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Implementation of Sustainable Drinking Water Infrastucture and "Pipe-in-Bottle" Solar Showers / Eco-Latrines in Pampoyo, Bolivia

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***Abstract*— During the summers of 2011 through 2014, students at the Virginia Military Institute used a sustainable, low-cost "pipe-in-bottle" technology to design and implement combination solar shower/eco-latrines to improve the quality of life in resource poor locations of rural Bolivia. This project promotes the use of sustainable, inactivated waste to enhance local soils for the improvement of crop yield, and the use of an abundant resource such as solar energy to promote improved sanitation and health. Results from this project include a sustained hot water delivery of 65°C for a period of 20 minutes and a <30 day dry-pit deactivation period for human waste. Health surveys show that the implementation of proper sanitation and improved diet within the community has reduced infant mortality by 45% with a 65% reduction in instances of preventable illness. On-site design and construction of facilities provided substantial cultural and hands-on engineering experience to the students involved. Most importantly, this project provided a preferential, life-saving option to the residents of Pampoyo, Bolivia whose drinking water was literally killing them.**

Keywords*— WateraAnd Sanitation Infrastructure, Bolivian Andes, Heavy Metal Water Contamination, Bolivian Drinking Water Health, Drinking Water Related Illness and Infant Mortality, Developing Country Water And Sanitation Construction

1. INTRODUCTION

The village of Pampoyo, located in the western Andes region of Bolivia, currently suffers from a multitude of preventable illnesses due to improper health and sanitation practices. Since 2011, students from the Virginia Military Institute (VMI) Civil & Environmental Engineering Department have collaborated to construct critical drinking water infrastructure for the community. Many members of the community suffer from vital organ bioaccumulation of heavy metals; a result of consuming surface waters contaminated with heavy metals such as copper, lead and silver (Pyatt et al., 2005). Although much advancement has been made in the area of safe drinking water consumption in Pampoyo, the community still lacked proper sanitation facilities such as showers and latrines. In fact, more than 80% of the residents of Pampoyo have never had the privilege of a shower and current community practice is open defecation on agricultural lands or within nearby surface waters. This practice has resulted in widespread contamination issues and contaminated crops, leading to illnesses such as diarrhea and contributing to high infant mortality rates (Hunter et al., 2010). During the fall and summer of 2014, the VMI student collaboration culminated in the design and construction of solar shower/eco-latrines and the implementation of sanitation and hygiene education. This marked the finalization of a four year project to further enhance the overall standard of living within the village, and reduce the frequency of preventable illness.

Students developed a sustainable combination solar shower/eco-latrine design capable of providing soil nourishing fertilizers through the heating and biological stabilization of human wastes (Tilman et al., 2002). The team created a solar shower design which innovatively employs low cost, state of the art "pipe-in-bottle" solar radiation infrared greenhouse technology capable of delivering water at a sustained temperature of 65°C for approximately 20 minutes. This combination solar shower/eco-latrine design is the first of its kind. The four year project involved the design and construction of a catchment basin, a sedimentation basin and the installation of more than 20,000-L of storage capacity (Figure 1). Stored water flows from the tanks through more than 7,600-m of 1.5-inch, ¾-inch and ½-inch black high-density polyethylene (HDPE) tubing to the solar shower/eco-latrine facilities. The intent was to provide one facility for each family within the community to facilitate pride of ownership and further reinforce the ideology of safety through proper sanitation.

Figure 1. Schematic overview of water and sanitation system constructed in Pampoyo, Bolivia between 2011 and 2014

Pampoyo is located 480-km south of the Bolivian capital city of La Paz and sits approximately 3,800-m above sea level (Figure 2). Due to the lack of clean water, extreme climate and geographic location of Pampoyo, the village economy is stagnant, leaving a majority of Pampoyans in a state of severe poverty. Pampoyans survive through a combination of subsistence farming as well as selling a small amount of potatoes and llamas (Killeen et al., 2007).

Figure 2. View of Pampoyo, Bolivia from the position of the in-line storage infrastructure

Circumstance forcibly infringes on a number of the community members and their basic human dignities, the most prominent being sanitation. This is most evident in an infant mortality rate of greater than 60% and a general mortality rate of over 40% by adolescence (Dickinson and Moore, 2015). Currently, villagers turn to a freshwater river that runs parallel to the village as a multipurpose resource. With more than eighty families bathing, cooking, drinking and defecating in the river, the water has become an extreme health hazard for the Pampoyans as well as those communities living downstream. Since the villagers use the river for such a wide variety of domestic purposes, they are developing symptoms that relate directly to improper hygiene and waste disposal such as: typhoid, diarrhea, bacterial infections, and high infant/child mortality rates (Boadi and Kuitunen, 2005, Genser et al., 2006).

2. SOLUTION

Beginning in the summer of 2011, significant advancements were made to improve the overall health of the village. Contaminant free spring water was piped into the village through infrastructure containing multiple pre-sedimentation implementations including a 10,000-L catchment basin structure, a 6,000-L sedimentation basin and more than 20,000-L of storage. The completed pipeline infrastructure consists of more than 7,600-m of HDPE pipeline. Approximately 80 homes were provided with a water service for daily washing and facilitation of solar shower operation. Combination "pipe-in-bottle" solar shower/eco-latrine facilities were constructed for each household and shower and sanitation education meetings were held to ensure proper use of all facilities provided through this humanitarian effort. All construction and field-level development of life-saving infrastructure was conducted utilizing community labor to ensure improved knowledge base and community acceptance. All construction was documented and as-built drawings developed to ensure continuity for future generations tasked with the maintenance of this system. Infrastructure installed included the following:

1. *Catchment/Sedimentation Basins and Storage*

The basins and storage tanks were constructed to encourage reduced sediment within the system as well as increased storage during the dry months of May through September. >40,000-L of catchment or storage were constructed to provide a source of security for the community in the event of drought or service interruptions.

2. *Pipeline*

7,600-m of 1.5-inch, ¾-inch and ½-inch HDPE pipe was installed at depths of approximately 1-m along the route of the source river and within the community. 80 service connections were installed for each home with future expansion of facilities in mind. Service connections were developed using ¾-inch HDPE and ½-inch HDPE pipe with accompanying fittings and appurtenances.

3. *Combination "Pipe-in-Bottle" Solar Showers/Eco-Latrines*

The design of the "pipe-in-bottle" solar showers combined with the eco-latrines is the first of its kind. Many prototypes of "pipe-in-bottle" showers were developed in our labs to optimize the final design. The design includes a 2-inch HDPE pipe, grid style configuration encapsulated within modified clear 2-L bottles. Much like a greenhouse, the bottles act to allow the pipe to absorb short-wavelength infrared (IR) radiation from the sun, which in turn gives off long-wavelength IR (Castilla et al., 2008, Williams et al., 2012). This radiative heat between the pipe/bottle interface is then trapped within the bottle, effectively maintaining a sustained temperature of 65°C for a period of approximately 20-minutes with a 25/75 hot to cold water mixture. The eco-latrines were designed with solar concepts in mind as well. The latrines use solar blanketing technology to improve solar radiation within the waste storage area of the latrine. Waste is captured for a period of time (~1-month) and then moved towards the front of the facility to reside within the solar compartment. This compartment effectively raises the temperature of the waste to the point of inactivation after only 7-days based on a sustained temperature in this region of 58°C (Mehl et al., 2011, Rajbhandari, 2008). Eco-latrines were also outfitted with urine diversion devices to eliminate waste cross-contamination and provide nitrogen recovery options for land and crop application (Haq and Cambridge, 2012, Mehl et al., 2011). Inactivated waste will be used to enhance overall soil characteristics, subsequently improving the yield rates of community grown crops. Percolation filters were constructed to contain and treat greywater (Chaillou et al., 2011). A detailed description of the infrastructure and appurtenances is presented below. All designs were produced by our team.

2.1 *Catchment Basin*

In order to properly develop the infrastructure for this project, it was necessary to develop a containment mechanism for the potable spring water upstream of the mine tailings waste currently plaguing the community. The catchment basin was developed to provide containment of approximately 10,000-L of water for delivery to the community. The catchment also acts as a preliminary sedimentation basin, eliminating the need for an oversized

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sedimentation basin prior to storage. Precast concrete is not an option in this location due to the absence of heavy equipment and difficulty of procurement; therefore, design of the catchment basin involved a cast-in-place form development. The catchment basin was also designed as a low-profile barrier style catchment to eliminate the possibility of damage from falling rocks, which according to community leaders are rare, but do occur in this particular area. Figure 3 provides an overview of the catchment basin design constructed for the community of Pampoyo.

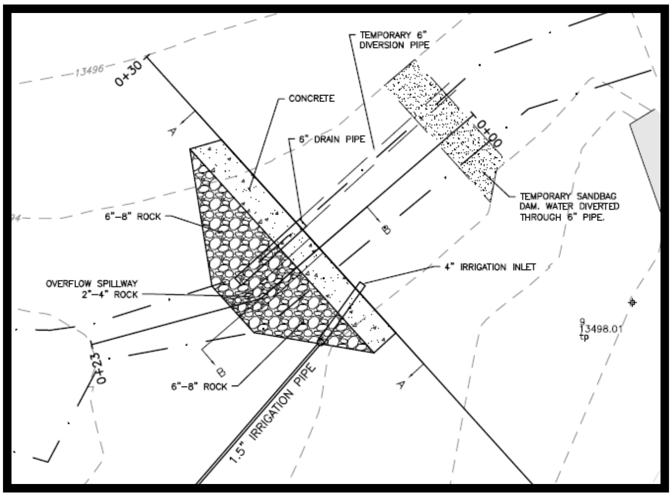

Figure 3. Plan view of catchment basin implemented in Pampoyo

As shown in the figure, concrete was measured as 3,500-psi cast-in-place concrete. The design utilized #3 rebar to provide additional strength and sustainability of the structure. The basin design also utilized the existing landscape by coring into adjacent large rocks to properly seat the rebar and the catchment basin within the profile of the existing river. This significantly reduces the possibility of rock damage, and allows the system to function during both low and high flow periods of the year.

2.2 Sedimentation Basin

To ensure that the system storage tanks and pipelines did not become inundated with sediment, a sedimentation basin was required. The required sizing of the sedimentation basin was reduced due to the sediment removal efficiency of the installed catchment basin. Specifically, the sedimentation basin was designed to accommodate approximately 6,000-L of water from the catchment basin. The sedimentation basin was also equipped with an overflow directed back into the stream to eliminate the need for regulated flow control. Similar to the catchment basin, the sedimentation basin was designed with 3,500-psi cast-in-place concrete and #3 rebar.

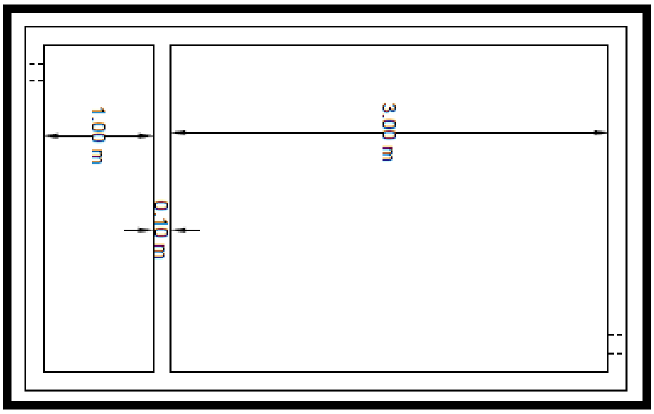

Figure 4. Plan view of sedimentation basin constructed in Pampoyo, Bolivia

As shown in Figures 4 and 5, the basin was built with dimensions of 4-m long by 2-m wide by 1.5-m deep. These dimensions yield a volume of water of 6,000-L which flows into 20,000-L of storage. The sedimentation basin was constructed with 10-cm thick walls as well as a 10-cm thick baffle to act as a weir for controlling sediment removal. The baffle was constructed approximately 10-cm below the top surface of the sedimentation basin to allow for water free of sediment to flow over and through the outlet to the storage tanks. Figure 5 shows that the partition was located approximately 3-m from the inlet to allow for effective sediment removal.

Figure 5. Working view of 6,000 L sedimentation basin constructed in Pampoyo

2.3 Storage Tanks

Four 5000-L storage tanks were utilized for this project. Tanks were made from dual-wall reinforced HDPE. Tanks were designed to store approximately 20,000-L of the water flowing from the sedimentation basin and were equipped with overflow devices to ensure that they are always full. Overflow devices were piped back to the stream similar to the sedimentation basin configuration. The tanks were positioned on a north facing spur close to the sedimentation and catchment basins (Figure 1) and under a pavilion style lean-to in order to prevent prolonged exposure to the sun, subsequently lengthening the life of the tank.

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Storage tanks were placed on a 15-cm thick, 3,500-psi cast-in-place concrete slab containing #3 rebar and mesh wire for added strength. Expansion joints were also provided within the concrete slabs. Tanks were bolted to the concrete and all appurtenance piping into the tank was 1.5-inch PVC for added connection strength. PVC fittings were threaded and sealed in an effort to further reinforce joints and reduce maintenance requirements. Figure 5 provides a schematic layout of the storage tanks constructed in Pampoyo, Bolivia.

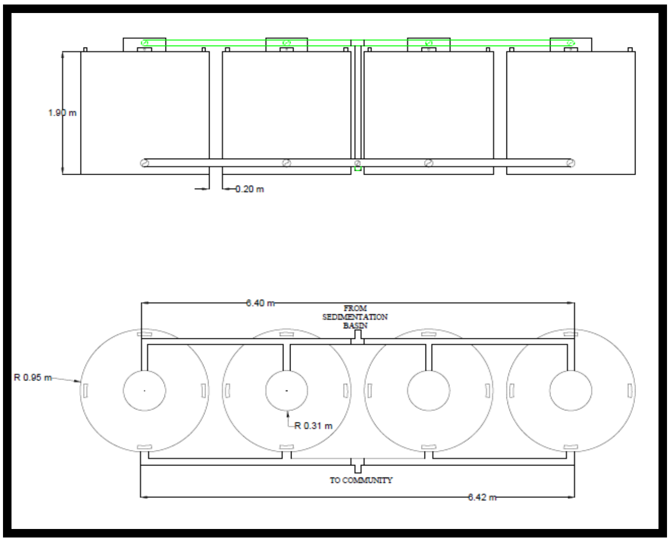

Figure 6. Plan and profile view of installed 5,000 L storage tanks

2.4 Pipeline

Approximately 7,600-m of 1.5-inch, ¾-inch and ½-inch HDPE tubing was used to complete the pipeline infrastructure for the Pampoyo project. As shown in Figure 7, the main pipeline ran from the catchment basin (elev. 3,785-m) to the sedimentation basin (elev. 3,775-m) to the storage tanks (elev. 3,761-m) and along the main road through the community to a final blow-off hydrant location (elev. 3,715-m). The blow-off hydrant was installed in order to periodically flush the line in the event of random sediment deposits.

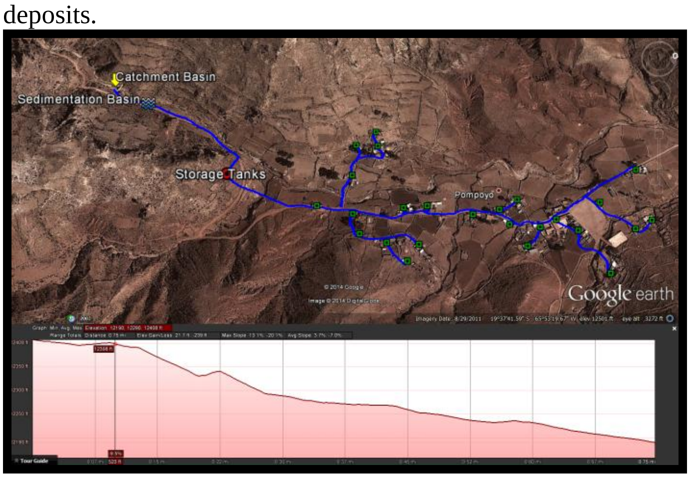

Figure 7. Plan view and elevation profile of pipeline constructed in Pampoyo

The pipeline was designed to provide a sustained velocity not exceeding 4.5-m/s and the slopes in most locations did not exceed 15%. High spots along the route of the pipeline were outfitted with air release valves and pressure relief valves were placed in multiple locations to prevent pipe damage due to water hammer. Also shown in the top right of Figure 7, HDPE tubing is available in 50-m rolls and is installed by unrolling the tubing within the excavated trench. All trenches were 1-m deep and excavation was conducted by hand using local labor. Trench beddings were comprised of small stone uncovered during excavation to prevent pipe damage, and valves were placed along the pipeline every 250-m to 300-m to allow for pipeline section isolation during repairs. 50-m sections of tubing were connected utilizing 1.5-inch unions for ease of pipe replacement. All pipeline installation took place using local labor. All pipes were hand threaded using a manual threading device and then fitted with the appropriate pipe connection using PVC glue. The pipeline branches off to accommodate various homes within the community. These branches were fixed with union style tee fittings and valves to provide for shut-off of individual areas of the community in the event of a repair or emergency. The pipeline was reduced to ¾-inch or ½-inch HDPE pipe to accommodate a service connection for each home and a shower stub out for the "pipe-in-bottle" solar shower/eco-latrine located at each home.

2.5 "Pipe-in-Bottle" Solar Shower, Eco-Latrine and Foundation Design

2.5.1 Solar Shower/Eco-Latrine Foundation

The foundation for the Shower-Latrine system was constructed of concrete reinforced with #3 rebar and welded-wire mesh (Figure 8). The soil under the foundation was excavated to a depth of 0.5-m prior to construction, and filled with approximately 8-cm of gravel and compacted using a hand tamp to allow for proper drainage. Due to the remote location, properly graded gravel was not readily available. For this reason, the subgrade of the foundation was comprised of materials found on the job site.

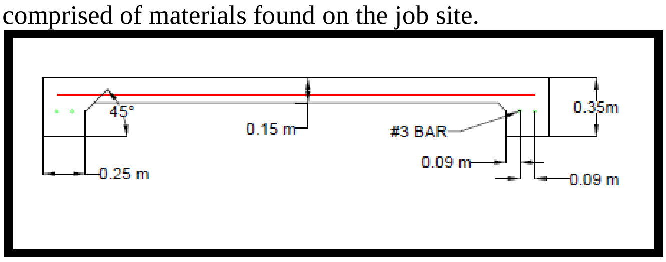

Figure 8. Profile view of slabs constructed for each solar shower/latrine

The foundation was composed of a turn-down slab, with thick outer edges and a thinner inside slab depth. The turn-down provides added support for the foundation, while preventing higher costs by thickening the rest of the slab. The turn-down edge also reduces the effects of frost heave, subsequently eliminating cracking of the concrete foundation. The foundation was also buried approximately one foot to help mitigate this issue. The thickness of the turn-down edge was designed to be 35-cm, with the center of the slab being 15-cm. Two reinforcing #3 bars were placed in the turn-down edge, and a sheet of welded-wire mesh was placed throughout the central slab. Upon completion of the slab, brick and mortar was used to construct a 1-meter tall wall around the perimeter of the solar shower/eco-latrine. Finally, a 3,500-psi cast-in-place concrete slab was constructed for use as the floor slab then stucco brushed for completion.

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2.5.2 "Pipe-in-Bottle" Solar Shower

The 'pipe-in-bottle solar shower system used in this project is the first of its kind used in conjunction with an eco-latrine and contained within the same building. The pipe in bottle system is what makes this project significantly unique in that we are harnessing sustainable energy from the sun to heat the water utilized for each shower. Specifically, we utilized a greenhouse style concept which incorporates the use of longwave and shortwave radiation to provide a sustainable 65°C temperature for approximately 20 minutes at a hot to cold water ratio of 25/75 (Castilla et al., 2008, Williams et al., 2012). The hot and cold water system is unique in that it runs completely off of the designed head pressure and solar energy. Due to the inability to access power in the remote area of Pampoyo, Bolivia, no pumps or electric heating systems are required. The foundation of the roof system is made up of large sheets of corrugated aluminum, spanning the length of the 2-meter by 3-meter latrine with the corrugated aluminum acting as an additional conductor for reflecting sunlight and heat. Figure 9 shows a completed solar shower system at a Pampoyo residence. Corrugated aluminum is a slightly more expensive choice but its durability and lifespan make it a more suitable building material. Each latrine was positioned in order for the roof to have maximum sunlight exposure. For this to occur, the structure's north facing portion of the roof was slanted at an angle between 7 and 10 degrees, to allow for maximum sunlight contact time.

Figure 9. "Pipe-In-Bottle" configuration installed on each solar shower/latrine combo constructed in Pampoyo

As shown in Figure 9, the "pipe-in-bottle" plumbing configuration used for the latrines was made up of 2-inch HDPE and ½-inch PVC pipes. The ½-inch diameter piping was used to carry water from the 1.5-inch HDPE main water line to the building and subsequently to the "pipe-in-bottle" heating system. The ½-inch PVC pipe was also installed from the "pipe-in-bottle" heating system into the building and to the shower head.

The 2-inch portions of pipe were laid in 6 parallel sections across the roof, with 90° PVC elbows connecting them. HDPE pipe was used for the water heating system since experiments revealed that painted PVC material became more brittle as the pipe's exposure to UV radiation from sunlight increased. Also, since these pipes were under substantial pressure, HDPE piping was deemed a more suitable material. The HDPE roof piping was black in color and the 90° PVC elbows were painted black in order to maximize the absorption of the sunlight's energy into the pipe.

In order to sustainably and efficiently heat the water in the roof piping system, 2-liter plastic bottles were determined to be the most practical implementation as they are readily available, effective and can easily be replaced. These bottles provide an insulated layer around the HDPE pipe much like the earth's layer of atmosphere. The sun's shortwave infrared radiation (IR) passes through the clear plastic bottles. These IR waves are absorbed by the black surface of the pipe and reflected back into and trapped within the space between the bottle and pipe as longwave IR, thus, heating the water within the pipes. As there is a physical barrier trapping the longwave IR from escaping, the pipe acts much like a greenhouse (Castilla et al., 2008). Therefore, the heat energy is mostly absorbed into the water within the pipes instead of being lost to the atmosphere. Through extensive laboratory experiments and multiple field trials our group determined that temperatures within the pipes reached 65°C, which is 20% hotter than the U.S. Department of Energy recommends for hot water heaters in the United States.

Additional appurtenances on this system included a low flow shower head (11.4 L/min) and multiple pressure valves that attach the 2-inch tubing to ½-inch reducer sections of pipe. The storage in the pipes allow for a 20-minute sustained hot shower at a 25/75 hot to cold mixing ratio. Pressure release valves were also required due to the pressure variations experienced due to diurnal temperature variations. The pressure valves also serve to protect the user against excessive pressure dissipation due to the build-up in the pipes during day-time heating.

2.5.3 Eco-Latrines

The combination eco-latrine system is required to provide a more appropriate means of human waste disposal and containment within the community. The eco-latrines that were implemented are designed to utilize rudimentary sanitation technology necessary to sanitize human waste as well as allow for facility reuse with minimal maintenance.

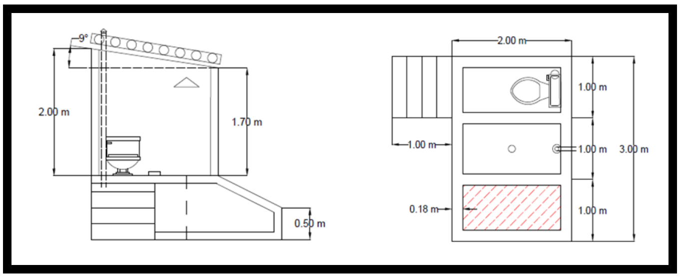

Figure 10. Plan and profile view of the constructed "pipe-in-bottle" solar shower/latrine

This type of "dry-pit" eco-latrine is ideal for resources available to the Pampoyans, as the latrine is a waterless system. Given the arid climate of Pampoyo, a waterless latrine allows for the construction of the structure without considering location of wastewater containment and disposal.

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Each latrine was enclosed in a 2-meter by 3-meter structure, the latrine and shower were separated by a 10-cm concrete lip, allowing for a complete bathroom with shower to be implemented (Figure 10).

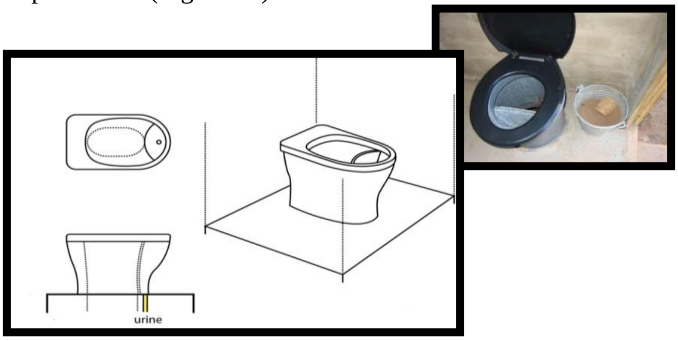

Figure 11. Urine diversion and "dry-pit" toilet configuration installed in each latrine (UDDT 2014)

The latrine portion of the bathroom utilizes a urine diverter (Figure 11), a device that aids in the separation of solid and liquid waste in order to maintain the properties of each. The exceptionality of this design is that both the solid and liquid waste are capable of being reclaimed and utilized as supplementary fertilizer for the village crops (Haq and Cambridge, 2012, Tilman et al., 2002). In an impoverished village stricken by hygiene related disease, the ability to not only decontaminate human waste but use it advantageously is a positive step for the community.

As solids are produced, they enter into a pit directly under the toilet seat where the waste accumulates until it reaches a critical level. Each time solid waste is generated by a user, the user will add a layer of organic material (sawdust, dry grass, etc.) into their waste. The organic material acts as a drying agent and an organic material booster for microbial breakdown of the waste. This is a very important step in the decontamination of the waste as moisture increases the retention time needed to destroy pathogens in the waste. Adjacent to the pit, below the shower, will be another pit separated by a metal partition. This secondary pit is where the solid waste will be transferred from the primary pit, after one month, and isolated to promote bacteriological break-down.

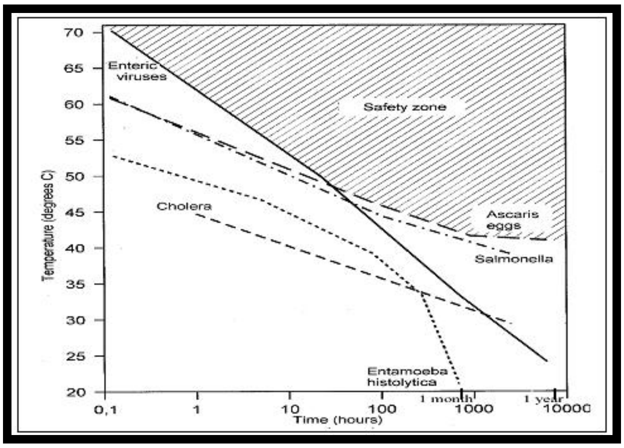

Figure 12. Graphical representation of "Zone-of-Safety" for solid waste (Mihelcic, Fry et al. 2009)

Once the waste has reached the secondary pit, it will be held for approximately 10-days to 1-month (depending on measured solid waste temperatures). This time frame is based on field experiments performed in our eco-latrine prototype, in which it was discovered that an enclosed space, covered with a solar blanket, with moderate sun exposure will reach temperatures of 55ºC after approximately 10-days. Using this data and the guidelines noted in Figure 12, a large majority (if not all) of pathogens found in human feces will be destroyed after approximately one month of contact time (Cairncross and Feachem, 1993, Mihelcic et al., 2009).

When the 30 days have passed, the dry solids will be able to then be applied to local crop lands and will serve as a nutrient rich fertilizer due to the nitrogen and phosphorus commonly found in biodegraded human waste.

2.6 Percolation Filter

The liquid waste that is separated as the latrine is in use is conveyed by a separate piping system to a leachate field beside the latrine. Nitrogen rich urea is directly applied to the percolation filter where natural vegetation absorbs the nitrogen, leaving a neutral substance to be absorbed by the environment. By diverting the urine from the solid waste, the solid waste's composting properties are not only preserved but the urine can also be utilized as a fertilizer. The percolation system is also used for greywater disposal. After passing through the porous soils, greywater seeps through as non-toxic fluid and is absorbed by the surrounding soil. This percolation system consists of a bed of graded coarse aggregate, onto which solar shower water is applied and allowed to filter through. Similar to a trickling filter, this process leaves the organic matter on the surface of the rocks, where it is oxidized and subsequently removed by biological growth.

While passing through the filter, the water is treated by an aerobic process that transforms the waste into organic minerals and oxidizes the nitrogen rich compounds supplied by the latrine-shower and urine diverter. Each latrine/shower system gravity feeds greywater to the accompanying percolation system adjacent to the facility. With each percolation filter dug to specifications of 1-m deep by 1-m wide by 1.5-m long (Figure 13), each filter is capable of holding approximately 500-liters of diverted urine and greywater.

Figure 13. Earth and course gravel trickling filter implemented in Pampoyo

All trenches contain a base layer of sand, and are backfilled with graded gravel, 20-30 mm in diameter, around the end of the pipe and throughout the trench. The backfill of gravel helps to aerate the soil and waste below, aiding in the filtration process and providing organic material for bacterial consumption. Plants or other vegetation will be grown within the filters to provide nutrient uptake and aid in overall waste reduction.

Once any and all waste generated by the community is deactivated, it is then used to provide valuable nutrient rich fertilizer to the surrounding crop lands. Finally, the villagers of Pampoyo underwent intense water and sanitation education classes for three days following the water and sanitation system installation. Classes included proper use of sanitation facilities, proper maintenance of water and sanitation infrastructure, use of eco-latrines, use of solar showers and proper hygiene maintenance (toilet usage, proper showering techniques and oral hygiene).

3. CONCLUSION

This project represents a highly novel approach to the capture and distribution of safe drinking water sources in developing countries. This research focuses on the use of low cost technologies such as “pipe-in-bottle” solar shower enhancements and solar blanket waste inactivation to improve the quality of life in resource poor locations. The use of inactivated human waste to enhance local soils for the improvement of crop yield challenges scientific and social norms, and the use of an abundant resource such as solar energy to promote improved sanitation and health illustrates a valuable use of sustainable practices. This project also represents a “cradle-to-grave” type of project, offering substantial hands-on engineering application and experience to the students involved in its design and construction. Results from this project will inform fields beyond environmental engineering such as global health organizations and agricultural facilities looking for alternative waste disposal methods. Most importantly, this project provides a preferential, life-saving option to the residents of Pampoyo whose drinking water was literally killing them.

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