An Experiment in Thermophilic Composting Toilet Design

a Final Project by

Abraham Noe-Hays

May 26, 2000

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Introduction

Humanure (the urine and feces of human beings) is a rich source of nutrients that has sustained agricultural systems around the world and throughout the ages. The human race produces 2,025,000,000 gallons of it every day, and it contains nearly all of the nutrients from the food we ingest, including copious amounts of nitrogen, potassium, and phosphorous, at 13, 4, and 3 percent of dry weight, respectively (Gotaas *in* Faechem, et al, 1980), as well as a host of micronutrients. Humanure was historically the cornerstone of sustainable traditional agricultural systems throughout Asia, and even in the present day it could provide all the nitrogen needs of the world's agricultural systems (Faechem et al, 1980)(Wolf, 1986)(Rockefeller, 1997).

Yet despite humanure's great potential value, and despite countless examples of its successful reuse set by 100 generations of Asian farmers, most technologically developed nations have come to treat humanure as a waste, fit only for disposal. Typically, it is mixed with pure drinking water and flushed into sewers where it mingles with all manner of industrial toxins. The sewage then flows through miles of pipes until it reaches a central treatment plant where it is screened, settled, digested, and eventually separated into black sludge and clear effluent water. The solid sludge, which consists of all the material that the treatment process manages to separate back out of the wastewater stream, contains some of the nutrients originating in the humanure, but also the entire array of industrial and household chemicals that were present in the raw sewage. Also, since the nitrogen and phosphorous in humanure are highly soluble, a large portion of both nutrients remains in the effluent where it is completely lost to agriculture and can also contribute to eutrophication of rivers and lakes (Van der Ryn, 1978)(Rockefeller, 1997).

While the effluent is discharged into surface waters, the sludge must be dealt with in some other way. In some parts of the United States people have landfilled this sludge, often causing groundwater contamination, while in others they have incinerated it, resulting in air pollution. Ocean dumping was historically very popular, but due to the accumulation of heavy metals and other toxins it turned the ocean floor at dump sites into dead wastelands and was eventually banned by the EPA in 1988 (Rockefeller, 1997).

Recently, with the backing of the EPA, the spreading of sludge on farmland has become a popular disposal method. However, the land application strategy contains the same flaws as ocean dumping. Heavy metals are often present in sludges, and they accumulate in the soil. The EPA recommends liming the farmland where sludge is applied, which raises the soil pH and report that biological factors such as microbial competition and predation in a moist, cool compost pile can in fact eliminate pathogens and make the compost safe (Rockefeller, 2000). Yet even if this is the case, regulatory agencies, (most importantly the EPA,) do not acknowledge it and require that all humanure compost that comes in contact with the edible portions of food crops first be exposed to temperatures of at least 55°C (132°F) for a minimum of three days.

There are a host of home-made systems for recycling humanure which aim at achieving high temperatures. Some people use outhouses built atop holding tanks and periodically shovel the contents into the center of a hot pile of yard trimmings and garden wastes. Others collect their humanure bucket by bucket and use it, along with straw, sawdust, leaves, grass, and kitchen scraps, to build a continuous-feed compost pile. Joseph Jenkins (1999) describes one variation of the latter system in great detail in his Humaure Handbook, and argues convincingly that the combination of high temperatures throughout *most* of the pile and the long retention time (up to three years) produces a compost safe to use without restrictions. There are probably a multitude of other such systems that can treat humanure effectively, provided the operator is knowledgeable, experienced, and conscientious.

Widespread adoption of these systems has not happened because it is a rare breed of person who has any interest in actively managing a compost pile or even thinking about their own excrement. Although it is really not much work to do so, especially when considering the value of the resulting compost, most people who would even entertain the though of a composting toilet would probably only be satisfied by a system they could use for months without service and then empty when the compost is finished. Additionally, fecophobia, the fear of fecal matter and anything derived therefrom, is so deeply entrenched in our culture, (even in the composting subculture,) that unless people's attitudes begin to change, the only way that the recycling and reuse of humanure is going to reach a larger audience is with the safety guarentee of complete thermophilic composting. Therefore, to be popularly acceptable a humanure composting system should expose all composting material to at least 55°C, and the only demands it should make on users is that they add of a scoop of sawdust (or other bulking material) every time they use it and that they empty it occasionally when the compost is ready. No such system exists today.

It is in this context that I present the following experiment, the goal of which was to develop a toilet system that could compost humanure at temperatures exceeding 55°C, guaranteeing the destruction of all human pathogens. Such a system would create a product that the user could freely, safely, and legally apply to all food crops, thereby closing the nutrient cycle and obviating the need for external fertilizer inputs.

Introduction to Vessel Design

50°C is not a particularly high temperature for a compost pile to reach. The centers of backyard grass and leaf piles measuring a cubic meter or more attain it routinely. However, there are three major obstacles that make it difficult to achieve similar temperatures in a composting toilet.

First, most compost piles that reach high temperatures are built all at once. During the first few days after construction the temperature rises to 50 or 60°C as microorganisms very rapidly break down the bounty of available compounds. It stays at this temperature for about two weeks, sustained by continued high rates of microbial activity. Then, after much of the available food is consumed and activity slows, the pile begins to cool off gradually.

In contrast to the batch system, a composting toilet is a continuous-feed system in which material accumulates steadily and gradually, with the result that at any moment the pile consists of a range of material from old, mostly-decomposed matter supporting little microbial activity to fresh, actively decomposing matter supporting large, active, heat-producing microbial communities. Since the periods of maximum heat production for each addition to a continuous-feed system do not coincide, the peak pile temperature is not as high as it would be in a batch system that was processing the same materials.

The second obstacle to treating humanure through thermophilic composting is that all compost piles tend to heat unevenly. The core is insulated by the rest of the pile and becomes very hot in comparison to the edges which remain quite close to ambient temperature. This is acceptable in a food or leaf compost pile where the function of heat is simply to speed decomposition; a turning or two gives most of the material a time in the hot center and the few bits that fail to reach the hot zone and remain undecomposed can be easily screened out.

However, when pasteurization is the goal, this system is not acceptable. An acceptable system must guarantee that absolutely all material be exposed to the high temperatures, for any that is not remains untreated. The EPA has ruled that a pile turned numerous times, with the edges turned into the center, meets requirements for destruction of pathogens, but this treatment method is of little use to the operator of a home composting toilet due to the amount of work that turning entails and the unpleasant nature of turning a toilet by hand.

These first two problems can be resolved with the same treatment: insulation. With a sufficient amount of insulation, any sustained rate of heat evolution can maintain a compost pile at a given temperature. Insulation also distances the outermost layers of the pile from the cooling effects of the environment, minimizing the difference between core and edge temperatures.

The third problem is that of the evaporative cooling. The ventilator fan which is included in the typical composting toilet to remove odors generally causes enough evaporative cooling to remove all the heat produced by the compost and to actually keep it below ambient temperature. Even the application of auxiliary electric heat can fail to increase pile temperatures because of this effect (Chapman, 1995). To solve this problem, air flow through and over the pile must be kept to the minimum level needed to ensure aerobic conditions. To keep odors from being a problem, the active composting chamber must somehow be separated from the toilet fixture.

Materials and Methods

In order to focus on the dynamics of a heavily insulated vessel with restricted air flow I decided to conduct the experiment using a free-standing vessel. I collected the humanure separately in 5-gallon buckets and combined it with wood shavings in the vessel. Of course, this system does not meet the criterion I set for ease of use. The user must empty buckets regularly and clean them. Instead, this experiment is intended to refine the design of a vessel that could eventually be incorporated into a single-piece toilet that would not require transportation of the humanure.

The vessel I used in this experiment was a cube 93 cm on a side with a hinged lid, built of 5/8" CD-X grade plywood. The vessel was airtight; all seams were caulked with 100 percent silicone caulking, and closed cell weatherstripping sealed the edges where the vessel walls met the lid. A drain hole fitted with a brass spigot, to which a two-liter bottle was attached, allowed excess liquid to drain from the vessel and be removed periodically.

The only airflow into and out of the vessel occurred through two 3/4" pipes which passed through holes near the upper edge of the west face of the cube (Face 1). The first pipe (the intake pipe) simply passed through the wall, connecting the upper interior part of the vessel with the outdoors. The second pipe (the outflow pipe) lead down the corner of the vessel and along the floor, connecting to a set of large (approx. 5") screened tubes which formed an "X" on the vessel floor and were covered by a porous layer of coarse wood chips. Thus, drawing air out of the outflow pipe would draw air from the screened tubes, creating an evenly dispersed partial vacuum near the floor of the vessel. Outdoor air would then flow into the vessel through the intake pipe and then downward through the vessel contents until it reached the partial vacuum in the screened tubes and exited the vessel through the outflow pipe.

An aquarium pump that I modified to operate in a suction mode drew air through the vessel at controlled rates which varied from 0 - 150 L/hr during the course of the experiment. An unanticipated result was that as soon as the compost heated, the hot, moist air leaving the outflow pipe began to condense in the hose that lead to the aquarium pump. This condensation was drawn directly into the pump, eventually causing the pump coil to corrode and fail. I replaced the coil and then added a drain at the low point of the hose to draw off the condensation into a flask. In addition to increasing the life of the second pump, this modification allowed me to measure the amount of water vapor exiting the vessel and thereby determine the approximate level of evaporative cooling. I only began measuring condensation on Day 32, and judging by the presence of some residual condensation in the air line even "downwind" of the collection drain, my figures for condensation volume must be slightly to considerably low.

Throughout the experiment I also measured the oxygen concentrations in the air exiting from the pump using a Sable Systems Oxygen Analyzer.

In early April I placed the vessel outdoors in a wooded area. It rested on a four-inch slab of foam construction insulation (R-20), which was held off the ground by wooden timbers. On April 21 I insulated the four sides and the top of the vessel with two inches of foam insulation (R-10). I added an additional two inches on May 6, bringing the R-value up to 20 on all faces of the vessel. I attached the insulation using drywall screws and boards, and caulked the corner seams with loose fiberglass.

An array of 25 thermistor/diode probes of my own design and construction sensed temperatures within the vessel, and a 12-bit precision analog-to-digital converter circuit (also of my design and construction) quantified the voltages returned by the probes. An IBM compatible laptop computer, running a custom data-logging program that I wrote in Microsoft QBasic, recorded the data, performed compensation calculations, and calculated final temperature values for each probe. Temperature values were precise to within 0.2°C and accurate to within 1°C.

To collect humanure I built three sawdust toilets out of salvaged chairs. In the seat of each chair I cut a hole big enough to accommodate a 5-gallon bucket, and I built a mechanism (different for each chair,) to support the bucket. I mounted a toilet seat on each chair and placed the finished toilets in public bathrooms on campus. I also wrote clear signs that accompanied the toilets, instructing people to add sawdust from a second bucket after every use of the toilet. Through the signs I encouraged people to, on any given day, try to use the sawdust toilets either exclusively or not at all, since I was trying to collect both urine and feces in a ratio as close as possible to the natural ratio produced by humans. If the experiment was to provide a model for recycling humanure it was important to use urine and feces in a natural ratio.

When the toilets buckets were full I removed and weighed them. I also weighed the now-partially-empty sawdust buckets. Since I had weighed the sawdust buckets before placing them in the bathrooms, I was able to determine the weight of the sawdust that had been added to the toilet bucket. By subtracting this figure (and the weight of an empty bucket) from the weight of the toilet bucket I could determine the weight of the humanure.

The humanure produced by an adult in one day weighs about 1.35 kg and contains approximately 13g nitrogen and 30g carbon (Gotaas *in* Faechem, 1980). This gives a C:N ratio of about 2. Since the generally accepted ideal for composting is between 25:1 and 30:1 I obviously needed to add more carbon. To determine how much to add, I did a test run in an insulated bucket, adding about 0.4 kg of wood shavings (C:N ration of over 100:1 (Cornell, 2000)), for every 1 kg humanure to achieve a C:N ratio near 30:1. This resulted in ammonia evolution, a sign of low C:N ratio. Although there was enough carbon in the wood shavings, it was not available to microorganisms. Based on these results, used to 0.7 kg shavings/1 kg humanure during the actual experiment.

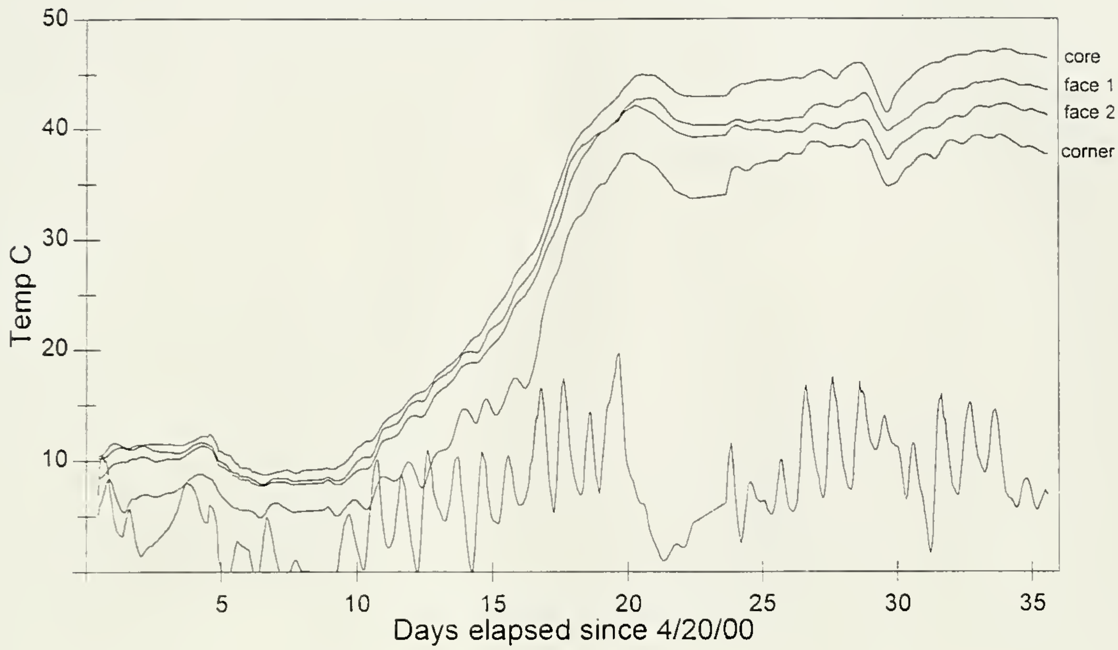
Results

People's responses to the sawdust toilets in the public rest rooms ranged from indifferent to extremely enthusiastic. Most of the people who gave me informal feedback told me they had been following my request and only used the toilet when they could use it all day. Users added wood shavings very consistently, with the result that the toilets created a slight saw-dusty odor but little more. On the rare occasions when the buckets took more than a few days to fill, a stronger, slightly sour odor was sometimes present, although it was not the odor of sewage, urine, or feces.

I made the first addition of humanure (approx. 22 kg) and wood shavings (approx. 14 kg) to the vessel on April 10, 11 days before I insulated it and 10 days before the beginning of data logging. On April 13 I added another 13 kg humanure and 9 kg shavings. On April 20 (Day 0) I began logging data and on April 21 (Day 1) I attached the first layer of insulation. Temperatures inside the composting material hovered at about 7°C above outside temperatures. On Day 6 I started the pump at a 20% duty cycle, drawing about 30 liters of air per hour through the vessel. I added another 11 kg humanure and 9 kg shavings on Day 7. On Day 10 the vessel temperature began to rise markedly, as did oxygen consumption, prompting me to increase the pump duty cycle to 40% (60 liters/hr) on Day 13, and then to 80% (120 liters/hr) on Day 15. (I tried to keep oxygen levels in the outflow above 10%.) Starting on Day 10 temperatures rose by 2.5°C/day for 6 days until, on Day 16, I added the second layer of insulation. The additional insulation caused an increase in the rate of temperature change and also dampened the diurnal temperature fluctuations that had been occurring near the vessel walls. The diurnal fluctuations are clearly visible in Figure 1, especially in the corner probes. Temperatures rose by 4°C/day for 4 days until Day 20, at which point they reached a plateau. I continued adding humanure and wood shavings, usually at about 10 kg humanure and 7 or 8 kg wood shavings per addition.

On day 28 the air pump failed, causing a complete halt of air flow. Vessel temperatures

Probes at Floor Level



Probes at approx. 10 cm above floor

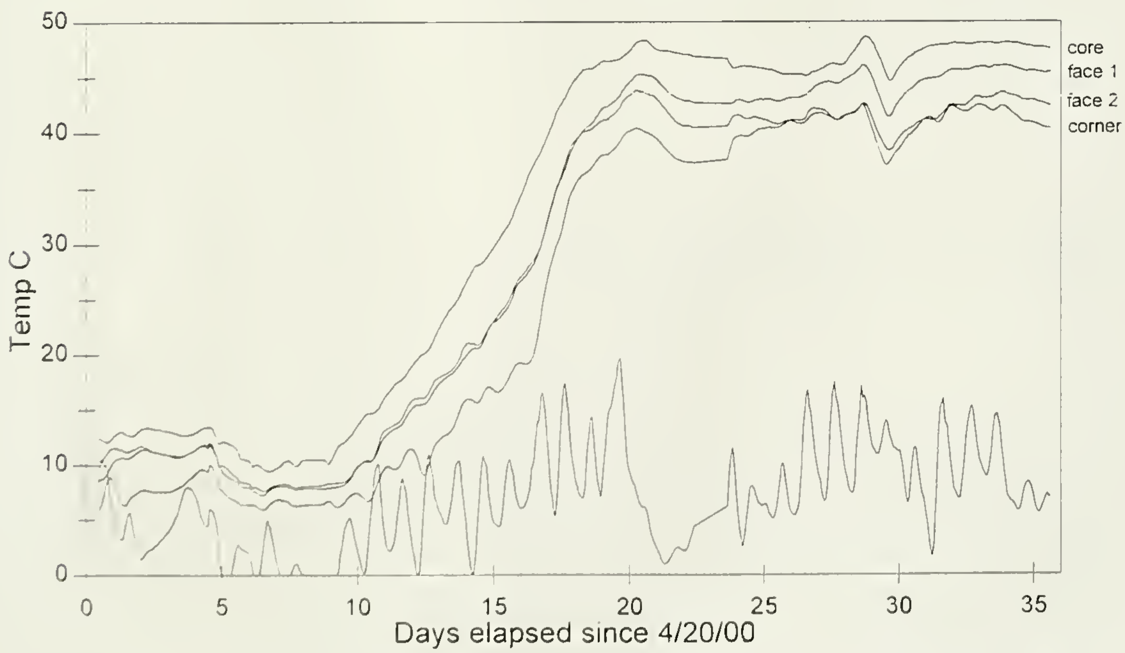
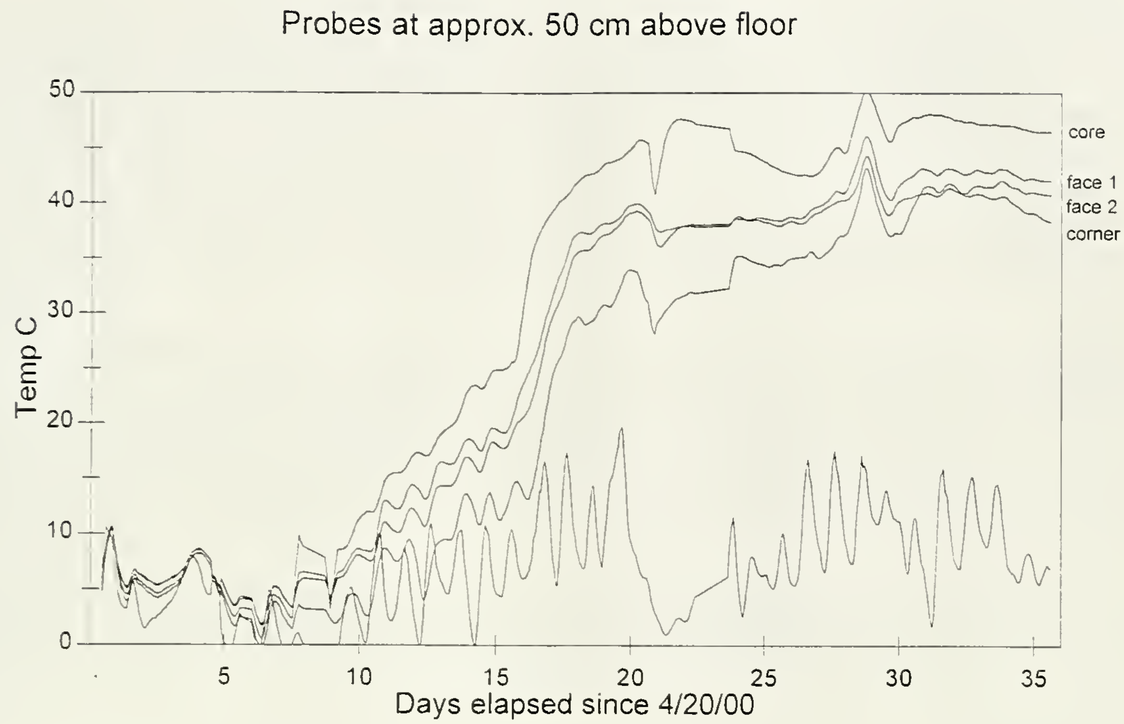


Figure 1. Temperatures measured throughout the duration of the experiment. Fig 1 continues on next page.



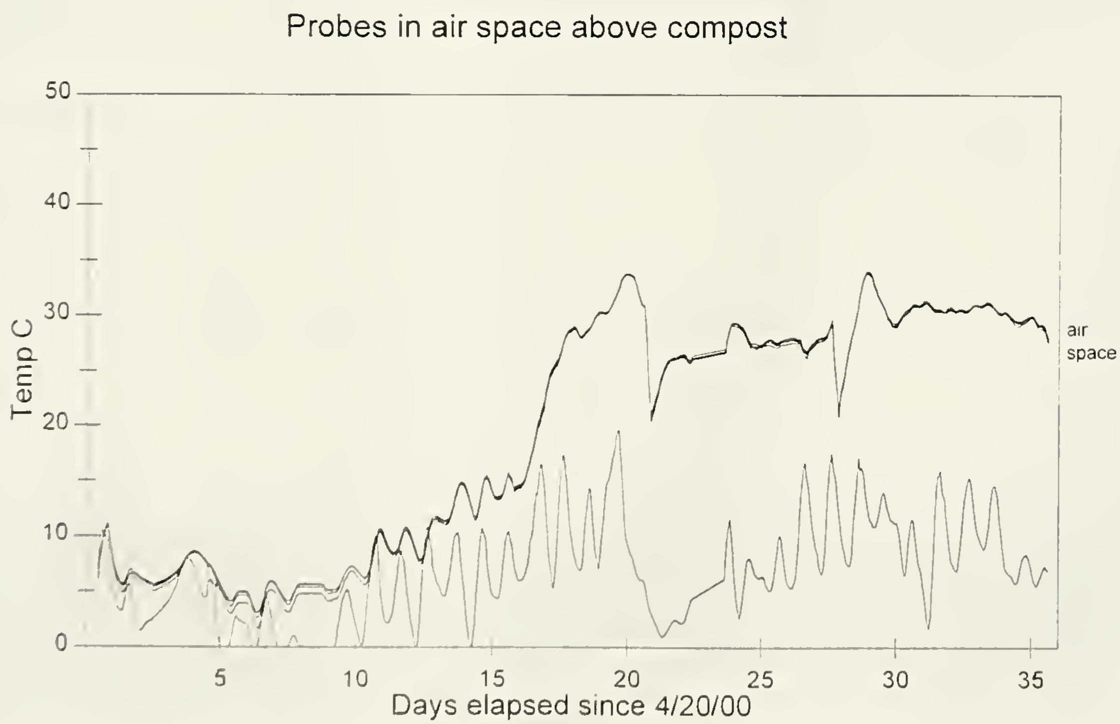


Figure 1(continued). Temperatures measured throughout the duration of the experiment. Fig. 1 begins on previous page.

dropped by nearly 5°C during the day that elapsed before I was able to replace the pump. Upon resumption of air flow temperatures climbed again. Other than this interruption, vessel temperatures fluctuated only slightly during the period from day 20 to the end of the experiment, driven by larger swings in average outdoor temperature.

Throughout the experiment the outflow air had a damp, musty odor, but never smelled sour or of ammonia. The odor was only detectable when crouching within a few feet of the aquarium pump.

In the 46-day period between April 1 and May 16 I collected 70 kilograms of humanure. Since an adult produces approximately 1.25 kg humanure/day (Faechem el al, 1980), this is the equivalent of full-time use by 1.2 adults. With the addition of wood shavings in a 0.7:1 ratio with the humanure (wet weight) the combined material filled the vessel to two-thirds capacity, or 0.5 cubic meters[1].

Core temperatures reached 48°C and the corners of the vessel (the coolest parts) all exceeded 39°C. Ambient temperature was about 12°C for this period.

Analysis and Discussion

Why did the vessel failed to heat up to 55°C? To answer this question let us look at the generation and loss of heat in and from the vessel. The rate of heat generation can be derived from the rate of oxygen consumption, which can be calculated using the following equation:

$$\text{L } O_2 \text{ consumed / hr} = (\%O_2 \text{ in ambient air} - \%O_2 \text{ in outflow air}) * \text{L air flow / hr}$$

The volumetric value L O_2/hr can be converted to mass units using

$$\text{g } O_2 \text{ / hr} = (\text{L } O_2 \text{ / hr}) * (\text{density of air}) * (\text{molecular weight of } O_2) / (\text{molecular weight of air})$$

[1]This gives a volume of 9.1 liters of combined material/person/day. This figure can be used to calculate vessel size needed when using wood shavings and humanure at a 0.7:1 ratio. However, it is important to note that due to the short period of this experiment I only observed a small portion of the eventual volume reduction that will surely occur as decomposition continues. For this reason, systems which take sustantially longer than a month and a half to fill would be oversized if designed with the 9.1 liter/person/day figure in mind.

where the density of air at sea level = 1.225 kg/m^3, molecular weight of air = 28.5, and the molecular weight of O_2 = 32 (Weast, 1983).

To find the heat generated by the reaction of this mass of oxygen, we determine the mass of compost with which it will react and multiply that figure by the compost's heat of combustion. Since the primary carbon source in this specific compost is wood shavings, the majority of the material being oxidized will be cellulose. Because of the difficulty of balancing the equation for the oxidation of cellulose, a very complex molecule, and because of my difficulty finding its heat of combustion, I am using values for glucose. Since cellulose is simply a complex and branching chain of simple sugars, this is a reasonable approximation. The balanced equation follows:

$$6\ O_2 + C_6O_6H_{12} \Rightarrow 6\ H_2O + 6\ CO_2$$

Thus 6 moles of O_2 (192g) react with 1 mole glucose (180g), or 0.94 g glucose/g O_2. Given the heat of combustion of glucose (3.72 kcal/g) (Weast, 1983), heat generated/hr is now easily calculated:

$$\text{kcal released} = (\text{g } O_2 / \text{hr}) * (0.94 \text{ g glucose} / \text{g } O_{2)} * (3.72 \text{ kcal} / \text{g glucose})$$

Rates of heat generation throughout the experimental period appear in Figure 2 as black circles. These rates are rather slow, compared to the rates of other common compost materials such as a grass clipping and leaf blend (Michel and Reddy, 1998).

The rate of heat loss through the vessel wall is calculated using the single following equation:

$$\text{BTU/hr} = \text{ft}^2 * {}^\circ\text{F/R}$$

where ft^2 refers to the area of the boundary across which heat is flowing, where °F refers to the temperature difference between the two sides of the boundary, and where R stands for the thermal resistance of the boundary. Multiplication of the BTU/hr value by 4 yields the rate of heat loss in kcal/hr. The solid line in Figure 2 represents the rate of heat loss from the vessel to the outside environment.

It is apparent from Figure 2 that the majority of heat generated by the compost is lost through the walls, as opposed to being lost through evaporative cooling into the ventilation air. During the plateau period (Days 21-36), 33 kcal/hr of the average 43 kcal/hr generated are lost

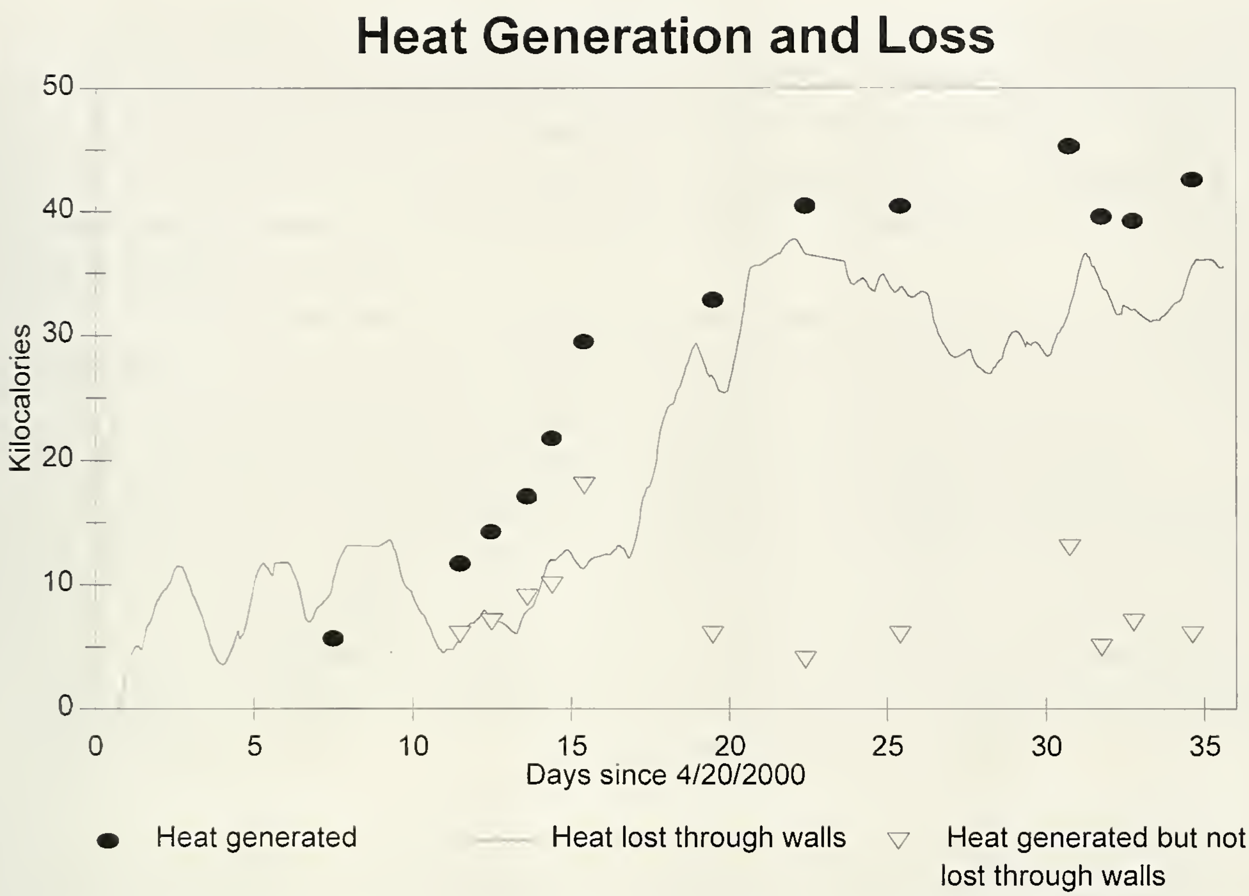


Figure 2. Heat generated by the compost and lost by conduction through the walls, lost by evaporative cooling, or retained within the system.

through the walls, leaving 5.3 kcal/hr which were presumably lost through evaporative cooling. In the last few days of the experiment I captured condensation in the outflow line at an average of 8 mL/hr, which represents about 4 kcal/hr heat loss. As I mentioned earlier, my condensation trap was not completely effective, meaning that part of the remaining 6 kcal/hr could be due to additional condensation. Alternatively, it could simply be the result of imperfect measurements and modeling assumptions.

The data from Days 12 to 16 illustrate another dynamic. The pile was cooler during this period than it was in the plateau period, so evaporative losses would have been lower, yet it is in this period that we see the highest difference between heat generated and heat lost through the walls. This is beacuse the heat in question was absorbed in the rapid increase in vessel temperature that was occurring at the time. This dynamic also explains the outlier on day 31. As is visible in Figure 1, at this time the pile temperature was just finishing its recovery from the dip after the failure of the pump.

6 kcal/hr approximates the heat lost from the pile when its temperature averaged 42°C and air flow was 140 L/hr. Since the partial pressure of water vapor is roughly twice as high at 55°C as at 42°C (Weast, 1983) evaporative losses would also double.

There are four possible design modifications to this system that would result in higher vessel temperatures. They are an increase in insulation, a change in shape of vessel shape to more resemble a sphere, the use of finer wood shavings, and the use of a heat exchanger on intake and outflow air.

A sufficient increase in insulation would undoubtedly be effective in attaining vessel temperatures in excess of 55°C. At a given rate of heat generation, a doubling of insulation results in a doubling of the inside-outside temperature differential. In the composting vessel, such a temperature increase would cause an increase in microbial activity, resulting in a greater rate of heat generation, which would further increase the temperature until a new equilibrium was reached. If we conservatively use the temperature of the coolest corner of the vessel (39°C) we see that doubling the insulation would increase the inside-outside temperature differential by 27°C, for a new differential of 54°C. Add to this the compound effect of increased microbial activity and it appears that the system would effectively treat humanure even when ambient temperatures were below 0°C.

As would be expected, the probes placed along the corner of the vessel measured distinctly lower temperatures than those placed along the faces. The lowest temperatures could therefore be brought up several degrees by using a vessel with a circular cross-section and by rounding the corner where the wall met the floor.

An increase in the rate of compost respiration would raise temperatures, and would probably occurr if finer shavings or sawdust were used. Since the nitrogen in humanure is mostly soluble (ie. very biologically available) the limiting factor is probably the availability of carbon in the wood. A finer carbon source would have a greater surface area/kg, resulting in higher respiration rate/kg compost. The increased carbon availability would allow the use of a smaller ammount of bulking material to achieve the same ratio of *available* C:N, creating a more compact and heat-conserving compost.

Enlargement of the vessel would also result in higher temperatures due to the surface area to volume ratio and the insulating effect of the compost itself, but only up to a certain size. A larger vessel would take longer for a household to fill, and depending on the heating life span of humanure/wood shavings compost, the the material at the bottom could become exhausted and begin to cool before the vessel filled. In this case, any liquid leaching from the newest additions might percolate to the now-cool bottom, bearing pathogens which could survive and contaminate the final compost. This would probably not be a problem until the vessel was many times its current size, since the wood shavings/humanure mixture proved to be a rather slowly composting material.

Conclusion

This experiment demonstrated that an insulated vessel with controled airflow can keep its contents significantly hotter than outdoor temperatures, even with only 0.5 m^3 of slow-decomposing compost. A vessel capable of handling the humanure volume of a household and treating it to 55°C would be larger than the experimntal vessel and have more insulation, and perhaps also be of a more rounded shape.

A popularly acceptable composting toilet would result if such a vessel were attached to a toilet fixture that routed huumanure to the vessel but prevented air exchange between the vessel and the bathroom. This toilet would meet EPA requirements for the treatment of humanure for unrestricted use on food crops.

Acknowledgements

My thanks go out to the Buildings and Grounds crew of the College of the Atlantic, especially to Millard Dority and Bob Nolan for their help in the construction and community acceptance elements of this project, to Mark King of the Maine Department of Environmental Protection for his valuable assistance throughout the permitting process, as well as to Profs. Cass, Anderson, and Feldman for the inspiration and assistance they supplied.

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