	27.5
Vinegar	4	3	4	4	3	-	28.5
Long-term Storage	**5**	**4**	**5**	**4**	**3**	**-**	**33.5**
Pasteurization	1	3	4	3	5	-	25.5
				Hydraulics			
Manual Siphon	5	5	2	5	1	1	28.5
Diaphragm Pump	3	3	2	2	5	3	28.5
Peristaltic Pump	**2**	**3**	**4**	**4**	**4**	**5**	**31.5**

Upon engagement with clients and members of the City of Golden Sustainability Advisory Board, the team concluded that long term storage would not be the most appropriate design decision for treatment; this selection was not preferred from a human health standpoint but was the most feasible due to budget constraints. Ultimately, the team determined that prioritizing human health was more important than adhering to the budget defined at the beginning of the semester. Therefore, the project was shifted to a conceptual, research-based project to explore stakeholder concerns and develop a solution to urine treatment that would satisfy regulations and ensure safety for the gardeners and their plants. With budget no longer a concern, the decision matrix used for selecting urine treatment methods was reevaluated with different weighting for each category. Financial viability was no longer as much of a concern, and the effectiveness of the solution was moved to higher importance. **Table 3** below highlights this shift and demonstrates why the team chose to move forward with pasteurization paired with long-term storage rather than long-term storage alone.

Table 3. Adjusted Treatment Methods Decision Matrix

Solution	Financial Viability (0.5x)	Feasibility (1x)	Durability (1.5x)	Environmental Sustainability (1x)	Effectiveness (3x)	Overall Score
Slaked Lime	3	3	4	3	4	25.5
Vinegar	4	3	4	4	3	24.0
Long-term Storage	4	4	5	4	3	26.5
Pasteurization	**1**	**3**	**4**	**3**	**5**	**27.5**

In the second semester, the team completed thorough research to justify a final design that used pasteurization as a urine treatment method along with a urine diverting seat and urinal as described in **Section 4 – Engineering Analysis**. Justification was provided both in terms of concept validation through literature reviews and calculations related to spatial aspects and function of the proposed design. Several other risk mitigation developments were also added based on client feedback including the implementation of secondary containment into the final design and a detailed monitoring plan (for pathogens and nitrogen). The team also further developed 3D and 2D models for both educational use as well as to guide future construction if pursued in the future. Lastly, the team began efforts to gauge community interest in this project to aid the client in determining if pursuing a urine diversion pilot program is a worthwhile investment.

2.2 Dead-Ends and Challenges

The primary challenge faced by the team over the course of this project was budget; the high cost of components required to construct and maintain a urine-diverting toilet was higher than expected, causing the team to have to make sacrifices in terms of selected design components. While pasteurization is the only World Health Organization approved method for eliminating pathogens in diverted urine, the team was forced to rely upon long-term storage in the initial design selection due to the high costs associated with pasteurizers. Ultimately, however, the team concluded that mitigation of human health risks is more important than meeting budget restrictions; if the City wishes to further pursue this program, it is crucial to assess if the cost of the proposed design is feasible, as the risks associated with a low-cost alternative may make pursuing a pilot program prohibitive. While cost is an important factor, safety should be prioritized over all else since this project involves the land application of human waste.

Another challenge recognized by the team was lack of regulatory restrictions and permitting for urine diversion applications. Because urine diversion technologies are not often applied within the United States, the team found that regulatory requirements to guide design were not available and that best judgements had to be made to determine how to promote mitigation of both human and environmental health risks. If the client pursues construction of a pilot program, it would be important for engineers to assess the proposed monitoring plan and design to identify any additional risks that may be presented by the use of urine diversion onsite.

Lastly, another major dead end faced by the team was that to build a pilot unit, the client must purchase a portable toilet unit. Communications with portable toilet rental companies led to the conclusion that any and all modifications to rental units are prohibited and can lead to fines and prevention of future rentals. Alternatively, the client could pursue constructing a standalone unit rather than a retrofitted portable toilet, although this would eliminate desired flexibility to move the unit within the site as needed.

3. Applications of Design Methodology

The first step used to address the problem was preliminary research, which was then used to dictate scoring in weighted decision matrices. Initially, the design was broken down into four subsystems (urine diversion methods, hydraulics, treatment of diverted urine, and storage) to facilitate better organization of research topics as described in **Section 2 – Project Review**. Objectives and constraints defined by the client were then used to assign categories and weighting criteria by which to assess different design options to determine the most appropriate solutions. Design options for each subsystem were primarily driven by those currently utilized in urine diversion applications for sale to consumers, applications from peer-reviewed scientific literature, and from direct guidance by experts in the field of urine diversion (the Rich Earth Institute).

After selections based on weighted decision matrices, the team further evaluated the appropriateness of the design using the Universal Design Scorecard. When proposing the design problem, the client indicated that the potential application of this design within the Golden Community Garden necessitated that it should be accessible to as many individuals as possible. The goal of the Universal Design Scorecard is to evaluate if a design is accessible to all people, regardless of age, disability, or other factors. Evaluation using this tool highlighted areas of the initial design that were easily accessible (such as utilizing motorized rather than manual pumping and electing to modify an ADA-accessible portable toilet unit). It also made more clear areas for improvement of the design that were implemented in later iterations, such as ensuring that pumping mechanisms were located outside of the unit to minimize prevention of user mobility or potential exposure to components that could be harmful if used incorrectly.

In addition to the Universal Design Scorecard, the team also utilized the Environmental Hazard Analysis tool outlined by the Environmental Protection Agency (EPA). The primary goal of incorporating this tool into the design process was to mitigate risk, both to potential users and to ecological receptors. The primary outcome from this analysis was a better understanding of potential project risks, which were then categorized based on those associated with construction, device use, pasteurization, and application. The team then made efforts to reduce risk by putting backup processes into place wherever possible to mitigate risk. Additionally, this analysis indicated the necessity to pursue human health risk mitigation further by developing a monitoring plan that helped to track the performance of the design (particularly related to pathogen presence) before land applying any diverted human wastes. The Environmental Hazard Analysis tool also highlighted the importance of community outreach to prevent user error; as a result, the team developed educational tools to show the gardeners how the design works. If the client decides to pursue a pilot program, however, it is recommended that further instructional guidance is provided.

Lastly, the team utilized a series of technical engineering analysis tools to validate the selected design. Foremost, the spatial characteristics of the design were verified by developing 2D and 3D SolidWorks renderings of the design; these renderings verified that components would fit together as intended since a physical prototype was not developed. Building the design in 3D also allowed for the development of a bill of materials; a bill of materials will allow the client to pursue construction in the future if desired and ensured that the design stayed within budget. The team then further developed the hydraulics system in a series of AutoCAD drawings and performed calculations based on spatial and material/component details to verify that head provided by the pumping system would be sufficient for conveying urine from the system inlet to exit (mitigating risk of pooling and ensuring high enough velocities to prevent urine precipitation). Hydraulics analysis was accompanied by calculations justifying that the selected solar power system would be sufficient for powering all pumps and pasteurizers incorporated into the system. Site analysis to determine the most appropriate sites for the potential design was also conducted using Autodesk Civil3D and ArcGIS Pro. These tools allowed the team to assess risk related to runoff potential in the event of potential leaks, determine slopes and soil types, and ensure that the selected site location would not result in interference with existing garden operations. In addition to engineering software and tools, the team also performed a series of literature reviews to analyze anticipated nutrient fate and transport, land application and dilution requirements, pathogen removal, and trace organics removal because physical testing could not be conducted (due to lack of a physical prototype).

4. Engineering Analysis

The primary goal of this system is to utilize diverted urine as a fertilizer resource. The effectiveness of urine as fertilizer is primarily dictated by nitrogen availability, as certain nitrogen compounds are more likely to volatilize upon application or may result in undesirable odors that deter users from the device. A literature review was conducted to understand the fate of nitrogen in stored urine and anticipated forms that could be expected if this system were to be implemented in the future. Anticipated nitrogen forms from this analysis were then used to calculate dilution factors and land application volumes that would be required for gardeners to best utilize diverted urine resources for crop production.

In addition to efficacy as fertilizer, another critical consideration for land applying urine is necessity to mitigate potential risks associated with land applying human waste. The primary concern with regards to land application is human health; although a solar pasteurizer is used in the design, a literature review on pathogen removal was conducted to verify that treatment is sufficient for land application. Additionally, a monitoring plan that could be used in the future to validate system performance before land-applying collected urine from this system was also developed. A literature review on treatment of and land application of trace organics was also conducted to alleviate concerns regarding the presence of pharmaceuticals in diverted urine. Lastly, further analysis of regulatory requirements was conducted to ensure that containment of stored urine is sufficient to mitigate risks associated with leaks or other system failures. Analysis of water flow paths onsite indicated that runoff from leaks could flow to drinking water resources, necessitating the use of secondary containment for all urine storage vessels included in the design. As a result, a secondary containment device that meets regulatory requirements is described and justified in this section.

Lastly, this section details technical considerations that are required for ensuring that the system operates properly. Foremost, an analysis of the selected hydraulics system was conducted to ensure that the selected pumps can provide the required driving head to accommodate for minor losses throughout the system. Additionally, calculations were conducted to ensure that solar is a sufficient solution for providing decentralized power to both the pumps and pasteurizer. All calculations indicate that selected parts are appropriate and will perform as intended if the design is to be implemented in the future. All literature reviews and calculations provided in the subsections below have been reviewed and approved by program-approved technical advisors.

4.1 Nitrogen Conversion Literature Review

As fresh urine is stored at ambient conditions, urea (CH_4N_2O) hydrolyzes into ammonia (NH_3) and ammonium (NH_4^+) as shown in **Equation 1**, although the distribution of molecules depends on pH. The rate at which this natural process occurs depends on several factors such as temperature, natural presence of the urease enzyme, and health [3]. Therefore, without the ability to monitor urine treatment with the chosen pasteurizer, the best way to understand potential performance is through an evaluation of existing literature on nitrogen conversion in stored urine.

$$CH_4N_2O + 2H_2O \xrightarrow{Urease} NH_4^+ + NH_3 + HCO_3^- \quad (1)$$

The hydrolysis process happens relatively quickly after urination, with ammonia levels steadily increasing at a similar rate of the urea concentration decreasing, as shown in laboratory testing conducted by Ray et al. in **Figure 1**, with solid squares representing real urine, and open squares representing synthetic urine. While these representations only show the hydrolysis of urine until 240 minutes, this process continues past the time frame presented. However, while understanding nitrogen breakdown is important, nitrogen can be applied as a fertilizer and will be beneficial for plant life in most forms (urea, ammonia, ammonium). When nitrogen is present as urea, plants can absorb nitrogen faster than in other forms; however, both forms are still effective as fertilizers, especially on small scales [1].

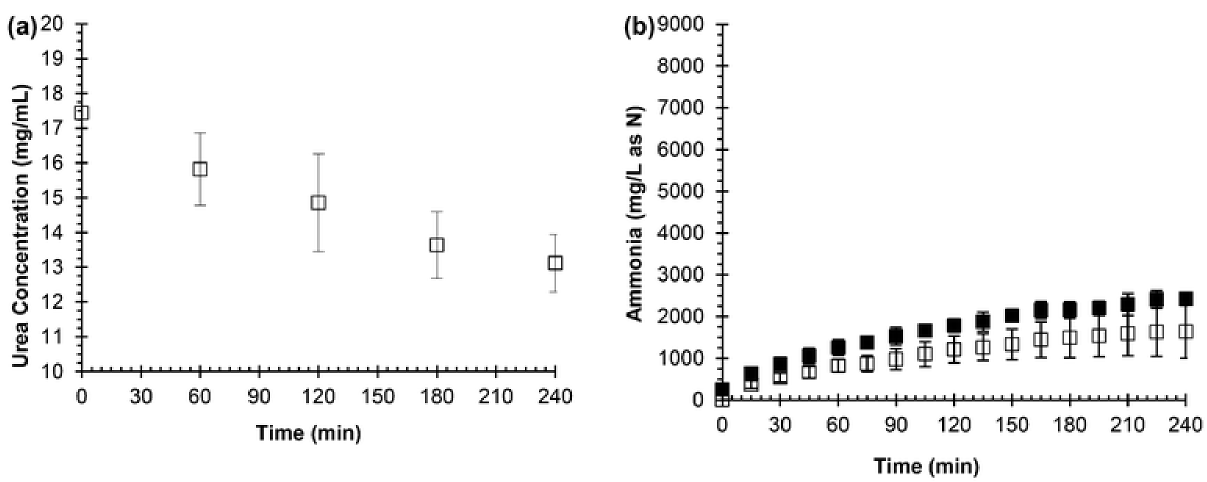


Figure 1. Urea and ammonia concentrations in urine over time [3]

Pasteurization, the process of heating urine to 60-80°C for 1.2-30 minutes, is the main method of treatment used in the design as it is the only method approved by the EPA for adequate pathogen reduction in urine [1]. Pasteurization partially prevents hydrolysis by inactivating urease, which acts as a catalyst to hydrolyzation. Therefore, it is assumed that the urine will be partially hydrolyzed by the end of pasteurization, and all nitrogen recovered would be both in the form of urea and ammonia.

To minimize nitrogen loss, a continuous flow pasteurizer would be preferred over a batch pasteurizer. While it varies from person to person, literature suggests that fresh urine can contain 5500-9000 mg/L as N. One study comparing nutrient and pathogen presence in fresh, stored, and pasteurized urine found that after pasteurization (80°C for 30 min), urine contained 4600-4800 mg/L as N [4]. Other studies have found that pasteurization of urine at 72°C for 15 seconds resulted in an average of 3,955 mg/L as N. For this project, calculations were done on the assumption that there is 5 g N per liter of urine to avoid any possibility of over-fertilization or nitrogen burn. However, more precise dilution factors could be calculated based on experimentally determined nitrogen concentrations measured as a part of the suggested monitoring plan, presented in **Appendix A – Pilot System Monitoring Plan**. It should also be noted that increasing the temperature of urine to above 65°C significantly prevents hydrolysis and stabilizes the nitrogen in the urea form if this is desired [5]

4.2 Dilution of Diverted Urine, Uptake by Plants, and Land Application Considerations

Assuming the nitrogen present in the diluted urine upon application is in the form of ammonia, ammonium, and urea, nitrogen loss once the urine encounters the soil surface is possible. Research suggests that 5-25% loss of ammonia upon application can be expected, particularly if nitrogen is in the form of urea, as shown in **Figure 2**. To minimize nitrogen loss upon application, a dilution factor of at least 1:3 is recommended but diverted urine can be diluted up to 1:10. Any further dilution is not recommended to avoid any excess nitrogen not taken up by plants seeping into the groundwater. However, this issue is not of large concern, as groundwater levels in the Golden area typically lie between 500-1,300 feet underground [6]. This information, accompanied by the fact that the garden beds are elevated, as well as specific application recommendations allows for confidence that groundwater contamination will not be an issue. When nitrogen-containing compounds are placed on top of soil, the interaction with air causes them to volatize and evaporate. If diluted with a heavy amount of water, the compounds will seep below the soil surface, theoretically leading to an increase in plant uptake. Another way to increase plant uptake of nitrogen and minimize loss is to till soil after application or apply a below ground irrigation system [7].

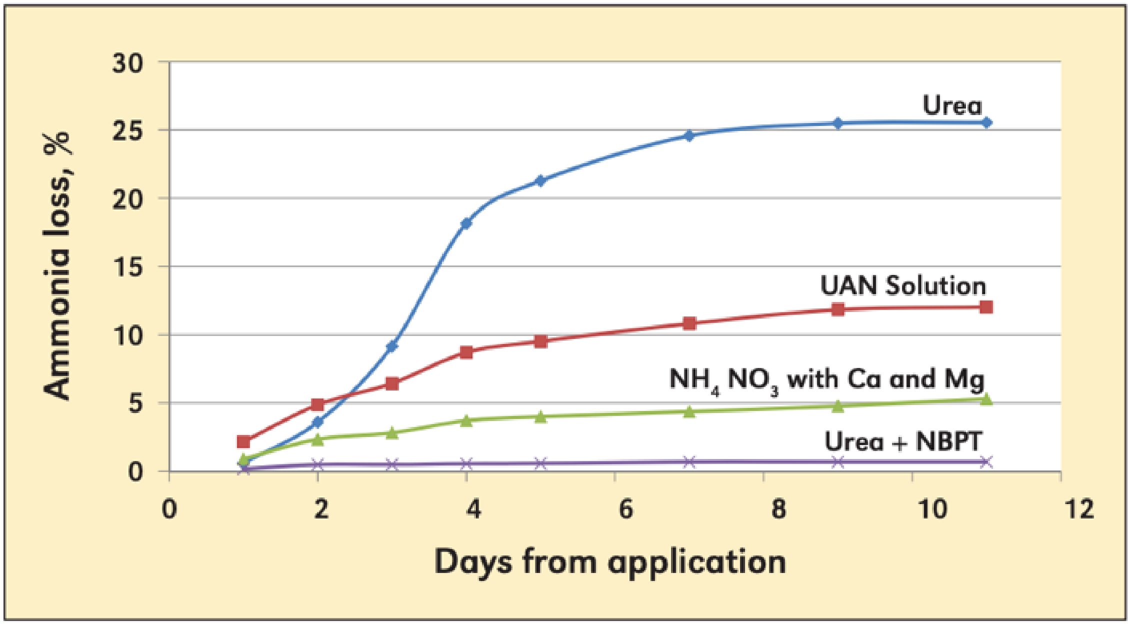


Figure 2. Volatilization from surface-applied fertilizer [7]

A test conducted in 2014 applied urine stored at 20°C for >30 days to hay subplots at a rate of 1000 gallons/acre. Results found that diluting urine with an equal volume of water was nearly as beneficial to hay yield as a synthetic fertilizer and was more effective than applying un-diluted urine, as shown in **Figure 3**. Therefore, diluted, pasteurized urine collected from this system may achieve similar results, decreasing the demand for synthetic fertilizers at the community garden.

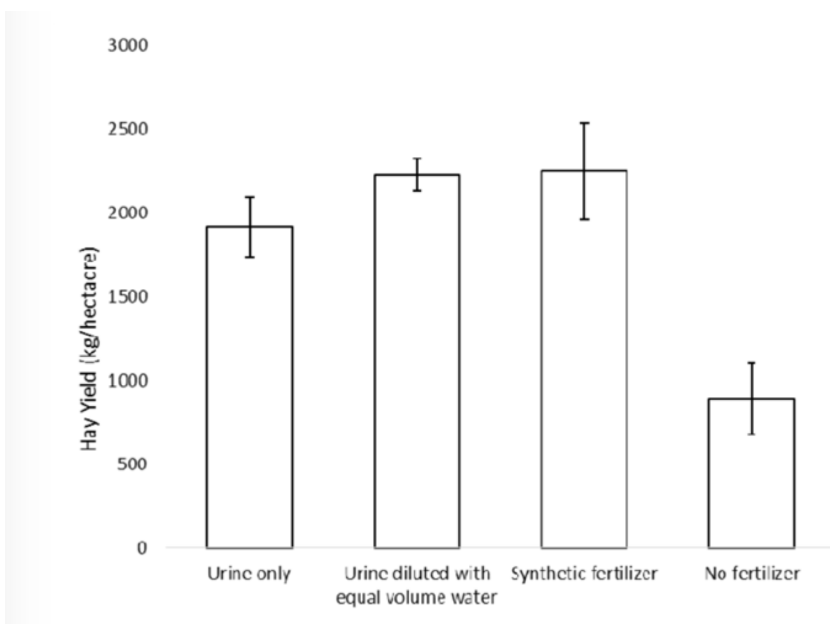


Figure 3. Effect of urine and synthetic fertilizer application on hay yield

The Golden Community Garden covers one acre of land, with gardening plots accounting for one half of the garden space. These plots are generally 10 ft x 10 ft. Using the lowest concentration estimate of 3 g N/L urine to calculate the maximum urine requirement for a 6-month operational period, the anticipated volume of undiluted required each year would be approximately 3,300 L (870 gallons). While the existing pilot design only accommodates for the storage of 110 gallons of storage per season to minimize cost and footprint, more storage drums could be added to reach this treatment volume if the initial pilot program were to be successful.

Calculations were performed for both a low range N concentration (3g N/L) and a high estimate (5 g N/L). Assuming that each 10 ft. x 10 ft. plot of garden is fertilized on a weekly basis, it is recommended that a dose of 0.174 - 0.291 L undiluted urine be applied to each plot. However, calculations utilizing actual nitrogen concentrations (obtained as described in **Appendix A – Pilot System Monitoring Plan**) and plot sizes could be used to provide a more precise volume if this system were to be implemented in the future. **Equation 2** provides a simplified calculation based on calculations further described in **Appendix B – Land Application Calculations**.

$$\frac{(8.77 \cdot 10^{-3}\ L - N/week) \cdot (Plot\ Area\ (ft^2))}{(Nitrogen\ Concentration\ \left(\frac{g}{L}\right))} = \boldsymbol{Application\ Volume}\ \left(\frac{\boldsymbol{L\ urine}}{\boldsymbol{plot - week}}\right) \quad (2)$$

Previous research using treated urine as fertilizer used 1000 gallons of urine per acre of hay field over the course of one growing season [8]. This dose translates to 8.69 L urine per plot (**Appendix B**). This large number comes from the fact that hay is typically fertilized once per season. Extrapolating the weekly dosage recommendations to a one-time, yearly application would result in the recommendation of using 9 - 15 L/urine per plot annually; this dosage is reasonably within range of that of the research-based dose, validating the recommended dose for this system.

4.3 Pathogen Reduction Literature Review

As previously mentioned, pasteurization is the only EPA approved method of pathogen reduction in urine [1] Bacterial presence in fresh urine varies widely based on human health and which organisms are analyzed. One study analyzed three scenarios of fresh urine and found between 2.4 E4 – 1.4 E6 CFU/L (colony forming units per liter) of fecal coliforms, and 0 – 2.0 E4 CFU/L of *E. coli*. That study showed that *E. coli* reached undetectable levels in 3 days at both 60°C and 70°C, and fecal coliform concentration saw a 3-log removal rate at both temperatures within the first day of storage [5].

Collected urine will likely be contaminated with fecal matter. Therefore, it is valuable to ensure that pasteurization will be adequate to remove fecal matter as well. Studies have found that in urine diverting efforts, urine is typically contaminated with anywhere between 1.6-18.5 mg/L of feces [9, 10]. Another study using pasteurization on biosolids found that no organism (*Ascaris, Toxocara, Trichuris, Taenia*) survived in fecal matter after either heating for 20 minutes 70°C or for 5 minutes at 90°C [11].

While pasteurization at 80°C for 1.2 minutes will result in adequate pathogen removal, long term storage (20°C for ~6 months) is also a method of treatment that is World Health Organization (WHO) approved to adequately remove pathogens [2]. As a fail-safe measure to prevent microbial regrowth, as well as ensure safety, it is recommended that any urine not used as fertilizer immediately after pasteurization be properly sealed and kept between 5- 20°C for as long as possible, until used as fertilizer. Long term storage is a form of urine treatment that requires the least amount of maintenance and energy input, and varying storage time lengths and temperatures are considered effective for treatment. Suggested treatment temperatures and times and their corresponding recommendations for use on crops are outlined in **Table 4**. Storing urine at 20°C for 6 months or greater yields the greatest amount of pathogen reduction and ensures that stored urine can be used as fertilizer on all crops. Long term storage does not prevent the hydrolysis of urea, however, which means that the available form of nitrogen for fertilization would be primarily ammonium and ammonia. Methods for monitoring pathogen reduction during the pilot program are proposed in **Appendix A – Pilot System Monitoring Plan**.

Table 4. Pathogen reduction and crop usage for varying long-term storage conditions [2]

Storage Temperature [°C]	Storage Time [months]	Possible Pathogens in the Urine Mixture	Recommended Crops
4	≥ 1	Viruses, Protozoa	Food and fodder crops that are to be processed
4	≥ 6	Viruses	Food crops that are to be processed, fodder crops
20	≥ 1	Viruses	Food crops that are to be processed, fodder crops
20	≥ 6	Likely None	All crops

4.4 Trace Organics Literature Review

A minor concern of recycling pasteurized urine as fertilizer for a garden is the issue of trace organics, specifically pharmaceutical presence and the potential effects of these constituents on plant life and human health. One study assessed analyzed impact of four commonly used pharmaceuticals (amoxicillin, sulfamethoxazole, trimethoprim, and ibuprofen) on the growth of radishes using two spiked water sources [12] This study found that despite the water source being spiked with two different concentrations of the pharmaceutical compounds (PhCs), no pharmaceuticals were found in the soils. However, the lack of measurable pharmaceutical presence could be due to natural degradation or leaching. Despite lack of pharmaceutical presence in the soil, sulfamethoxazole and amoxicillin were both found in the shoots and roots of the radish plants. Pants watered with the spiked water saw a greater loss of leaves, and a higher death rate than those treated with non-spiked water [12].

While this study is useful to determine the effects of pharmaceuticals on plants, the concentrations used for the analysis were 1mg/L and 5 mg/L, which are orders of magnitude higher than concentrations commonly found in wastewater. For example, one study analyzing pharmaceutical presence in septic effluent (Skaneateles Lake, New York) found that all seven pharmaceuticals studied ranged from 0-37,000 ng/L [13] However in the same area, the presence in lake water only ranged from 0-78.0 ng/L [13].

Other studies evaluated were conducted to determine plant uptake of PhCs. One study found that the highest absorption was present in leaf and stem vegetables, such as lettuce, celery, and cabbage [14] That study used treated wastewater, with lower PhC concentrations, as well as "fortified" water, spiked with higher concentrations of pharmaceuticals that more closely mimic the concentrations found in raw sewage. Extrapolations from the data found from crops irrigated with fortified (higher PhC concentration) water were used to estimate exposure to pharmaceuticals from consumption of those crops. Annual per capita exposure to drugs in µg per year are summarized in **Table 5** below. Typical single doses of each pharmaceutical have been added to the table for context.

Table 5. Annual per capita exposure to drugs in µg per capita per year [14]

	Carrot	Celery	Lettuce	Cabbage	Spinach	Cucumber	Bell Pepper	Tomato	Typical Dose
Caffeine	1.16	0.09	-*	-	-	-	-	-	200,000
Meprobamate	-	-	-	0.01	0.001	-	-	-	1,400,000
Primidone	-	0.12	0.25	0.07	-	-	-	-	500,000
Carbamazepine	0.14	0.05	0.19	0.07	0.002	0.04	0.07	0.08	400,000
Dilantin	0.19	0.05	0.09	-	0.01	-	-	-	600,000
Naproxen	-	-	-	0.10	-	-	0.07	-	700,000
Triclosan	0.84	-	-	-	-	-	-	-	NA
Total	2.33	0.31	0.53	0.25	0.01	0.04	0.14	0.08	

"-" Indicates below detection limit value

One commonality among these studies is that they all found soil to act as a filter that encourages biological degradation of PhCs [12, 13, 14]. Pharmaceutical presence in plants is highly dependent on the PhCs' individual chemical properties and half-lives, which makes anticipating concentrations in specific scenarios difficult. Results of the literature review also indicate that antibiotic medications not only have the highest rate of transmission to soil and plants, but also have some of the worst effects on plant life. Thus, clear communication asking those who are currently taking any kind of antibiotic to not use the portable toilet is recommended. While it is impossible to prevent all antibiotic presence from reaching the garden due to the potential for misuse, communicative risk mitigation efforts will decrease the need for possible concern.

4.5 Flow Path Analysis and Secondary Containment

Although the conceptually based design does not require a finalized decision regarding the location of the device, flow path analysis was performed to assess the potential implications of leaks based on siting. Assessment of two possible sites for the unit found that the site that was most optimal in terms of accessibility and maintenance poses the most risk with regards to runoff to drinking water holding ponds. Therefore, the need for secondary containment to mitigate environmental and human health risk justified the inclusion of secondary containment for all drums used to store diverted urine.

4.5.1 Flow Path Analysis (Civil3D)

The Golden Community Garden is formally located at 1506 8th St, Golden, CO 80401. To the north of the garden site is a hotel and apartment building, and to the east is the City of Golden Planning Department as well as Golden Traffic Engineering buildings. To the south of the garden are two holding ponds that the City of Golden uses as a drinking water source, which must be taken into consideration when approaching the storage of human waste. Only foot traffic is allowed inside the property, and ease of access for a sanitary waste disposal truck will be factored into a decision on final location. Additionally, the City of Golden anticipates around 200 users per week. Within the Golden Community Garden site are two proposed locations for the final toilet design. These locations are labeled as A and B on aerial imagery of the site (**Figure 4**).

Figure 4. Site map with potential locations

The nature of a portable toilet structure allows it to be mobile if needed. However, slopes, convenience, sun availability, and other factors must be considered when deciding upon the optimal implementation location. Water droplet analysis was conducted using Civil3D and topography data obtained from the Denver Council of Regional Governments (DRCOG). The water droplet analysis uses topography data to determine where liquid would flow if it were introduced at a particular location. This method was used at both locations A and B to determine where any potential leakage would end up if overflow measures were not taken. Aerial imagery and flowpaths from Civil3D are provided in **Appendix C – Flow Path Analysis**.

Location A provides a flat, suitable surface. The soil here is sandy silt with small amounts of coarse aggregate, with solid soil surface underneath the layer of soil (indicating low levels of permeability). Plant life lines the fence on the north and south side of Location A, and bee habitat is located around 70 feet south of the proposed site. If the toilet was placed at location A, any overflowing liquid would flow onto the gravel path and then to the west. However, this location is not as accessible to a waste removal truck, raising concerns about ease of maintenance at this location.

The second proposed location, B, is located towards the entrance of the garden. The spot that the toilet would rest on is a flat surface, however the biggest issue with this location is the slope of the driveway leading to the south. Any seepage or spillage would cause nitrogen-rich urine to flow directly into the water holding ponds at the drinking water treatment plant. The soil here is comprised of sandy silt with significant amounts of coarse aggregate like the material used on the gravel pathway. This location would have a higher level of convenience than Location A for visitors entering the garden and is much more accessible for pumping trucks due to its proximity to the parking lot and road. Location B is also more secluded, which is desired by the client to prevent overuse or damage from visitors not affiliated with the garden.

In terms of client desires (maintenance, accessibility, seclusion), Location B is preferable. However, much more risk is associated with this site in terms of runoff; this concern can be mitigated, however, by including secondary containment to prevent leakages (as described in **Section 4.5.2**, below). Input from gardeners should still be taken into consideration before a final site decision is made, however, as these stakeholders may hold other location preferences if a pilot program is implemented.

4.5.2 Secondary Containment for Diverted Urine

Secondary containment is required for tanks used to store diverted urine. The project site is located upgradient of surface water ponds used for storing the City's drinking water, making containment a critical aspect of risk mitigation for this project to prevent contamination. Per EPA 40 CFR 264.175 - Containment of Containers Containing a Free Liquid [15], a containment system must be designed and operated as follows:

1. The containment unit must underlie the containers and must be free of cracks or gaps and be sufficiently impervious to contain leaks spills, and accumulated precipitation.
2. The base of the containment unit must be sloped or designed to drain and remove liquids resulting from leaks, spills, or precipitation unless the containers are elevated or otherwise protected from contact with accumulated liquids.
3. The containment system must have sufficient capacity to contain 10% of the volume of containers or the volume of the largest container, whichever is greater.

The selected addition to the design to achieve these goals is to include a polyethylene containment vessel that prevents loss of stored urine into the environment in the case that either of the two 55-gallon HDPE drums used for storage fails. It is important to include storage for both containers, as it is possible for either the drum actively being used to collect urine or the drum storing urine from earlier in the season to fail. In the Preliminary Design Report, it was suggested that storage containment could be achieved using a concrete containment basin, which was estimated at $1,100. However, a more cost-effective option that also meets EPA 40 CFR 264.175 guidelines (which have been confirmed for this device but may not be met by a concrete basin) is to purchase a 2-drum polyethylene containment tank. This addition has been incorporated into the SolidWorks model of the system, as shown in **Appendix D - System Overview Design Drawings**.

The suggested containment tank features double wall construction for dual containment; if the inner wall is compromised, the outer wall will prevent loss of chemical. The walls are made of rotationally molded polyethylene with UV stabilizers, which prevent cracking and degradation when the device is exposed to sunlight. It is designed to contain corrosive chemicals with a specific gravity of 1.7 or lower; the specific gravity of urine is 1.005 to 1.03 [16]. Lastly, this device allows the tanks to be nested together to improve ease of transport and storage and can be moved by forklift. The price of this unit is $300, which is only 27% of the estimated price of pouring a concrete pad for containment [17].

4.6 Hydraulics Calculations (Head Losses and Pumping Requirements)

Validation of the chosen peristaltic pump used to convey urine in the system was provided by determining theoretical head losses to be expected in the urine conveyance tubing between the urine diverting insert and the inlet at the top of the diverted urine storage tank. These head losses were then integrated into the Bernoulli equation to verify that the head provided by the pump was sufficient for conveying urine to the storage tank.

The determined flow path for urine was determined based on the dimensions of components used for the overall system. The primary assumption for the estimated conveyance path was that, where possible, HDPE tubing curves were estimated to have a radius of 25 times the nominal pipe diameter (6.25" radius for 0.25" ID tubing) as suggested by the manufacturer [18]. Otherwise, curve radii were used to develop 90-degree bends as needed based on system dimensions. CAD drawings describing the flow path and fittings used for analysis are provided in **Appendix E – Hydraulics and Electrical Drawings**.

Minor head losses were calculated as both head losses in fittings and/or bends and as frictional losses in HDPE tubing. For losses in fittings and bends, head losses were calculated using **Equation 3**, where K is the loss coefficient, v is fluid velocity (ft/s), and g is gravity (ft/s^2). Frictional losses were calculated using the Hazen-Williams equation as defined in **Equation 4**, where C is the Hazen-Williams coefficient, RH is hydraulic radius (ft), and S is slope (ft/ft). Loss coefficients for both scenarios were obtained from literature and are referenced in the calculation of cumulative head loss through the system in **Appendix F – Hydraulics Calculations**. Lastly, the flow rate used throughout calculations was defined as 1260 mL/min, which will ensure that the minimum required velocity for limiting precipitation (1.64 ft/s) is met in all tubing [19]. This flow rate can be accommodated by the chosen pump, which can be operated at up to 1500 mL/min [20],

$$h_L = K\frac{v^2}{2g} \tag{3}$$

$$h_L = 1.318CR_H^{0.63}S^{0.54} \tag{4}$$

The Bernoulli equation, **Equation 5**, was used to describe the relationship between kinetic energy and gravitational potential energy of urine travelling through the HDPE conveyance tubing (variables defined in **Appendix F**). The goal of utilizing this equation was to determine how much head would need to be provided by the pump for conveyed urine to reach the outlet at the storage tank. Pressure was negated for this calculation because both the inlet and exit occur at atmospheric pressure. Required pump head was not calculated prior to the pasteurizer because although the solar pasteurizer unit features a pump, the driving head from elevation change alone is sufficient to overcome minor losses in the longest run to the pasteurizer (from the urinal). The driving head for this section is 1.3 feet and minor losses in head are approximately 0.41 feet (**Appendix F**). It can be assumed that the pumping mechanism within the solar pasteurizer is sufficient for conveying liquid through the device.

$$z_1 + \frac{v_1^2}{2g} + h_{pump} - h_L = z_2 + \frac{v_2^2}{2g} \tag{5}$$

Overall, the required pump head for this application is 0.447 feet, which is much less than the head that is available using the chosen peristaltic pump. Therefore, the pump selected for the application will be suitable for conveying urine from the solar pasteurization system to storage. The difference between these values also indicates that even if assumptions regarding exact configurations of the tubing path are not entirely correct, the designed hydraulics system will be sufficient for its intended purpose. The user interface for the pumping system will be a switch contained within the portable toilet that must be activated to turn on the pumps and reactivated to turn them off after the flush is complete; this design could be modified to be more automatic by incorporating microcomputers if the design is pursued for construction.

4.7 Electrical and Power Calculations

4.7.1 Pumping Systems

The selected pump for transporting urine from the solar pasteurizer to the storage tank is a 12 volt (DC) peristaltic pump with a power requirement of 21 Watts. The required runtime for one "flush" of the system is 0.3175 minutes based on a urine flowrate of 1260 mL/min and anticipated urination volume of 400 mL (**Appendix G – Electrical Calculations**). The system will be flushed using a switch that turns the system on/off, which does not require power draw.

The anticipated usage of the toilet when implemented at the garden is 200 uses per week. This indicates that the required power draw per day, assuming that usage is uniform across the week, is 0.13 watt-hours/day (**Appendix G**). The maximum solar output that can be anticipated from a 100 watt in Colorado is 440 watt-hours/day [21], indicating that the draw from the pumping systems will be far less than the potential power provided by the solar panels. Additionally, the inclusion of a battery in the solar power system ensures that power could be provided to the pumps even on cloudier days with minimal sun.

4.7.2 Solar Pasteurization

The power requirement for the solar pasteurizer (including the inlet pump contained in the unit) provided by the Rich Earth Institute is 13 watt-hours/L [2]. The anticipated weekly volume of collected diverted urine is 80 L/week, resulting in a power draw of 149 watt-hours/day (**Appendix G**). The daily power draw from this system is only 30% of the daily power provided by a 100-watt solar panel on a clear day, which is 440 watt-hours/day [19]. Therefore, the solar power system in place will be sufficient to provide power to the pasteurizer. The inclusion of a battery will also ensure that power can be provided to the pasteurizer even on cloudier days with minimal sun.

4.8 Outstanding Testing/Analysis and Path Forward

Due to limitations associated with the conceptual nature of this project, a number of anticipated testing and analysis tasks were not conducted by the end of the project timeline. While a literature review on pharmaceutical presence in wastewater and the impacts of these chemicals on crops was conducted previously, further analysis may be necessary to determine if specific pharmaceuticals are present in the urine of those using the proposed toilet system that may be problematic if land applied. The pharmaceutical literature review conducted focused on several medications, as well as general over the counter drugs such as acetaminophen, ibuprofen, and caffeine. Pinpointing if any other pharmaceuticals are present and of concern for the Golden Community Garden would be an important step to success of the system if implemented.

Additionally, to mitigate potential human health effects associated with land-applying human waste to crops, it is also crucial to monitor diverted urine for pathogens upon the implementation of the system. Raw water should also be monitored to understand pathogens present in dilution water since this resource is provided directly from Clear Creek. The team also recommends that nitrogen concentrations are monitored to allow for more precise determination of appropriate dilution factors to prevent nitrogen burn and other adverse effects on plants. Although the performance of the system is most critical to monitor during the first season of operation, the team also recommends that monitoring occurs during each growing season to mitigate risk. The suggested monitoring plan is provided in **Appendix A – Pilot System Monitoring Plan.**

The primary path forward for the client should be to determine if a urine diversion pilot program is worthwhile to pursue in the Golden community garden based on community interest and proposed costs. Foremost, because this project was primarily conducted while the garden was not operational (semester did not include summer months), further community outreach is encouraged to gain further insight to public opinion and interest beyond what was collected by the team at the end of the spring semester. Additionally, the only components of the system that have been purchased by the team include the Urine Diverting Toilet Insert, and one peristaltic pump. All other components, including the storage tanks, secondary containment basins, pump housing, tubing, pasteurizer, solar panels, and the portable toilet itself, have not been purchased. Thus, a vital next step for the City of Golden would be to purchase these parts and perform visual inspection to ensure compatibility between all components if a pilot program is pursued. In particular, it should be noted that the pasteurizer used in the design was a custom design created by the Rich Earth Institute that is not mass-produced; therefore, communicating with this organization regarding availability of this component should be the first step when ordering parts for construction.

5. Final Deliverables

Technical drawings and electrical schematics detailing the final design can be found in **Appendix D – System Overview Design Drawings** and **Appendix E – Hydraulics and Electrical Drawings**. In addition to 2D drawings developed in SolidWorks and AutoCAD, 3D models representing the design have also been developed in SolidWorks and are included as a part of the package delivered with this document. This project did not require the construction of prototypes; therefore, this potential course deliverable is not provided. However, a Bill of Materials and Anticipated Project Budget is provided in **Appendix H – Bill of Materials and Project Budget** to provide an understanding of costs that can be anticipated if the client chooses to pursue developing this system in the future. The budget was divided into two subsections: initial costs associated with construction as well as annual costs associated with maintenance and testing. Additionally, a monitoring plan has been developed to assess performance before land-applying diverted, pasteurized urine to crops within the garden (**Appendix A – Pilot System Monitoring Plan**).

In addition to the development of a technical design for this project, the client also requested that the team begin the process of introducing this project to members of the community garden. A simple brochure for presenting the idea of a urine-diverting toilet was created and a virtual survey was delivered to the gardeners to assess their current fertilization practices and their thoughts/opinions regarding urine diversion. Although this should just be a starting point for community engagement, this effort allowed for an understanding of existing perceptions and desires for a urine-diverting pilot program that should be helpful to the client for determining if it is worthwhile to further pursue this project.

Lastly, in addition to presenting the team's work at the Mines Senior Design Showcase, the team also presented all work completed at the Golden City Council meeting, as requested by the client. The goal of attending this meeting was to provide City Council members with a better understanding of this project since the last City Council meeting attended by the group (at the end of the first semester). This knowledge can be used to guide the City regarding if this is a project that they would like to continue to pursue in the future.

6. Project Management

6.1 Work Breakdown Structure, Project Schedule, and Budget

The finalized work breakdown schedule for the project is provided in **Appendix I – Work Breakdown Structure**. This document was used to structure the project in a manageable way by dividing it into five subsections. It should be noted that various communicative documents were also produced over the course of the entire project to keep the client informed on the team's progress, including preliminary/intermediate/final design reports and associated presentations as well as biweekly communicative meetings. The schedule used to keep the team on track over the course of this project is provided in **Appendix J – Project Schedule**.

The beginning of the project was primarily focused upon research related to mechanisms used to divert urine, hydraulics systems, storage methods, and systems for treating diverted urine for pathogens. The team then developed a preliminary design package including preliminary design drawings and 3D models, electrical and hydraulic calculations, and a strategy for solids removal. The initial design was proposed in December 2021 alongside the final version of the Preliminary Design Report.

During the second semester of the project, the project was moved to a conceptual design rather than a project requiring a working pilot prototype. This allowed the team to further investigate and validate the system through an assessment of a variety of topics including nutrient transformation, land application, and the removal of both pathogens and trace organics. As detailed in **Section 2 – Project Review**, the switch to a conceptual project allowed the team budget flexibility to pursue other design options that had previously been inaccessible; in particular, the client wanted the team to pursue the implementation of pasteurization into the design. The incorporation of pasteurization required a complete restructuring of the electrical and hydraulics systems, but alleviated concerns regarding human health risk associated with land applying human waste.

The final steps of this project were associated with stakeholder engagement efforts. Because the client has not decided on whether this project will be constructed in the future, efforts were focused upon gaining an understanding of current fertilization practices in the garden, gardener perceptions and concerns about urine diversion, and educating interested parties on the fundamentals of urine diversion. A survey was sent out to the gardeners and a handout was developed to inform them of urine diversion principles as well.

6.2 Path Forward

This report provides a complete set of design drawings, a corresponding bill of materials, and other documentation to guide construction if the client chooses to further pursue this project. However, the primary task of the client moving forward is to determine if it is appropriate to proceed with the implementation of construction and a pilot program. This decision should be guided not only by budget and cost considerations (both initial construction costs and annual maintenance/testing costs have been outlined in this report), but also upon availability of individuals to maintain and support this pilot program. It would also be valuable for the client to further engage with stakeholders, both garden members and members of the surrounding community, to confirm willingness to engage with and utilize the fertilizer products created by this device.

Before making any purchases, the team also suggests confirming the availability of solar pasteurization equipment produced by the Rich Earth Institute. While this organization is a national leader in urine diversion technologies, their products are not manufactured on a large scale. Therefore, it is critical to confirm the availability of this equipment before purchasing parts required to construct a full-scale design. Additionally, if the client chooses to move forward with construction, the team suggests further testing and monitoring before land applying wastes as outlined in **Section 4.8 - Outstanding Testing/Analysis and Path Forward**.

6.3 Cost Analysis

The final anticipated cost for constructing this design is $9,500 (**Appendix H - Bill of Materials and Project Budget**). Additionally, the anticipated costs for maintenance (solid waste removal and cleaning) and routine monitoring of both nitrogen and fecal coliforms is just under $3,000 annually. The original anticipated budget provided at the beginning of the project was $10,000; therefore, the final anticipated cost aligns with initial estimates. Of the expenses associated with construction, the cost of a portable toilet was the component with the highest cost relative to what was anticipated. Initially, the client suggested renting a portable toilet; however, modifications required to convert the toilet to a urine-diverting unit were found to be disallowed by rental vendors. Therefore, purchasing a portable toilet was pursued; however, the breakeven time associated with purchasing the unit was only 3.6 years (or 4 seasons). This indicates that although this cost was higher than was expected, if the pilot program is carried out long-term, the client will actually save money relative to renting.

Maintenance and testing costs, on the other hand, were much higher than was originally anticipated. The initial budget provided was defined for the cost of construction; however, the necessity to service the toilet (weekly removal of solid waste and cleaning) and test diverted, treated urine to mitigate risks was not considered. The annual cost of the toilet was calculated to be approximately one-third of the construction cost due to the high cost of maintenance and testing kits (for total nitrogen and fecal coliforms). It is also important to consider that costs could be even higher if any components of the system break or wear out over the course of the pilot project. Higher costs may also be incurred if the client must rely on third-party laboratories for testing defined in the monitoring plan. Therefore, the biggest concern that the client must consider with regards to pursuing this project further is the annual costs, which will be higher than initial construction assuming a 4-year or longer project lifetime.

7. Lessons Learned

The largest takeaway from Senior Design was developing the skills needed to work as a team to create a foolproof design that tied together the wishes of the client with advice from technical advisors. The team learned how to define a "good" design by assessing design options based on financial viability, feasibility, durability, environmental sustainability, effectiveness, and user experience. The team also used how to use project management tools to effectively delegate tasks for a long-term project among team members with differing skillsets. The team also learned from mistakes – in retrospect, it would have been beneficial for the team to have researched and discussed regulations with the client prior to any design decisions. Selecting design decisions that were appropriate but not feasible based on site-specific constraints was one of the largest setbacks for the team early in the project. Other roadblocks encountered along the way were those concerning wastewater and EPA approved methods of pathogen reduction.

In early stages of the design process, the team focused on a design that prioritized a low budget to meet the client's needs. Once the scope of the project transitioned to conceptually based, it allowed the team to prioritize safety. In particular, the team implemented several fail-safe measures to ensure ease of use and maintenance that previously would not have been permitted by the initial budget. Due to original priorities, the team's initial design did not involve an EPA approved method of pathogen removal. It would have been beneficial to have made this decision earlier in the project timeline to better incorporate the pasteurizer into later drawings and calculations. The initial budget also did not account for the cost of ongoing monitoring of *E.coli* and nitrogen levels, but further analysis proved that this would be an essential step to minimize the potential of plant harm; the current budget now reflects this plan. The help of technical advisors was extremely helpful in the design process, as having outside eyes look on progress often brought to light concerns or changes that could be implemented that the team had not previously considered. For example, groundwater contamination is something that had not been considered prior to a technical advisor mentioning this concern. Additionally, the idea to provide a monitoring plan for the city was a useful piece of information that secured the feasibility of the project and was proposed by city engineers during the second half of the project.

Overall, the team learned that outlining regulations and safety concerns should be the very first step of any design consideration and doing such would have better made use of the time in the project. However, the team has continued to work together efficiently, acknowledging the importance of weekly standup meetings to stay on track. Progress reporting was consistently communicated throughout the team to maintain deadlines and keep everyone involved in every step of the process. Utilizing each team member's individual skills determined the success of this project, with several external programs requiring use that not each member had knowledge of.

Appendix A – Pilot System Monitoring Plan

Nitrogen

As elaborated further in the Nitrogen Conversion Literature Review section, exact nitrogen concentrations present in urine can vary widely; additionally, nitrogen is most often present in multiple forms. For this reason, it is recommended to monitor nitrogen using the Nitrogen (Total) TNTplus Vial Test from HACH® (TNT 832). This test can identify ranges of nitrogen between 1-16 mg/L [22], which is ideal for the ranges of nitrogen concentrations that can be anticipated to be present based on a review of relevant literature. This specific test can be conducted in a singular vial and does not require a reagent blank, which minimizes costs and contamination risks.

Purchasing 25 tests costs $108.25, which will be sufficient for weekly testing of stored, pasteurized urine over a 6-month period. If nitrogen concentrations are found to be variable on a weekly basis, more frequent sampling may be warranted to allow for the most accurate calculation of dilution factors as presented in **Section 4.2**. A necessary component of this test is a compatible HACH® Spectrophotometer (DR3900, DR6000, DR1900, DR2800, DR3800, DR5000). It is assumed that the City of Golden already possesses a compatible spectrophotometer for other water quality monitoring purposes, however if one needs to be purchased, they can range from $4,600 - $6,200 through HACH® [22].

Fecal Coliforms

In addition to weekly total nitrogen monitoring, weekly Fecal Indicator Bacteria (FIB) testing is recommended. Testing should be performed using the Colilert system on the raw irrigation water that is used on site, as well as for the pasteurized urine. Colilert simultaneously detects both total coliforms and *E. coli* in water samples, providing results in just 18 hours [23]. Testing both raw water and stored, pasteurized urine separately will inform the City if there ever is a concern of *E. coli* presence and the potential source of contamination.

While running water is generally the cleanest natural water source, animal or human feces can still contaminate rivers, necessitating testing of raw water diverted from Clear Creek that will be used for dilution. Most importantly, however, this test will help to detect fecal contamination resulting from failure or misuse of the urine-diverting insert that is not properly mitigated by the solar pasteurization system. Conducting Colilert tests of water from both sources on a weekly basis will provide reassurance to the community gardeners that using pasteurized diverted urine as fertilizer is safe and reliable. If weekly sampling of pasteurized urine results in conclusions that fecal indicator bacteria are present in pasteurized urine, more frequent sampling may be warranted; however, if this outcome occurs, it is not recommended to land-apply stored urine until this problem is mitigated.

Colilert is commonly used among municipalities, as the method is EPA approved for drinking water, wastewater, and source waters [23]. Given the assumption that the City of Golden already possesses the device used to analyze *E.coli* concentrations, the only cost associated with this test is the purchase of single-use Colilert trays, as shown in **Appendix H**.

Appendix B – Land Application Calculations

Yearly Estimated Application Volume (Full-Scale):

$$\frac{1\ L\ urine}{3\ g\ N} * \frac{1\ g\ N}{.00220462\ lb\ N} * \frac{2\ lb\ N}{1000\ ft^2 * year} * \frac{43560\ ft^2}{1\ acre} * \frac{0.5\ acre}{1} * \frac{0.5\ year}{1} = \mathbf{3300\ L\frac{urine}{year}}$$

Low Range Nitrogen Concentration Weekly Land Application Volume:

$$\frac{2\ lb\ N}{1000\ ft^2 - year} * \frac{453.59\ g\ N}{lb\ N} * \frac{1\ year}{52\ weeks} * \frac{1\ L\ urine}{5\ g\ N} * \frac{100\ ft^2}{plot} * \frac{.5\ year}{1} = \mathbf{0.174\ \frac{L\ urine}{Plot - week}}$$

High Range Nitrogen Concentration Weekly Land Application Volume:

$$\frac{2\ lb\ N}{1000\ ft^2 - year} * \frac{453.59\ g\ N}{lb\ N} * \frac{1\ year}{52\ weeks} * \frac{1\ L\ urine}{3\ g\ N} * \frac{100\ ft^2}{plot} * \frac{0.5\ year}{1} = \mathbf{0.291\ \frac{L\ urine}{plot - week}}$$

Generalized Land Application Equation (simplified from above calculation):

$$\frac{(8.77 \cdot 10^{-3}) \cdot (Plot\ Area\ (ft^2))}{(Nitrogen\ Concentration\ \left(\frac{g}{L}\right))} = \mathbf{Application\ Volume}\ \left(\mathbf{\frac{L\ urine}{plot - week}}\right)$$

Literature Review Suggested Urine Dose per Plot:

$$\frac{1000\ gal\ urine}{acre} * \frac{3.785\ L}{1\ gal\ urine} * \frac{1\ acre}{43560\ ft^2} * \frac{100\ ft^2}{plot} = \mathbf{8.69\ L\ urine/plot}$$

Appendix C – Flow Path Analysis

Figure C1. Location A Detailed Aerial Imagery and Water Drop Analysis

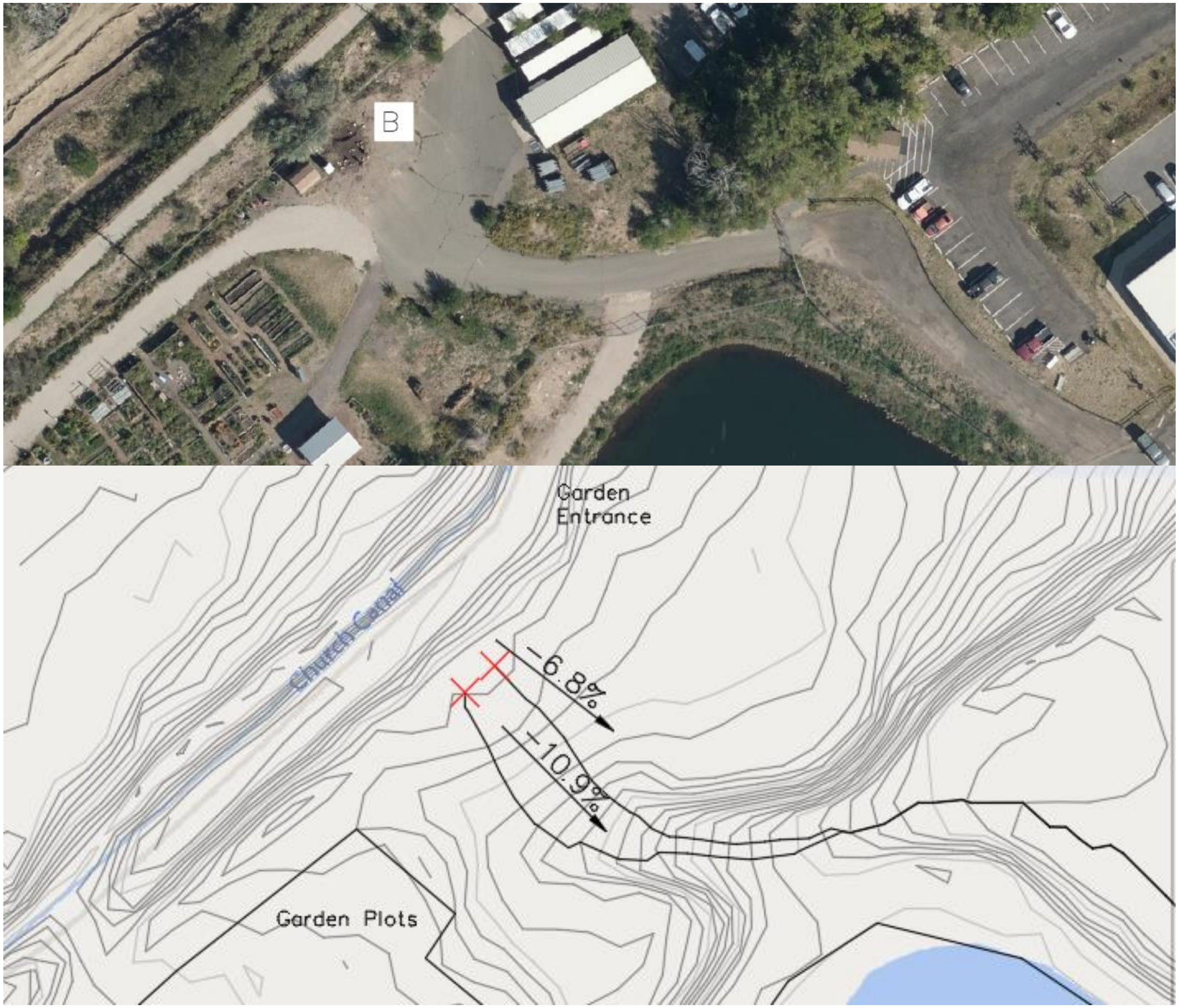


Figure C2. Location B Detailed Aerial Imagery and Water Drop Analysis

Appendix D – System Overview Design Drawings

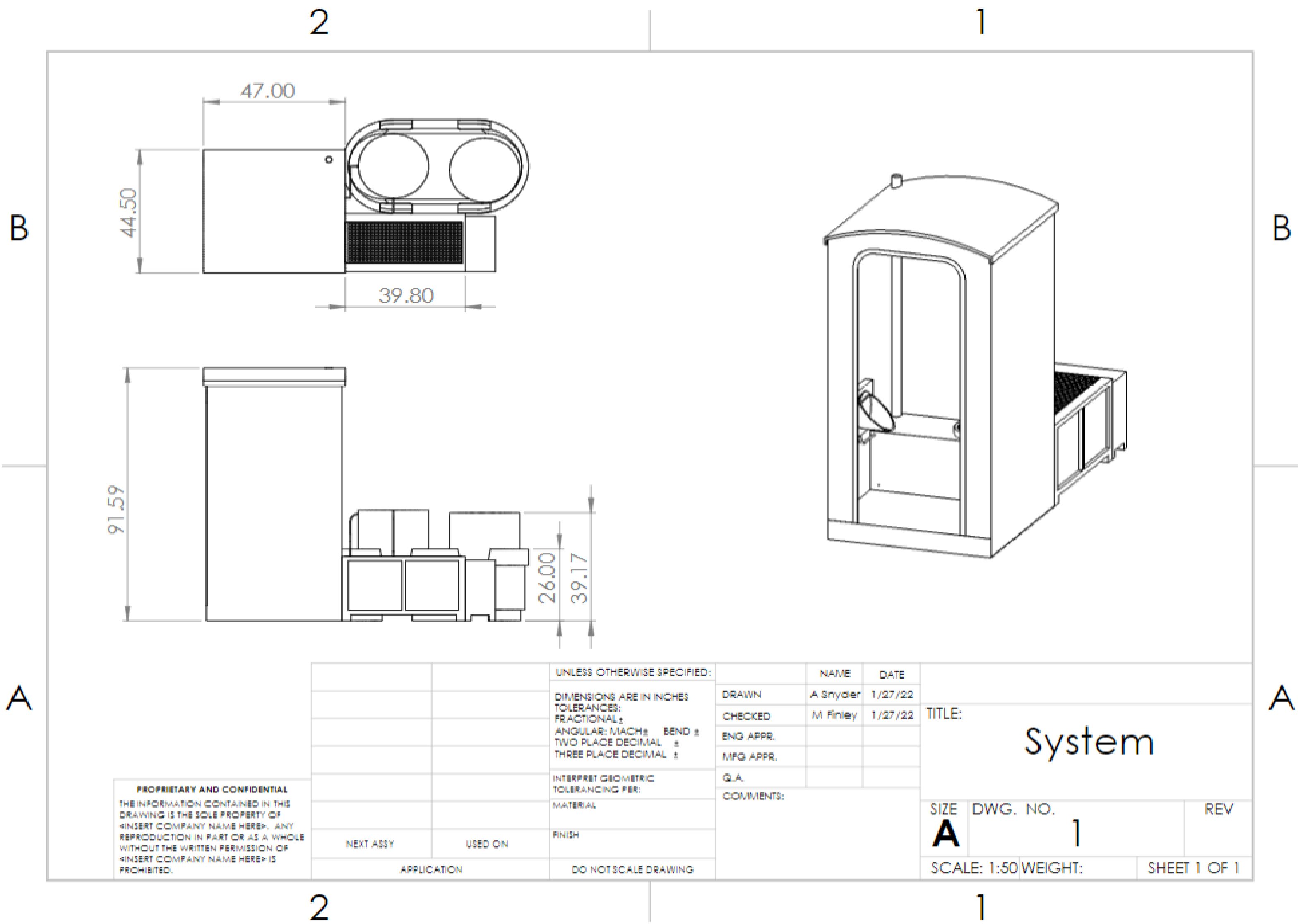
SolidWorks drawings were drafted to showcase the details of the subsystems that comprise the overall design. A summary of these subsystems is provided below, along with the corresponding drawing numbers.

Drawing 1 – Overall Design: Provides multiple perspectives of the overall system.

Drawing 2– Pump System: Peristaltic pump and battery used to pump diverted urine into storage barrels. A charge controller is also included in this system to divert charge to the battery for storage.

Drawing 3– Urine Diverting Insert: A screened insert that will collect the liquid waste and convey it to HDPE tubing for transport to storage.

Drawing 4 – Reducer: A reducer will be used to connect the urine diverting seat insert to the HDPE tubing used for conveyance to storage.


2
1
B
A
47.00
44.50
39.80
91.59
26.00
39.17
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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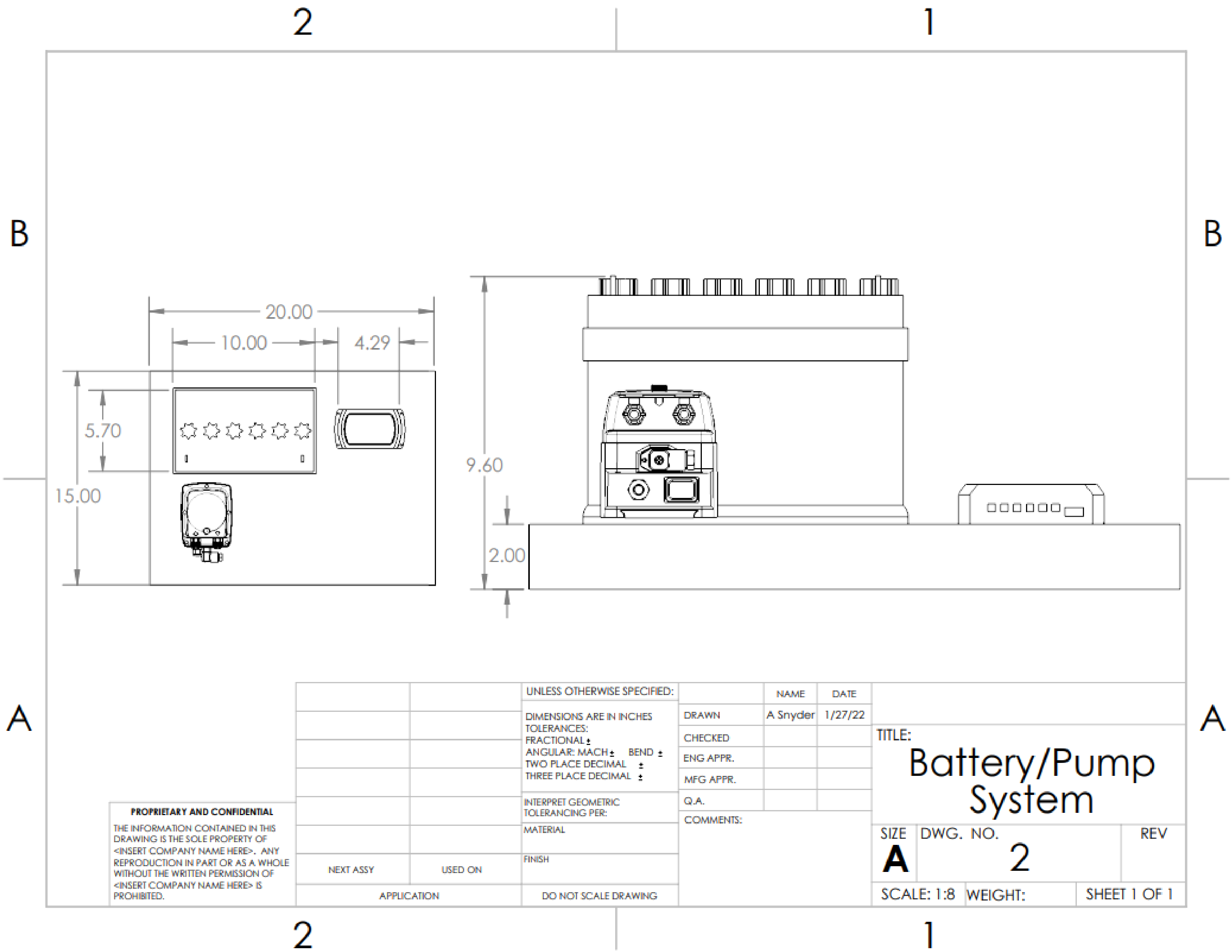
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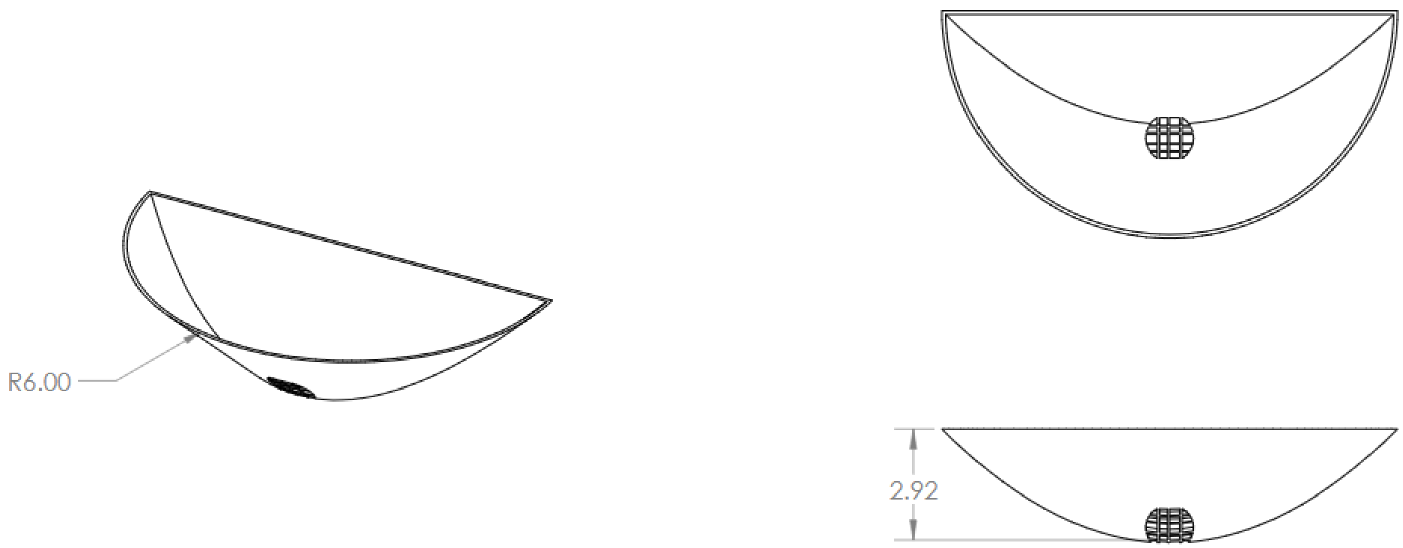

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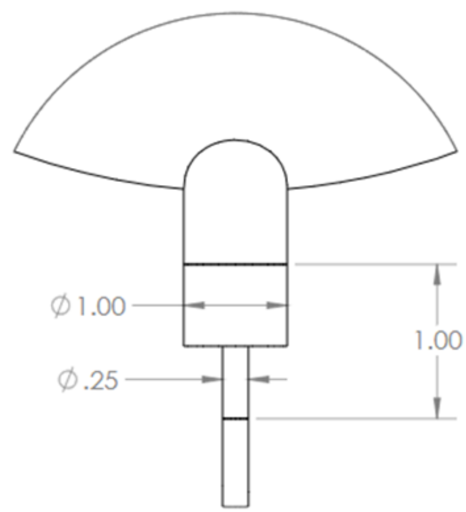

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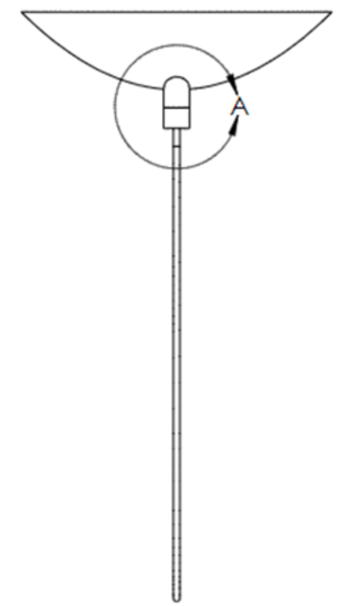

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Appendix E – Hydraulics and Electrical Drawings

CAD drawings provided for the hydraulics subsystem detail the flow path of urine through HDPE tubing to the storage tank from both the urine diverting insert and the urinal. These drawings were used to calculate required pump head and losses as communicated in **Section 4.6 - Hydraulics**. A summary of provided drawings is detailed below.

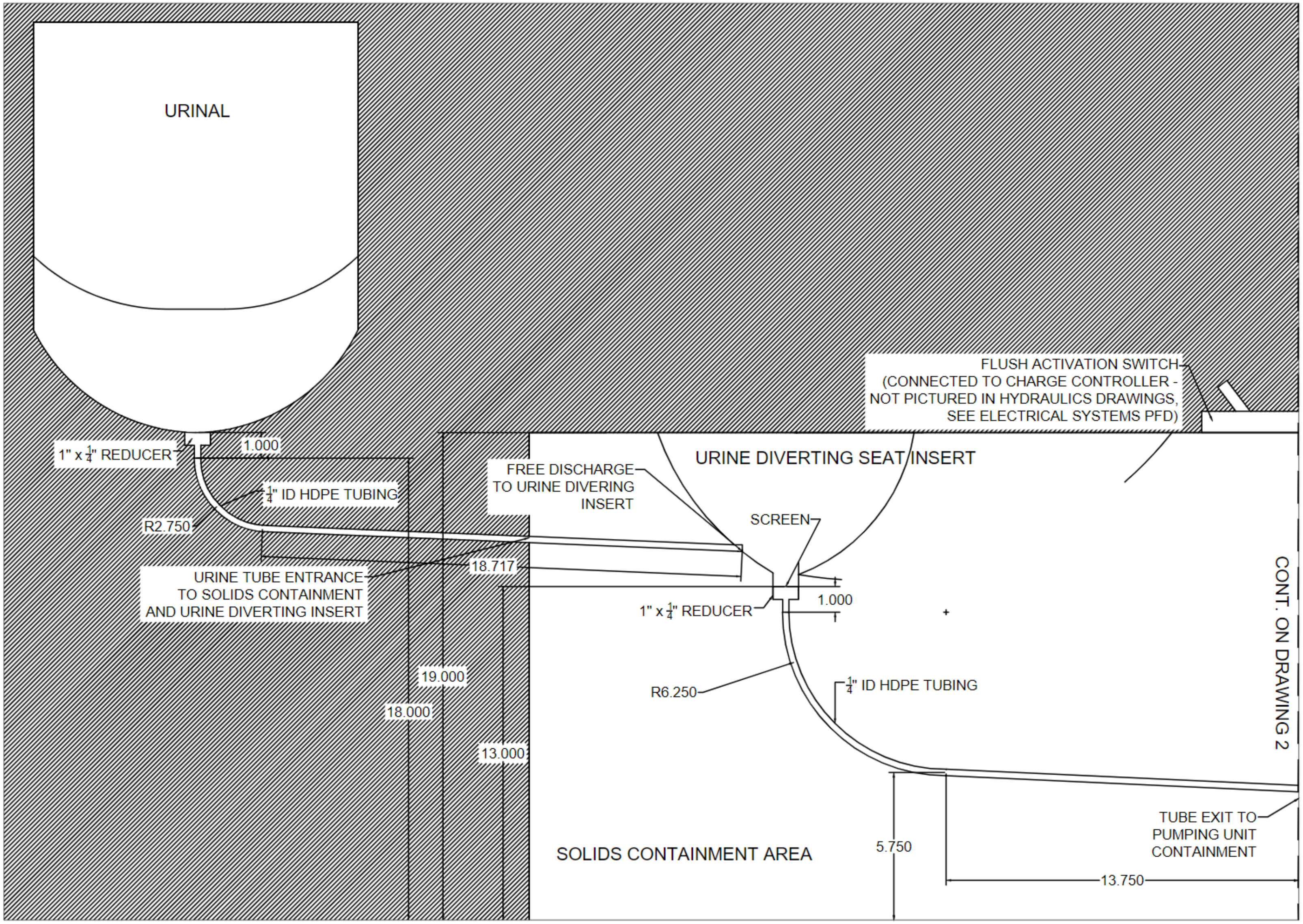
Drawing 1 – System Inlets and Solids Containment: Describes the flow path of urine from the screen in the urine diverting seat insert to the conveyance exit at the back of the portable toilet unit. This drawing also describes the flow path of urine from the urinal to the urine-diverting insert, which is gravity-fed.

Drawing 2 – Pump Containment Area: Describes the flow path of urine from the conveyance exit at the back of the portable toilet unit to the exit from the pumping platform. This drawing also includes the solar pasteurizer appended to the system.

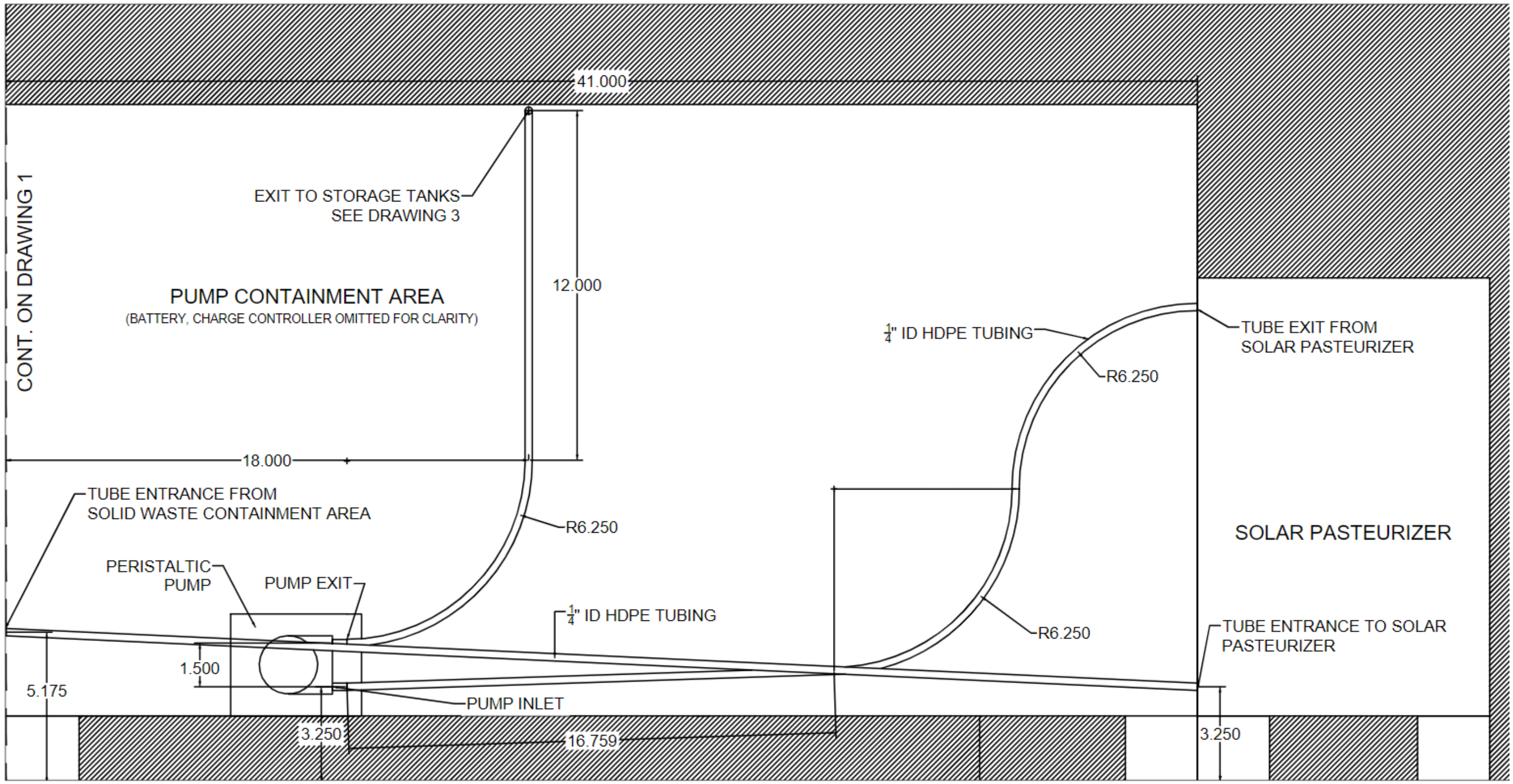
Drawing 3 – Pump Containment Area to Storage: Describes the flow path of urine from the pump within the pumping platform to the drum used for storage.

Drawing 4 – Electrical Schematic: Describes how a solar panel, charge controller, switch, solar pasteurizer unit, and peristaltic pump should be connected to provide power to the pumping system. Only one pump and switch are required despite two urine sources because urine from the urinal is gravity-fed to the urine-diverting insert in the conventional toilet. Electrical diagrams for the solar pasteurizer are detailed separately (Drawing 5) because this is a self-contained unit that has its own solar power system and inlet pump (provided by the Rich Earth Institute).

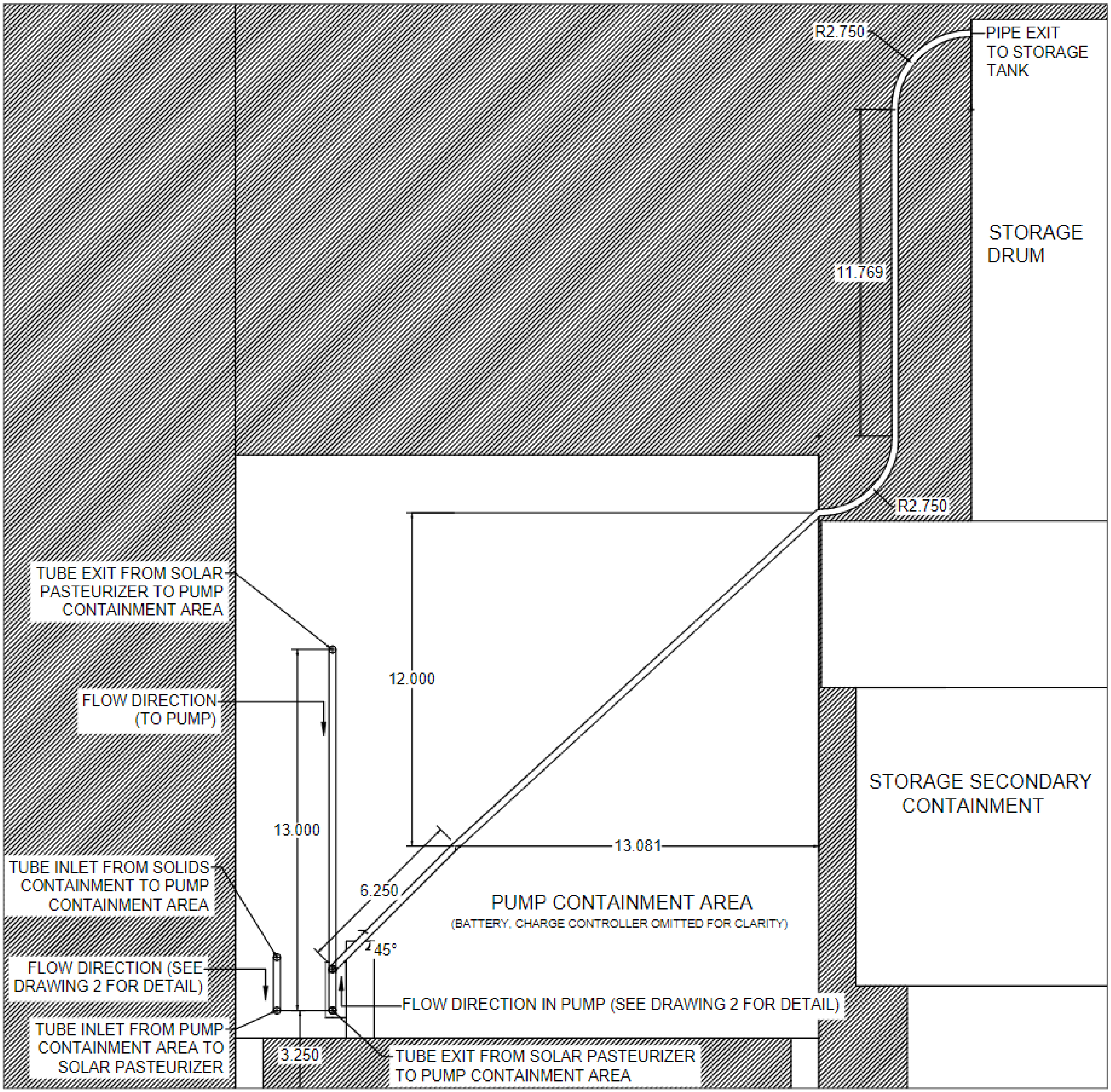
Drawing 5 – Solar Pasteurizer: Describes the solar pasteurizer unit provided by the Rich Earth Institute; derived and adapted from schematics provided in the “Guide to Starting a Community-Scale Urine Diversion Program" [2]



SITE: 17.4 DECENTRALIZED TOILET	DRAWING NO. 1		PROJECT NO. N/A	DATE. 2/13/22	REV: DESCRIPTION: BY: DATE: AMENDMENTS:
TITLE: SYSTEM INLETS AND SOLIDS CONTAINMENT	SCALE AT A4. 1:5	DRAWN. EP	CHECKED. N/A	REVISION. 2	



SITE: 17.4 DECENTRALIZED TOILET	2 DRAWING NO.		N/A PROJECT NO.	2/13/22 DATE.	REV: DESCRIPTION: BY: DATE: AMENDMENTS:
TITLE: PUMP CONTAINMENT AREA	1:5 SCALE AT A4.	EP DRAWN.	N/A CHECKED.	2 REVISION.	



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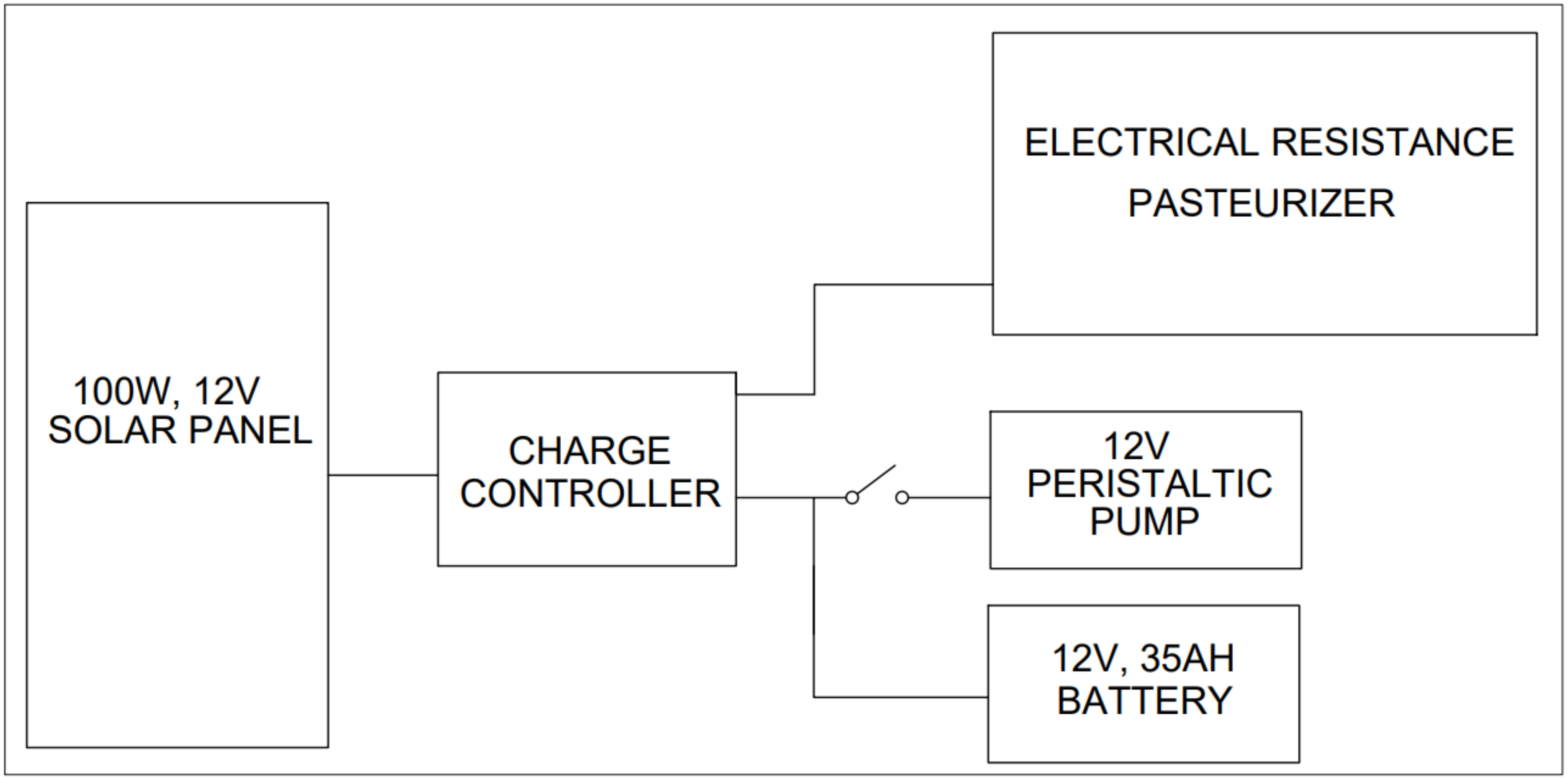
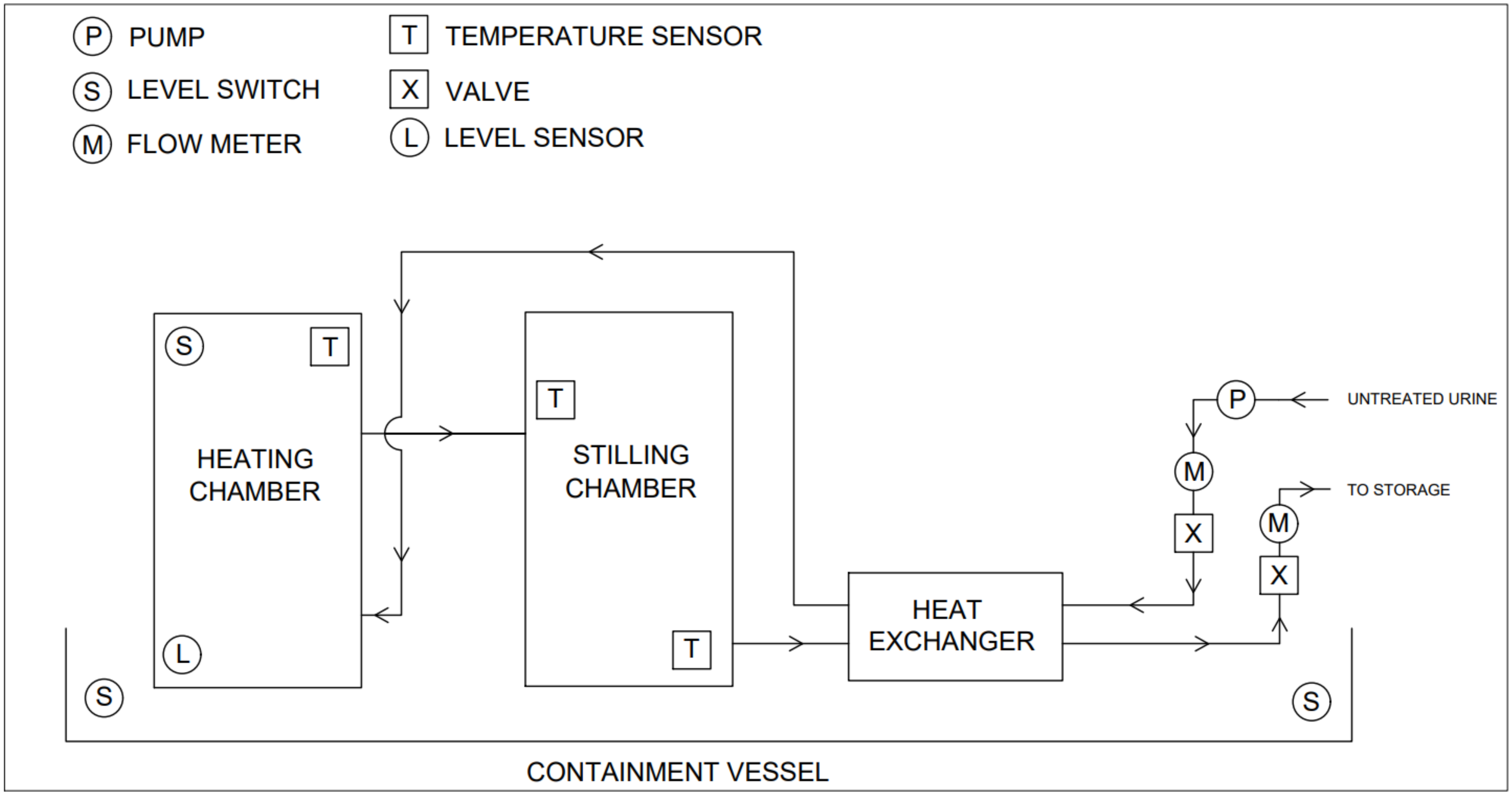
TITLE: PUMP CONTAINMENT AREA TO STORAGE	1:5 SCALE AT A4.	EP DRAWN.	N/A CHECKED.	2 REVISION.	



SITE: 17.4 DECENTRALIZED TOILET	DRAWING NO.: 4		PROJECT NO.: N/A	DATE.: 2/15/22	REV: / DESCRIPTION: / BY: / DATE: — AMENDMENTS:
TITLE: ELECTRICAL SCHEMCATIC	SCALE AT A4.: N/A	DRAWN.: EP	CHECKED.: N/A	REVISION.: 1	



SITE: 17.4 DECENTRALIZED TOILET	5 DRAWING NO.		N/A PROJECT NO.	2/16/22 DATE.	REV: DESCRIPTION: BY: DATE: AMENDMENTS:
TITLE: SOLAR PASTEURIZER	N/A SCALE AT A4.	EP DRAWN.	N/A CHECKED.	1 REVISION.	

Appendix F – Hydraulics Calculations

Table F1. Cumulative Head Loss Calculations

Component	K/C Value[1]	Length (ft)	Diameter (ft)	Velocity (ft/s)	Head Loss (ft)	Source[2]
1" x 1/4" Reducer	0.49	--	0.083	0.136	0.146	1
HDPE Tubing (6.25" Bend)	140	0.360	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing	140	1.56	0.021	2.176	0.0003	2
Exit Loss (To Insert)	1	--	0.021	2.176	0.074	1
1" x 1/4" Reducer	0.49	--	0.083	0.136	0.146	1
HDPE Tubing (6.25" Bend)	140	0.818	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing	140	4.57	0.021	2.176	0.0003	2
				Cumulative Head Loss (ft) Before Pasteurization	**0.41**	**ft**
Solar Pasteurizer						
HDPE Tubing (6.25" Bend)	140	0.818	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing (6.25" Bend)	140	0.818	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing	140	1.40	0.021	2.176	0.0003	2
HDPE Tubing (6.25" Bend)	140	0.818	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing	140	1.48	0.021	2.176	0.006	2
HDPE Tubing (2.75" Bend)	140	0.360	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
HDPE Tubing	140	0.981	0.021	2.176	0.021	2
HDPE Tubing (2.75" Bend)	140	0.360	0.021	2.176	0.001	2
90 Deg Bend	0.3	--	0.021	2.176	0.022	3
Exit Loss (to storage)	1	--	0.021	2.176	0.074	1
				Cumulative Head Loss (ft) After Pasteurization	**0.22**	**ft**

1. K values used for fittings and bends, C values used for Hazen Williams calculations of frictional losses in HDPE tubing

2. Sources: 1 – San Diego State University, "Operating Discharge and Head in a Pipe-Pump System" [24]; 2 – Engineering Toolbox, "Hazen-Williams Coefficients" [25]; 3 – Engineering Toolbox, "Minor Loss Coefficients" [25]

Table F2. Bernoulli Equation Values (After Pasteurization)

Key Values			Equivalent SI Units	
Parameter	Value	Units	Value	Units
Inlet Elevation (z_1)	16.25	in	1.1	ft
Outlet Elevation (z_2)	38.3	in	3.2	ft
System Flow	1260	mL/min	0.00074	ft^3/s
Inlet Area	0.0055	ft^2		
Inlet Velocity[1] (v_1)	0.16	ft/s		
Outlet Area	0.00034	ft2		
Outlet Velocity[1] (v_2)	2.18	ft/s		
Gravity (g)	32.2	ft/s^2		
Cumulative Head Loss (h_L)	0.22	ft		
Required Pump Head (h_{pump})	**0.446**	**ft**		
Available Pump Head	**20**	**ft**		

1. All velocities were calculated as the product of system flow and the associated area of flow

Appendix G – Electrical Calculations

Flush Time:

$$Flush\ Time = \frac{400\ mL}{1260\ mL/min} = \mathbf{0.3175\ min/use}$$

Anticipated Daily Power Draw (Pumping):

$$21\ Watts * \frac{200\ uses}{week} * \frac{1\ week}{7\ days} * \frac{0.3175\ min}{use} * \frac{1\ day}{1440\ min} = \frac{\mathbf{0.13\ watt - hrs}}{\mathbf{day}}$$

Anticipated Daily Power Draw (Pasteurization):

$$\frac{200\ visitors}{week} * \frac{400\ mL}{visitor} = \frac{80L}{week}$$

$$\frac{80L}{week} * \frac{13\ Watt\ hours}{Liter} = \frac{1040\ watt - hrs}{week}$$

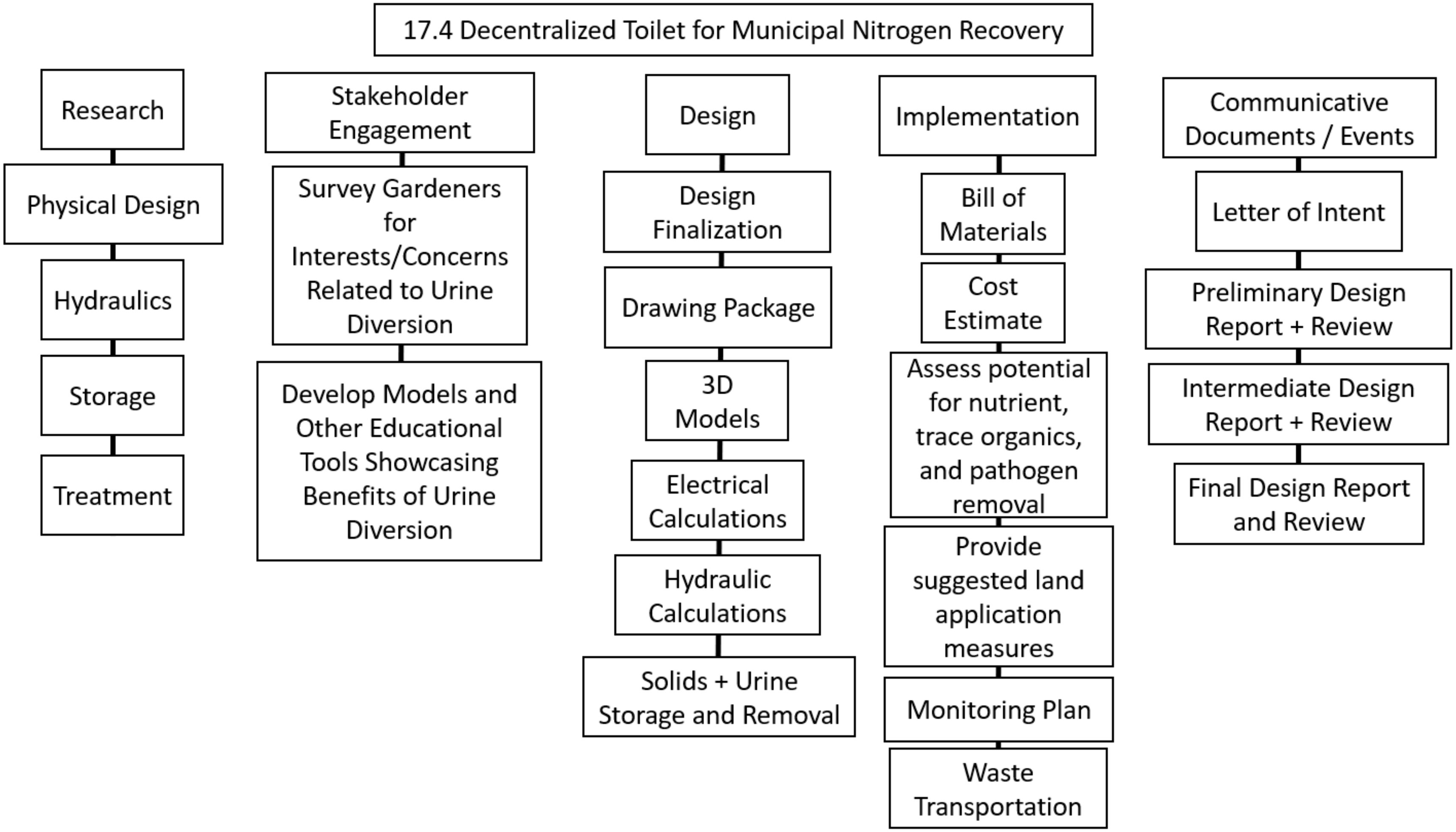
$$\frac{1040\ Watt\ Hours}{week} * \frac{1\ week}{7\ days} = \frac{\mathbf{149\ watt - hrs}}{\mathbf{day}}$$

Appendix H – Bill of Materials and Project Budget

Item	Manufacturer	Quantity	Total Cost	Notes
Separett Privy Kit 501 with Folding Seat	Separett	1	$159	Urine diverting seat
PMP310 Peristaltic Pump	Simply Pumps	1	$129	Peristaltic pumps (1 for urinal, 1 for conventional toilet)
VFC20P Variable Flow Controller	Simply Pumps	1	$29	Flush mechanism activation for both pumps
HDPE Tubing, ¼" ID x 3/8" OD, 100 ft	Cole-Parmer	1	$55.50	Corrosion resistant conveyance tubing
100 Watt, 12 Volt Monocrystalline Solar Starter Kit	Renogy	1	$145	Charge controller, solar panel, and accessories (pumping and storage)
12V 35AH Battery (Rechargeable Sealed Lead Acid)	Weize	1	$75	Battery (for powering pumps and heating pads)
16 Gauge Wire (4x 100 ft spools)	GS Power	1	$22	Sufficient for all solar connections
55 Gallon HDPE Industrial Drum with Lid	EarthMinded	2	$280	Storage tanks for diverted urine
Porta Potty, PH03-1005 XL Pewter, Wheelchair Accessible	PolyJohn	1	$2,250	Portable toilet: price includes delivery as quoted from manufacturer
Solar Pasteurizer	Rich Earth Institute	1	$5,000	Quoted cost for constructed pasteurization system from the Rich Earth Institute
50 Gallon Outdoor Resin Deck Storage Box	Suncast	1	$99	Storage for pumping platform, solar panel mounting on lid
2-Drum Secondary Containment	Den-Hartog	1	$296	Secondary containment for two 55-gallon drums, meets EPA regulatory requirements and is designed for outdoor containment of corrosive materials
HDPE Connections	N/A	N/A	$50	Conservative estimate
TOTAL INITIAL COST			**$9,448.45**	Includes conservative assumption of the inclusion of 11% sales tax on all items and services ($8589.50 pre-tax)

Item	Manufacturer	Quantity	Total Cost	Notes
Weekly Solids Removal and Cleaning	Colombia Sanitary Services	N/A	$2,236	Seasonal maintenance costs
Colilert Tests	IDEXX	64	$352	Seasonal weekly testing of Clear Creek raw water and diverted urine (see monitoring plan)
HACH Total Nitrogen Tests	HACH	1	$110	Seasonal weekly testing of diverted urine for calculations of dilution factors
ANNUAL COSTS			**$2,968.80**	Includes conservative assumption of the inclusion of 11% sales tax on all items and services ($2698.00 pre-tax)

Appendix I – Work Breakdown Structure



Appendix J – Project Schedule

Task	Subtask	Assigned To	Start	End
Research	Urine Diversion	Amelia	9/9/2021	9/28/2021
	Hydraulics	Emily	9/9/2021	9/28/2021
	Storage	Maddie	9/9/2021	9/28/2021
	Chemicals	Chloe	9/9/2021	9/28/2021
Letter of Intent	Project Charter	Emily	9/16/2021	9/26/2021
	Project Schedule	Emily	9/16/2021	9/26/2021
	Client Needs Table	Chloe	9/16/2021	9/26/2021
	Work Breakdown Structure	Amelia	9/16/2021	9/26/2021
	Letter of Intent	Chloe, Maddie	9/16/2021	9/26/2021
	Editing and Delivery	Emily	9/26/2021	9/28/2021
Design Comparison and Review	Hydraulics Decision Matrix	Emily	9/28/2021	10/7/2021
	Diversion Decision Matrix	Amelia	9/28/2021	10/7/2021
	Storage Decision Matrix	Maddie	9/28/2021	10/7/2021
	Treatment Decision Matrix	Chloe	9/28/2021	10/7/2021
	Rich Earth Institute Meeting	All	9/28/2021	10/5/2021
	Other Stakeholder Meetings	All	9/28/2021	10/5/2021
Design Development	SolidWorks Drawings	Amelia, Maddie	10/7/2021	10/21/2021
	Hydraulics Design Calcs	Emily	10/7/2021	10/21/2021
	SolidWorks 3D Modeling	Amelia, Maddie	10/21/2021	11/18/2021
	Site Assessment	Maddie, Chloe	10/21/2021	11/18/2021
	Solids Management	Maddie, Emily, Chloe	11/18/2021	12/2/2021
	Cost Estimate / Budget	Emily	11/18/2021	12/2/2021
	Bill of Materials	Emily	11/18/2021	12/2/2021
Preliminary Design Report and Review	PDR Slides	All	10/7/2021	10/28/2021
	PDR Presentation	All	11/2/2021	11/2/2021
	Background, Boundaries, Characteristics	Emily, Maddie	10/7/2021	10/28/2021
	Design Specifications	Emily	10/7/2021	10/28/2021

Task	Subtask	Assigned To	Start	End
	Concept Selection - Urine Diversion	Emily, Amelia	10/7/2021	10/28/2021
	Concept Selection - Treatment and Storage	Maddie, Chloe	10/7/2021	10/28/2021
	Concept Selection - Hydraulics	Emily	10/7/2021	10/28/2021
	Functional/Spatial Basis	Maddie	10/7/2021	10/28/2021
	Solidworks Drawings / Model	Maddie, Amelia	10/7/2021	10/28/2021
	Project Budget	Emily	10/7/2021	10/28/2021
	Bill of Materials	Emily, Chloe	10/7/2021	10/28/2021
	Project Progress	Emily, Amelia	10/7/2021	10/28/2021
	Universal Design Scorecard	Chloe	10/7/2021	10/28/2021
	Next Steps Letter Post PDR	All	11/28/2021	12/2/2021
Intermediate Design Report and Review	Design Narrative	Emily	1/11/2022	1/25/2022
	Path Forward, Risk Mitigation, Detailed Design Critique	Maddie	1/11/2022	1/25/2022
	Suggested Testing / Monitoring Plan	Chloe	1/11/2022	2/22/2021
	Nitrogen Conversion Literature Review	Chloe	1/11/2022	2/22/2021
	Land Application Literature Review	Chloe	1/11/2022	2/22/2021
	Pathogen Reduction Literature Review	Chloe	1/11/2022	2/22/2021
	Storage Secondary Containment	Emily	1/11/2022	2/22/2021
	Hydraulics Calculations	Emily	1/11/2022	2/22/2021
	Hydraulics CAD Drawings	Emily	1/11/2022	2/22/2021
	Electrical/Power Calculations	Amelia, Emily	1/11/2022	2/22/2021
	Electrical Schematics (CAD)	Emily	1/11/2022	2/22/2021
	SolidWorks Drawings	Amelia, Maddie	1/11/2022	1/25/2021

Task	Subtask	Assigned To	Start	End
	SolidWorks 3D Modeling	Amelia, Maddie	1/11/2022	1/25/2021
	IDR Slides	All	2/1/2022	2/4/2022
	IDR Presentation	Emily, Chloe, Amelia	2/8/2022	2/8/2022
	Next Steps Letter Post IDR	All	2/22/2022	2/24/2022
Final Design Report and Review	Executive Summary	Emily	3/1/2022	3/31/2022
	Introduction	Chloe	3/1/2022	3/31/2022
	Project Review	Maddie	3/1/2022	3/31/2022
	Application of Design Methodology	Maddie	3/1/2022	3/31/2022
	Engineering Analysis - Overall	Emily	3/1/2022	3/31/2022
	Engineering Analysis - Trace Organics Literature Review	Chloe, Emily	3/1/2022	3/31/2022
	Engineering Analysis - Flow Path Analysis and Secondary Containment	Emily, Maddie	3/1/2022	3/31/2022
	Engineering Analysis - Outstanding Testing/Analysis and Path Forward	Chloe	3/1/2022	3/31/2022
	Final Deliverables	Emily	3/1/2022	3/31/2022
	Gardener Engagement Pamphlet and Survey	Chloe	3/1/2022	3/31/2022
	Project Management	Amelia, Emily	3/1/2022	3/31/2022
	Lessons Learned	Amelia, Chloe	3/1/2022	3/31/2022
	Bill of Materials and Project Budget	Emily	3/1/2022	3/31/2022
	Work Breakdown Structure	Emily	3/1/2022	3/31/2022
	Project Schedule	Emily	3/1/2022	3/31/2022
Capstone Design Showcase	Poster	All	3/22/2022	3/31/2022
	Project Synopsis	Emily	3/22/2022	3/31/2022
	Design Showcase Pitch Video	All	3/22/2022	4/4/2022
	Final Design Review Slides	All	4/5/2022	4/19/2022

Task	**Subtask**	**Assigned To**	**Start**	**End**
	Final Design Review Presentation	All	4/21/2022	4/21/2022
	Capstone Design Showcase	All	4/28/2028	4/28/2022

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[1] "Guidelines for the Safe Use of Wastewater, Excreta, and Greywater - Volume 2, Wastewater Use in Agriculture," World Health Organization, Geneva, Switzerland, 2006.

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