Solar Compartment Design Methods, Performance Analysis and Thermal Data for Solar Composting Latrines: A Full Scale Experimental Study

By

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Abstract

Developing nations require improved sanitation technology implementations to reach Millennium Development Goal 7-C. Unfortunately, to date, the goal does not look attainable by the 2015 deadline – 2.5 billion lake access to improved sanitation. Pathogen resistance to disinfection or inactivation in latrines is multifaceted. The full-scale solar composting compartment studies at the University of Kansas have advanced the knowledge about feces composting in solar compartments based on climate and materials. The thrust of the studies has been to record temperatures within simulated compost and compost - thermal disinfection can be reached with various designs. Four design types were proposed as having a significant beneficial effect on temperature profile in the compost. Two design methodologies are recommended for thermal disinfection: capturing heat from the sun or protecting compost heat from escaping the compost. Both designs require moisture loss to be reduced with an evaporation cover (e.g. sheet of plastic). Under desiccating conditions decomposition is slowed dramatically, which results in little to no heat production from the composting process. Insulating moist compost with slab insulation (e.g. rigid polystyrene) will increase temperatures in the compost. Insulating all six sides of a compartment will yield appropriate composting conditions for extended periods. Extensive thermal data for simulated and actual compost has been placed in a supplemental appendix. For access to the supplemental appendix, please contact the author at joeren115@gmail.com. Further studies are required to determine effects of compost age and oxygen on compost pile temperatures for solar composting compartments.

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Annotations and Abbreviations

AIDS - Acquired Immunodeficiency Syndrome
ASHRAE - American Society of Heating Refrigerating and Air Conditioning Engineers
C - Carbon
CCD - Center for Clean Development
DAFF - Double Vault Dry Alkaline Fertilizer Family
DALYS - Disability Adjusted Life Years
DVST-ES - Dual Vault Solar Toilet, El Salvador
DVUDT - Dual Vault Urine Diversion Toilet
DVUDT - Double Vault Urine Diverting Toilets
EcoSan - Ecological Sanitation
EPA - United States Environmental Protection Agency
EUR - Euro Monetary Unit
GTZ - Deutsche Gesellschaft fur Technische Zusammenarbeit (German Agency for Technical Cooperation)
GWC - Gravimetric Water Content
HIV - Human Immunodeficiency Virus
IT - Infiltration
kg_{DM} - Dry Mass (kg)
KU - University of Kansas
MDG - Millennium development goals
min - Minute
ml - milliliters
MTU - Michigan Technological University
N - Nitrogen
PFL - Pour Flush Latrine
pH – strength (German: potenz) of the hydrogen ion concentration (a measure of acidity)
PV - Photovoltaic
SIRDO - Sistema Integral De Reciclamiento De Desechos Organicos (Integrated System for Recycling Organic Waste)
Type T - Copper and Constantan Thermocouple Wire
UNICEF - United Nations Children's Fund
UV - Ultraviolet Radiation
VDVT - Vietnamese Double Vault Composting Toilet
VIP - Ventilated Improved Pit
VWC - Volumetric Water Content
WASH - Water, Sanitation and Hygiene
WHO - World Health Organization
XT - Exfiltration

Equation Abbreviations

α_x – Absorptivity (unit-less)
σ – Stefen-Boltzman Constant (5.67 x 10^{-8} J/m^2 s K^4)
ε – Emissivity (unit-less)
E_x – Energy (watts)
G_s – Tilted Pryanometer Reading Output (watts/m^2)
h_0 – Solar Compartment Convection Coefficient (watts/°C-m^2)
h – Convection Coefficient (watts/°C-m^2) or Enthalpy (joules/gram)
k – Conduction Coefficient (watts/°C-m)
M_x – Mass (grams)
T – Temperature (°C)
$\frac{x^2}{s}$ – Goodness of Fit Variable with s = Sample Size

Sensor Descriptions used in Graphs

NE_High - Thermocouple placed 4" deep into the North East corner of the solar compartment (°C)
Mid_High - Thermocouple placed 4" deep into the middle of the solar compartment (°C)
Mid_Mid - Thermocouple placed 6" deep into the middle of the solar compartment (°C)
Mid_Low - Thermocouple placed 8" deep into the middle of the solar compartment (°C)
SW_Low - Thermocouple placed 8" deep into the South West corner of the solar compartment (°C)
Soil 4 inches – Thermocouple 10 cm (4 in.) deep into ground by solar compartments (°C)
Solar Radiation (VDC) - Total Solar Radiation (kilowatts/m^2)
TOBS.I-1 - wet bulb temperature (°C)
TMAX.H-1 - ambient temperature maximum (°C)
TMIN.H-1 - ambient temperature minimum (°C)
TAVG.H - ambient average temperature (°C)
PRCP.H-1 - precipitation in inches (°C)
STO.I-1:-40 - ground temperature 40 in, deep (°C)
WSPDX.H-1:30 - wind speed maximum (mph)
WDPDV.H-1:30 - wind speed average (mph)
RHUM.I-1 - relative humidity (%)
DPTP.H-1 - dew point temperature (°C)
WDIRV.H-1:30 - wind direction; North = 0 NE = 90 (°)
SRADV.H-1 - total solar radiation (kilowatts/m^2)

Chapter 1 Introduction

Need for Sanitation and Development

“In many parts of the world, the main source of water contamination is due to sewage and human waste” (Moe and Rheingans, 2006). The United Nations brought the world the global issue of development to the attention of by setting the Millennium Development Goals (MDG) and asking for help funding, researching and providing infrastructure to reach the goals.

Millennium Development Goals

MDG have eight major thrusts: (1) eradicate extreme poverty and hunger, (2) achieve universal primary education, (3) promote gender equality and empower women, (4) reduce child mortality, (5) improve maternal health, (6) combat HIV/AIDS, Malaria and other diseases, (7) ensure environmental sustainability, and (8) global partnership for development (UN, 2012). Goal 7 has four sub categories: (A) integrate the principle of sustainable development into country policies and programs and reverse the loss of environmental resources, (B) reduce biodiversity loss, achieving a significant reduction in the rate of loss by 2010, (C) halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015, and (D) to have achieved a significant improvement in the lives of at least 100 million slum dwellers by 2020. Indicators are used to gauge the progress towards each MDG and the indicators for goal 7-C are the proportion of the population using improved drinking water sources and improved sanitation facilities. The progress towards MGD 7-C is split, with improved drinking water sources target having been met on March 6, 2012 and sanitation lagging behind: “… The world is still far from meeting the MDG target for sanitation… Only

63% of the world's people have improved sanitation access, a figure projected to increase only to 67% by 2015, well below the 75% aim in the MDGs. Currently 2.5 billion people still lack improved sanitation" (UNICEF WHO, 2012). Improved sanitation is required for development, because diseases associated with improper disposal of human excrement reduce people's health (Mihelcic *et al*., 2009).

Solar composting latrines can make progress on MDGs 1, 4, and 7 by supplying people in developing nations design choices for composting (1) of human feces and proper disinfection (4,7). The work done by Engineers Without Borders at the University of Kansas (EWB KU) is closely tied to the research presented in this paper. EWB KU is quantitatively adding to the sanitation indicator for development by installing insulated solar latrines (EWB KU, 2012).

Diseases Caused by Feces

Bacteria, protozoa, helminthes and viruses found in the feces that can cause the following illnesses: Gastroenteritis, Legionnaires' disease, Leptospirosis, Salmonella, Typhoid fever, Shigellosis, Cholera, Yersiniosis, Balantidiasis, Cyptosporidiosis, Cyclosporasis, Amebiasis, Giardiasis, Ascariasis, Enterobiasis, Hymenolepiasis, Taeniasis, Trichuriasis, Respiratory disease, Heart anomalies, Meningitis, and Hepatitis (Mmolawa, 2005; Jimenez *et al*., 2002; Tchobanoglous *et al*., 2003). To quantify the effect of illness on people disability adjusted life years (DALYS) was defined, "one DALY is equal to one year lost due to death or inability to work because of illness" (Mihelcic *et al*., 2009; WHO, 2002). The third leading cause of DAYLS in developing countries is unsafe water, sanitation and hygiene, which contributes to 5.5 % of the DALYS in developing countries (WHO, 2002). The global burden of disease of 4.3% can be reduced by 88% by improved water, sanitation and hygiene; rigorous studies have shown that improved sanitation can reduce illness by 36%. Thus, sanitation improvements alone could reduce the global burden of disease by 1.4%; similarly, hygiene is also very important and can reduce the global burden of disease by 1.2% (WHO, 2004; Mihelcic *et al*., 2009).

Chapter 1.1 The Experiment

Experiment Aim and Type

The experiment aims to: (1) find the variance of thermal and disinfection performance of solar composting compartments based on climate and design; (2) provide data for researchers and development workers for selected designs; (3) determine the effect of materiality on the performance of the solar compartments; and (4) develop designs that disinfect the hardest to disinfect pathogens such as helminth eggs and Enterovirus. Eleven full-scale composting compartments were built to determine if disinfection conditions were being reached in solar compartments – over 100 permutations were tested and analyzed.

Chapter 1.2 Designs

Two Major Design Types

Solar energy can be combined with heat generated by the compost or by insulating around the compost on all sides (e.g. bottom, walls and top) to reach thermal disinfection levels. Both design types allow for thermal disinfection levels to be reached in parts of the compost piles. Wet composting or desiccation can take place in solar compartments depending on whether a plastic evaporation cover (e.g. 3-mil polyethylene sheet) is used. If an evaporation-cover is not used, most of the moisture will leave the compost pile over time (e.g. one week to below composting requirements and six months to full desiccation). Insulated compost designs allow for higher-temperatures for longer periods when the whole pile is undergoing aerobic decomposition. Solar heating designs yield higher surface temperatures.

Chapter 1.3 Sanitation Technologies

Sanitation Technologies

In developing nations there are two general categories of sanitation technologies, improved and un-improved. Bucket latrines, public latrines and open latrines are all unimproved sanitation technologies and have a significant chance of infecting the users (Mihelcic *et al*., 2009). Connection to a public sewer, connection to a septic system, pour flush latrines, ventilated improved pit (VIP) latrines, composting latrines and simple pit latrines are all improved sanitation technologies (WHO UNICEF, 2006).

Connection to a public sewer is the most common developed nation improved sanitation technology but requires significant infrastructure and in most cases uses large quantities of potable water. Simple pit latrines provide 20% of the developing nation improved sanitation but can cause pollution of ground water and illness to users if not managed correctly (Hoglund, 2001). There are advantages and disadvantages associated with improved sanitation technologies based on hygiene, financial cost, water use and environmental sustainability (Table 1).

Table 1. Improved sanitation technologies advantages and disadvantages (WHO UNICEF, 2006; GTZ, 2012; Peasey, 2000; Mihelcic et al., 2009)

Improved Sanitation Technology	Advantages	Disadvantages
Connection to public sewer systems	Hygienic	Uses water, costly, public scale infrastructure required
Connection to septic systems	Hygienic, no public scale infrastructure required	Uses water, moderate costs, can pollute ground water in some locations
Pour flush latrines (PFL)	Hygienic, lower costs	Requires water, will pollute ground water in some locations
VIP latrines	Inexpensive, no water required, no waste handling required	Requires organic material addition, may pollute ground water in some locations
Composting latrines	Inexpensive, no water required, produces fertilizer for agriculture	Requires organic material addition, harder to operate correctly, negative stereotype for putting on crops, disinfection methods/effectiveness under review
Simple pit latrines	Least expensive, no water required, easy to build	Will pollute ground water in some locations, attracts disease vectors when operated incorrectly

Connection to a septic system requires large quantities of potable water and with unfavorable-ground conditions (low permeability soil and/or high water tables) the septic tank can pollute fresh water aquifers. Pour flush latrines (PFL) are similar to septic systems but have two distinct differences: (1) the option of using grey water to flush the toilet, (2) no drain field attached to a holding tank which can cause ground water pollution (Hoglund, 2001). The holding tank in a PFL becomes a pit, similar to simple pit latrines but receives larger quantities of water than pit latrines, which will form higher quantities of lower concentration leachate. Ventilated improved pit latrines are (as the name states) improved simple pit latrines that have a ventilation stack placed on the leeward side of the latrine to reduce odors in the toilet hut. The air movement also desiccates part of the excrement pile in VIP latrines.

Composting latrines have the added advantage of using the excrement (after treatment) as a fertilizer for non-edible plants and edible plants, the latter application for development enhancement – MDG 1 and MDG 4. The main drawback to composting latrines is people getting sick because of improper treatment of human compost, an issue that causes development retardation (Jimenez *et al*., 2002; Moe and Rheingans, 2006). The design and resulting disinfection method of composting toilets has been studied heavily and many options exist when selecting a composting toilet.

Disinfection Methods for Sewage Sludge

Most of the disinfection methods for sewage sludge are not applicable to developing nations because of expensive infrastructure requirements, although low costs designs use some of the same disinfection methods as described for sludge (Moe *et al*., 2006). Sewage sludge is composed of feces, urine and mostly water. Human compost found in latrines varies widely in its composition and can include feces, organic material, urine and ash. For this research project, it is assumed that the disinfection methods for sewage sludge are similar to those for human compost.

The disinfection stressors for sewage sludge are: (1) Temperature, (2) pH, (3) Irradiation, (4) Desiccation, (5) Pressure, (6) Ultrasound/Cavitation, (7) Oxidant Chemicals and (8) Non-charged Chemicals/Biochemical by-products (i.e. ammonia, amines, hydrogen sulfide) for sewage sludge (Acquisto *et al*., 2006). A report to the EPA Acquisto *et al*. (2006) found the more stressors placed upon sewage sludge the more likely Class A bio-solids (free of detectable levels of pathogens) would be found. Also, compost treated in a static aerated pile or within a vessel requires no additional treatment before use if 55 °C (131 °F) is maintained for 3 consecutive days or 40 °C (104 °F) for 5 days (Acquisto *et al*., 2006). Non-charged biochemical by-products, temperature, desiccation and pH are the stressors most often active in composting latrines.

Similarities between Composting Latrines and Static Aerated Sewage Sludge Piles

Composting latrines are similar to constantly aerated static-pile sewage sludge composting facilities except that it is harder to control the moisture and temperature levels, especially at the edges of the compost including the concrete slab-compost contact area (Chapman, 1995). Because the fresh-human compost is added daily, the age of the compost in the pile varies. *Composting latrines* is a general term that is used for latrines that use aerobic decomposition, possibly anaerobic decomposition (in saturated conditions), and (more loosely) desiccation, pH, and storage time to disinfect human excrement.

Chapter 1.4 Disinfection Methods

The disinfection methods and associated disinfection stressors (in parenthesis) that occur in human compost are: desiccation (desiccation), solar composting (temperature, desiccation and non-charged chemicals/biochemical by-products), aerobic digestion (non-charged chemicals/biochemical by-products), anaerobic digestion (non-charged chemicals/biochemical by-products), composting (non-charged chemicals/biochemical by-products), addition of pH changing materials (pH), and storage time (food reduction) (Peasey, 2000; Acquisto. *et al*., 2006). Multiple disinfection stressors reduce pathogens in solar composting latrines.

Temperature Disinfection Method

Cairncross and Feachem's (1993) plot is ubiquitous throughout the literature for temperature disinfection of pathogens over time (Figure 1). The graph is read by (1) knowing a temperature that sludge was above for given duration of time or (2) duration of time that the sludge was at or above a given temperature. *Ascaris* eggs and Enterovirus require the longest times and highest temperature conditions.

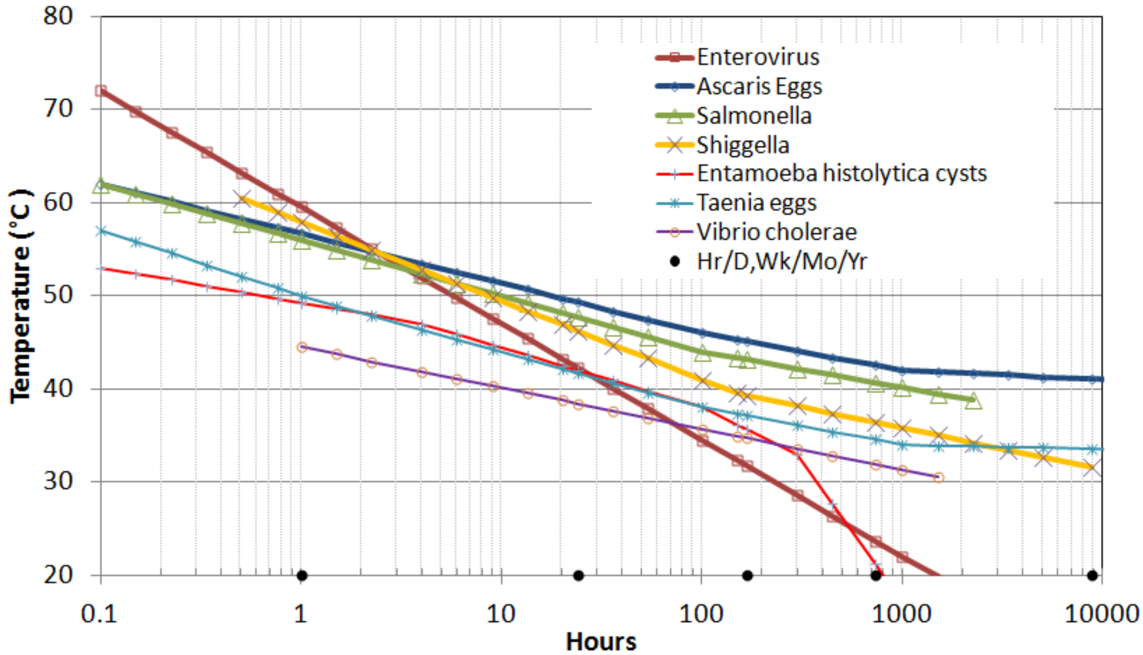

Figure 1. Reproduced Cairncross and Feachem time-temperature disinfection graph (Cairncross and Feachem 1993)

Note Enterovirus and ascaris eggs have the longest/highest time/temperature requirements.

Temperature Disinfection Method in Composting Latrines

Usually, a high temperature needs to be achieved for a duration for pathogen destruction to happen in composting latrines – as the Cairncross and Feachem (1993) graph suggests. Bin composters used along the Appalachian Trail in Eastern United States have reached thermophilic temperatures (Leonard and Fay, 1978). Bin composters described by Leonard and Fay are batch systems about the size of solar composting compartments. The maximum heat generation rates for sewage sludge found by Chapman (1995) was 14 watts/kg_{DM}, which would be 1500 watts per compartment in solar composting compartments of the size used at the KU field site. Chapman goes on to summarize that the edge effects of small pile composting are not well understood and evaporative cooling and conduction heat loss are the dominant heat loss mechanisms in small piles. Toilets with simple convection and leachate drainage perform better (Crenna, 1992). Full disinfection in compost piles may be hard to reach without additional methods to stop or slow edge effect.

Masters students at Michigan Technological University studied composting latrines in rural Panama and found pile temperatures lower (on average a few degrees below ambient) than what is required for disinfection (Hurtado, 2005; Kaiser, 2006; Mehl, 2008). Their field data falls in the range Chapman suggested in 1995.

Desiccation Disinfection Method in Composting Latrines

There are questions to how safe desiccated feces are, with some reports claiming disinfection and other experiments showing that desiccating feces with a short storage time doesn't disinfect helminth eggs. Mmolawa (1995) outlines these differences in her master's thesis:

> "Dry sanitation claimed to achieve sufficient destruction of disease causing organisms to enable safe handling of compost (Esrey *et al*., 1998). In community settings, sanitation toilets are safe to handle and use as soil conditioners and plant fertilizers (Peasey, 2000). In dry sanitation, for developing countries, helminth ova are highly resistant and not all processes used for disinfection are always applicable in developing countries (Barrios *et al*., 2004)".

Most viruses and bacteria require water to survive, although helminth eggs can transform into a cyst form that requires little to no water to be active (Moe and Izurieta, 2006). This agrees with the findings of Mmolawa (1995) in an experiment where EcoSan desiccated feces were mixed in the soil used for vegetables and helminth ova were found.

By passive or active ventilation, feces are dried out to reduce pathogen viability due to low moisture availability. Dry organic material also helps reduce the overall moisture content of the feces, by wicking moisture out of the feces into the drying material or through diffusion.

During wet seasons, moisture may become an issue due to moisture wicking up through the concrete or condensing on cool cement surfaces. When urine is diverted from composting latrines the moisture content of the human compost can fall below the requirements for aerobic or anaerobic decomposition.

Mmolawa (2005) found that pasteurization times of 20 min. at 70 °C (158 °F) and 5 min. at 90 °C (194 °F) did not inactivate all *ascaris* eggs, and 82% found were viable. This finding is concerning because the given duration and temperatures are above Cairncross and Fechem's (1993) graph for temperature disinfection of *ascaris* eggs.

Storage Time Disinfection Method in Composting Latrines

If pathogens are placed in an environment where they cannot reproduce for a long enough period of time, they will become inactive. With storage time, the important factors are limited supply of food needed for pathogens to survive and/or reproduce. Storage time must be coupled with one of the other disinfection methods to guarantee a limit of reproduction or survival of the pathogens. The time required for disinfection of *ascaris* eggs (notably a tough helmith egg to disinfect) under different ambient conditions ranges from 15 days to 2-3 years (Strauss, 1994). This statement was taken from a secondary source: "Health and safety aspects of the use of products from urine-diversion toilets," a report by Peasey (2000). The original transcripts from the lecture Strauss gave in 1994 could not be found.

pH Disinfection Method in Composting Latrines

Most pathogenic microorganisms cannot live under highly acidic or caustic conditions. Ash, a highly basic material, is easily made from organic material that has been burned. pH disinfection in composting latrines usually means that ash, or sometimes lime, is added to the human compost after each use (Mihelcic *et al*., 2009). Most rapid inactivation of *ascaris* ova happens at high pH, >11 (Moe and Izurieta, 2006). Without true composting, adding NaOH to humanure (EcoSan dried feces) reduced pathogens but not to safe levels - *ascaris* eggs were still prevalent (Mmolawa, 2005).

Aerobic Decomposition in Composting Latrines

Aerobic compositing is an unsaturated process and compost should look like a well wrung sponge (Porto and Stienfeld, 2000). The temperatures reached in aerobic decomposition are higher than those reached in anaerobic decomposition. It is unclear if the high temperatures or competition for food causes disinfection in human waste decomposition (Chapman, 1995). Chapman went on to suggest further research of pathogen reduction at mesophilic temperatures, which are below aerobic thermophilic temperatures.

General Composting Disinfection Method in Composting Latrines

General composting can be defined as aerobic or anaerobic decomposition. The EPA also states that composting of sewage sludge can produce class A biosolids (Acquisto *et al*., 2006). Composting disinfection happens at different speeds in composting latrines based on the conditions in the latrine for composting (Haug, 1993). Optimizing the composting process will allow safe materials to be produced from the latrine at a faster pace.

Solar Disinfection Method in Composting Latrines

Solar disinfection should not be confused with irradiation methods of sewage sludge by gamma or beta rays from radioactive sources. Although the sun is radioactive, gamma rays do not reach earth's surface in the required amount for disinfection (Acquisto *et al*., 2006; NASA, 2012). In a 90-sample survey Redlinger *et al*. (2001) found solar exposure to SIRDO had the greatest odds ratio (10.22) of finding class A biosolids in the solar compartment and a 0.95 odds ratio associated with elevated pile temperature. Assuming a 90 sample survey size, the goodness of fit variable reduced chi-squared ($\frac{X^2}{s}$) for their experiment is 0.04, which is almost 2 orders of magnitude smaller than one. The theoretical value for ($\frac{X^2}{s}$) is one. It is unclear to the author why the reduced chi squared for this data is so low but the discussion of the application of the statistics in the paper suggests a misapplication of the statistical software or misunderstanding in the relationships between the variables used in the software. Redlinger *et al*. goes on to state, "pile temperatures should rise due to microbiotic aerobic metabolism and may reach 70 °C (158 °F)" (Porto and Steinfeld, 2000). This statement is not definitive but bin toilets, which the SIRDO can be classified as, have been found to reach thermophilic temperatures (Chapman, 1995).

Ultra violet rays do not penetrate deep into the compost when thin transparent covers are used for solar composting compartments, because the compost is not transparent, unlike water that can be disinfected by UV rays (Mihelcic *et al*., 2009). The pathogen reduction method that occurs in solar composting latrines involves high temperatures, pH and/or desiccation, not irradiation.

Chapter 1.5 Composting Latrines

Composting Latrines General Designs

Many composting latrine designs have been realized. The designs have been influenced by six major designs: (1) chamber, (2) single or dual vault, (3) solar disinfecting, (4) EcoSan, (5) below grade and (6) Clivus Multum latrines. Chamber composting latrines are usually pre-manufactured and made of plastics. Plastics often cannot be manufactured in most developing nations. Chamber composting latrines are frequently the most expensive of composting latrines.

There has been successful wide spread applications of the SIRDO toilet in Mexico, which is a plastic chamber modification of the Clivus Multum design (Redliner *et al*., 2001). Dual vault latrines usually have a compartment for initial use that is converted to storage. High pH materials (ash) are often added to dual vault latrines to reduce odors and aid in pathogen disinfection (Peasey, 2000). Solar disinfection latrines are modified dual vault latrines that include a chamber in which solar heat is utilized to reduce pathogens by creating high temperatures and/or by drying the compost. EcoSan toilets vary in design; the traditional model has a screw process that dehydrates the feces. EcoSan also provides toilets with plastic chambers for composting or placement over a pit latrine (EcoSan, 2012). Below grade composting sanitation, technologies are similar to pit latrines but organic material is added to increase the possibility of composting – trees are sometimes planted over the pit after it is backfilled with soil. Saturated conditions will happen if the pit latrine is dug below the water table leading to ground water pollution. The Clivus Multrum composting toilet is a design proposed by Feachem in the 1980's. The Multrum toilet includes an angled false floor allowing dehydration of the feces as the feces fall (or are raked) down into a secondary compartment. In some Multrum designs, this secondary compartment acts as a solar compartment, or a small fan (run off photovoltaic panels) is installed to improve airflow (Peasey, 2000).

The advantages and disadvantages of composting sanitation technologies are based on economics, operation issues, disinfection effectiveness and ease of construction (see Table 2). Where pathogen infection levels are low, possibly due to good sanitation practices, robust disinfection may not be necessary and killing bacteria, such as E. Coli, may be all that is required. E. Coli requires lower temperature for disinfection as opposed to *ascaris* eggs (Mihelcic *et al*., 2009).

Table 2. Composting latrines design type advantages and disadvantages by category (WHO UNICEF, 2006; GTZ, 2012; Peasey, 2000; Mihelcic et al., 2009)

Composting Sanitation Technologies	Advantages	Disadvantages
Chamber	Hygienic, produces fertilizer for agriculture, varies in price, some prefabricated (consistent performance)	Varies in price, disinfection methods/effectiveness under review, most prefabricated and cannot be built in some developing countries
Single or Dual vault	Can be built locally, inexpensive, with long storage times may provide pathogen free compost	Requires desiccating, composting or high pH material. One study found increase in *ascaris* infections among users over open defecation (Corrales *et al*., 2003).
Solar disinfection	Produces fertilizer for agriculture, can be built locally	Harder to build correctly than single or dual vault latrines. Requires desiccating or composting material. One study found same amount of *ascaris* infections among users as open defecation (Corrales *et al*., 2003).
EcoSan	Prefabricated (consistent performance), waterless, fuel source, many models, varies in price, franchising opportunity	Can be expensive. Disinfection effectiveness under review, shouldn't be used as fertilizer for food (Mmolawa, 2005).
Below grade	No handling, inexpensive	May not reach requirements for aerobic or anaerobic composting
Clivus Multum	Can be built locally or pre-manufactured, waterless	Requires desiccating, composting or high pH material.

Selected Composting Toilets or Latrines, Description, Cost and Materials

The German Technical Cooperation (GTZ), the Water, Engineering and Development Centre at Loughborough University and the South Pacific Applied Geoscience Commission (SOPAC) list details about composting toilet and latrine designs. Selecting an appropriate sanitation technology for development workers requires an ability to compare designs. See Table 3 and Table 4 to compare designs by cost, materials, electricity requirements, ventilation scheme, insulation method, pathogen reduction method and if urine is diverted from the toilet or latrine.

The World Health Organization suggests the cost of the sanitation technology be not more than 1.5% of the household income (Mihelcic *et al*., 2009). High pH materials are added after usage in many composting toilets but the high pH may make the compost unsuitable for most crops (Peasey, 2000). Plastic materials have relatively low thermal conductivities but their insulation value highly depends on the thickness of the plastic.

The *Clivus Multrum Bin* composting toilet is a design proposed by Feachem in the 1980's. The Multrum toilet includes an angled false floor that allows dehydration of the feces as the feces falls (or is raked) down into a secondary compartment. In some *Clivus Multrum Bin* designs, this secondary compartment acts as a solar compartment. A small fan (an active system run off photovoltaic panels) can be installed to improve air flow (Peasey, 2000). The cost of the *Clivus Multrum Bin* is 2,000 to 5,000 EUR and multiple models are available (GTZ, 2012). The urine and feces is mixed which does not allow for the option of urine reuse, because of contamination by the feces (Hoglund, 2001).

The makers of the *Berger Biotechnik* composting toilet suggests that urine be diverted and the toilet system can be installed in multistory buildings, which would allow for installation in developing megacities. Infrastructure would be required to take the compost to farms or to incinerate it. The cost of the *Berger Biotechnik* is 4,000 EUR. (GTZ, 2012)

The *Envirolet* composting toilet requires electricity for a heater and fan. For this reason it may not be applicable to rural locations in developing nations without reliable electricity. The heater requires significant amounts of energy that a small photovoltaic (PV) panel could not easily supply. The heater and fan act together to evaporate excess moisture from the mixed urine and feces. If the heater and fan reduce the moisture, lower than that of composting requirements, desiccation disinfection will start taking place. The cost of the *Envirolet* toilet is 1,400 – 1,700 EUR (GTZ, 2012).

The *High Phoenix* composting toilet requires electricity for a fan, which a PV panel may be able to supply enough electricity. The *High Phoenix* is constructed of polyethylene and acrylonitrile butadiene styrene plastic and is 3,500 – 6,000 EUR (GTZ, 2012). The *Biolan* composting toilet has an insulated (polyurethane foam) composter whose main construction material is polythene plastic: this insulation should allow for higher composting temperatures and quicker pathogen removal. The Biolan diverts urine and costs 600 EUR (GTZ, 2012). The *Biolan* is one of the few composting toilets with insulation.

EcoTech Carousel composting toilet required electricity for a heater and blowers (blowers usually require more energy than fans but are more efficient) thus, the toilet requires a significant power source (e.g. reliable grid connection) in developing countries. Urine is not diverted from the feces in the *EcoTech Carousel* composting toilet. The *EcoTech Carousel* also features a black painted metal shaft, a passive ventilation system, which helps draw air away from the compost, four chambers and a suggested storage time of 1-2 years. Organic material is added during usage. Before usage gravel and soil is placed in the bottom of the container to help leachate drainage. The cost of the *EcoTech Carousel* is 3,000 – 4,000 EUR (GTZ, 2012).

The *Carousel Toilet* used in the Pacific Islands is similar to the *EcoTech* toilet. The toilet has a heat and fan, uses dehydration, and high temperatures for pathogen reduction (Peasey, 2000). The *Ekolet* composting toilet features four compartments, no urine diversion and is made of polyethylene plastic. The cost of the *Ekolet* composting toilet is 800 – 1,400 EUR (GTZ, 2012).

The *Roto-Loo* composting toilet has leachate drainage and the option for urine diversion. The *Roto-Loo* features six compartments and prices start at the low range for composting toilets (GTZ, 2012). The *Sirdo Seco* composting toilet has two compartments is constructed of fiberglass (GTZ, 2012).

The Mexican *SIRDO* (Societatea Independenta Romana a Drepturilor Omului) is a prefabricated solar heated composting toilet that is constructed of polyethylene. The compost is anaerobic (saturated) for the first 24-48 hours then pulled down to the solar chamber for storage times of up to six-months. Various models allow for the different disinfection methods of dehydration or composting at high temperatures (e.g. 70 °C (158 °F)). The *SIRDO* toilet is said to turn human waste into bio fertilizer (Peasey, 2000).

The *Environ-Loo* was designed by Trobe and Trobe (2003) as a toilet to produce humus-like material and reach high disinfection temperatures. Urine is diverted in the *Environ-Loo* and the designers suggest a forced aeration to insure aerobic decomposition (Trobe and Trobe, 2003).

The *Center for Clean Development* (CCD) composting toilet nick named “the coffee maker,” suspends feces with polyester netting that promotes dehydration by allowing air, which is pulled through the compartment by a vent, to contact the compost. The polyester also wicks away moisture (SOPAC 1997).

The *Vietnamese Double Vault* composting toilet (VDVT) has been used as a base design for many subsequent composting toilets. UNICEF (2006) found short storage times (1-2 months) not adequate for pathogen disinfection. Wood ash additives are often used to increase high pH disinfection. One vault is used until 75% full then the vault is sealed for various storage times. Once sealed, anaerobic decomposition may take place and dehydration occurs in the chamber.

McMicheal (1978) reported temperatures reaching 50 °C (122°F) and suggests a reduction of 85% of helminth eggs in two months (SOPAC, 1997). Unfortunately, the data taken by the masters' students in rural Panama does not confirm McMichael and SOPAC's findings (Hurtado 2005; Kaiser 2006; Mehl 2008). Insulating the VDVT chambers should allow for higher thermal disinfection temperatures. Peasey (2000) labels the VDVT as a dehydration toilet as opposed to a composting toilet. Our studies show that possibly during the rainy seasons moisture will wick up the concrete into the dehydrated compost allowing pathogens to regenerate. The VDVT is a very common design used throughout the world.

The *African Batch* compost latrine has two designs, a concrete slab bottom (closed) or a leach pit bottom (open). The designs include no urine diversion, a maximum temperature of 50 °C (122 °F) and vaults are capped off similar to the VDVT (SOPAC 1997). The *Kiritimati Alternating Batch with Evapotranspiration Trench* composting latrine is similar to the VDVT but has a leach pipe that leads into an evapotranspiration trench. The latrine costs 2,000 – 2,500 AUD. The plants in the evapotranspiration trench remove nutrients from the leachate (SOPAC, 1997). The *Mexican Dry Ecological* composting toilet is a modified VDVT that includes urine separation seat that costs $150 in addition to the base price of a VDVT (Peasey, 2000).

The *Guatemalan Double Vault Dry Alkaline Fertilizer Family* (DAFF) is a modified VDVT that has lined chambers, a pot for urine collection with the suggestion of high pH material addition after each use and storage times of 10-12 months. After the being stored for a year in the vault the compost is stored in sacks until use in the field (Peasey A., 2000). The *South African Urine Diversion Dry* toilet is a modified VDVT that has urine diversion sent to a soak pit; high pH materials are also added to reduce pathogens (Peasey, 2000). The *Tecpan Solar Heated* toilet prototype is a modified DAFF that has one solar chamber and 2-3 month storage time suggestion. The *Tecpan Solar Heated* toilet is $150 US (Peasey, 2000).

The *EcoSan toilet* has the urine diverted to a container, high pH materials added and when the compost is used in the field the manufacture suggests that the compost be applied under the soil. The *EcoSan toilet* costs $100 US for the toilet version (Peasey, 2000). The *One-chamber Dehydrating Toilet* is a urine-diversion toilet system for multistory buildings. The feces is dried out and then used as a fuel (Peasey, 2000). The urine is drained into a soak pit, although in hot dry climates most of the urine is evaporated, by a passive system, in a black painted metal pipe (Winblad, 1985).

The makers of the *Two-chambered Solar-heated* composting toilet, when installed in high altitudes suggest that urine diversion may not be required because of high evaporation rates. High pH or sawdust materials are added after each use. The solar chamber has a black painted metal cover and the vaults are made of sun-dried bricks (Peasey, 2000). It is unclear if the toilet acts as dehydration or composting toilet (Dudley, 1993). This is a similar design to the EWB KU design pre-retrofits (EWB KU, 2012).

Table 3. Latrine design with associated power requirement, cost, urine diversion, soil conditioning or pathogen reduction method and reference

Latrine Design	Power Required	Cost	Urine Diversion	Possible Soil Conditioning and/or Pathogen Reduction Method	Reference
Clivus Multrum Bin	yes (fan)	2.000 - 5.000 EUR	no	Dehydration/High Temperature Composting	ecosan website (May, 2012)
Berger Biotechnik	no	4.000 EUR	recommended	Dehydration	ecosan website (May, 2012)
Envirolet	yes (heater/fan)	1.400 - 1700 EUR	no	Dehydration/High Temperature	ecosan website (May, 2012)
Phoenix	yes (fan)	3.500 - 6.000 EUR	no	Dehydration	ecosan website (May, 2012)
Biolan	no	600 EUR	yes	Dehydration	ecosan website (May, 2012)
EcoTech (Carousel)	yes (heater/blower)	3.000 - 4.000 EUR	no	Dehydration/High Temperature	ecosan website (May, 2012)
Ekolet		800 - 1.400 EUR	no	Dehydration	ecosan website (May, 2012)
Rota-Loo	no	500+ EUR	yes or no	Dehydration	ecosan website (May, 2012)
Sirdo Seco	no	500 EUR	no	Dehydration	ecosan website (May, 2012)
SIRDO (Mexico)	no	ND	yes or no	Dehydration/Anaerobic decomposition/Aerobic decomposition/High temperatures 70 °C	Anne Peasey (2000)
Carousel Toilet (Pacific Island)	yes (heater/fan)	ND	no	Dehydration/High temperatures	Anne Peasey (2000)
Environ-Loo	no	ND	yes	Dehydration/High temperatures	IWA 2nd int. symp. (2003)
Center for Clean Development "coffee maker"	no	ND	no (leach pit)	Dehydration	South Pacific Applied Geoscience Commission (1997)
Composting Latrine (Vietnam)	no	ND	yes	pH	South Pacific Applied Geoscience Commission (1997)
Batch Compost Latrine (Africa)	no	ND	no (leach pit)	Dehydration/Aerobic decomposition/High temperature 50 °C	South Pacific Applied Geoscience Commission (1997)
Kiritimati Alternating Batch Latrine with Evapotranspiration Trench (ET)	no	2000 - 2500 AUD	no (Evapotranspiration trench)	Dehydration	South Pacific Applied Geoscience Commission (1997)
Clivus Multrum Vault	no	ND	no	Dehydration	South Pacific Applied Geoscience Commission (1997)
Double Bin Toilet (VDBT) (Vietnam)	no	ND	yes	pH/Anaerobic 2 months/High temperature 50 °C	Anne Peasey (2000)
Dry Ecological Toilet (modified VDBT) (Mexico)	no	seat $150 US	yes	pH/Anaerobic 2 months/High temperature 50 °C	Anne Peasey (2000)
DAFF (modified VDBT) (Guatemala)	no	ND	yes (w/pot)	pH/Anaerobic 10 - 12 months/High temperature 50 °C	Anne Peasey (2000)
Urine Diversion Dry Toilet (modified VDBT) (South Africa)	no	ND	yes (soak pit)	pH/Anaerobic/High temperature 50 °C	Anne Peasey (2000)
ECOSAN Toilet (Ethiopia)	no	$100 US	yes	pH/Decomposition	Anne Peasey (2000)
One-Chamber Dehydrating Toilet (Yemen)	no	ND	yes (evaporation/soak pit)	Dehydration/Burning	Anne Peasey (2000)
Tecpan Solar Heated Toilet Prototype (modified DAFF) (El Salvador)	no	164 US	yes (soak pit)	pH/Dehydration	Anne Peasey (2000)
Two-chambered Solar-Heated Composting Toilet (Ecuador)	no	ND	no	pH/Dehydration	Anne Peasey (2000)

ND = no data

Table 4. Latrine design with associated construction material, insulation level, ventilation scheme and moisture barrier

Latrine Design	Construction Material	Significant Insulation	Ventilation Scheme	Moisture Barrier in Construction Material	Reference
Clivus Multrum Bin	Plastic (assumed HD Polyethylene)	maybe	yes (passive)	yes	ecosan website (May, 2012)
Berger Biotechnik	Fiberglass	maybe	no	yes	ecosan website (May, 2012)
Envirolet	Plastic (assumed HD Polyethylene)	maybe	yes (active)	yes	ecosan website (May, 2012)
Phoenix	Polyethylene & ABS	maybe	yes (active)	yes	ecosan website (May, 2012)
Biolan	Polythene & Polyurethane foam insulation	yes	yes (passive)	yes	ecosan website (May, 2012)
EcoTech (Carousel)	ND	ND	yes (passive and active)	yes	ecosan website (May, 2012)
Ekolet	Plastic, steel reinforced	maybe	yes (active)	yes	ecosan website (May, 2012)
Rota-Loo	Plastic (assumed HD Polyethylene)	maybe	no	yes	ecosan website (May, 2012)
Sirdo Seco	Fiberglass	maybe	yes (passive)	yes	ecosan website (May, 2012)
SIRDO (Mexico)	Polyethylene	maybe	yes (passive)	no	Anne Peasey (2000)
Carousel Toilet (Pacific Island)	ND	maybe	yes (active)	no	Anne Peasey (2000)
Environ-Loo	Plastic (assumed HD Polyethylene)	maybe	yes (passive)	no	IWA 2nd int. symp. (2003)
Center for Clean Development "coffee maker"	Local building materials and wicking polyester	no	yes (passive)	yes	South Pacific Applied Geoscience Commission (1997)
Composting Latrine (Vietnam)	Local building materials	no	no	no	South Pacific Applied Geoscience Commission (1997)
Batch Compost Latrine (Africa)	Local building materials	no	no	no	South Pacific Applied Geoscience Commission (1997)
Kiritimati Alternating Batch Latrine with Evapotranspiration Trench (ET)	Concrete block, wood false floor	no	yes (passive)	no	South Pacific Applied Geoscience Commission (1997)
Clivus Multrum Vault	Plastic (assumed HD Polyethylene)	no	yes (passive and active)	no	South Pacific Applied Geoscience Commission (1997)
Double Bin Toilet (VDBT) (Vietnam)	Concrete, stone, unbaked brick	no	no	no	Anne Peasey (2000)
Dry Ecological Toilet (modified VDBT) (Mexico)	Concrete, stone, unbaked brick	no	no	no	Anne Peasey (2000)
DAFF (modified VDBT) (Guatemala)	Concrete, stone, unbaked brick	no	no	no	Anne Peasey (2000)
Urine Diversion Dry Toilet (modified VDBT) (South Africa)	Concrete, stone, unbaked brick	no	no	no	Anne Peasey (2000)
ECOSAN Toilet (Ethiopia)	Local building materials	no	no	no	Anne Peasey (2000)
One-Chamber Dehydrating Toilet (Yemen)	Local building materials	no	yes (passive)	no	Anne Peasey (2000)
Tecpan Solar Heated Toilet Prototype (modified DAFF) (El Salvador)	Concrete, stone, unbaked brick	no	no	no	Anne Peasey (2000)
Two-chambered Solar-Heated Composting Toilet (Ecuador)	Concrete, stone, unbaked brick, black painted metal solar cover	no	yes (passive)	no	Anne Peasey (2000)

ND = no data

Composting Requirements

Composting or decomposition requires the combination of: (1) moisture (2) oxygen (3) carbon (4) nitrogen and (5) organic material, all in the proper balance (Agnew and Leonard 2003). Carbon-Nitrogen (C:N) ratios are recommended to be 30:1 to 25:1 to begin the composting process (Agnew and Leonard, 2003) but composting can still occur (at a slower rate) with C:N ratios below 15:1 (Haug, 1993). Optimum moisture content is 40-70 percent by mass but varies by materials used to compost (Haug, 1993). Optimum oxygen rate for composting pig feces is 0.48 L/[kg_{DM}-min] (Guo *et al*., 2012). Guo *et al*. went on to conclude that C:N ratios (from 15:1 to 21:1) affect compost final maturity and moisture contents from 65-75% (by mass) had no effect on compost quality. Composting can convert pathogenic waste and organic material into hygienic, biologically stable products. During the composting process, water is required and given off by microbial activity; which makes moisture-control difficult with building materials. When too much moisture is in the compost, the water can leach out of the compartment into the soil reducing the amount of nutrients in the compost and potentially putting pathogens into the ground water (Agnew and Leonard, 2003).

Composting Requirements in Composting Latrines

A carbon-rich, bulking material (wood shavings, straw, etc.) helps allow oxygen to flow through the compost pile and helps get the carbon-nitrogen ratio up. Leachate drainage helps reduce saturated conditions, urine-diversion reduces water content but improves carbon to nitrogen ratios – urine has a carbon to nitrogen ratio of 1:100. Ammonia combined with ash may be a disinfection method useful in composting latrines (Nordin *et al*., 2008). Compost in latrines should look like a well-wrung sponge and be sized for 0.2 m^3 per human (Hazeltine and Bull, 2003). Standard practice in composting latrines is to put a handful or two of dry organic bulking material in after each use.

Composting in Solar Compartments

Direct solar radiation may form a crust on the upper layer of the pile that insulates the compost (Hazeltine and Bull, 2003). Solar radiation, under a transparent cover, will result in surface temperatures around 60 to 80 °C (140 to 176 °F) in the solar compartments during typical summer conditions, which may stop bioactivity at the surface. The materials used to make the compartment should allow for proper aeration rate of the compost. Compost covers can reduce the evaporation of the moisture from the compost but may not be practical in dual vault systems.

Chapter 1.6 Case Studies (Conference and Journal Paper Review)

Solar Desiccating, Pit Latrine and Double Vault Urine Diversion Desiccating Latrines

Compared to no latrine usage, Corrales *et al*. reported no reduction of *ascaris* infections among users of solar desiccating latrines or pit latrines and found an increase in *ascaris* infection among users of double vaulted urine-diverting desiccating toilets (DVUDT). There was a reduction in Trichuris and hookworm infections with solar and pit latrines compared to no latrine use, but again, there was an increase in infection when double vault urine-diverting desiccating latrines were used. This report could be associated with improper usage of dual vault latrines, but the design is flawed if people do not use the latrine correctly.

Giardia and E. histolitica infections were decreased when DVUDT, solar and pit latrines were used. There was a slight increase of E. histolitica infection incidence in pit latrines, compared to no latrine usage. These findings imply bacteria and viruses are inactivated by desiccation but helmiths are not (Corrales, Izurieta, Moe, 2003). Two of the authors continued the research in El Salvador and published more information about the disinfection methods in double vault urine diverting toilets.

Disinfection of Pathogens in Double Vault Urine Diverting Toilets

Moe and Izurieta found the main disinfection methods in DVUDT were storage time with high pH levels. The one-year study found zero mature female *ascaris* worms in solar toilets and the die off worms to be associated with high temperatures (Moe, Izurieta, 2003). Higher numbers of fecal coliforms (bacteria) were found in solar toilets than DVUDT's and the researchers predicted all *ascaris* would be inactivated in approximately two years (Moe, Izurieta, 2003). A research question that came from this work was how the climate affects microbial inactivation in composting latrines (Moe and Izurieta, 2003).

Challenges and Research Questions for Sanitation in Developing Nations

Double vault solar toilets used in rural El Salvador (DVST-ES) that were studied by Moe and Rheingans in 2006 are similar to the KU solar composting latrine except that the solar compartment in the KU design is above ground. Insulation is not included in the (DVST-ES) and the heat loss to the ground is high. The KU designs reduce the evaporation of moisture from the compost to compartment air. The DVST-ES has a corrugated metal cover that has been painted black (similar to some permutations tested at KU). In El Salvador, Moe and Rheingans reported *ascaris* ova disinfection but there was no mention of *ascaris* egg populations, suggesting that disinfecting the female worms should stop egg production.

The research questions posed by Dr. Moe and Dr. Rheingans were, "what is the nutritional benefit of EcoSan toilets, how does climate effect microbial die-off, how does high pH conditions affect the fertilizer value of the bio solids and what are effective approaches for marketing dry sanitation in low-income and middle-income countries" (Moe and Rheingans, 2006). The studies presented in this paper attempt to answer the climate effects on solar composting compartments by supplying high quality data and analysis.

Composting Latrines in Rural Panama

Dual vault latrine designs were studied by three master's students from Michigan Technological University (MTU) in rural Panama. They found average compost temperatures were slightly above ambient temperature (Hurtado, 2005; Kaiser, 2006; Mehl, 2008). In the MTU studies, the desiccant pathogen reduction method was used, 3-6 month storage times were suggested and *ascaris* eggs were found in all samples taken before the 6-month storage time – nothing was reported about pathogens after the 6-month storage time (Mehl, 2008).

The Enviro Loo Designer Claims

The Enviro Loo is a zero discharge unit driven by radiant heat and wind power. A storage time of 2-3 years is recommended. Forced aeration is used for deodorization. An increase of 10 degrees over ambient temperature in radiant heat ventilation systems does not inactivate helminthes. "Forced aeration composting can have temperatures up to 65 to 70 °C (149 to 158 °F) and produces humus-like material" (Trobe and Trobe, 2003). If temperatures of 65 to 70 °C (149 to 158 °F) are reached for one hour, high-temperature disinfection is taking place (Cairncross and Feachem, 1993).

Control of Aeration in Static Pile Composting

Static pile composting is similar to composting in latrines because they are not usually turned. Composting in a static pile poses issues with aeration rate and a fixed rate aeration system would cool the static pile when microbial activity was low and a variable forced-air system would be hard to operate on small scales (Leton and Stentiford, 1990). The optimum oxygen rate for composting pig feces (the animal feces most similar to human) is 0.48 L/[kg_{DM}-min] (Guo *et al*., 2012).

Control of Aeration in Static Pile Composting in Solar Compartments

Natural convection loops inside the compartment will allow for hot-moist air to rise through the pile, and wind on the outside of the compartments will create negative pressure on the leeward side of the compartment causing infiltration on the windward side and exfiltration on the leeward side. This convection loop allows fresh air to enter the pile.

Chapter 2 Objectives and Approach

Objectives

The objectives for the research were to:

1. Develop composting latrine technology to achieve full thermal disinfection using solar and/or composting heat generation.
2. Construct and instrument eleven full-scale solar composting compartments to examine construction materials, cover materials, insulation, and other factors.
3. Compare concrete and wood construction materials for thermal effectiveness.
4. Compare various clear, translucent and opaque lid materials for thermal effectiveness.
5. Examine effects of bottom, top and side insulation, and temperatures achieved throughout the simulated compost.
6. Examine effects on compost moisture of various design and operational approaches.
7. Develop guidance for solar and composting heat generation approaches to thermal disinfection of compost.

Approach

Full-scale solar composting compartments were built and thermocouples were used to record temperatures in simulated compost, simulated compost with simulated heat generation and actual horse-manure compost. By simulating compost and heat generation, compost heat generation could be controlled in the experiments. With heat generation controllable, the affects of building material properties could be studied. By using horse-manure compost, the affects of weather on thermal performance of the compost could be studied.

Chapter 3 Materials and Methods

Experiment Design

Full-scale solar compartments of various materials and constructions were built at the Nelson Environmental Study Area North of the University of Kansas (Figure 2). To test reproducibility, calibration, and verification experiments were conducted on some of the sensors used at the field site. Key equipment used for logging data includes high quality weather sensors and twisted thermocouple wire.

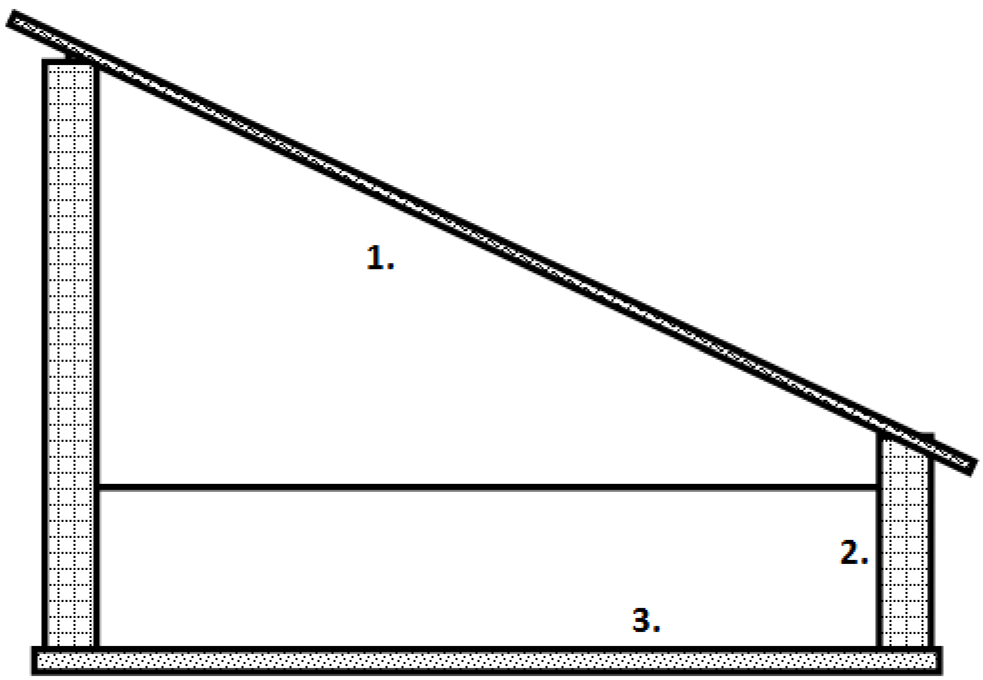

Figure 2. Schematic of a typical solar composting compartment

1: Transparent, translucent and opaque materials were used as cover materials.
2: Concrete block, wood, polycarbonate and hay insulation materials were constructed as walls for the solar compartments.
3: Concrete slabs were poured and rigid extruded polystyrene (post construction) or plastic wrapped straw (post and pre construction) was used for insulation.

To determine the performance of cover materials, wall constructions or slab insulation techniques direct comparisons were set up with only one variable changed. Direct comparisons were analyzed because weather variables (e.g. solar radiation, ambient temperature and wind) vary significantly day to day. All designs tests were given permutation numbers and can be compared indirectly when weather parameters are similar. Simulated compost had simulated heat generation added to compost by an experimental method. This allowed the distribution and control of the heat generation process in the simulated compost. Simulated compost (pulverized-loamy soil) was used because of its low potential for undergoing decomposition and producing heat – skewing thermal performance results.

Chapter 3.1 Equipment, Sensor Verification and Sensor Calibration

An Agilent 34980A data logger with three 20-channel multiplexers was connected to a laptop to record analog signals from twisted-wire thermocouples. Extension and thermocouple grade type T 20 and T 24 gauge wire was used in the experiments. To verify the accuracy of different thermocouple wire grades, gauges, and treatments, an experiment was conducted in an ice water bath. The accuracy was within one degree Celsius (Figure 3). It was determined that compensated-barrier strips reduce noise from temperature changes at connection points compared to uncompensated barrier strips when connection points were warmed with a torch (not shown). To test thermocouple accuracy at water-boiling conditions an experiment was run but inhomogeneity of the fluid temperature by depth made it difficult to test multiple thermocouples and thus boiling-water verification data were disregarded.

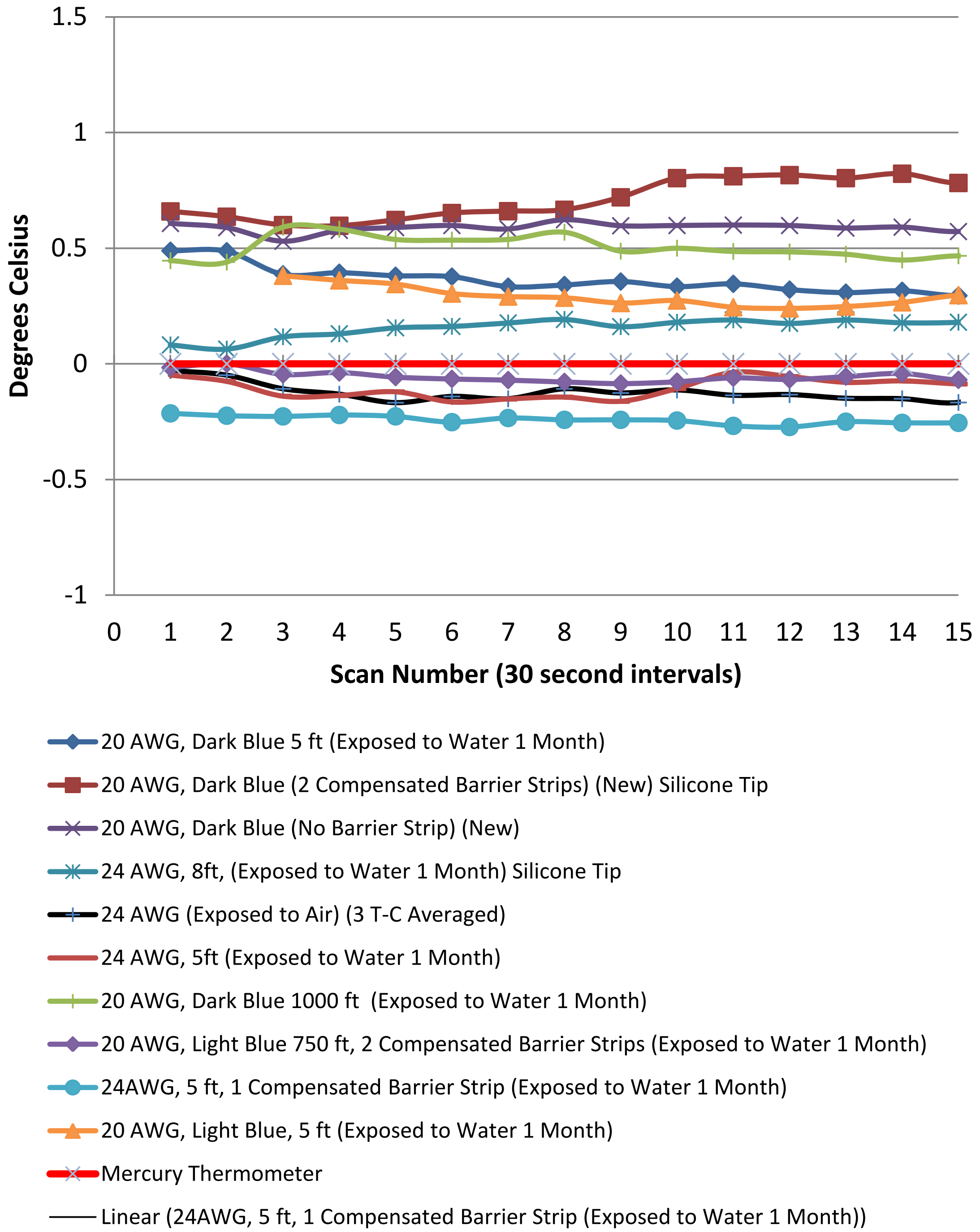

Figure 3. Pre-installation thermocouple accuracy by: (1) gauge (2) length (3) color (4) barrier strip configuration and (5) water exposure

After one year of logging data, ice-bath-verification experiments were conducted for random sensors and sensors with the longest wire-run from the logger box. The results of the verification experiment showed thermocouple grade wire connected to extension grade with no barrier strips were ± 0.25 °C (0.45 °F) and extension grade wire as thermocouples were ± 1 °C (1.8 °F) accurate on average (Figure 4). Compartment Five has extension grade twisted thermocouples and compartment 11 has extension grade wire connected to twisted thermocouple grade thermocouples. Compartment One was verified as having accuracy within 0.75 °C after one year of use (not shown).

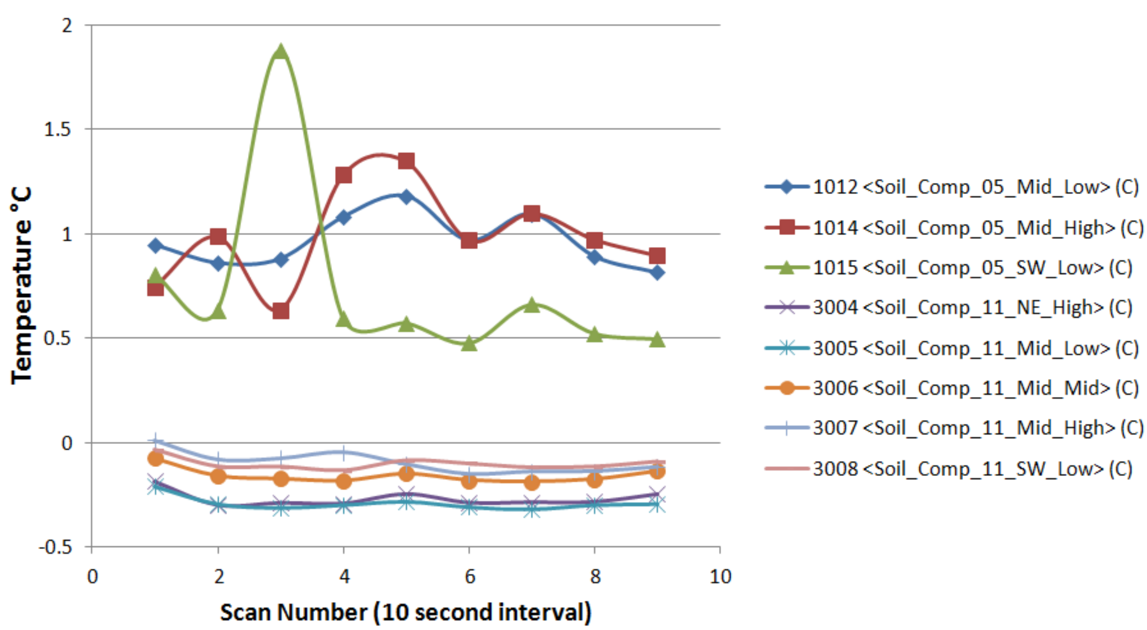

Figure 4. Compartment 5 and 11 temperature readings when sensors were placed in ice bath

Pulverized loamy soil (simulated compost) was used in the first year to determine the thermal performance of the compartments under desiccation disinfection conditions. To assure no thermal activity in the simulated compost, an experiment was conducted where one 700 ml sample of soil was baked overnight at 121 °C (250 °F) and the other sample was left as a control. As expected, the baked sample reaches slightly higher peak temperatures because all the water had been removed by the baking process in the simulated-compost thermally inert experiment (Figure 5). The simulated compost in the compartments had a volumetric water content of zero to ten percent depending on the ambient conditions. During the wet spring, a shortened version of some developing countries "rainy season", moisture would wick up through the concrete into the desiccated simulated compost increasing the moisture content at the lowest levels of the compartments.

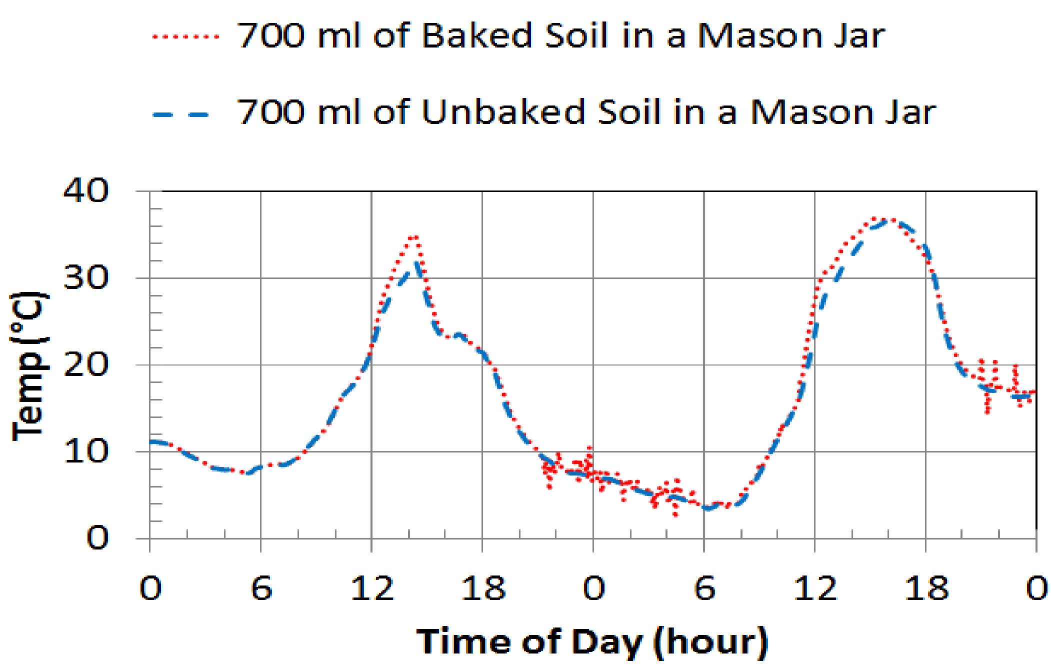

Figure 5. Simulated compost thermally inert experiment

Simulated Heat Generation Details

Christmas lighting was used to generate heat (incandescent lights are 10% efficient with 90% of energy given off as heat) in the simulated compost at a rate of 200 Watts/m^3 throughout the simulated compost. No significant amount of light left the simulated compost and it was assumed that 100% of the energy being sent to each light was ultimately converted to heat. The strip lighting energy output for each compartment was switched and controlled by one autotransformer (see Figure 6). Wattage output was read by a P3 Kill –A-Watt monitor (P3I, 2012). The energy being sent to each set of strip lights was the same because the light strips for each compartment were wired in parallel.

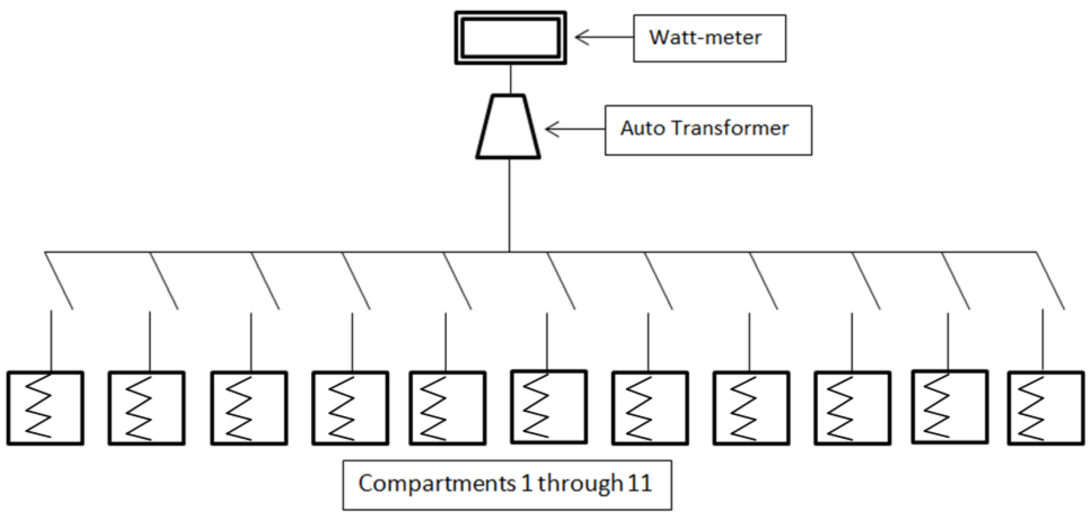

Figure 6. Diagram of the electrical setup for heat generation from the watt-meter to the strip lighting (heaters) in the compartments

All compartments were outfitted with strip lighting at three levels (3", 6" and 9" deep from the top of the compost) in the simulated compost. Seven rows of lighting were placed per level separated by 12.7 cm (5 in.) per row (appendix D Figure 22). In the mounded compartment, lights were placed in a reducing square fashion (appendix D Figure 23). Four levels of light strips were installed in the mounded compartment.

Simulated Compost and Compost

Simulated compost density and compost density were measured by cylinders and mason jars, respectively (Table 5-6). A compost sample was also separated by taking out the manure clods to determine the initial moisture content of the manure and bulking materials (e.g., straw and wood shavings). The bulking materials had a gravimetric water contents (GWC) of 60.0% and the manure had a GWC of 76.6%. The compost samples that were placed into the solar compartments had been taken from a pile one-week old that was rained on several times during that week.

Table 5. Simulated compost density table

Weight of Sample (g)	Weight of bag (g)	Weight of Pipe (g)	Volume of pipe (m^3)	Density (g/m^3)
129.7	9.95	71.7	4.12E-05	1.17E+06
129	9.95	70.8	4.00E-05	1.21E+06
127.34	9.95	70.9	4.14E-05	1.12E+06
128.3	9.95	70.8	4.11E-05	1.16E+06
			Average Denisty	1.16E+06

In Table 5 $Density = \frac{weight\ of\ sample - weight\ of\ bag - weight\ of\ pipe}{Volume\ of\ pipe}$. The average density of the simulated compost was 1.2 g/ml at dry conditions (<10% GWC). The average density of the horse manure compost used for experimentation is 0.14 under dry conditions and 0.38 g/ml at 70 % GWC. The methods for obtaining compost density were similar to that of simulated compost but mason jars, filled to 700 ml with compost, were used (table not shown). The compost was initially wet, which is why wet and dry densities were measured. The compost held its form during the drying process and the level of compost in the jar did not recede.

One-week-old compost was added to four compartments. The age of the compost added to solar composting latrines currently used is from one-day to one-year old. The effect of compost age on heat generation needs further research, but average values of 200 Watts/m³ was used in the simulated compost.

When water leaked into the mason jars used to test the thermal inertness of the soil, an opposite result was observed (Figure 7). This result suggests that the temperature readings in the simulated compost can become inaccurate when moisture has leaked into the compartments.

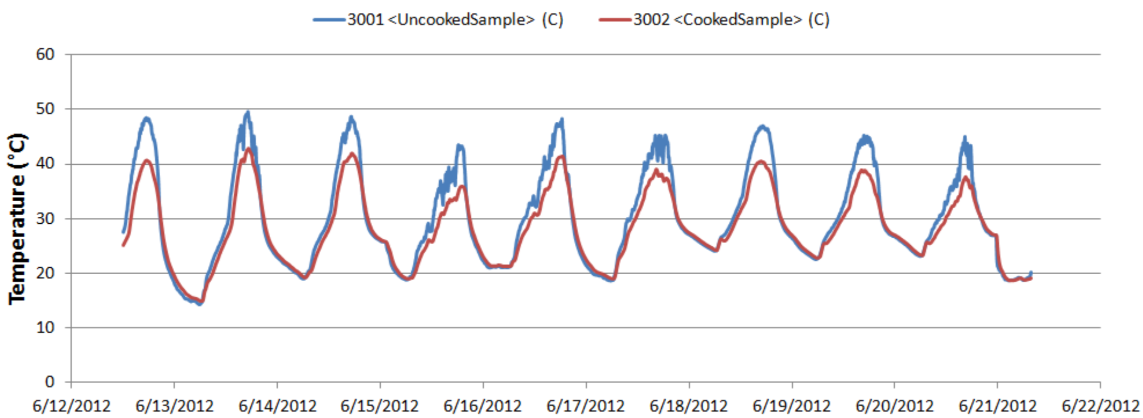

Figure 7. Simulated compost thermally inert experiment after one year

The unbaked/uncooked sample recorded higher internal temperature than the baked/cooked sample. Green mold was seen in both jars, suggesting organic activity.

All compartments had six averaged thermocouple readings logged but in two compartments, sensors were also placed on the cover, the slab and the slab insulation. The data for the additional sensors is graphed (compartment 3 and compartment 4) when available.

Water was added to the simulated compost to determine the effects of water on the thermal performance of the compartments. An un-insulated double wood compartment had 45 gallons of water added. The water addition theoretically, brings the GWC of the simulated compost to 50%, although some of the water leaked out the bottom of the compartment.

The volumetric water content (VWC) probes were placed towards the middle of the compartment and inserted into the compost with the top of the probe level with the compost (about 4” deep). The estimated error for the installed probes was ± 5% volumetric water content for the handheld DSMM500 moisture probe (GT, 2012) in compost. Error in Vegetronix probes in soil was suggested by the manufacture to be 2% (Vegetronix, 2012). The error for the Vegetronix probes in compost was estimated to be 5% because of an offset of 5% of the probes when the probes were placed in dry compost (graph not shown). Linear curve fits were used to enter coefficients into the data logging program to record moisture for each Vegetronix probe in simulated compost (Figure 8) and compost (Figure 9).

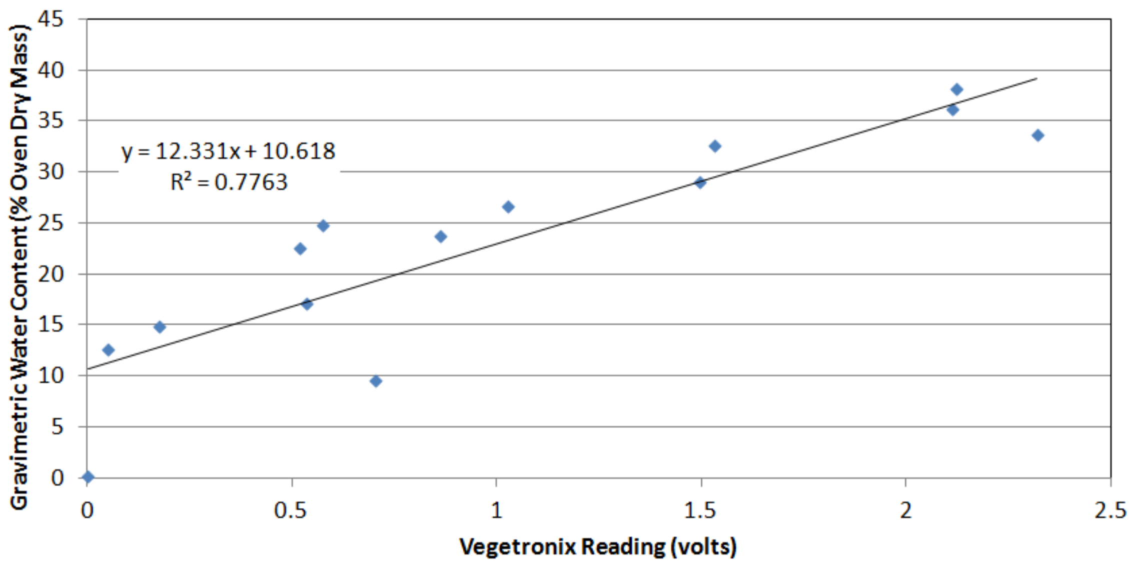

Figure 8. Example of linear-curve-fit for Vegetronix probe in simulated compost

For actual compost, the curve fit found using Vegetronix probes was worse (Figure 9) than for the simulated compost (Figure 8). This is likely due to increased air space of the compost compared to simulated compost (loamy-soil). When the coefficients from the curve fits for the four individual probes were entered into the logger software for gain and offset, the readings at 0% compost moisture varied up to 5 % (graph not shown). The manufacture literature claims that for soil the probe was accurate to within 2%.

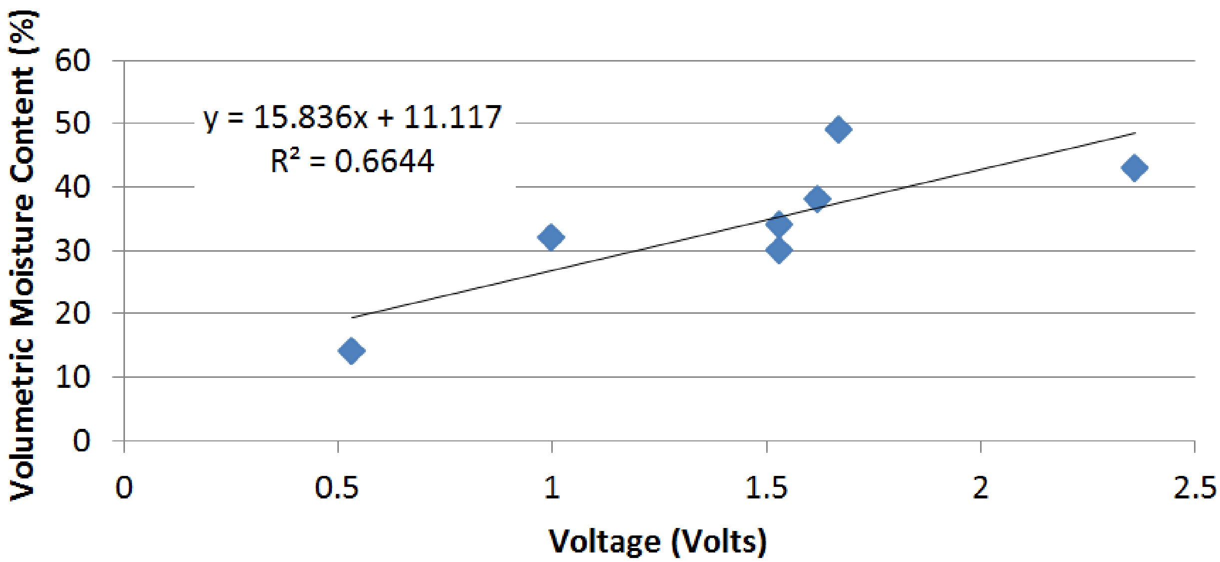

Figure 9. Example of linear-curve-fit for Vegitronix probe in compost

A hand held DSMM500 volumetric moisture content probe was used to report moisture data in compost and simulated compost over time. The maximum reading the probe was capable of handling was 50% VWC, thus readings above 50% VWC were reported as 50% VWC in the moisture graphs.

An Apogee SP-110 Pyranometer (Apogee, 2012) was set at an elevation angle of 39° and azimuth angle of 342° (appendix D Figure 18); the same angles as the compartment walls and cover. A rule of thumb for selecting the elevation angle for solar composting latrines is setting the angle equal to the latitude at the location of the latrine. Regression analysis was performed for two weeks of solar radiation data, logged from two sensors in early July. The slope of the regression between horizontal Pyrometer and tilted Pyranometer was 0.96 (Figure 10) thus, 1 – 0.96 = 0.04 or 4%. It was assumed that both meters could not record reflected radiation, as the manufacture of the Pyranometer stated such (Apogee, 2012) and no manufacture data could be found for the Pyrometer.

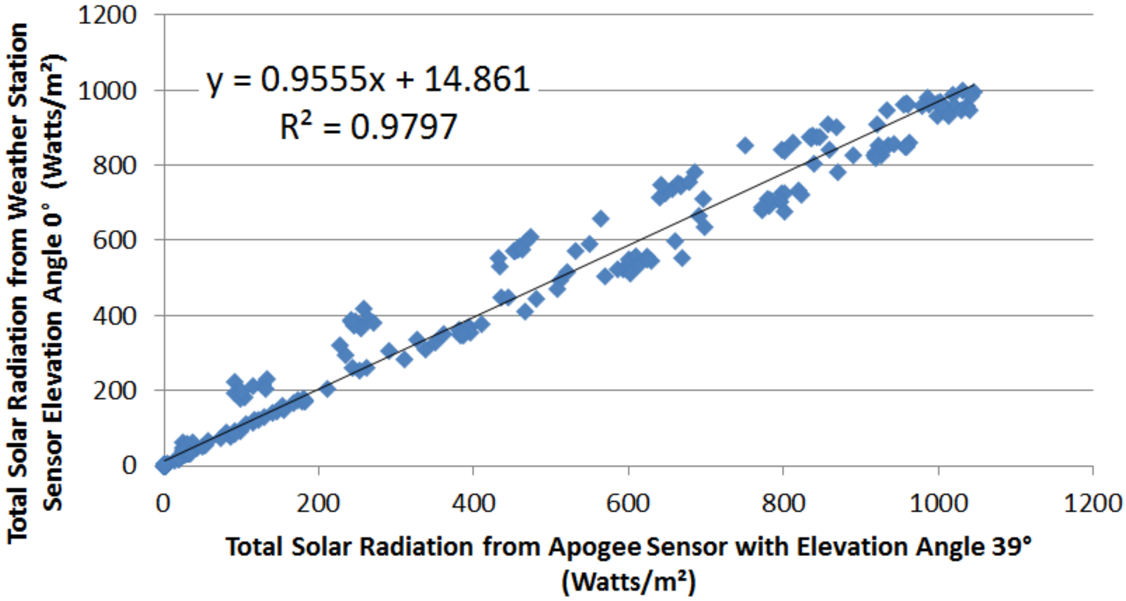

Figure 10. Sensor readings (5 minute interval averaged to hourly) vs. weather station readings (hourly)

The tilted radiation sensor recorded higher radiation values by 4%. Suggesting, a cover with an elevation angle of 39° will increases the flux of radiation to the cover surface by 4% during the early summer months. The accuracy for the Pyranometer (tilted sensor) was 1% for an elevation angle of 45° (Apogee, 2012), which is close to the angle it was set at (39°). The Pyrometer (horizontal-weather-station sensor) was assumed to have equal or greater accuracy than the tilted sensor.

Chapter 3.2 Reproducibility and Data Management

Eight of the eleven compartments were set up with the same cover material to check the variability of wall construction, and temperatures in the simulated compost were compared between the as-built compartments. The highest variance of 2.5 °C (4.5 °F) (Figure 11) was between hay insulated wood wall designs over a typical two-day span. The hay insulation acts as an infiltration/exfiltration retarder in double wood designs and the method of installing the insulation was difficult to keep consistent.

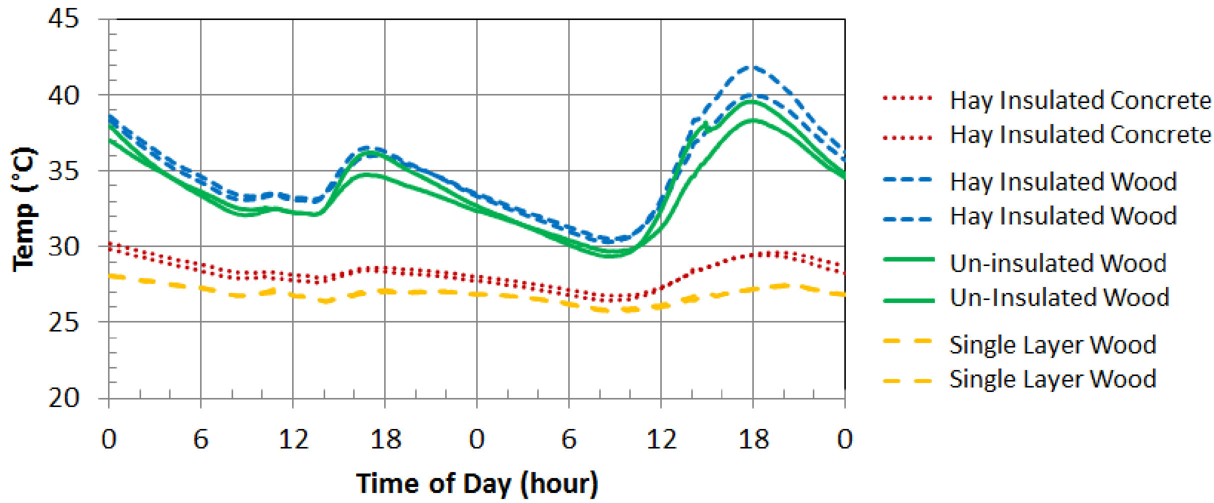

Figure 11. Reproducibility of "as built" compartment designs

Sensor Locations

By wiring twelve twisted wire thermocouples in parallel, the temperature recordings were averaged into six readings. Five readings from the simulated compost or compost, and one reading from the compartment air temperature. The sensor locations for all non-mounded compartment designs are spread out throughout the compartment (Figure 12).

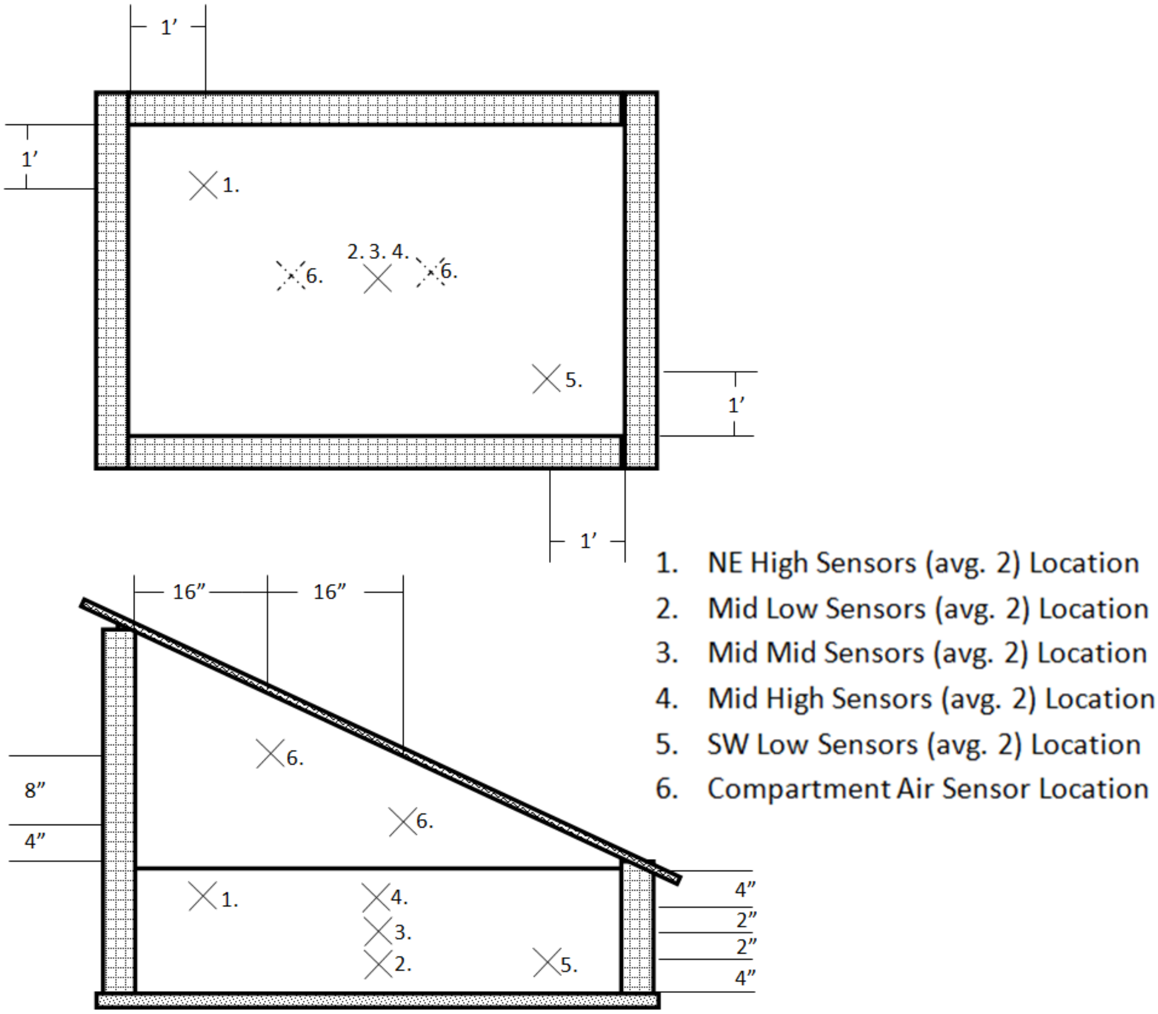

Figure 12. Typical sensor locations (figure not to scale)

Sensors were at three levels: 4", 6" and 8" (10cm, 15.2cm and 20.3cm) (measured from the top of the compost) in the middle of the compartment. The sensors in the North East (NE) and South West (SW) corners were placed 1 foot in from each wall. Two air sensors were averaged to obtain the compartment air temperature, sometimes called interior temperature

Data Acquisition

Eleven compartments were constructed on concrete slabs rotated eighteen degrees west of north (15 degrees west of true south) within 300 feet of the National Resources Conservation

Services KU-NESA site 2147 weather station which is located at the Nelson Environmental Study Area. The weather variables recorded at the weather station are numerous (Figure 13). The weather station also records many soil characteristics.

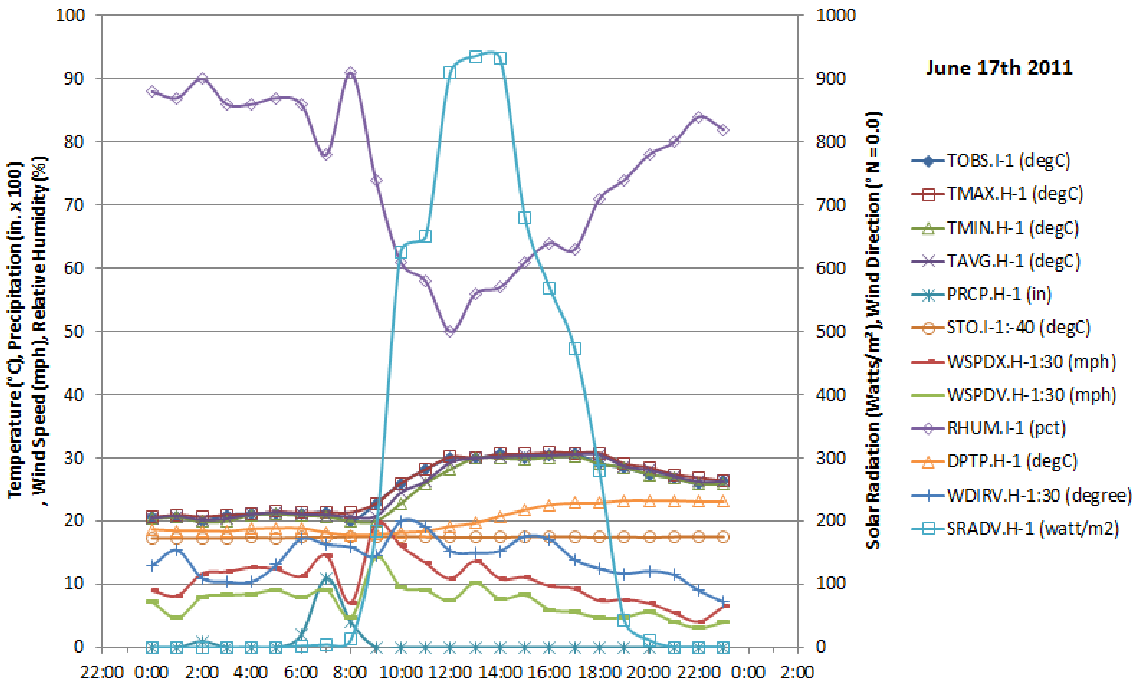

Figure 13. Example weather station data, averaged hourly

TOBS.I-1 (wet bulb temperature), TMAX.H-1 (ambient temperature max), TMIN.H- 1 (ambient temperature min.), TAVG.H (ambient average temperature), PRCP.H-1 (precipitation in inches), STO.I-1:-40 (ground temperature 40" deep), WSPDX.H-1:30 (wind speed maximum), WDPDV.H-1:30 (wind speed average), RHUM.I-1 (relative humidity), DPTP.H-1 (relative humidity), WDIRV.H-1:30 (wind direction; North = 0 NE = 90), SRADV.H-1 (total solar radiation).

Weather data was recorded starting when the compartments went online in March of 2011. Average ambient temperature, wind speed, wind direction, precipitation, and solar radiation were the most important weather data for solar composting compartment performance.

Compost moisture and simulated compost moisture was recorded for various periods during the experiments.

Data Treatment

Data was averaged and graphed for all permutations (supplemental appendix). The permutations were then compared by average compartment compost or simulated compost temperature. Sensor readings (average of two thermocouples) for selected permutations were graphed and analyzed based on profiles. Peak temperatures at durations of 2, 4, and 12 hours was determined from the profiles and recorded in appendix B.

Solar Compartment Constructions

Various materials were used to construct the 11 solar compartments and fall into three main categories: wall (Table 6), insulation (Table 7) and cover construction (Table 8). All compartments were built with an 8.9 cm (3.5 in.) concrete slab and similar support structure for the cover materials.

Table 6. Solar compartment experimental wall constructions

Abbreviation	Name	Wall Construction
SW	Single Sided Wood	2"x6" Pine Lumber
MWP	Mounded White Plastic	6 Mil White Translucent Polyethylene
MBP	Mounded White Plastic	6 Mil Black Opaque Polyethylene
UDW	Un-insulated Wood	2"x6" Pine Lumber, 3.5" Air Gap, 2"x6" Pine Lumber
UC	Un-insulated Concrete	6"x8"x12" Concrete Block
SIDW	Insulated Wood	2"x6" Pine Lumber, Hay Insulation, 2"x6" Pine Lumber
SIC	Insulated Concrete	6"x8"x12" Concrete Block Loosely Filled with Hay
DP	Double Layer Polycarbonate	1/4" Polycarbonate Sheeting, 1.5" Air Gap, 1/4" Polycarbonate Sheeting

The wall thicknesses are different for the various wall constructions, which lead to the exterior dimensions being different between the designs. The difference is most noticeable between the single sided wood and the concrete block. The interior dimensions in the concrete block compartments are slightly smaller (3” (7.6 cm) in each direction) than the wood compartments. The actual difference in volume of compost between the concrete block compartments and the wood compartments is one cubic foot.

Table 7. Solar compartment experimental insulation constructions

Abbreviation	Name	Insulation Construction
SI	Top of Slab R15 Insulation	3.5" Concrete, 1.5" Extruded Polystyrene XPS Sheeting (R-7.5 ft^2 °F h / Btu), 1.5" Extruded Polystyrene XPS Sheeting (R-7.5 ft2 °F h / Btu)
none	Top of Slab Straw Insulation	3.5" Concrete, 6 Mil Black Opaque Polyethylene, 6" Loosely Filled Straw, 6 Mil Black Opaque Polyethylene
none	Bottom of Slab Bag Insulation	3.5" Air Gap Filled with Plastic Shopping Bag (Stuffed Loosely with Straw), 3/4" Plywood
none	Top of Compost Straw Insulation	6 Mil Black Opaque Polyethylene, 6" Loosely Filled Straw, 6 Mil Black Opaque Polyethylene
TI	Top of Compost R15 Insulation	1.5" Extruded Polystyrene XPS Sheeting (R-7.5 ft2 °F h / Btu), 1.5" Extruded Polystyrene XPS Sheeting (R-7.5 ft2 °F h / Btu)
SC	Compost Evaporation Cover	3 Mil Transparent Polyethylene

Extruded polystyrene XPS sheeting, sometimes called pink-board, was fitted with butt joints between the cut pieces of the board. The black opaque polyethylene straw insulation was duct taped together at the seams. The plastic shopping bags were loosely stuffed with straw and the handles of the bags were tied together.

Table 8. Solar compartment experimental cover constructions

Abbreviation	Name	Cover Construction
SCP	Single Layer Polycarbonate	1/16" Transparent Corrugated Polycarbonate
DCP	Double Layer Polycarbonate	1/16" Transparent Corrugated Polycarbonate, 3/4" Air Gap, 1/16" Transparent Corrugated Polycarbonate
WFG	White Fiberglass	1/32" Corrugated Translucent White Fiberglass
M	Metal	1/32" Corrugated Galvanized Steel
BMP	Black Painted Metal	1/32" Corrugated Galvanized Steel Painted Black (Flat Sheen)
WP	White Plastic	6 Mil Translucent White Polyethylene

Covers were attached to wood frames with screws that had rubber washers. The black painted metal covers were spray painted with a flat black paint. The 6-mil white plastic covers were secured by folding the plastic under boards that were screwed to the cover frame.

Chapter 4 Heat and Mass Transfer Theory in Composting Latrines

In this chapter, empirical data is not reported but sometimes used in attempts to develop mathematical models of the heat and mass transfer between composting latrines and their environment. Analysis of observations, literature reviews, order of magnitude hand calculations and class work led to the qualitative results discussed. The chapter is intended to give the reader background information to the heat and mass transfer that occurs in composting latrines.

Hypothesis

The variables that may affect thermal-disinfection are construction materials permeability, thermal insulation and cover transparency. These construction variables allow for appropriate levels of moisture (e.g. 40% to 70% GWC) and oxygen (e.g. 0.48 L/[kg_{DM}-min] in composting disinfection, high temperatures for temperature disinfection and evaporation/high temperatures for desiccation (Haug, 1993; Guo *et al*., 2012).

Theoretical Thermal-Disinfection Composting Compartment Design Goals

The design goal for composting latrines is to provide safe hummus-like material for use on crops for developing nations. In the literature, no composting latrine design has guaranteed complete disinfection. The design methods suggested in this paper for composting compartments are (1) to protect composting heat generation or (2) to heat the compost with solar energy. Because not all material from the latrine chamber is composted when the material is moved to the second composting chamber, Method (1) is a theoretically more viable solution than solar-heat disinfection. Method (2) may also kill good biological activity in the top layer of the compost due to excessively high temperature and dry the compost (even with a evaporation cover). Reducing evaporative losses in both designs will steady the amount of water in the compost and avoid heat losses associated with evaporation.

Chapter 4.1 Heat and Mass Transfer in Solar Composting Latrines

The Three Modes of Heat Transfer

The three heat transfer mechanisms are conduction, radiation and convection. The definition of convection can include evaporation and boiling. Conductive heat transfer is present in non-moving gases but is assumed negligible in this thesis. Radiation between interior wall surfaces is assumed negligible when insulation is placed on top of the compost and an opaque cover is used, because the interior surfaces are very near the environment temperature.

Generalized Steady State Energy Balance

A non-steady state generalized energy balance for composting has been proposed by Mason (2005) but for use of selecting construction materials, a generalized steady state energy balance was determined for chamber static pile composting. The steady state energy balance for chamber static pile composting is:

$$E_{comp.gen.} + E_{sun\,rad.} + M_{air\,in} \times h_{air} + \sum M_{water\,in} \times h_{water} = E_{conv.env.} + E_{cond.grnd.} + E_{sky\,rad.} + M_{air\,out} \times h_{air} + M_{water\,out} \times h_{water}$$

Eq. (1)

where, $E_{comp.gen.}$ is the energy generated by the decomposition and this term can be limited by many parameters (Haug, 1993), $E_{sun\ rad.}$ is the amount of sun energy reaching the compartment and is highly dependent on cloud cover. $M_{air\ in} \times h_{air}$ is the amount of energy entering the chamber due to air infiltrating the compartment, where h_{air} is the enthalpy of the air and is temperature dependent. $\sum M_{water\ in} \times h_{water}$ is the amount of energy entering the compartment via water and comes into the compartment in different ways, moisture in the infiltrated air and moisture wicking up through the concrete. The amount of water infiltrating by air movement is negligible when true composting designs are used (high moisture). $E_{conv.env.}$ is the amount of energy transferred between the wall surfaces and the environment by convection. $E_{cond.grnd.}$ is the amount of energy transferred between the concrete slab and the ground (sink). During changes in season, the ground is sometimes a source of heat for the slab. $E_{sky\ rad.}$ is the amount of energy radiated from the compartment surfaces to the sky and is significant heat loss path between the cover and the sky. $M_{air\ out} \times h_{air}$ is the energy lost to the environment due to dry air exfiltration. $M_{water} \times h_{water}$ is the energy loss due to moisture diffusing and exfiltrating from the compartment after evaporating from the compost.

Heat and mass transfer diagram

A diagram (Figure 14) of the heat and mass transfer methods helps visualize the movement of heat and mass throughout the compartment.

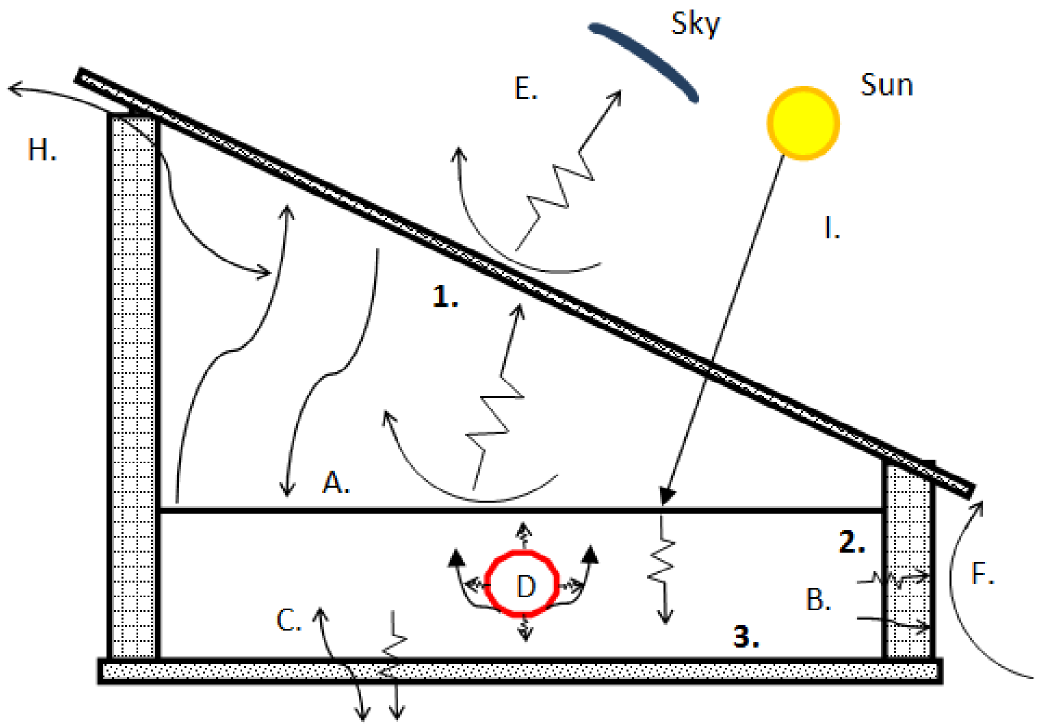

Figure 14. Heat and mass transfer diagram for solar composting compartments

A: Mass and heat are transferred by evaporation/condensation, convection, and long wave radiation.
B: Mass and heat are transferred by diffusion and conduction.
C: Mass and heat are transferred to the ground by capillary forces and conduction.
D: Heat is generated by biological decomposition and conducted (in all directions) convected upwards.
E: Heat is transferred by radiation and convection to the sky and ambient conditions.
F: Heat is transferred by radiation to the sky and heat and mass is transferred by convection to the ambient conditions.
H: Mass and heat are transferred by infiltration and exfiltration through connection points and materials.
I: Heat is transferred through the transparent lids by short wave solar radiation and conduction into the compost.

The sun warms the surface of the compost when translucent covers are chosen and the heat is conducted down through the compost. When opaque covers are used, the solar radiation does not reach the compost surface.

Moisture Transfer Methods

Moisture is transferred by diffusion, wicking and condensation in the materials of composting latrines. Moisture can wick up through the concrete slab into the desiccated compost when the soil becomes saturated with water during rainy seasons. For example, water can diffuse through the walls of a compartment into the desiccated compost when the ambient conditions are more humid than in the compost. Condensation occurs on cool materials that come into contact with warm humid air (e.g., on the inside of compartment covers at night, on cement walls in the early morning, and on plastic placed directly on top of the compost). Evaporation produces a cooling effect on compost and should be avoided, in general, when trying to reach composting conditions in solar composting compartments.

Heat Transfer Properties of Building Materials Commonly Used in Latrines

Lower conductivities, emissivities, permeabilities, convection coefficients and solar absorptivities will increase the thermal performance of the solar compartment walls, covers and concrete slabs. Higher transmissivity of the cover materials result in higher temperatures in the compost under solar-heating conditions.

Chapter 4.2 Qualitative Descriptions of Heat and Mass Transferred in Composting Latrines

Radiation Heat Transfer in Composting Latrines and Solar Compartments

The equation $q_{1\text{-}2} = \sigma (T_1^4 - T_2^4)/ [(1 - \varepsilon_1)/(\varepsilon_1 A_1) + 1/(A_1 F_{12}) + (1 - \varepsilon_2)/(\varepsilon_2 A_2)]$ was used to calculate radiation heat exchange ($q_{1\text{-}2}$) between surfaces with emissivities (ε_x) of similar areas (A_x), where σ is the Stephen-Boltzmann radiation constant. Radiation heat loss between the cover and the sky is the most signification source of radiation heat loss - about 30% of radiation heat exchange based on the equation $q_{1\text{-}2} = \sigma\, \varepsilon_1\, A_1\, (T_1^4 - T_2^4)$ assuming the sky area is much greater than the compartment cover. Absorbing heat is the most significant source of radiation heat gain in solar composting compartments (e.g. compost surface under clear cover or opaque cover with high emissivity). Heat transferred from the sun to the compartment materials or compost is estimated by taking the tilted Pyranometer readings and applying the appropriate solar absorptivity, transmissivity and view factor. Heat transfers between the hot compost and cover materials as well as the inside of the compartment walls, but when the top of the compost is insulated the radiation heat transfer through the compartment air between the insulation and the interior walls were negligible. When there is no insulation on top of the compost, the radiation exchange between the compost surface and the interior of the walls is about 1% of the radiation heat exchange.

Infiltration and Exfiltration in Composting Latrines and Solar Compartments

To compare infiltration (IT) or exfiltration (XT) of the various wall designs a FLIR i7 thermal imaging camera was used (FLIR, 2012). The gaps between insulated double and single wood boards lead to a higher IT and XT than concrete walls (Figure 15).

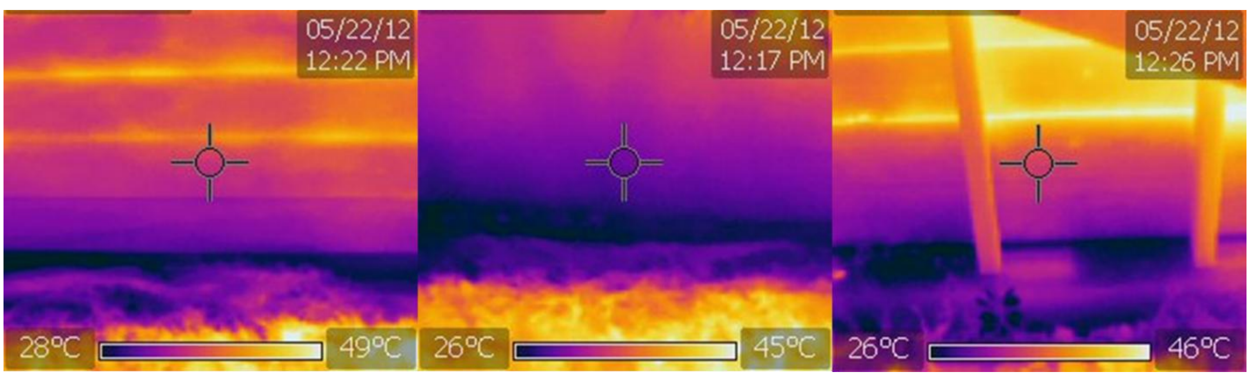

Figure 15. Thermal imaging pictures of compartment walls

From left to right, insulated double wood, concrete block and single wood.

Conductive Heat Transfer in Composting Latrines and Solar Compartments

Conduction is a heat transfer method between vibrating molecules, which is most often the major heat transfer mechanism in solid materials (Incropera *et al*., 2006). The slab and wall materials of composting compartments have heat transferred via conduction through the solid portion of the wall's construction and through the slab. In the compost, there is combined conduction (particle to particle) and convection (air movement from buoyant forces). In the energy balance calculations conduction through the cover materials is assumed negligible because the cover material is very thin.

Convective Heat Transfer in Composting Latrines and Solar Compartments

Convection is due to energy transfer from random molecular motion (diffusion) or fluid motion. Fluid motion falls into two broad categories, free (natural) convection and forced convection (Incropera *et al*., 2006). The natural definition can be misleading because one may think atmospheric winds are considered natural convection, but these are usually defined as forced convection (Incropera *et al*., 2006). The distinction between free and forced involves surface conditions where laminar (free) or turbulent (forced) flow occur. In the heat transfer charts seen in appendix C.2 characteristic lengths L along with fluid speed are used to determine if turbulent flow or laminar flow equations should be used. Heat transfer between a surface and fluid vary significantly by the flow types.

Evaporative Moisture Transfer in Composting Latrines and Solar Compartments

Evaporative heat losses are significant in the compost because they lower surface temperatures, similar to the cooling effect felt when people sweat. Evaporation needs to be controlled in composting latrines for two reasons, the cooling effect and more importantly the loss of moisture from the compost that results in unfavorable composting conditions. In the steady state energy balance calculations evaporation is treated as either stopped by a plastic cover or negligible in desiccating conditions.

Diffusive Moisture Transfer in Composting Latrines and Solar Compartments

Diffusion is part of the definition of convection. Compost, simulated compost and solar compartment's building materials diffuse water at different rates. Permeability is a property that describes how easily water is transferred through materials. This process is described by a modification to Fick's Law (ASHRAE, 2005). Diffusion of compost and simulated compost was not studied in this thesis but Chapman (2008) studied diffusion in compost extensively in his dissertation. Permeability for some of the materials used in the compartments can be found in appendix C.1.

Wicking Moisture Transfer in Composting Latrines and Solar Compartments

Wicking of moisture in the liquid state allows water (due to capillary forces) to overcome gravity's force and move upward. Thus, this method allows moisture to travel from the ground up into the compost. Water's gaseous form will travel upwards because it is less buoyant than dry air. Thus, water that evaporates at the bottom of the compost pile will make its way up and out of the compost pile that does not have a moisture barrier. The bottom of the wall where the air gaps between brick walls and the inner wall structure could have an organic rope installed that would allow for moisture and/or leachate to wick towards the exterior of the compartment. These organic ropes could be used to help regulate leachate in the bottom of the composting latrine or solar compartment where excess moisture is an issue. Further study would be required to determine if pathogens could move along with the water through the rope. The sun on the exterior of the compartment would evaporate leachate in the rope.

Chapter 4.3 Heat and Mass Transfer Properties for Composting Latrine Materials and Environment

Thermal Properties of Building Materials for Composting Latrines

The thermal properties of the building materials used to construct the composting compartment affect the overall compost temperature and temperature profile throughout the compost pile, as discussed in the results section. The important factors for compost cover materials, when solar-heating is used, are solar absorptivity and transparency. See appendix C for thermal properties of materials commonly used in constructing composting latrines, simulated compost and potential latrine insulations.

As water is added to compost or is soaked into cementitious materials the conductivity increases (Agnew and Leonard, 2003; ASHRAE 2005). Jean *et al* (2011) performed lab experiments to determine the best sustainable insulation material for composting latrines and found that hay was a good candidate. Theoretically, hay insulation will slow convection loops, although it will increased the conductivity because it increases the friction of air flow and increases the solid material in the wall. The thermal conductivity of a still air gap varied by reference up to 100 percent. The conservative value found in ASHRAE's 2005 handbook was used.

Emissivity was assumed to equal solar absorptivity where no data for solar absorptivity could be found (e.g. polyurethane coated wood walls and compost). Emissivity for polystyrene insulation and white fiberglass were assumed because no emissivity data could be found. appendix C tabularizes measured lengths, areas, masses, view factors, emissivities, solar absorptivities, conductivities and permeabilities for materials used in solar composting latrine calculations.

Concrete Block and Wood Construction Conductivities

To determine the conductivities of the wall constructions tested at the field site Jean *et al* (2011) performed lab experiments on un-insulated concrete, un-insulated double wood, hay-insulated concrete and hay-insulated double wood designs by a hotbox experiment (appendix C). The result of the lab experiments were lower conductivity for un-insulated constructions. This result is because the top of the wall constructions in the experiment were not air tight resulting in more hot air escaping with no insulation between the walls. Direct comparisons between un-insulated wall structures and hay insulated wall structures showed insulated walls having better thermal-performance in the simulated compost.

Glazing Systems for Cover Materials

Transitivity of solar radiation is the major physical property that affects performance of the cover design of the composting compartments, which is determined by the rankings of the covers in the results section. Solar transmission was assumed equal to zero for opaque materials and one minus solar absorptive for transparent materials (e.g. reflectivity equals zero). No transitivity analysis of translucent materials was done and no spectral dependent analysis was performed.

Thermal Properties of Compost

Experimental results suggest that under proper composting conditions, compost can produce enough heat to reach pile temperatures above the disinfection levels proposed by Feachem and Cairncross (1993) throughout most of the pile. The wetness and density of the compost (e.g. manure and organic materials) will affect, along with the total mass, the evaporation rate, conductivity and thermal heat storage capacity (Agnew and Leonard, 2003).

Adding organic bulking material to composting latrines increases the bulk density and porosity of the compost but reduces conductivity. Adding water will increase conductivity, specific heat and evaporation. Experimental results show a larger increase in temperature when composting heat is simulated than when conductivity and heat storage is increased by the addition of water. Thus, balancing the heat transfer properties of compost is less important than balancing proper moisture levels and aeration rates because a change in compost conductivity or heat storage will have less effect on temperature than the average heat generation rate of microbes that have the required oxygen and moisture conditions.

Sky Emissivity and Temperature

The emissivity of the sky was calculated by the equation $\epsilon_{sky} = 0.732 + 0.00635 \times T_{dewpoint}(°C)$ which was developed by the passive solar research group at the University of Nebraska for Bennington, Nebraska (Chen B. *et al.*, 2012). The sky temperature is the theoretical average temperature at which radiation exchange is happening between the surface of the earth and the sky. The sky temperature was calculated by the equation $T_{sky} = T_{air}\left[0.8 + \frac{(T_{dewpoint} - 273)}{250}\right]^{0.25}$ that is valid for 50% cloud cover - sky temperature with no cloud cover will be a few degrees cooler (Straube and Burnett, 2005).

Gas Flow through Building Materials for Composting Latrines

The permeability of the building material used in construction of composting latrines has a significant impact on the ability for composting inside the latrine. Materials or construction methods that allow for airflow (oxygen) to transfer to the compost will cool the pile but may increase microorganism heat production – experimental results showed an increase in pile temperature when the wind was stronger. A thin layer of cement water mix placed on the outside of the concrete block can retard the absorption of water (Mihelcic J. et al., 2009) through the block (appendix D Figure 1). In addition, a thin plastic sheet can be used to retard gaseous moisture and oxygen transfer between compost and the concrete slab (ASHRAE, 2005).

Specific Heat of Compost and Simulated Compost

Specific heat is defined as the amount of energy required to raise the temperature of a given substance one degree per mass unit (Incropera *et al*., 2006). The material used for simulated compost was soil. Adjepon (1997) found the specific heat of sandy loam soil for various gravimetric water contents increased with water content (Table 9). The simulated compost specific heat for sandy loam soil at 10% GWC and 25% GWC are from the 5th figure in Adjepon (1997). The 50% GWC simulated compost data point is an invalid linear extrapolation because sandy loam soil will become saturated at this point. Mears *et al* (1975) sampled pig manure and straw compost (5% straw by dry weight) for specific heat and thermal conductivity (Table 9). As discussed in the experimental methods section, simulated compost will not generate heat and was a good thermally inert compost-like material. Although the specific heat, conductivity and ability to hold moisture was not exactly like real compost.

Table 9. Specific heats of compost and simulated compost

Specific Heat	kJ/kg-°C	Reference
Compost Dry (10% GWC)	1.05	Mears R. D. et al. 1975
Compost Wet (50% GWC)	2.43	Mears R. D. et al. 1975
Simulated Compost Dry (10% GWC)	0.9	Adjepong K. S. 1997
Simulated Compost Wet (25% GWC)	2.0	Adjepong K. S. 1997
Simulated Compost Wet (50% GWC)	3.8	Adjepong K. S. 1997

Thermal Conductivities of Compost and Simulated Compost

Because the thermal conductivity for compost is about four times smaller than that of simulated compost, conductive heat transfer will be four times higher in simulated compost (Table 10). When comparing desiccated actual compost to simulated compost (during one of the hottest days in the summer of 2012) the increase in thermal conductivity results in an 6 °C (10.8 °F) decrease at 4” deep in the compost pile, a 8 °C (14.4 °F) decrease at 8” deep in the compost pile and a 10 °C (18 °F) decrease at 8” deep in the compost pile when composting is not taking place. During cooler periods the amount subtracted from the tables and graphs will be less than previously discussed but the maximum (hot difference) is a good conservative number for designs. Thus, when comparing simulated compost performance to compost (on average) 8 °C (14.4 °F) needs to be subtracted from the data if desiccating designs are to be used. If wet-composting is taking place in the composting compartment heat will leave the compost at a slower rate and less heat will be stored (thermal lag) than the simulated compost results suggest. Due to the inability to record the amount of heat generation in the experimental compartments, no correction for composting conditions is recommended to the data for simulated compost.

Table 10. Thermal conductivity of compost and simulated compost

Thermal Conductivities	W/m-°C	Reference
Wet Compost (60% GWC)	0.48	Mears R. D. et al. 1975
Dry Compost (10% GWC)	0.27	Mears R. D. et al. 1975
Wet Simulated Compost (50% GWC)	2.25	Salomone A. L. Marlow I. J. 1989
Dry Simulated Compost (10% GWC)	0.952	Salomone A. L. Marlow I. J. 1989

Chapter 4.4 An Independent Variable for Compost Temperature Prediction

Solar Air Temperature

To estimate the heat transfer from the solar compartment, $T_{Sol\text{-}air}$, a fictitious surface temperature used for combined solar heating and sky cooling, was calculated based on incident solar radiation, compartment convection coefficients and other material properties (Medina, 2012). The aim of the work by Medina (2012) was to find an independent variable to predict the compost thermal performance. The equation proposed by Medina (2012) for ($T_{sol-air^*}$) is:

$$T_{sol-air*} = T_{ambient\ air} + \frac{\alpha_s G_s}{h_0} + \frac{\varepsilon\sigma(T_s^4 - T_{sky}^4)}{h_0}$$

Eq. (2)

where G_s is the solar radiation read from the Pyranometer, not global radiation because the Pyranometer was tilted to the compartment top angle, α_s is the solar absorptivity, ε is the emissivity, σ is the Stephen-Boltzmann radiation constant, T_s is the surface temperature, $T_{sky}$is the theoretical sky temperature and h_0 is a combined convection coefficient – all temperatures are in Kelvin (Medina M., 2012).

Using ArcGIS to Predict Compost Temperatures in Solar Composting Latrines

The research group attempted to make a predictive map of the world that would guide latrine users on which composting latrine design should be used by their community. To meet this goal, ArcGIS information was used in an attempt to predict temperatures reached in compartments throughout the world. First, temperatures were predicted for the experimental site at Lawrence, Kansas. Unfortunately, the ambient temperature data published for ArcGIS is very low resolution (one temperature for the state of Kansas) and usually a monthly or yearly average. Predicting peak temperatures or temperatures achieved for a period in composting compartments based off data found was not possible due to the multiple weather variables that ultimately effect compost temperature (e.g. solar radiation, ambient temperature and wind speed). The solar radiation analysis program within ArcGIS is powerful, allows for variable cloud clearness factors and has high resolution. If solar composting compartment performance could be correlated to solar radiation directly, the program could be used as a predictor of temperatures for compost with no thermal storage effects. Qualitatively, insulating the compost and relying on the compost internal heat generation is much less dependent on climate than solar-heating designs.

5. Results

Temperature duration plots for compost and simulated compost

To estimate if thermal disinfection was achieved, temperature duration plots were compared with time-temperature data published by Cairncross and Feachem (1993). For example, thermal data for a 6-mil plastic sheet covered pile (base design) is plotted for the hottest day in the summer of 2011 (Figure 16).

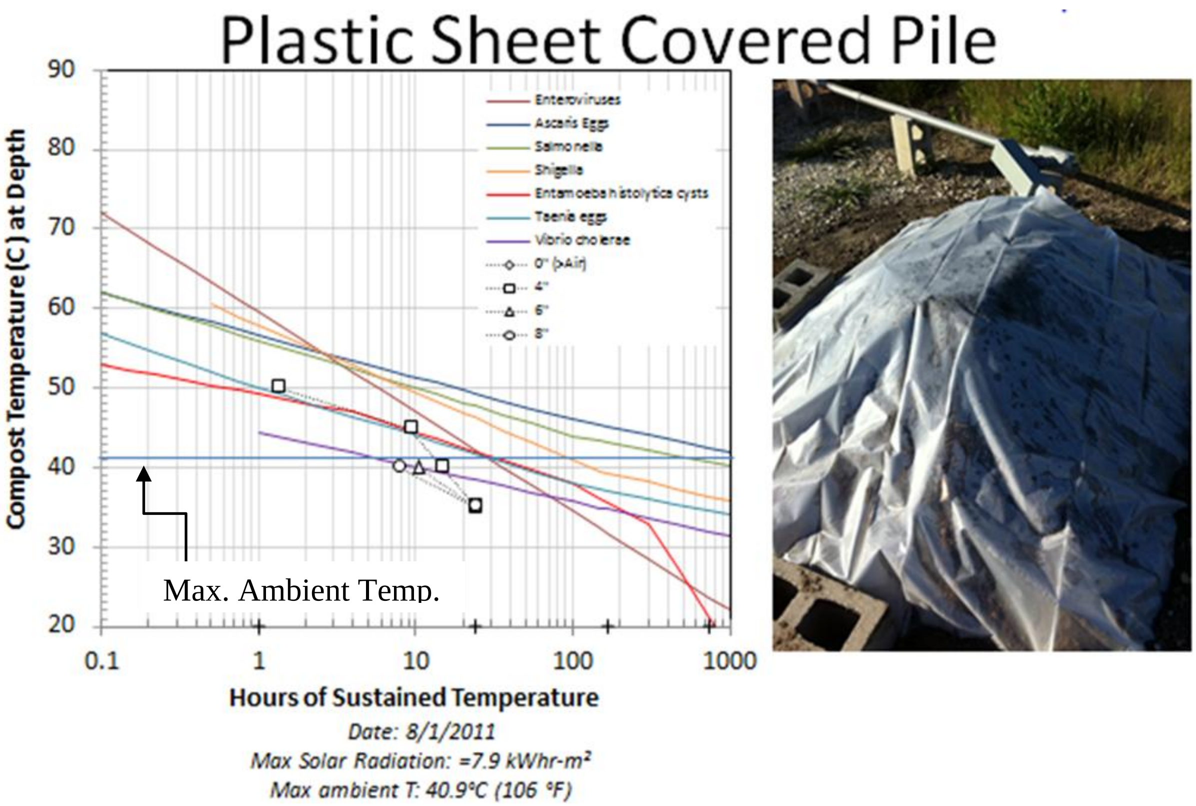

Figure 16. Plastic sheet cover pile sustained temperatures plotted over disinfection data (presented by C. Adams at the 2011 Water Conference, Norman, Nebraska).

The results were that disinfection temperatures were achieved throughout the whole pile in simulated compost (without internal heat generation). With internal heat generation temperature disinfection can be reached throughout most of the pile in hot ambient (peak ambient temperature > 35 °C (95 °F)) conditions. The flat blue line is the maximum environment air temperature reached. Plastic is not a robust cover material and degrades in three to six months when placed in the ambient environment.

Based on average soil temperatures, experimental results showed the best solar compartment design (without internal heat generation) in many climates was two layers of ¼" polycarbonate on four sides of the compartment (Figure 17).

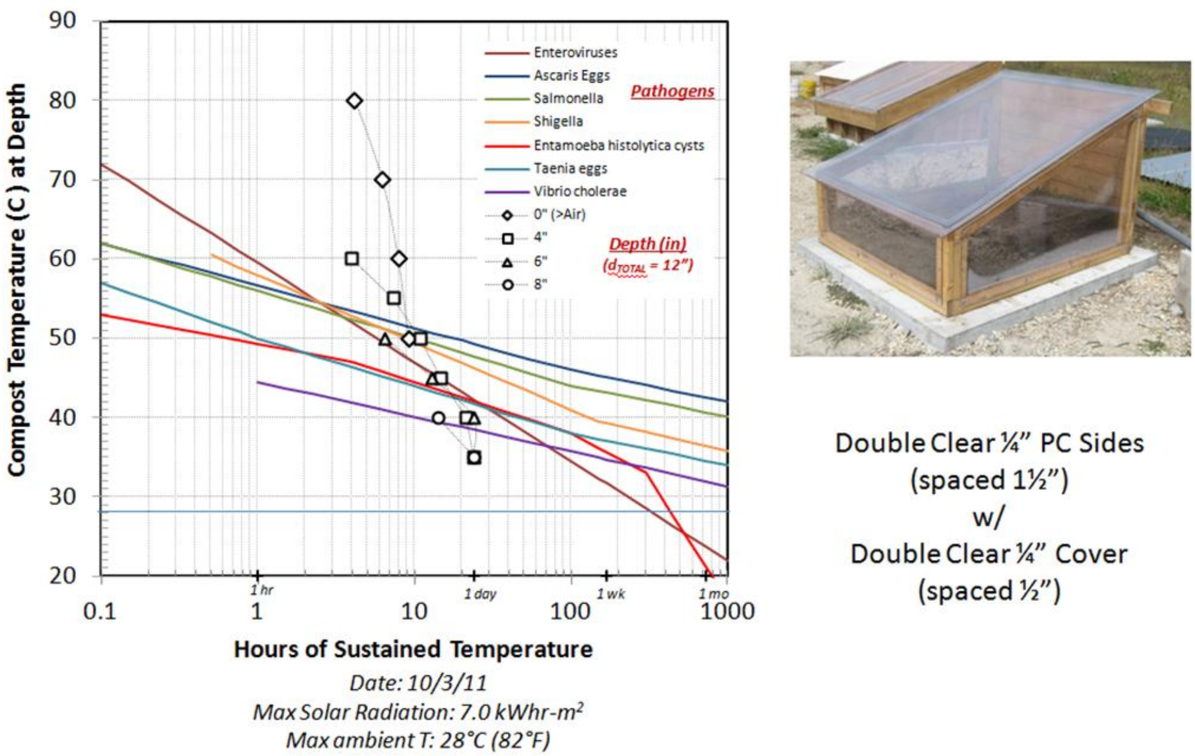

Figure 17. Clear double polycarbonate sides and top with internal heat generation sustained temperatures plotted over disinfection data (presented by C. Adams at the 2011 Water Conference, Norman, Nebraska).

The clear sides allowed solar radiation to warm more of the compost surface and the design had caulked seams, which reduced infiltration and exfiltration heat losses. However, this design has many practical issues for developing nations such as, expensive materials, the cover was heavy and hard to move and the polycarbonate is thick and hard to cut without electricity.

The results show disinfection temperatures were achieved throughout parts of the middle of the simulated compost and towards the edges in the compost for a warm day. Double clear polycarbonate for a wall design may not be appropriate for individuals in developing nations because of the high cost. The compartment air temperatures reached in this design, during selected direct comparisons between compartments with simulated compost, were the highest of the designs tests, due to the tight construction. There is likely a tradeoff between tight construction and pile temperatures in real compost because of oxygen increasing the exothermic activity of the microbes that are present in decomposition.

Temperature Profiles by Type of Compost Compartment Design

By analyzing temperature profile data, four major designs that change the temperature profiles in the compartments are: (1) using a transparent or opaque cover material to help heat compost via solar radiation (SR), (2) installing slab insulation to design type SR (SRSI), (3) insulating around the heat producing (wet) compost (IC) and (4) mounding the compost (MC).

Design type SR results in the highest temperatures in the top and middle of the compost stack; theoretical isothermal lines have been drawn for the design profile shown in Figure 18. The isothermal lines were based off thermocouple readings in the simulated compost.

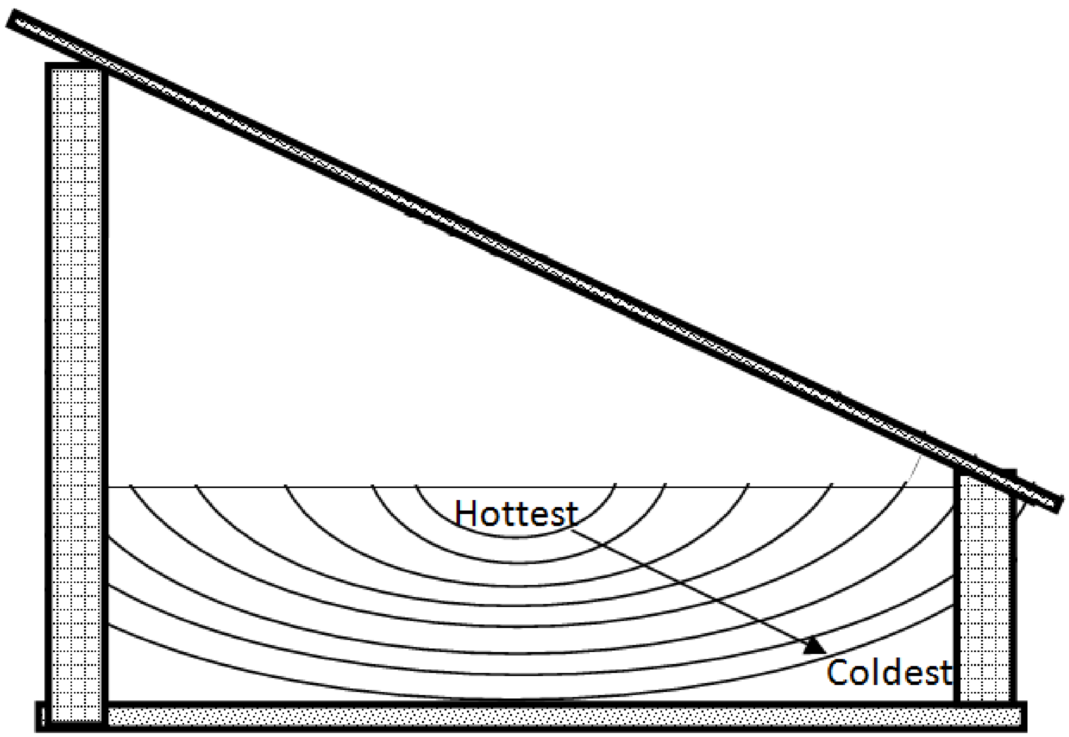

Figure 18. Typical solar radiation heating temperature profile

The isothermal lines for design form a trough in profile or a depressed circle in three dimensions. SRSI results in temperature profiles similar in shape to SR but with higher temperatures lower in the pile – less isothermal lines from top of the compost to the bottom (Figure 19).

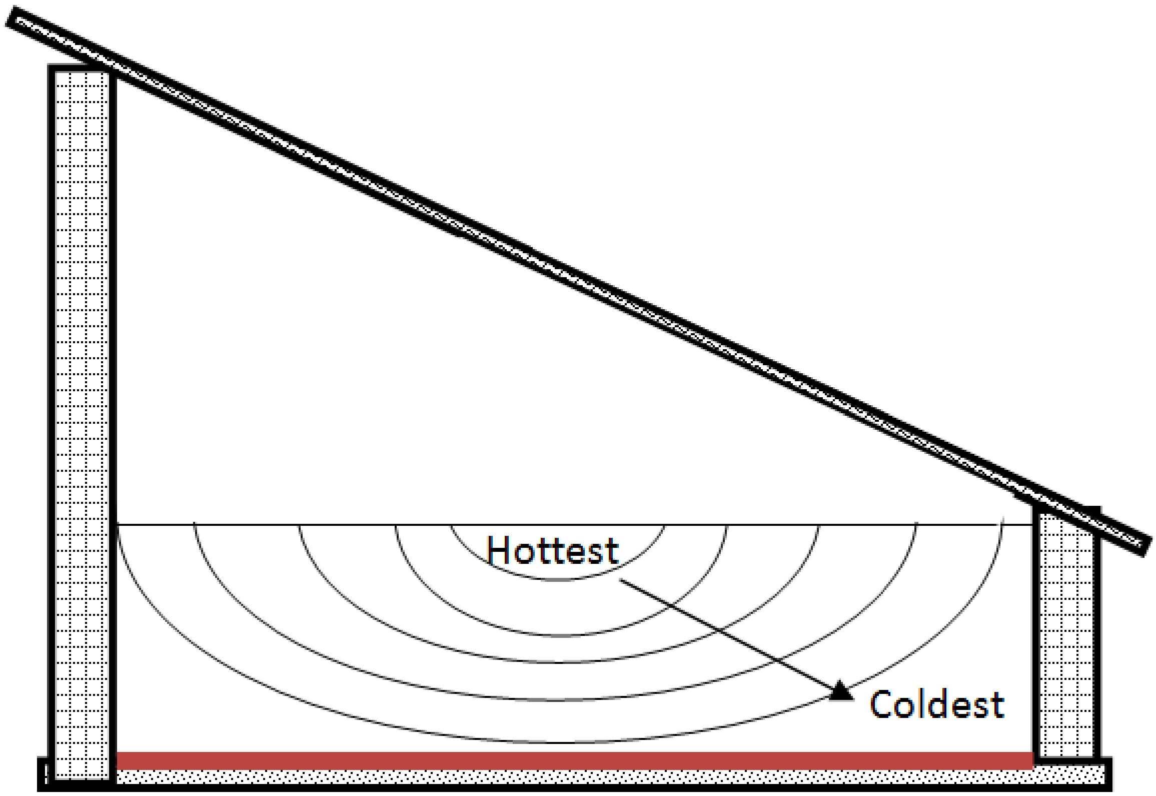

Figure 19. Typical solar radiation heating design with slab insulation temperature profile

The shape of SRSI isothermal lines is very similar to the shape of SR but the lines are spaced out more because less heat is lost to the slab because of the increased insulation. During direct comparisons between SRSI and SR higher temperatures at the bottom of the compost were recorded.

ICH results in the hottest temperatures are in the middle of the compost and are no longer directly affected by diurnal radiation and temperature swings (Figure 20).

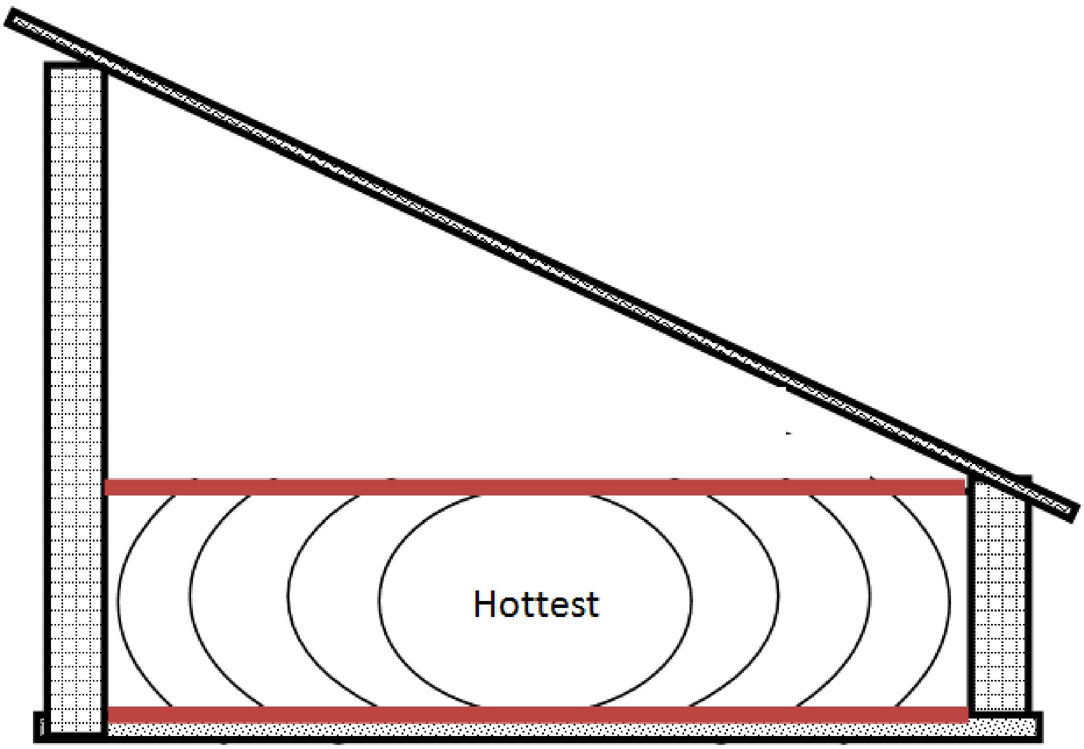

Figure 20. Typical compost insulating temperature profile for IC

The isothermal lines in design three, in profile, form ovals and in three dimensions form an egg shape. Design IC is negligibly affected by climate variables and can take up to a week to reach steady thermal performance. The other three designs are affected by diurnal temperature swings, cloud cover and will lose the heat they gain from one day to the next.

Design type MC results in temperature decreases as the depth increased in the pile and due to the lack of sensors deep in the pile the isothermal lines are somewhat uncertain (Figure 21). When the compost is generating heat the isothermal line pattern is unknown at this time and further experiments are required.

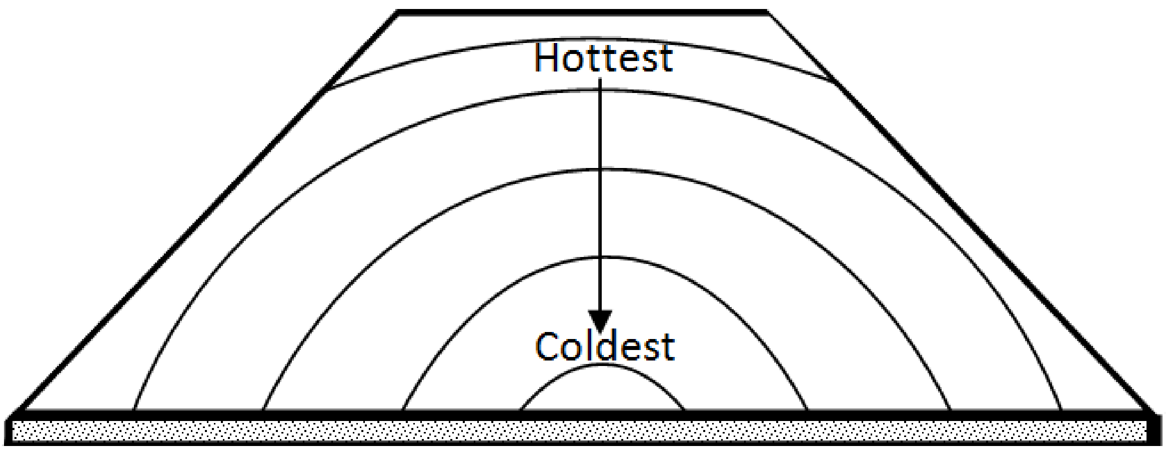

Figure 21. Mounded compost theoretical isothermal lines

Data points cannot be used to determine the shape of the isothermal lines in the mounded compartment because the depth of the mounded pile does not have thermocouples. But an experiment was done to show that as depth increases through the middle of the pile the temperature decreases in a parabolic fashion – without internal heat generation (Figure 22).

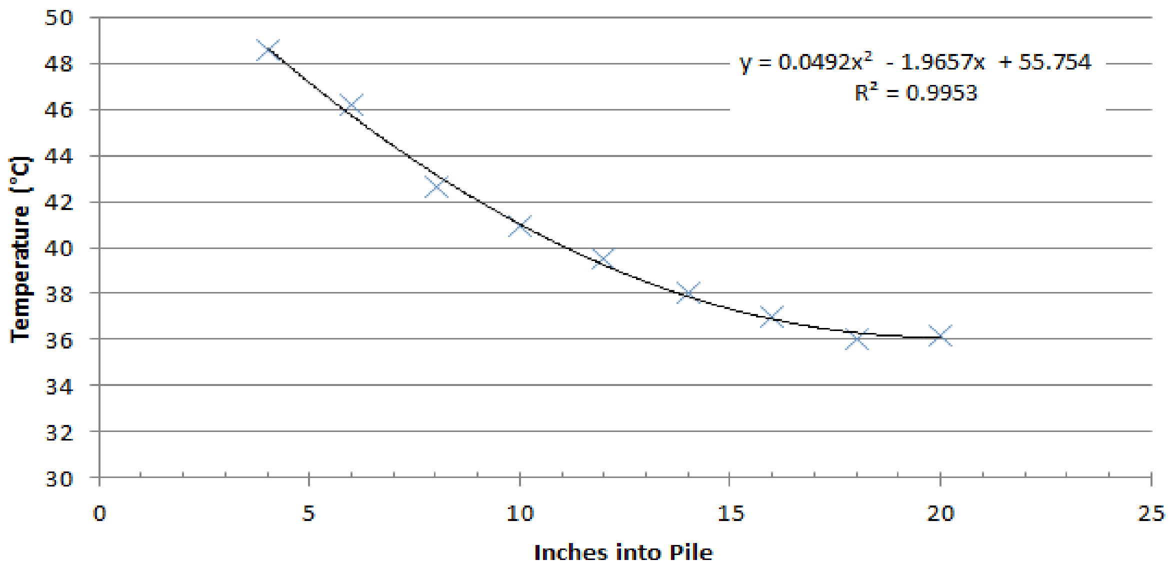

Figure 22. Simulated compost temperatures, due to solar heating, in middle of pile

The distance from the middle of the pile to the edge of the pile that is heated by solar radiation is also parabolic. When heat generation is simulated (with strip lighting) in pile designs, the peak temperatures recorded are similar up to the deepest sensor (8”).

Compost Moisture in Solar Compartments

In the four compartments where compost (horse manure and horse bedding materials) was placed, the starting moisture content of the mix was about 25% VWC or 78% GWC. Two compartments were intentionally dried out with no compost cover and two compartments were protected from evaporation and high-surface temperatures with insulation. The compost with top insulation and a moisture barrier had more moisture in the depths of the pile over time (Figure 23 and Figure 24). Readings of 50% VWC in actuality may be greater than 50% VWC but cannot be read by the DSMM500 probe, thus are reported as 50% VWC. Leachate was not observed leaking from the protected compartments and when digging into the pile saturated conditions were also not observed; suggesting anaerobic decomposition is not taking place.

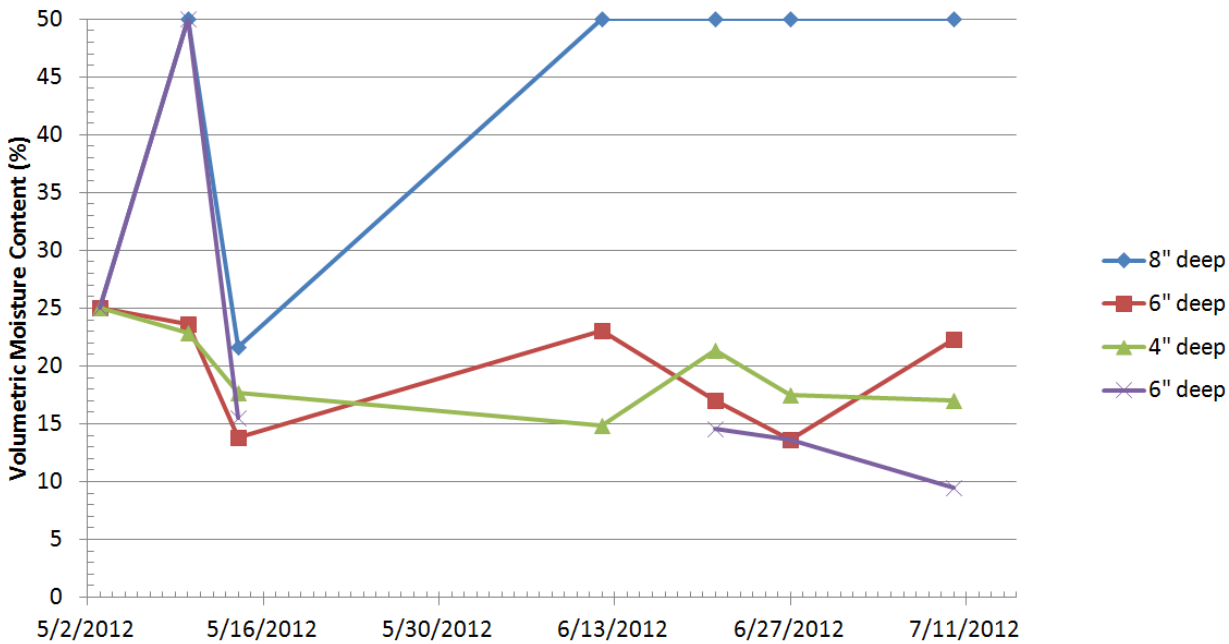

Figure 23. Example, moisture throughout 2 months in the compost (by depth) that has been thermally insulated and has moisture barriers on top and bottom of the compost

Fluctuations over 5% of the moisture content should be due to the fact that compost gives off moisture and takes in moisture during various stages of the decomposition (Porto and Steinfeld, 2000).

In the compartments without evaporation covers or compost-top insulation (Figure 24) the top of the compost dried out quickly and composting in the upper level appeared to stop – clumps of feces were dried out and hard to break apart. In the bottom 5cm (2 in.) of the compartment the results of composting was witnessed (feces clumps were wet and falling apart) 3 months after the compost was added to the compartments.

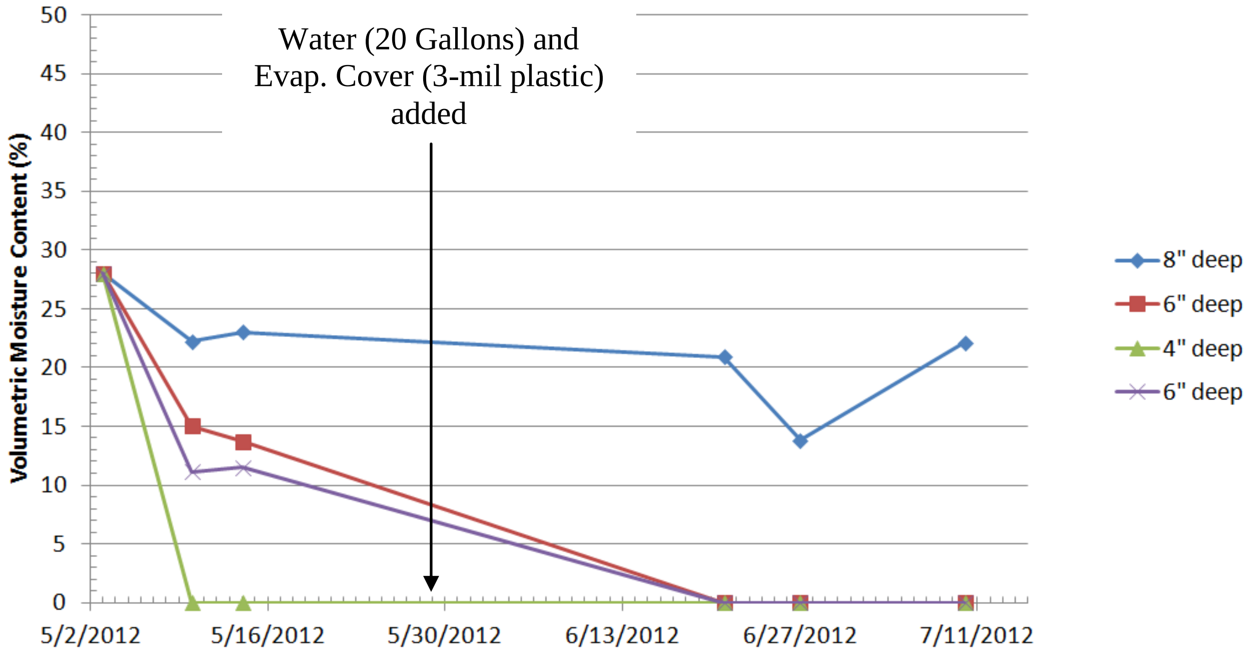

Figure 24. Example, moisture in compost initially not protected with evaporation cover

On May 29, 2012 twenty gallons of water was added to the compartments, with a significant portion of the water leaching out shortly after it was added. After the water was added, a compost evaporation cover (thin piece of plastic) was added. The moisture readings continued to decrease as if no water had been added. Most of the water leaked out of the compartment during the addition and water will not easily reabsorb into desiccated compost.

When simulated compost (loamy soil) was initially placed in the solar compartments it usually had about 10% VWC. Desiccation then started taking place (Figure 23). After sustained rainy periods, moisture was found (8-12% VWC) in the bottom 10.1 cm (4 in.) of the simulated compost that was not protected by a water retarder (e.g. polystyrene insulation). The mounded pile compartment soaked up the most moisture reaching almost 20% VWC at the bottom of the pile.

Simulated Compost Moisture in Solar Compartments

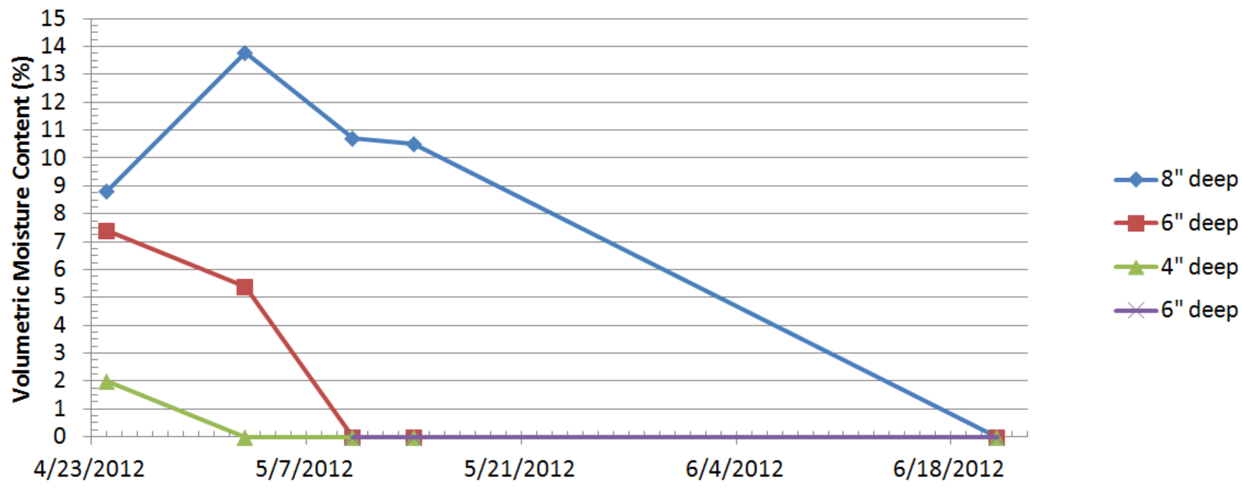

Figure 25. Simulated compost drying out after placement in solar compartment

When 45 gallons of water were added to the simulated compost it took 2 months for the compartment to dry out - with no evaporation cover (Figure 26). The initial water content in the top 20.3 cm (8 in.) was mixed and about at saturation (appendix D Figure 17).

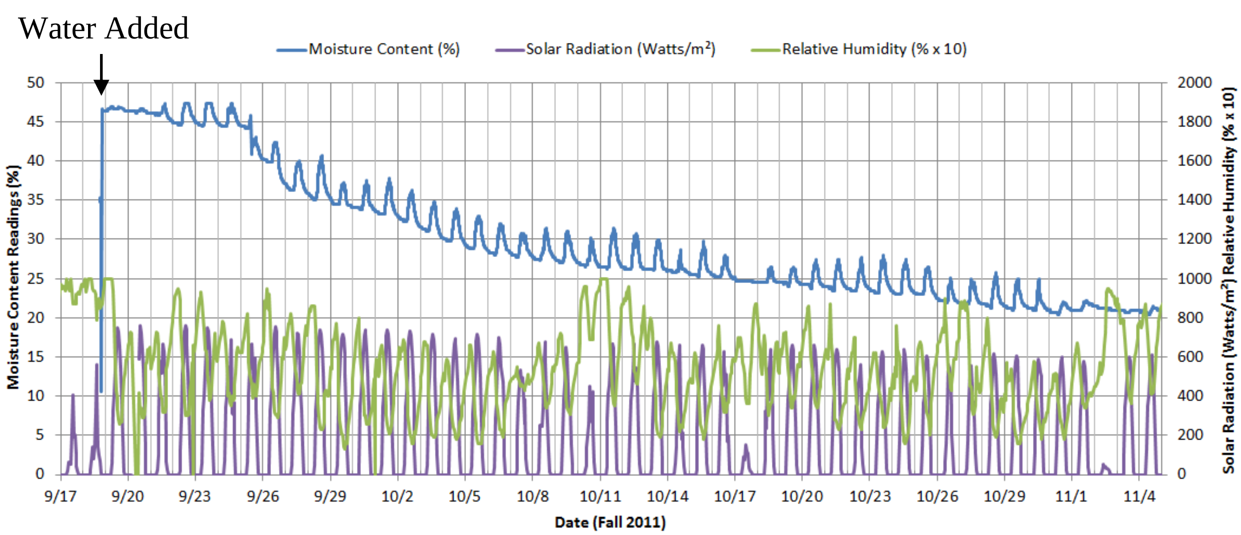

Figure 26. Moisture in simulated compost (4" deep) after 45 gallons of water was added

Moisture content was recorded 4" deep into the compartment, solar radiation is total solar radiation at a horizontal angle and relative humidity is the relative humidity of the environment.

The moisture increased as solar radiation increased. It is hypothesized, that this result is due to water evaporating up from depths of the pile (below 4” (10.1 cm)) to where the moisture probe was placed. Moisture is slowly lost due to evaporation and exfiltration. On November 14, 2011 when the moisture content flat-lines at 20%, an 8” (20.3 cm) rock-hard layer of simulated compost was observed (appendix D Figure 2). This result suggests use of a plastic compost cover to reduce evaporation losses. The rate of drying in new simulated compost and very wet simulated compost is about two months in solar compartments.

Graphing T-Solair vs. Compartment Air, External Air and Simulated Compost Temperatures*

When attempting to find an independent variable to predict compost temperatures, a equation was proposed by Dr. Mario Medina (eq. 2). The results for the equation when graphed against compartment temperatures was mostly linear for external air temperature, slab temperature and compartment air temperature but more oval for temperatures in the simulated compost (Figure 27). Actual equations for the relationships were not formulated.

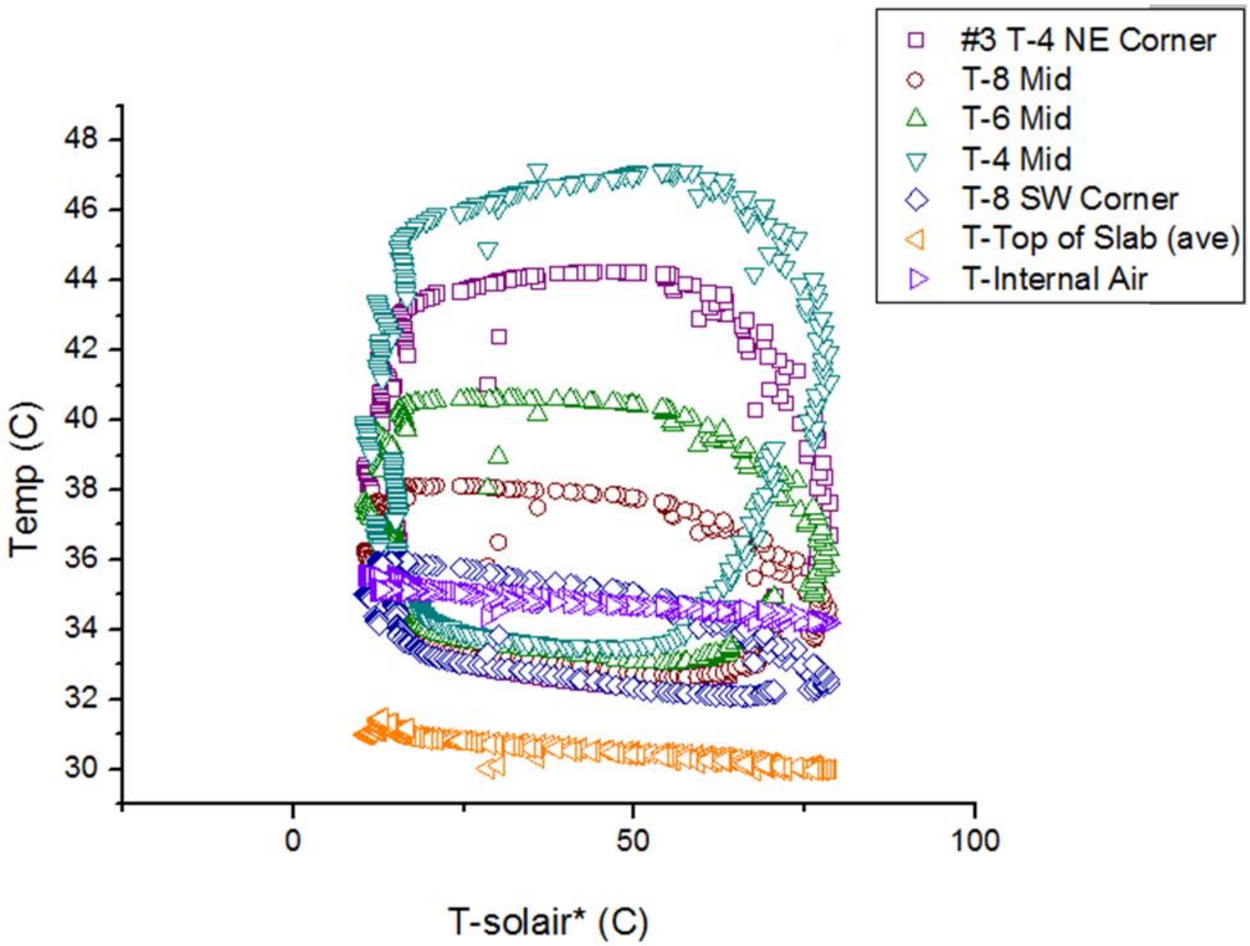

Figure 27. T-solair* vs. Compartment Air, External Air and Simulated Compost Temperatures

The compartment for which the data were graphed was constructed of un-insulated concrete with a double clear polycarbonate cover with internal heat generation of 100 watts on a warm day (25 °C (77 °F) max). Internal compartment temperature (purple triangles) and top of the slab average temperature (orange triangles) appear to have linear relationship with T-solair*. All other sensors have an oval relationship with T-solair*.

The relationship proved interesting to the author with respect to the top of the slab temperature. The thermal sink (ground temperature) may be related to solar radiation and thus the independent variable T-solair*. Although, combined average convection coefficient (H_0) was modeled as the convection coefficient for the compartment cover, varying H_0 in (eq. 2) did not result in shape changes. Variation in data points away from a true shape was reduced when H_0 was held constant. Increased variance of shape was seen when H_0 was varied dramatically.

Energy Balance Results

An energy balance was found for a compartment based on thermal properties of the materials used to make the compartment, surface temperature readings, environmental temperature readings and thermocouple readings in the compost. Solving the steady-state energy balance based on weather data may also be a way to predict the performance of the compartment in various climates. To help reduce computation time of various designs, charts were made for convection coefficients, conductivities, emissivities, absorptivities, view factor, and various sizes or areas of compartment components (appendix C.1). The generalized energy balance equation for the compartments when most of the moisture is removed or blocked from transferring out of the compost with the assumption of no infiltration is:

$$E_{comp.gen.} + E_{sun\,rad.} = E_{conv.env.} + E_{cond.grnd.} + E_{sky\,rad.} + M_{air\,out} \times h_{air}$$

Eq. (3)

In addition, the energy balance around the control volume of the compartment air is (solved for exfiltration):

$$M_{air\,out} \times h_{air} = E_{conv.compost\,surface} + E_{conv.interior\,wall\,surface} + E_{conv.interior\,cover\,surface}$$

Eq. (4)

These two equations can be used to verify the balances by solving for exfiltration. Unfortunately, the equations do not yield the same answer for exfiltration when the infrared camera (FLIR i7) was used to get the appropriate surface temperatures for the two equations. When (eq. 4) was solved for exfiltration, a number 30 times smaller was calculated, compared to when exfiltration was solved for in (eq. 3). It is hypothesized that these results are different due to thermal energy storage. Because steady state was assumed, thermal storage does not show up in (eq. 3) or (eq. 4). Future research should include a thermal storage variable.

There is some error involved in these equations because not all temperatures can be directly recorded, such as the temperature at the top of the concrete slab. When checking an energy balance exclusively around the cover material, only 10% of the energy is not accounted for – a positive result for the assumptions associated with the incident solar radiation and internal convection equations.

Cover Results Based on Average Temperatures in the Compost

Direct comparisons between cover materials were experimentally examined by keeping all variables constant besides cover material, thus a ranking could be determined for cover performance under the climatic conditions in which the comparisons were conducted. When comparing experimental data, the average differences in temperature was 4 to 10 °C (7.2 to 18 °F); so with a thermocouple accuracy of 1 °C (1.8 °F) and reproducibility errors up to 2.5 °C (4.5 °F), the relative error in the rankings is 10% to 40%. At the low end of the error, results are conclusive that clear polycarbonate performs better than unpainted metal covers for solar heating designs. Ranking the thermal performance of translucent clear 6-mil polyethylene, a single clear polycarbonate and white fiberglass covers had higher experimental error (up to 40% relative error). The rankings (without statistical analysis) are: double clear polycarbonate > 6-mil translucent polyethylene > single clear polycarbonate > white fiberglass > black painted metal > unpainted metal for solar heating designs. Clear or translucent covers should not be used with compost insulated heating designs because the UV light and high temperatures can degrade the insulation (appendix D Figure 16).

Data Corrections to Ambient Air Temperature for Designers

When two months of data were graphed, ambient air temperature readings were 3 to 5 degrees Celsius higher when the sun was out than the actual ambient temperature recorded from the weather station. When first installed, the aluminum-foil wrapped thermocouple used to measure temperature was reading correctly; but as the materials used to shade the thermocouple degraded (and in some instances the probe fell down on the ground), the probe started reading temperatures higher than actual. A rule of thumb for using the data is, subtract 3 degrees Celsius for data from the spring of 2012 and 5 degrees Celsius for data from the summer of 2012 for ambient air temperature recordings. When ambient air temperature is listed as 'environment temperature' data is correct, as it is gathered from the weather station.

Material Ruggedness

Experimental results show rigid polystyrene and 6-mil plastic degraded when placed under the conditions solar composting compartments face (appendix D Figure 16). Three-mil polyethylene did not degraded when placed under a transparent cover. Wood not protected with polyurethane showed some surface rotting after a half year in contact with dry simulated compost. Wood protected by polyurethane performed well in a humid sunny climate.

The BMP cover had some chipping of paint (<2%) after significant exposure to the elements on one top but not another, suggesting it was a paint application issue. Manufactures suggest sheet metal should be cleaned with a weak acid, such as vinegar, before painting.

Hay was used as insulation in most designs and had a little dry mold along with a modest decrease in volume within the concrete block cells but a more significant decrease in the wood walls (which left up to a 1-foot gap at the top of the tallest wall). It is hypothesized that the volume decrease was due to settling and decomposition.

Material Results

Concrete block, cement, wood and corrugated metal are common in many locations worldwide. In insulated composting designs, the double wood design allowed for higher peak temperatures initially, then had a few weeks where it underperformed the concrete design, and then overtook the concrete design by a few degrees (on average) towards the 3rd month of composting. This result is due to increased infiltration (oxygen) into the wood compartment compared to the concrete compartment. Composting heat generation is the dynamic process controlling the temperatures in the insulated designs. More research about how the microbes consume fuel and obtain oxygen needs to be done to explain why the wall constructions performed differently. Using polycarbonate, polystyrene and (to a lesser extent) polyethylene may be an issue for some developing nations as these plastics require manufacturing and/or shipping.

6. Discussion

Significant Weather Parameters

For insulating composting designs, weather parameters have less impact on the thermal performance of the compost. Radiation loss to the sky is a significant heat loss mechanism for solar heating designs. During wet seasons, significant moisture may wick up through the concrete slab. The effect of this moisture on the overall performance of desiccating designs is unknown.

Construction Design Process

For composting latrines, solar heating with a clear cover material and protecting the compost from evaporation with a thin piece of plastic placed on the compost and insulating the slab will result in time-temperature disinfection levels being reached for most of the compost. For the solar heating designs, the top layer may exceed temperatures in the thermophilic range and pasteurization (70 °C (158 °F)) may occur. Surface temperatures of the compost under a clear cover can reach up to 80 °C (176 °F) under many climatic conditions. When the sun goes down, the performance of solar heated composting designs will be reduced.

Insulating compost on all six sides is also a viable solution to reaching time-temperature disinfection levels. Insulating the compost on all sides reduced the diurnal effect on the thermal performance in the compost. The amount of 'fuel' for the microbes in composting compartments is limited and trade-offs between air infiltration cooling the pile and increasing the viability of the microbes will be researched in the future.

Two major findings are: (1) slab insulation (e.g. R-15) will also help the piles reach higher pile temperatures at the lowest depths and (2) thin piece of clear plastic on the top of the compost will slow down evaporative heat loss and keep moisture in the compost when wet composting conditions are desired.

Mounded Pile Design

Mounded compost covered with 6-mil plastic, under wet composting conditions, may reach disinfection temperatures throughout most of the pile during hot summer conditions (>35 °C (95 °F)). This design is the cheapest but most likely to fail in bad weather and leak any leachate that may accumulate as the moisture levels change in the pile.

Wet versus Dry Composting

Dry composting is a misnomer because decomposing microorganisms require water to survive. Pathogens also require water to survive and thus desiccation will reduce the amount of pathogens found in desiccated compost but helminth cysts may still be active. The author believes wet composting has a better chance of providing hot temperatures throughout the pile and producing a better final product than desiccating or pH disinfection methods because the pH of the compost will be closer to neutral and the microbes will decompose the fuel in the compost into nutrients plants can use. Although, currently the literature for pH disinfection and dry composting suggests these methods are appropriate for many pathogens.

7. Conclusions

Objective One, Achieve Full Thermal Disinfection

Fresh horse-manure compost performed well in the compartments and EPA class A bio-solid time-temperature levels were reached. Wind speed and direction affect the composting process in the compartments. Neither solar or composting heat generation designs reached time-temperature disinfection levels for the toughest organism at the edges of the compost under simulated compost and simulated heat generation (100 watts/compartment) conditions. Composting heat generation methods allowed for most (about two-thirds) of the pile to reach disinfection levels and solar heating provided disinfection levels up to 15.2 cm (6 in.) deep in the simulated compost.

Objective Two, Construct and Instrument 11 Full-Scale Composting Compartments

Thermocouples successfully recorded (<1°C (1.8 °F) error) compost pile temperatures in 11 full-scale composting compartments. Continuous logging of volumetric water content (VWC) in simulated compost worked well and the compartment took about two months to dry out (without an evaporation cover). Logging VWC for actual compost proved more difficult due to the inhomogeneity of the compost and the results were accurate to 5%. A handheld moisture probe was used to report compost VWC over time and the manufacture suggested an accuracy of 5%.

Objective Three, Compare Concrete and Wood Constructions

When using simulated compost (with or without heat generation) the wood and concrete block wall construction performed similarly. When actual compost was tested, the piles enclosed with wood and concrete block walls reached disinfection levels but at different temperatures and durations. More experimentation with how the construction materials effect moisture retention and air movement will be conducted.

Objective Four, Compare Cover Materials

For solar heating designs, clear and translucent cover materials out performed opaque materials by about 5 to 10 °C (9 to 18 °F) (based on average peak compartment temperature) depending on weather conditions. When a compost heat generation design is used, the cover material should not be clear or translucent because the sun will damage most such insulating materials. Plastic should be placed directly on top of the compost to reduce moisture evaporation.

Objective Five, Examine Effects of Insulation

Insulating the bottom of the compost brought temperatures in the lower parts of the pile but not always to disinfection levels. Insulating inside the compartment wall structure with hay increased pile temperatures in most climate conditions, but the effect on the composting process (e.g. oxygen transfer) is expected to be more significant, though this has not been studied yet. Insulating the top of the compost significantly changes the duration of temperatures reached.

Objective Six, Examine Effects of Moisture

The addition of water increases the thermal conductivity of the pile and evaporation associated with the addition of water cools the compost pile. An evaporation cover (thin sheet of plastic) placed on top of the compost reduced moisture loss. Without a cover, the simulated compost dried out in two months. Actual compost without a cover dried out in the top 15.2 (6 in.) in about one month. With insulation and an evaporation cover, the compost stayed moist enough for composting throughout the pile for about three months.

Objective Seven, Develop Guidance for Composting Designs for Thermal Disinfection

Mixing the compost in both solar and composting heat generation designs may increase the likelihood of disinfection through the entire compost pile over time due to increase the likelihood of proper conditions throughout the whole compost pile. Retaining the initial moisture before desiccation, and protecting the compost from temperatures above and below the thermophilic range, will allow for better decomposition based on visual inspection but further study is required about the final quality of the compost.

Approach

Appendix B has tabulated data from simulated compost, simulated compost with heat generation, and compost experiments. With this data comparisons between the selected permutations can be compared by similar climate conditions (e.g. peak environment temperature and peak solar radiation. The tabulated data is good representation of desiccated compost performance or compost producing the average amount of heat (100 watts/compartment). Eight °C is a conservative temperature to be subtracted (on average) from the tabulated data to correct for thermal property differences between simulated compost and actual compost.

Wet simulated compost experiments suggest a 5 °C decrease in peak temperature compared to dry compost. Thus, if wet composting solar compartment temperatures want to be estimated based on tabulated data 13 °C should be subtracted for the permutation in question.

8. Recommendations

Research Questions

- How does air infiltration affect temperature in active composting?
- How does adding new compost, once the composting process has begun (or stopped), affect the composting process in the compartments?
- How does solar heat combined with an evaporation cover affect the composting process?
- Will an additional solar heat, transferred via heat an exchanger to the bottom of the pile, hamper the composting process?
- How does pH affect the temperatures reached in composting?
- Is there a method to passively-control moisture transfer in solar compartments?
- Can compartments serve as an incubator for bacteria and viruses when not operating under optimum conditions?
- Why is the ground temperature linearly related to T-solair*
- Is there a database of maximum summer temperatures for the world with good resolution?
- Would a mathematical model including thermal storage for compost based on compartment materials and weather conditions provide a service to developing nation workers?

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10. Appendices

Appendices List

Appendix C Tables

Appendix D Figures

Appendix A: Permutation Lists

Permutation	Bottom	Top	Additional
P1	hay Insulated Concrete	Double Clear Poly	
P1A	hay Insulated Concrete	Double Clear Poly	Lights on 100 W and Aluminum Foil inside walls
P2	hay Insulated Concrete	Double Clear Poly	Aluminum Foil inside walls
P3	hay Insulated Concrete	Single Clear Poly	
P4	hay Insulated Concrete	Single Clear Poly	Aluminum Foil inside walls
P5	hay Insulated Concrete	Metal Painted Black	
P6	hay Insulated Concrete	White Fiber Glass	
P7	hay Insulated Concrete	6 Mil Plastic	
P8	hay Insulated Concrete	Metal Unpainted	
P9	Uninsulated Concrete	Double Clear Poly	
P10	Uninsulated Concrete	Double Clear Poly	Lights on 100 W
P11	Uninsulated Concrete	Single Clear Poly	
P12	Uninsulated Concrete	Metal Painted Black	
P13	Uninsulated Concrete	White Fiber Glass	
P14	Uninsulated Concrete	6 Mil Plastic	
P16	Uninsulated Concrete	Metal Unpainted	
P17	Uninsulated Double Wood	Double Clear Poly	
P17PW	Uninsulated Double Wood	Double Clear Poly	Post Water Addition "Caked Soil"
P18	Uninsulated Double Wood	Single Clear Poly	
P18PW	Uninsulated Double Wood	Single Clear Poly	Post Water Addition "Caked Soil"
P19	Uninsulated Double Wood	Single Clear Poly	Aluminum Foil inside walls
P20	Uninsulated Double Wood	Single Clear Poly	Lights on 100 W
P20A	Uninsulated Double Wood	Single Clear Poly	Water Added (30-50%)
P21	Uninsulated Double Wood	Metal Painted Black	
P21PW	Uninsulated Double Wood	Metal Painted Black	Post Water Addition "Caked Soil"
P22	Uninsulated Double Wood	White Fiber Glass	
P23	Uninsulated Double Wood	White Fiber Glass	Aluminum Foil inside walls
P24	Uninsulated Double Wood	White Fiber Glass	Water Added (30-50%)
P25	Uninsulated Double Wood	6 Mil Plastic	
P26	Uninsulated Double Wood	Metal Unpainted	
P27	hay Insulated Double Wood	Double Clear Poly	
P28	hay Insulated Double Wood	Single Clear Poly	
P29	hay Insulated Double Wood	Single Clear Poly	Lights on 100 W
P30	hay Insulated Double Wood	Metal Painted Black	
P31	hay Insulated Double Wood	White Fiber Glass	
P32	hay Insulated Double Wood	White Fiber Glass	Lights on 100 W
P33	hay Insulated Double Wood	6 Mil Plastic	

Permutation	Bottom	Top	Additional
P34	hay Insulated Double Wood	Metal Unpainted	
P35	Single Wood	Double Clear Poly	
P36	Single Wood	Single Clear Poly	
P37	Single Wood	Metal Painted Black	
P38	Single Wood	White Fiber Glass	
P39	Single Wood	6 Mil Plastic	
P40	Single Wood	Metal Unpainted	
P41	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Caulked North Wall
P41A	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Caulked North Wall, Lights On 100 W
P42	1/4" Double Poly Carb, Single Wood North	1/4" Single Poly Carb	Caulked North Wall
P43	1/4" Single Poly Carb, Single Wood North	1/4" Single Poly Carb	Caulked North Wall
P44	1/4" Single Poly Carb, Single Wood North	1/4" Single Poly Carb	Caulked North Wall
P45	1/4" Single Poly Carb, Single Wood North	1/4" Single Poly Carb	Lights on 100 W
P46	Mounded 6 mill White Plastic		
P47	Mounded 6 mill Black Plastic		
P48	Uninsulated Concrete	Single Clear Poly	Soil Cover
P49	Uninsulated Concrete	Single Clear Poly	Slab Insulation
P50	Uninsulated Concrete	Single Clear Poly	Soil Cover, Slab Insulated
P51	Uninsulated Concrete	Single Clear Poly	Soil Cover, Slab Insulated, Lights on 100 watts
P52	Uninsulated Concrete	Single Clear Poly	Soil Cover, Lights On 100 watts
P53	Uninsulated Concrete	Single Clear Poly	Slab Insulation, Lights On, 100 watts
P54	Uninsulated Concrete	Single Clear Poly	Soil Cover, Slab Insulated, Lights on 190 watts
P55	hay Insulated Double Wood	Metal Painted Black	Soil Cover, Slab Insulated
P56	hay Insulated Double Wood	Single Clear Poly	Slab Insulation
P57	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Slab Insulated
P58	hay Insulated Double Wood	Single Clear Poly	Slab Insulated, Lights on 100 watts
P59	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Lights On 100 watts
P61	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Slab Insulated, Lights on 190 watts
P62	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Soil Cover, Caulked North Wall
P63	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Soil Cover, Caulked North Wall, lights on
P64	hay Insulated Double Wood	Metal Painted Black	Soil Cover, Slab Insulated, Lights on 190 watts
P65	hay Insulated Double Wood	Double Clear Poly	Soil Cover, Slab Insulated, Lights on 190 watts
P66A	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Lights on 190 watts
P66	Uninsulated Double Wood	Single Clear Poly	Slab Insulation

Permutation	Bottom	Top	Additional
P67	hay Insulated Double Wood	Single Clear Poly	Soil Cover
P68	hay Insulated Double Wood	Single Clear Poly	Soil Cover Lights on 190 watts
P69	hay Insulated Concrete	Metal Painted Black	Lights on 190 watts
P70	hay Insulated Double Wood	Double Clear Poly	Soil Cover, Slab Insulated
P71	hay Insulated Double Wood	Double Clear Poly	Soil Cover, Slab Insulated, Lights on 190 watts cycling 12hrs on and off
P72	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Lights on 190 watts cycling 12hrs on and off
P73	hay Insulated Concrete	Single Clear Poly	Aluminum Foil inside and lights 100 watts
P74	hay Insulated Concrete	Double Clear Poly	Lights on 100 watts
P75	hay Insulated Concrete	Single Clear Poly	Lights on 100 watts
P76	Uninsulated Double Wood	Single Clear Poly	Slab Insulation and Soil Cover
P77	hay Insulated Double Wood	Double Clear Poly	Lights on 100 watts
P78	Single Wood	Metal Painted Black	Lights on 100 watts
P79	1/4" clear poly carb	Metal Painted Black	
P80	Single Wood	Single Clear Poly	Lights on 100 watts
P81	Double clear 1/4" poly carb	Single Clear 1/4" PC	Lights on , caulked north wall, 100 watts
P82	Mounded 6mil white plastice		Lights on 100 watts
P83	Un-Insulated Concrete	Metal Unpainted	Soil Cover, top insulation, Slab Insulation, and 100 watts
P84	hay Insulated Double Wood	Single Clear Poly	Soil Cover, top insulation, Slab Insulation, and 100 watts
P85	hay Insulated Concrete	Single Clear Poly	Soil Cover, top insulation, Slab Insulation, and 100 watts
P85A	post construction hay Insulated Concrete	Single Clear Poly	Soil Cover, top insulation, Slab Insulation, and 100 watts
P86	hay Insulated Double Wood	Metal Unpainted	Soil Cover, top insulation, Slab Insulation, and 100 watts
P87	hay Insulated Double Wood	Single Clear Poly	Soil Cover, top insulation, Slab Insulation
P88	hay Insulated Concrete	Metal Unpainted	Lights on 100 watts
P89	hay Insulated Concrete	6 mill plastic	Lights on 100 watts
P90	hay Insulated Concrete	metal black painted	Lights on 100 watts
P91	Single Wood	Metal Unpainted	Lights on 100 watts
P92	Single Wood	6 mill plastic	Lights on 100 watts
P93	Single Wood	White Fiberglass	Lights on 100 watts
P94	Single Wood	double Clear Poly	Lights on 100 watts
P95	hay Insulated Double Wood	6 mill plastic	Lights on 100 watts
P96	hay Insulated Double Wood	Metal Unpainted	Lights on 100 watts
P97	hay Insulated Double Wood	metal black painted	Lights on 100 watts
P98	hay Insulated Concrete	White Fiberglass	Lights on 100 watts
P99	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Soil Cover, Lights on 190 watts cycling 12hrs on and off

Permutation	Bottom	Top	Additional
P100	hay Insulated Concrete	metal black painted	Soil Cover, top insulation, Slab Insulation, and 100 watts
P101	hay Insulated Double Wood	metal black painted	Soil Cover, top insulation, Slab Insulation, and 100 watts
P102	hay Insulated Double Wood	unpainted metal	top insulation, lights on 100 watts
P103	hay Insulated Concrete	Single Clear Poly	Slab Insulated, Lights on 100 watts
P104W	hay Insulated Concrete	Single Clear Poly	Soil Cover, Wet
P105W	hay Insulated Concrete	Single Clear Poly	Soil Cover, Slab Insulation, Wet
P106	1/4" Double Poly Carb, Single Wood North	1/4" Double Poly Carb	Soil Cover, Slab Insulation
P107	hay Insulated Concrete	Single Clear Poly	Soil Cover, Top Insulation
P108W	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Wet
P109W	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Slab Insulation, Wet
P110	Mounded 6mil white plastice		Slab Insulation
P111	hay Insulated Concrete	Single Clear Poly	Soil Cover, Slab Insulation
P112	hay Insulated Double Wood	Single Clear Poly	Soil Cover, Slab Insulated, Lights on 100 watts
P113	hay Insulated Concrete	Single Clear Poly	Soil Cover, Slab Insulated, Lights on 100 watts
P114	hay Insulated Double Wood	Single Clear Poly	Plastic Wrapped Slab and Top Insulated, Lights on 100 watts, dampish soil
P115	hay Insulated Double Wood	Single Clear Poly	Plastic Bag/Straw Under Slab Insulated, Lights on 100 watts, dampish soil
P116	hay Insulated Double Wood	Single Clear Poly	Slab Insulation, Compost
P117	hay Insulated Double Wood	Single Clear Poly	Plastic Wrapped Slab Insulated, Lights on 100 watts
P118	hay Insulated Double Wood	Single Clear Poly	Plastic Bag/Straw Under Slab Insulated, Lights on 100 watts
P119	hay Insulated Double Wood	Black Metal Painted	Soil Cover, top insulation, Slab Insulation, and compost, no insulation between cover and walls
P120	hay Insulated Concrete	Black Metal Painted	Soil Cover, top insulation, Slab Insulation, and compost, no insulation between cover and walls
P121	hay Insulated Concrete	Single Clear Poly	Slab Insulation, Compost
P122	hay Insulated Double Wood	Single Clear Poly	Plastic Wrapped Slab Insulated
P123	hay Insulated Double Wood	Single Clear Poly	Plastic Bag/Straw Under Slab Insulated,
P124	hay Insulated Concrete	Black Metal Painted	Slab Insulation, Soil Cover, Compost
P125	hay Insulated Concrete	unpainted metal	Slab Insulation, Top Insulation, Soil Cover, Compost, no insulation between cover and walls
P126	hay Insulated Double Wood	unpainted metal	Slab Insulation, Top Insulation, Soil Cover, Compost, no insulation between cover and walls
P127	hay Insulated Double Wood	Black Metal Painted	Slab Insulation, Soil Cover, Compost, no insulation between cover and walls
P128	hay Insulated Concrete	Black Metal Painted	Slab insulation, top insulatino 6" wrapped straw, compost
P129	mounded	black 6 mill plastic	lights on 100 watts

Appendix B: Maximum and Sustained Temperatures for Selected Permutations For Hot and Cold Days

Nomenclature for Sustained Temperature Tables

interior air - Peak compartment Air Temperature (°C)

exterior air - Peak environment Air Temperature (with corrective temperature subtraction) (°C)

A NE 4” - Sustained temperature for two thermocouples placed 4” deep into the North East corner of the solar compartment (°C)

Mid 8” - Sustained temperature for two thermocouples placed 8” deep into the middle of the solar compartment (°C)

C Mid 6”- Sustained temperature for two thermocouples placed 6” deep into the middle of the solar compartment (°C)

B Mid 4” - Sustained temperature for two thermocouples placed 4” deep into the middle of the solar compartment (°C)

D SW 8” - Sustained temperature for two thermocouples placed 8” deep into the South West corner of the solar compartment (°C)

Slab Temp - Sustained temperature for the top of the concrete slab (°C)

Top of ins. - Sustained temperature at the top of the slab insulation (°C)

Moisture - VWC 4” deep into compost or simulated compost (%)

Solar Rad. - Solar radiation peak for days analyzed

Permutation	Dates	exterior air °C	interior air °C	Temp. for 2-hour sustainment: A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 1	2/16 - 2/17 2012	18	49	18	11	16	24	10	NA	NA	NA	0.92
P 3	9/5 - 9/6 2011	20	67	37	35	38	40	35	NA	NA	NA	1.1
P 3	6/10 - 6/11 2012	29	61	44	34	40	49	33	NA	NA	NA	1
P 4	9/5 - 9/6 2011	25	69	44	36	39	47	34	NA	NA	NA	1.1
P 5	2/16 -2/17 2012	18	24	7	6	7	8	7	NA	NA	NA	0.91
P 9	9/5 - 9/6 2011	20	70+	43	37	40	47	38	NA	NA	NA	1.1
P 18	9/5 - 9/6 2011	20	69	41	35	39	45	36	NA	NA	NA	1.1
P 19	9/5 - 9/6 2011	20	70+	45	37	38	40	36	NA	NA	NA	1.1
P 28	11/3 2011	9	34	18	18	19	22	17	16	18	NA	0.92
P 29	11/11 - 11/12 2011	17	NA	31	28	33	35	22	NA	NA	NA	0.9
P 29	4/22 - 4/23 2012	23	61	40	35	43	46	30	NA	NA	NA	1.4
P 29	4/2 - 4/3 2012	30	62	46	40	47	50	34	NA	NA	NA	0.99
P 29	5/23 - 5/24 2012	30	48	52	45	49	53	42	NA	NA	NA	1.15
P 31	9/5 - 9/6 2011	20	48	29	30	31	33	30	NA	NA	NA	1.1
P 32	9/5 - 9/6 2011	18	48	31	34	35	34	33	NA	NA	NA	1.1
P 35	5/19 - 5/20 2012	29	52	46	30	33	39	31	NA	NA	NA	1.3
P 43	9/5 - 9/6 2011	20	69	48	40	41	46	36	NA	NA	NA	1.1
P 46	9/5 - 9/6 2011	20	29	40	34	40	39	38	NA	NA	NA	1.1
P 47	9/5 - 9/6 2011	19	32	41	36	40	39	38	NA	NA	NA	1.1
P 49	11/11 - 11/12 2011	17	44	18	18	19	21	17	12	17	NA	0.9
P 56	11/11 -11/12 2011	17	47	23	17	20	21	14	NA	NA	NA	0.9
P 57	11/12 - 11/13 2011	17	45	23	19	22	25	14	12	17	NA	0.9
P 57	11/15- 11/16 2011	21	53	25	22	24	27	17	13	19	NA	0.89
P 58	11/17 - 11/18 2011	13	33	37	35	37	37	30	NA	NA	NA	0.89
P 58	11/23 - 11/24 2011	18	41	38	35	37	37	32	NA	NA	NA	0.85
P 58	11/15- 11/16 2011	21	55	41	35	37	38	32	NA	NA	NA	0.88
P 58	4/22 - 4/23 2012	22	65	51	47	52	53	43	NA	NA	NA	1.4
P 58	3/26 - 3/27 2012	27	56	51	NA	51	52	45	NA	NA	NA	1
P 58	4/2 - 4/3 2012	30	62	57	53	57	58	50	NA	NA	NA	1

				Temp. for 2-hour sustainment								
Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 59	11/17 - 11/18 2011	13	35	30	28	34	35	21	NA	NA	NA	0.9
P 59	11/23 - 11/24 2011	18	43	31	28	33	35	21	NA	NA	NA	0.88
P 61	1/12 - 1/13 2012	3	34	36	48	46	45	42	9	42	NA	0.85
P 63	2/12 - 2/13 2012	5	57	32	24	34	39	14	NA	NA	NA	1
P 64	1/12 - 1/13 2012	4	14	34	41	38	37	37	NA	NA	NA	0.86
P 64	1/19 - 1/20 2012	5	12	32	41	38	37	36	NA	NA	NA	0.83
P 65	1/19 - 1/20 2012	5	31	39	50	50	49	42	8	42	NA	0.82
P 65	2/5 - 2/6 2012	11	51	40	42	44	45	35	NA	NA	NA	0.9
P 65	1/28 - 1/29 2012	18	23	20	22	25	26	22	NA	NA	NA	1
P 66A	2/12 - 2/13 2012	5	34	27	24	31	32	15	NA	NA	NA	0.98
P 66A	2/5 - 2/6 2012	10	47	34	29	37	39	20	NA	NA	NA	0.9
P 66A	1/28 - 1/29 2012	17	48	37	33	40	42	22	NA	NA	NA	1
P 75	4/2 - 4/3 2012	30	57	44	34	43	49	30	NA	NA	NA	1
P 75	5/23 - 5/24 2012	31	62	49	39	47	55	34	NA	NA	NA	1.15
P 77	3/10 - 3/11 2012	21	55	34	29	36	39	22	NA	NA	NA	0.99
P 82	11/14 - 11/15 2011	21	NA	31	28	28	27	28	NA	NA	NA	0.89
P 85	4/22 - 4/23 2012	23	64	40	56	58	58	45	18	47	NA	1.1
P 90	4/22 - 4/23 2012	22	32	27	24	28	29	22	NA	NA	NA	1.4
P 100	3/10 - 3/11 2012	20	28	34	52	54	53	40	11	42	NA	1
P 100	4/2 - 4/3 2012	31	38	45	61	63	62	51	22	52	NA	1
P 101	4/22 - 4/23 2012	22	60	45	46	49	54	42	NA	NA	NA	1.4
P 101	3/26 - 3/27 2012	28	37	48	NA	60	60	48	NA	NA	NA	0.98
P 101	4/2 - 4/3 2012	30	40	52	62	64	64	50	22	50	NA	1
P 103	3/26 - 3/27 2012	27	57	44	47	49	50	43	NA	NA	NA	0.98
P 103	4/2 - 4/3 2012	30	62	49	52	53	57	47	NA	NA	NA	0.99
P 114	4/22 - 4/23 2012	23	73	34	36	NA	40	31	NA	NA	0	1.45
P 116	5/12 - 5/13 2012	24	70+	46	44	45	45	37	NA	NA	NA	1.3
P 116	5/19 - 5/20 2012	28	69	45	49	49	48	39	NA	NA	NA	1.3
P 116	6/10 - 6/11 2012	29	71	53	57	58	60	42	NA	NA	NA	1
P 116	5/23 - 5/24 2012	31	55	43	38	39	40	32	NA	NA	NA	1.15
P 116	6/2 - 6/3 2012	39	70	44	54	54	57	35	NA	NA	NA	1

				Temp. for 2-hour sustainment								
Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 117	5/5 - 5/6 2012	31	66	47	42	45	47	39	NA	NA	NA	1.05
P 117	5/23 - 5/24 2012	31	62	54	45	51	55	45	NA	NA	NA	1.15
P 118	5/5 - 5/6 2012	30	72	51	45	49	54	44	NA	NA	NA	1
P 119	5/12 - 5/13 2012	24	47	58	68	68	68	58	NA	NA	NA	1.3
P 119	5/19 - 5/20 2012	28	36	44	63	62	63	48	NA	NA	NA	1.3
P 119	5/23 - 5/24 2012	31	39	39	49	50	50	44	NA	NA	NA	1.15
P 119	5/5 - 5/6 2012	31	49	68	75	75	75	69	NA	NA	NA	1
P 119	6/2 - 6/3 2012	34	48	32	45	44	46	36	NA	NA	NA	1
P 120	5/12 - 5/13 2012	24	43	53	56	57	58	54	NA	NA	NA	1.3
P 120	5/19 - 5/20 2012	29	36	45	57	58	59	50	NA	NA	NA	1.3
P 120	5/5 - 5/6 2012	30	70	64	69	70	68	64	NA	NA	NA	1
P 120	5/23 - 5/24 2012	31	39	40	59	59	59	52	NA	NA	NA	1.15
P 120	6/2 - 6/3 2012	34	45	34	54	54	54	38	NA	NA	NA	1
P 120	6/18 - 6/19 2012	34	44	40	54	53	52	45	NA	NA	NA	1.2
P 121	5/12 - 5/13 2012	24	70	40	50	49	46	41	NA	NA	NA	1.3
P 121	5/19 - 5/20 2012	28	62	42	44	43	45	40	NA	NA	NA	1.3
P 121	6/10 - 6/11 2012	29	68	52	54	58	60	45	NA	NA	NA	1
P 121	5/23 - 5/24 2012	30	58	39	37	39	43	35	NA	NA	NA	1.15
P 121	6/18 - 6/19 2012	34	68	NA	49	55	58	43	NA	NA	NA	1.2
P 122	6/10 - 6/11 2012	29	70	48	36	45	52	39	NA	NA	NA	1
P 123	6/10 - 6/11 2012	28	71	46	34	42	47	32	NA	NA	NA	1

Permutation	Dates	Max exterior air °C	Max interior air °C	Temp. for 4-hour sustainment: A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 1	2/16 - 2/17 2012	18	49	17	10	16	23	10	NA	NA	NA	0.92
P 3	9/5 - 9/6 2011	20	67	36	34	36	39	34	NA	NA	NA	1.1
P 3	6/10 - 6/11 2012	29	61	42	33	39	47	32	NA	NA	NA	1
P 4	9/5 - 9/6 2011	25	69	42	35	38	45	33	NA	NA	NA	1.1
P 5	2/16 -2/17 2012	18	24	7	5	7	8	6	NA	NA	NA	0.91
P 9	9/5 - 9/6 2011	20	70+	42	36	38	44	36	NA	NA	NA	1.1
P 18	9/5 - 9/6 2011	20	69	39	35	38	43	34	NA	NA	NA	1.1
P 19	9/5 - 9/6 2011	20	70+	43	35	36	39	34	NA	NA	NA	1.1
P 28	11/3 2011	9	34	17	17	18	20	16	16	17	NA	0.92
P 29	11/11 - 11/12 2011	17	NA	30	28	33	34	22	NA	NA	NA	0.9
P 29	4/22 - 4/23 2012	23	61	39	35	43	45	29	NA	NA	NA	1.4
P 29	4/2 - 4/3 2012	30	62	45	40	46	49	34	NA	NA	NA	0.99
P 29	5/23 - 5/24 2012	30	48	50	45	49	52	42	NA	NA	NA	1.15
P 31	9/5 - 9/6 2011	20	48	28	30	31	32	30	NA	NA	NA	1.1
P 32	9/5 - 9/6 2011	18	48	31	33	33	33	32	NA	NA	NA	1.1
P 35	5/19 - 5/20 2012	29	52	41	29	32	38	31	NA	NA	NA	1.3
P 43	9/5 - 9/6 2011	20	69	45	38	41	44	35	NA	NA	NA	1.1
P 46	9/5 - 9/6 2011	20	29	39	33	38	37	37	NA	NA	NA	1.1
P 47	9/5 - 9/6 2011	19	32	40	35	39	38	37	NA	NA	NA	1.1
P 49	11/11 - 11/12 2011	17	44	17	18	19	20	16	12	17	NA	0.9
P 56	11/11 -11/12 2011	17	47	22	17	19	20	14	NA	NA	NA	0.9
P 57	11/12 - 11/13 2011	17	45	21	19	20	23	14	11	17	NA	0.9
P 57	11/15- 11/16 2011	21	53	25	22	23	26	17	13	19	NA	0.89
P 58	11/17 - 11/18 2011	13	33	35	35	36	36	30	NA	NA	NA	0.89
P 58	11/23 - 11/24 2011	18	41	37	35	37	37	31	NA	NA	NA	0.85
P 58	11/15- 11/16 2011	21	55	39	35	37	38	32	NA	NA	NA	0.88
P 58	4/22 - 4/23 2012	22	65	49	46	50	52	42	NA	NA	NA	1.4
P 58	3/26 - 3/27 2012	27	56	50	NA	51	52	45	NA	NA	NA	1
P 58	4/2 - 4/3 2012	30	62	55	52	55	56	50	NA	NA	NA	1

Permutation	Dates	Max exterior air °C	Max interior air °C	Temp. for 4-hour sustainment A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m^2
P 59	11/17 - 11/18 2011	13	35	29	28	34	35	20	NA	NA	NA	0.9
P 59	11/23 - 11/24 2011	18	43	31	28	33	34	21	NA	NA	NA	0.88
P 61	1/12 - 1/13 2012	3	34	35	47	45	44	41	9	41	NA	0.85
P 63	2/12 - 2/13 2012	5	57	29	24	33	37	14	NA	NA	NA	1
P 64	1/12 - 1/13 2012	4	14	34	41	38	37	37	NA	NA	NA	0.86
P 64	1/19 - 1/20 2012	5	12	32	41	38	36	36	NA	NA	NA	0.83
P 65	1/19 - 1/20 2012	5	31	38	50	50	48	42	8	41	NA	0.82
P 65	2/5 - 2/6 2012	11	51	39	42	44	45	34	NA	NA	NA	0.9
P 65	1/28 - 1/29 2012	18	23	20	22	25	26	22	NA	NA	NA	1
P 66A	2/12 - 2/13 2012	5	34	26	23	29	31	14	NA	NA	NA	0.98
P 66A	2/5 - 2/6 2012	10	47	33	28	34	38	19	NA	NA	NA	0.9
P 66A	1/28 - 1/29 2012	17	48	37	33	40	41	22	NA	NA	NA	1
P 75	4/2 - 4/3 2012	30	57	43	34	42	48	30	NA	NA	NA	1
P 75	5/23 - 5/24 2012	31	62	47	39	47	53	34	NA	NA	NA	1.15
P 77	3/10 - 3/11 2012	21	55	33	28	34	37	22	NA	NA	NA	0.99
P 82	11/14 - 11/15 2011	21	NA	28	27	27	26	28	NA	NA	NA	0.89
P 85	4/22 - 4/23 2012	23	64	40	55	58	57	44	18	45	NA	1.1
P 90	4/22 - 4/23 2012	22	32	26	24	27	28	22	NA	NA	NA	1.4
P 100	3/10 - 3/11 2012	20	28	34	52	54	53	40	11	42	NA	1
P 100	4/2 - 4/3 2012	31	38	44	61	63	62	51	22	52	NA	1
P 101	4/22 - 4/23 2012	22	60	44	45	49	51	41	NA	NA	NA	1.4
P 101	3/26 - 3/27 2012	28	37	48	NA	60	60	48	NA	NA	NA	0.98
P 101	4/2 - 4/3 2012	30	40	52	62	64	64	50	22	50	NA	1
P 103	3/26 - 3/27 2012	27	57	44	47	48	48	43	NA	NA	NA	0.98
P 103	4/2 - 4/3 2012	30	62	48	51	53	54	47	NA	NA	NA	0.99
P 114	4/22 - 4/23 2012	23	73	35	35	NA	40	31	NA	NA	0	1.45
P 116	5/12 - 5/13 2012	24	70+	46	44	45	44	36	NA	NA	NA	1.3
P 116	5/19 - 5/20 2012	28	69	41	48	48	48	38	NA	NA	NA	1.3
P 116	6/10 - 6/11 2012	29	71	50	57	57	58	42	NA	NA	NA	1
P 116	5/23 - 5/24 2012	31	55	39	37	38	39	32	NA	NA	NA	1.15
P 116	6/2 - 6/3 2012	39	70	42	53	53	55	34	NA	NA	NA	1

				Temp. for 4-hour sustainment								
Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 117	5/5 - 5/6 2012	31	66	45	42	44	46	39	NA	NA	NA	1.05
P 117	5/23 - 5/24 2012	31	62	53	45	50	54	45	NA	NA	NA	1.15
P 118	5/5 - 5/6 2012	30	72	50	45	49	51	44	NA	NA	NA	1
P 119	5/12 - 5/13 2012	24	47	58	67	68	68	58	NA	NA	NA	1.3
P 119	5/19 - 5/20 2012	28	36	44	63	62	63	46	NA	NA	NA	1.3
P 119	5/5 - 5/6 2012	31	49	68	75	75	75	68	NA	NA	NA	1
P 119	5/23 - 5/24 2012	31	39	38	49	49	50	44	NA	NA	NA	1.15
P 119	6/2 - 6/3 2012	34	48	32	45	44	46	45	NA	NA	NA	1
P 120	5/12 - 5/13 2012	24	43	52	56	57	58	54	NA	NA	NA	1.3
P 120	5/19 - 5/20 2012	29	36	44	57	58	59	50	NA	NA	NA	1.3
P 120	5/5 - 5/6 2012	30	70	62	68	69	67	64	NA	NA	NA	1
P 120	5/23 - 5/24 2012	31	39	39	59	59	59	52	NA	NA	NA	1.15
P 120	6/2 - 6/3 2012	34	45	34	54	54	54	38	NA	NA	NA	1
P 120	6/18 - 6/19 2012	34	44	40	54	53	52	45	NA	NA	NA	1.2
P 121	5/12 - 5/13 2012	24	70	39	50	48	45	40	NA	NA	NA	1.3
P 121	5/19 - 5/20 2012	28	62	40	43	42	42	39	NA	NA	NA	1.3
P 121	6/10 - 6/11 2012	29	68	50	54	55	56	44	NA	NA	NA	1
P 121	5/23 - 5/24 2012	30	58	38	36	38	38	35	NA	NA	NA	1.15
P 121	6/18 - 6/19 2012	34	68	NA	48	54	55	42	NA	NA	NA	1.2
P 122	6/10 - 6/11 2012	29	70	47	35	44	48	38	NA	NA	NA	1
P 123	6/10 - 6/11 2012	28	71	45	34	41	46	32	NA	NA	NA	1

Temp. for 12-hour sustainment

Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 1	2/16 - 2/17 2012	18	49	15	9	15	18	9	NA	NA	NA	0.92
P 3	9/5 - 9/6 2011	20	67	32	33	34	34	32	NA	NA	NA	1.1
P 3	6/10 - 6/11 2012	29	61	36	33	37	39	32	NA	NA	NA	1
P 4	9/5 - 9/6 2011	25	69	33	33	34	35	31	NA	NA	NA	1.1
P 5	2/16 -2/17 2012	18	24	5	5	5	7	5	NA	NA	NA	0.91
P 9	9/5 - 9/6 2011	20	70+	34	34	36	38	33	NA	NA	NA	1.1
P 18	9/5 - 9/6 2011	20	69	32	33	34	35	31	NA	NA	NA	1.1
P 19	9/5 - 9/6 2011	20	70+	33	33	34	34	31	NA	NA	NA	1.1
P 28	11/3 2011	9	34	13	16	14	13	14	15	16	NA	1.2
P 29	11/11 - 11/12 2011	17	NA	28	27	31	31	21	NA	NA	NA	0.9
P 29	4/22 - 4/23 2012	23	61	36	34	39	40	28	NA	NA	NA	1.4
P 29	4/2 - 4/3 2012	30	62	42	38	44	45	33	NA	NA	NA	0.99
P 29	5/23 - 5/24 2012	30	48	43	43	46	46	39	NA	NA	NA	1.15
P 31	9/5 - 9/6 2011	20	48	26	28	28	29	27	NA	NA	NA	1.1
P 32	9/5 - 9/6 2011	18	48	28	30	30	29	29	NA	NA	NA	1.1
P 35	5/19 - 5/20 2012	29	52	30	28	29	31	29	NA	NA	NA	1.3
P 43	9/5 - 9/6 2011	20	69	33	35	35	35	32	NA	NA	NA	1.1
P 46	9/5 - 9/6 2011	20	29	29	31	31	30	31	NA	NA	NA	1.1
P 47	9/5 - 9/6 2011	19	32	30	33	32	31	33	NA	NA	NA	1.1
P 49	11/11 - 11/12 2011	17	44	16	17	18	19	16	11	16	NA	0.9
P 56	11/11 -11/12 2011	17	47	18	16	18	19	14	NA	NA	NA	0.9
P 57	11/12 - 11/13 2011	17	45	14	17	16	15	13	11	15	NA	0.9
P 57	11/15- 11/16 2011	21	53	21	20	22	22	16	13	18	NA	0.89
P 58	11/17 - 11/18 2011	13	33	34	33	35	35	29	NA	NA	NA	0.89
P 58	11/23 - 11/24 2011	18	41	34	34	35	35	30	NA	NA	NA	0.85
P 58	11/15- 11/16 2011	21	55	35	34	36	36	32	NA	NA	NA	0.88
P 58	4/22 - 4/23 2012	22	65	45	45	48	49	41	NA	NA	NA	1.4
P 58	3/26 - 3/27 2012	27	56	45	NA	48	49	44	NA	NA	NA	1
P 58	4/2 - 4/3 2012	30	62	49	51	53	53	48	NA	NA	NA	1

Temp. for 12-hour sustainment

Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 59	11/17 - 11/18 2011	13	35	28	27	30	30	20	NA	NA	NA	0.9
P 59	11/23 - 11/24 2011	18	43	28	27	32	32	20	NA	NA	NA	0.88
P 61	1/12 - 1/13 2012	3	34	34	46	44	43	40	8	40	NA	0.85
P 63	2/12 - 2/13 2012	5	57	23	22	28	30	13	NA	NA	NA	1
P 64	1/12 - 1/13 2012	4	14	33	40	37	36	36	NA	NA	NA	0.86
P 64	1/19 - 1/20 2012	5	12	30	40	37	35	35	NA	NA	NA	0.83
P 65	1/19 - 1/20 2012	5	31	36	49	49	46	41	8	40	NA	0.82
P 65	2/5 - 2/6 2012	11	51	34	39	40	40	32	NA	NA	NA	0.9
P 65	1/28 - 1/29 2012	18	23	19	21	24	25	21	NA	NA	NA	1
P 66A	2/12 - 2/13 2012	5	34	18	20	23	23	13	NA	NA	NA	0.98
P 66A	2/5 - 2/6 2012	10	47	28	34	29	30	17	NA	NA	NA	0.9
P 66A	1/28 - 1/29 2012	17	48	35	32	38	38	21	NA	NA	NA	1
P 75	4/2 - 4/3 2012	30	57	38	33	39	42	29	NA	NA	NA	1
P 75	5/23 - 5/24 2012	31	62	43	38	45	46	33	NA	NA	NA	1.15
P 77	3/10 - 3/11 2012	21	55	30	27	32	34	21	NA	NA	NA	0.99
P 82	11/14 - 11/15 2011	21	NA	17	26	23	23	27	NA	NA	NA	0.89
P 85	4/22 - 4/23 2012	23	64	38	54	57	56	44	18	45	NA	1.1
P 90	4/22 - 4/23 2012	22	32	24	24	26	27	21	NA	NA	NA	1.4
P 100	3/10 - 3/11 2012	20	28	34	52	54	53	40	11	42	NA	1
P 100	4/2 - 4/3 2012	31	38	43	60	62	61	50	22	52	NA	1
P 101	4/22 - 4/23 2012	22	60	40	44	46	46	40	NA	NA	NA	1.4
P 101	3/26 - 3/27 2012	28	37	47	NA	60	60	48	NA	NA	NA	0.98
P 101	4/2 - 4/3 2012	30	40	51	62	64	64	50	22	50	NA	1
P 103	3/26 - 3/27 2012	27	57	40	46	46	44	42	NA	NA	NA	0.98
P 103	4/2 - 4/3 2012	30	62	44	50	51	49	45	NA	NA	NA	0.99
P 114	4/22 - 4/23 2012	23	73	34	34	NA	39	30	NA	NA	0	1.45
P 116	5/12 - 5/13 2012	24	70+	41	43	44	40	35	NA	NA	NA	1.3
P 116	5/19 - 5/20 2012	28	69	34	46	46	44	35	NA	NA	NA	1.3
P 116	6/10 - 6/11 2012	29	71	39	52	53	50	40	NA	NA	NA	1
P 116	5/23 - 5/24 2012	31	55	32	35	36	35	30	NA	NA	NA	1.15
P 116	6/2 - 6/3 2012	39	70	33	49	48	47	33	NA	NA	NA	1

Temp. for 12-hour sustainment

Permutation	Dates	Max exterior air °C	Max interior air °C	A - NE 4" °C	B Mid 8" °C	C Mid 6" °C	D - Mid 4" °C	E - SW 8" °C	Slab Temp. °C	Top of Ins. °C	Moisture %	Solar Rad. kW/m²
P 117	5/5 - 5/6 2012	31	66	41	40	42	42	38	NA	NA	NA	1.05
P 117	5/23 - 5/24 2012	31	62	46	44	46	48	43	NA	NA	NA	1.15
P 118	5/5 - 5/6 2012	30	72	46	44	45	46	43	NA	NA	NA	1
P 119	5/12 - 5/13 2012	24	47	56	66	67	67	57	NA	NA	NA	1.3
P 119	5/19 - 5/20 2012	28	36	42	63	61	61	46	NA	NA	NA	1.3
P 119	5/5 - 5/6 2012	31	49	65	75	75	75	67	NA	NA	NA	1
P 119	5/23 - 5/24 2012	31	39	38	49	49	50	44	NA	NA	NA	1.15
P 119	6/2 - 6/3 2012	34	48	31	44	43	45	35	NA	NA	NA	1
P 120	5/12 - 5/13 2012	24	43	52	56	57	58	54	NA	NA	NA	1.3
P 120	5/19 - 5/20 2012	29	36	44	56	57	57	49	NA	NA	NA	1.3
P 120	5/5 - 5/6 2012	30	70	59	66	67	65	62	NA	NA	NA	1
P 120	5/23 - 5/24 2012	31	39	38	58	58	58	51	NA	NA	NA	1.15
P 120	6/2 - 6/3 2012	34	45	33	54	54	53	38	NA	NA	NA	1
P 120	6/18 - 6/19 2012	34	44	40	54	53	52	44	NA	NA	NA	1.2
P 121	5/12 - 5/13 2012	24	70	38	48	46	42	39	NA	NA	NA	1.3
P 121	5/19 - 5/20 2012	28	62	37	42	40	38	37	NA	NA	NA	1.3
P 121	6/10 - 6/11 2012	29	68	44	50	50	49	43	NA	NA	NA	1
P 121	5/23 - 5/24 2012	30	58	33	36	36	34	34	NA	NA	NA	1.15
P 121	6/18 - 6/19 2012	34	68	NA	46	47	46	40	NA	NA	NA	1.2
P 122	6/10 - 6/11 2012	29	70	39	34	38	41	37	NA	NA	NA	1
P 123	6/10 - 6/11 2012	28	71	37	32	38	39	31	NA	NA	NA	1

Appendix C: Physical Properties Heat Transfer Charts for a Typical Compartment Constructions and Materials

Appendix Table 1 Lengths of construction materials used in composting latrines

Lenghts	m	Reference
Depth of Compost and Simulated Compost	0.30	Measured
R-15 Insulation Thickness	0.08	Measured
Double Wall Wood Thickness	0.17	Measured
Concrete Block Wall Thickness	0.20	Measured
Slab Thickness	0.10	Measured
Depth to Assumed Constant Ground Temperature	1.02	Measured
Average Width from Middle of Compost to Wall	0.69	Measured

Appendix Table 2 Areas of construction components

Areas	m^2	Reference
Cover Surface	3.9	Measured
Cover Surface over Compost	2.1	Measured
Compost Surface (Wood Chambers)	2	Measured
Compost Surface (Concrete Chambers)	1.82	Measured
Top of Compost Insulation Surface (Wood Chambers)	2	Measured
Top of Compost Insulation Surface (Concrete Chambers)	1.82	Measured
Slab Surface (Contact with Compost Wood Chambers)	2	Measured
Slab Surface (Contact with Compost Concrete Chambers)	1.82	Measured
Slab Surface (Contact with Ground)	3.1	Measured
North Wall Wood	1.58	Measured
South Wall Wood	0.53	Measured
East Wall Wood	1.24	Measured
West Wall Wood	1.24	Measured
North Wall Concrete	1.58	Measured
South Wall Concrete	0.53	Measured
East Wall Concrete	1.24	Measured
West Wall Concrete	1.24	Measured

Appendix Table 3 Masses of compost and simulated compost

Masses	kg	Reference
Compost Dry (Wood Chambers)	113	Calculated by Measurement
Compost Wet (Wood Chambers)	312	Calculated by Measurement
Compost Dry (Concrete Chambers)	104	Calculated by Measurement
Compost Wet (Concrete Chambers)	284	Calculated by Measurement
Simulated Compost Dry (Wood Chambers)	719	Calculated by Measurement
Simulated Compost Wet (Wood Chambers)	889	Calculated by Measurement
Simulated Compost Dry (Concrete Chambers)	657	Calculated by Measurement
Simulated Compost Dry (Mounded Chamber)	848	Calculated by Measurement

Appendix Table 4 Thermal convection coefficient ranges for compartment components

Thermal Convection Coefficents	W/m^2-°C	Reference
Cover to Environment (1-30 mph)	7.3-54.5	Straube J. Burnett E. 2005
Cover to Chamber Air (ΔT 5-45 °C)	0.66-1.15	Straube J. Burnett E. 2005
Compost to Chamber Air (ΔT 5-45 °C)	1.7-3.0	Straube J. Burnett E. 2005
Insulation to Chamber Air (ΔT 5-45 °C)	1.7-3.0	Straube J. Burnett E. 2005
Walls to Chamber Air (ΔT 5-45 °C) and (0.5 to 4 mph)	2.4-4.2	Straube J. Burnett E. 2005
Compost Internal Convection (ΔT 5-45 °C)	1.4-2.1	Straube J. Burnett E. 2005
North Wall Wood (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
South Wall Wood (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
East Wall Wood (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
West Wall Wood (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
North Wall Concrete (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
South Wall Concrete (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
East Wall Concrete (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005
West Wall Concrete (1-30 mph)	2.33-35.4	Straube J. Burnett E. 2005

Appendix Table 5 Emissivity of compartment components

Emmisivities	%	Reference
Simulated Compost	0.66	Siegel R. Howell J. 2002
Compost	0.9	Siegel R. Howell J. 2002
Metal	0.25	Siegel R. Howell J. 2002
Black Painted Metal	0.97	Siegel R. Howell J. 2002
White Fiberglass	0.85	Assumption
Polycarbonate	0.86	Thermoworks.com, 06/12
Sky (5-22-2012 1 pm)	0.772	Chen B. et al.
Urethane on Wood	0.85	Straube J. Burnett E. 2005
Cement Block	0.85	Straube J. Burnett E. 2005
Polystyrene	0.7	Assumption

Appendix Table 6 Solar absorptiveness of compartment components

Solar Absorptivities	%	Reference
Metal	0.38	Siegel R. Howell J. 2002
Black Painted Metal	0.9	Siegel R. Howell J. 2002
Clear Polycarbonate	0.1	Manufacturer Data, DynaGlas Plus
Compost	0.9	Siegel R. Howell J. 2002
Concrete Block Walls	0.65	Charpin J. et al. 2004
Polyurathaned Wood Walls	0.85	Siegel R. Howell J. 2002

Appendix Table 7 Thermal conductivities of composting compartment constructions and compost

Thermal Conductivities	(W/m-°C)	Reference
Hay Insulated Wood	0.018	Experiment Jean A. 2011
Un-Insulated Wood	0.013	Experiment Jean A. 2011
Hay Insulated Concrete	0.4	Experiment Jean A. 2011
Un-Insulated Concrete	0.34	Experiment Jean A. 2011
Wet Compost (60% GWC)	0.48	Mears R. D. et al. 1975
Dry Compost (10% GWC)	0.27	Mears R. D. et al. 1975
Wet Simulated Compost (50% GWC)	2.25	Salomone A. L. Marlow I. J. 1989
Dry Simulated Compost (10% GWC)	0.952	Salomone A. L. Marlow I. J. 1989
Slab Dry	0.5	ASHRAE, 2005
Top of Slab R15 Insulation	0.01	ASHRAE, 2005
Top of Slab Straw Insulation	0.9	engineeringtoolbox.com 2012
Still Air Gap (varies by reference up to 100%)	0.312	ASHRAE, 2005

Appendix Table 8 Permeability of composting compartment materials and constructions

Permeabilities	Perms	Reference
Insulated Wood	unk	
Un-insulated Wood	unk	
Insulated Concrete	unk	
Un-insulated Concrete	2.4	ASHRAE, 2005
Compost Soil Cover	0.07	ASHRAE, 2005
White/Black Plastic	0.06	ASHRAE, 2005
Top of Slab R15 Insulation	0.4	ASHRAE, 2005
Still Air	34.3	ASHRAE, 2005
Concrete Slab	0.91	ASHRAE, 2005

Appendix Table 9 View factors for composting compartment constructions

View Factor	%	Reference
Cover to Sky	0.883	A. Siraki, P. Pillay, 2012
Compost to Cover	0.68	Siegel R. Howell J. 2002
Cover to Compost	0.49	Siegel R. Howell J. 2002
Compost to Interior North Wall	0.13	Siegel R. Howell J. 2002
Compost to Interior East and West Wall	0.07	Siegel R. Howell J. 2002
Compost to Interior South Wall	0	Assumption
North Wall Exterior to Sun	0	Assumption
South Wall Exterior to Sun	0.49	Straube J. Burnett E. 2005
East Wall Exterior to Sun	0.49	Straube J. Burnett E. 2005
West Wall Exterior to Sun	0.49	Straube J. Burnett E. 2005
North Wall Exterior to Sky	0.49	Straube J. Burnett E. 2005
South Wall Exterior to Sky	0.49	Straube J. Burnett E. 2005
East Wall Exterior to Sky	0.49	Straube J. Burnett E. 2005
West Wall Exterior to Sky	0.49	Straube J. Burnett E. 2005

Appendix D: Pictures of observations, compartments and construction details

Appendix D.1 Significant Observations

Appendix Figure 1. Compartments 1, 2, 3 (left to right) north exterior wall after significant rainy period

Treatment of slab and concrete block affects moisture uptake

Appendix Figure 2. Soil removed from compartment that underwent wetting and desiccation

Appendix D.2 Compartments

Appendix Figure 3. Single sided base with single sided polycarbonate lid

Appendix Figure 4. Double sided wood base with 6 mil plastic cover

Appendix Figure 5. Double wood base with straw insulation and single sided clear polycarbonate top

Appendix Figure 6. Concrete base with unpainted corrugated metal cover

Appendix Figure 7. Concrete base with white fiberglass cover

Appendix Figure 8. Double sided clear polycarbonate cover set aside while other permutations were being tested

Appendix Figure 9. Black painted metal cover, set aside while other permutations were being tested

Appendix Figure 10. 6 mill transparent white polyethylene on mounded pile (compartment 10)

Appendix Figure 11. ¼" double clear base with ¼" double clear cover

The north wall was left as wood because in the latrine design this edge would be connected to the latrine compartment. The cover was separated by 1.3 cm (0.5 in.) and the sides were separated by 3.8cm (1.5 in.). Under some weather conditions the gaps between the polycarbonate were fill with condensation and this will reduce the thermal performance of the compartment because less solar radiation would reach the simulated compost

Appendix D.3 Compartment Details

Appendix Figure 12. Detail of indents left by single sided polycarbonate on compressible foam insulation

Appendix Figure 13. Detail of compressible foam and black rod insulation solution for larger gaps

Appendix Figure 14. Top insulation, two layers of R-7.5 rigid polystyrene insulation

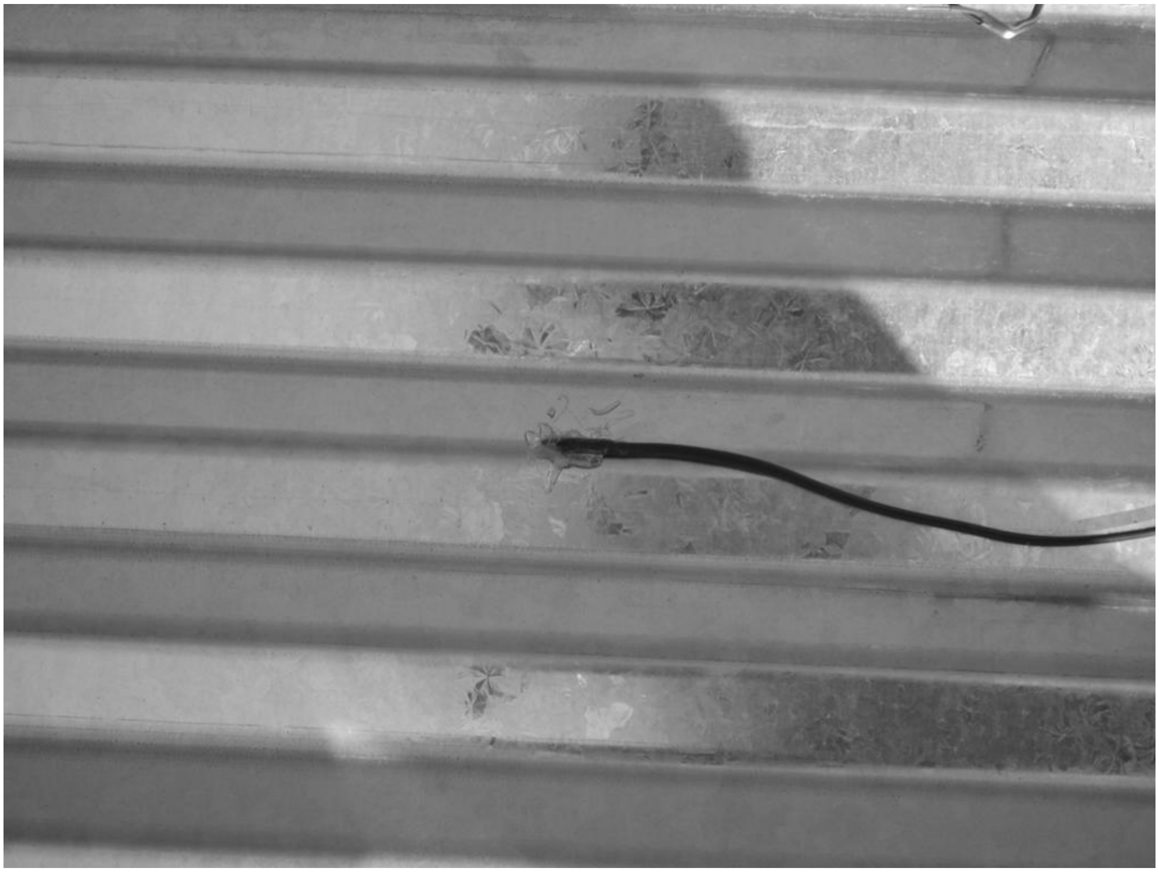
Appendix Figure 15. 6" of loosely placed straw inside plastic wrap for simulated compost top insulation

Appendix Figure 16. Polystyrene insulation that degraded when placed under double clear polycarbonate top

Appendix Figure 17. Un-insulated double wood compartment after 45 gallons of water was added

Appendix Figure 18. Solar radiation meter on stand at average height of compartments

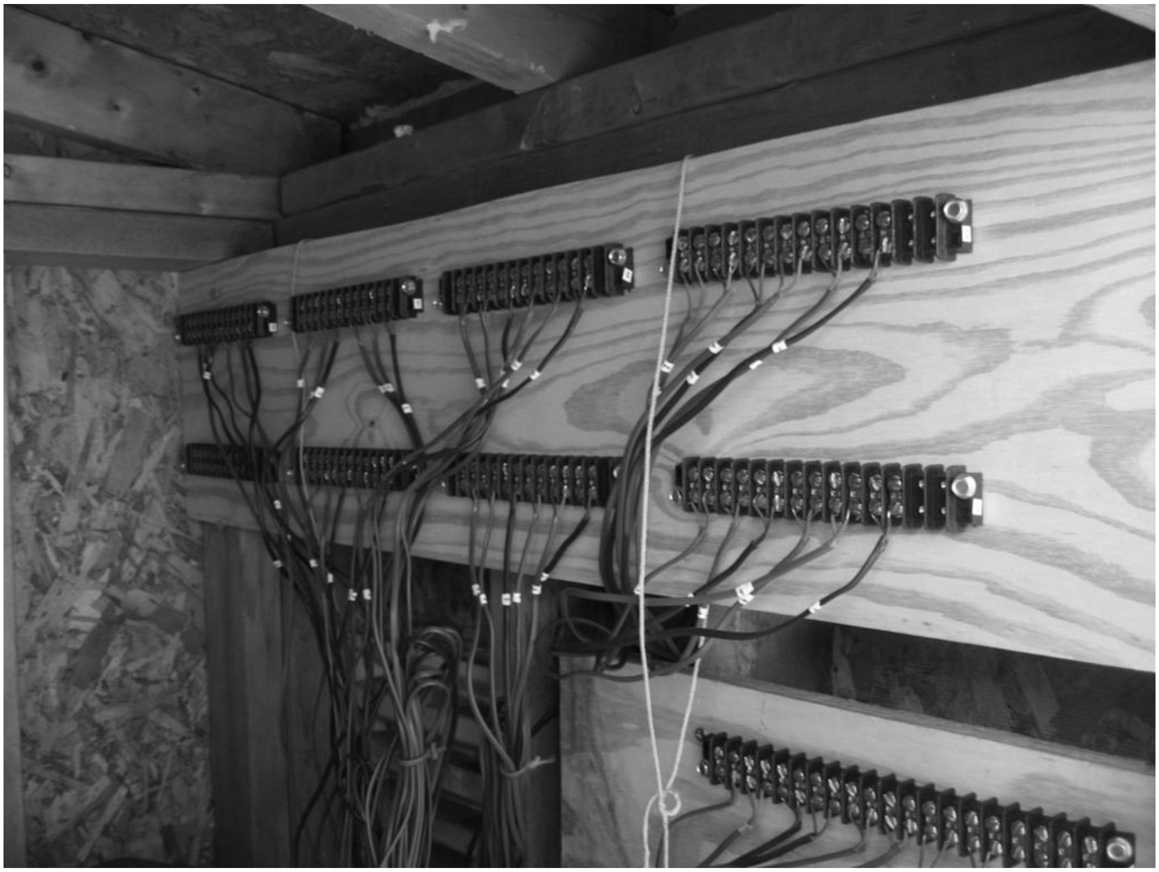
Left screw adjusts angle to compartment angle 39° with the far right screw used to set angle.



Appendix Figure 19. One of two thermocouples glued to the bottom of unpainted black metal cover material

Appendix Figure 20. Un-insulated concrete compartment with simulated soil

White wire is the power for the strip lighting and the blue wires are thermocouples placed in the NE corner, middle and SE corner of the compartment at various depths. Air sensors have foil to reduce direct solar radiation energy from skewing air temperatures. Wires that are ran up the north wall record concrete slab temperature (see figure x.x for cover thermocouples that are glued to cover material).



Appendix Figure 21. Thermocouple compensated barrier strip hookups being installed inside the logging box

Appendix Figure 22. Strip lighting placed 9” deep in simulated compost

Appendix Figure 23. Strip lighting being installed in simulated compost of mounded compartment #10 Sarah Eberhart, Undergraduate Research Assistant