University of Alberta

Development of Time-Temperature Probes for Monitoring Pathogen Inactivation during Composting

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Environmental Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta
Spring 2007

Your file Votre référence
ISBN: 978-0-494-30038-1
Our file Notre référence
ISBN: 978-0-494-30038-1

Abstract

Pathogens sometimes survive in composting systems seeming to meet required pathogen reduction criteria. To investigate the reasons for this survival, a method to monitor temperatures as experienced by random compost particles was desired. A temperature data logger/probe was developed and testing carried out to determine if it would perform as required in a composting environment. A commercially available device was also tested. Power loss due to battery connection breakage was a problem in high-impact situations (e.g. windrow turning). Tests of case strength indicated that aluminum was a suitable case material, but should be anodized to prevent corrosion. Initial testing also implied that probes of densities ranging from 800 to 2000 kg/m^3 would distribute randomly, as desired, during windrow turning events. Though the operation of these devices was promising, improvements were necessary. Once the design is optimized, the devices will be useful in future research regarding pathogen inactivation during composting.

Acknowledgements

Curt Stout, Mark Ackerman, Glenn Alloway, Greg Brandon, Skyler Hudson, and Janet Jackson from the University of Alberta's Mechanical Engineering Department provided invaluable assistance with and suggestions regarding the design of the temperature probe housing.

Will Bauer provided many useful insights into the electronics design, and Dr. Andy Knight from the University of Alberta kindly allowed use of his electronics laboratory for circuit-building and testing.

Many people at the Edmonton Waste Management Centre of Excellence provided input into the design specifications, information about composting operations and equipment at the Centre, and/or assistance with setting up experiments. These people include Brent Hamilton, Jim Lapp, Jerry Leonard, Norm Piche, Matt Scott, and Allan Yee.

Nadiya Balukh provided much-needed assistance with digging for probes in a compost cure pile.

Funding for this project was provided by the National Sciences and Research Council of Canada (NSERC) and the Edmonton Waste Management Centre of Excellence.

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List of Symbols, Nomenclature, and Abbreviations

α	significance level for a statistical test
ρ	density
$\varnothing$	diameter
Ω	ohm
°C	degrees Celsius
A	area
ANOVA	analysis of variance
CCME	Canadian Council of Ministers of the Environment
CDN	Canadian dollars
cm	centimetre(s)
d	distance (from ground to compost pile volume mid-point (vertical))
DF (or df)	degrees of freedom
diff.	difference
DPDT	double pole, double throw (switch type)
E	tolerable error (absolute error, use when determining required sample size)
ECBO	enteric cytopathogenic bovine orphan virus (a bovine enterovirus)
EDS	egg-drop syndrome
ESD	electrostatic discharge
EWMCE	Edmonton Waste Management Centre of Excellence
F	f-statistic
freq.	frequency
ft.	foot/feet
g	gram
ga.	gauge
h	height
HAV	hepatitis A virus
HEV	hepatitis E virus

HPAI	highly pathogenic avian influenza
ID	identification
in.	inch(es)
incl.	including
k	kilohm
kΩ	kilohm
kB	kilobytes
kg	kilogram(s)
kHz	kilohertz
L	litre(s)
M	mass
m	metres
mA	milliamps
mAh	milliamp hours
max.	maximum
min.	minute
mL	millilitre
mm	millimetre
MS	mean square
MSW	municipal solid waste
n	number (of samples)
n.d.	no date/not dated
no.	number
op.	operation
P	probability
pF	picofarad
PFU	plaque forming unit
PPE	personal protective equipment
psi	pounds per square inch
PVC	polyvinyl chloride

SD	standard deviation of a sample set
SM	surface mount
sp.	species
SS	sum of squares
std. dev.	standard deviation
T	temperature
t	t-statistic
temp.	temperature
TMECC	Test Methods for the Examination of Compost and Composting
typ.	typical(ly)
uF	microfarad
USD	United States dollars
USEPA	United States Environmental Protection Agency
V	volts or volume (depending on context)
w	width
yr.	year
z	standard normal deviate for the z-distribution

Chapter 1.

INTRODUCTION

1.1. Background

Compost is produced from a variety of organic feedstock materials, including food and agricultural waste, yard waste, biosolids, manure, and municipal solid waste, all of which may contain pathogens. Biosolids and manure are likely to contain human and/or animal enteric pathogens since they are largely composed of fecal materials. Municipal solid waste may contain these same pathogens as a result of the disposal of soiled diapers, personal care products, home medical supplies, and pet feces. Yard wastes often contain plant pathogens, and enteric pathogens may be present due to the inclusion of animal feces. Contaminated meat, eggs, or other food can introduce pathogens to kitchen waste. Animal bedding materials such as straw or sawdust can be contaminated by feces and other secretions (Haug 1993; Hay 1996; Epstein 1997). The pathogens of major concern in compost are enteric in origin, and include organisms from the bacterial, viral, and parasitic (i.e. protozoans and helminths) groups (Burge and Millner 1980; Epstein 1997).

The use of compost as a soil amendment for activities such as landscaping, agriculture, roadside construction, and oilfield reclamation (EWMCE 2002) can result in transmission of pathogens to humans. This can occur through inadvertent intake of improperly treated materials (e.g. inhalation of compost dust) or through consumption of contaminated food and water supplies (USEPA 1992; Haug 1993; Epstein 1997; Lafond et al. 2002). For example, surface and ground water supplies can be contaminated when improperly treated compost is land-applied; this occurs due to pathogen transport across the surface via runoff and vertically through the soil via percolation (Jamieson et al. 2002; Islam et al. 2004; Rimhanen-Finne et al. 2004). Food crops may be contaminated by field application of pathogen-containing compost (Salter and Cuyler 2003). Pathogens can adhere to unwashed and uncooked

vegetables or other crops; this is a concern because many pathogens can survive in soil for periods longer than the growing cycles of food crops (Haug 1993; Islam et al. 2004). It has even been demonstrated that pathogens may be able to contaminate food crops without the edible portion of the plant coming into contact with contaminated soil; results of a study by Solomon et al. (2002) indicated that pathogenic *Escherichia coli* were transported into the edible portion of lettuce plants via the root system.

Human contact with enteric pathogenic organisms could potentially result in infection and adverse health effects. Since the infective dose for many of these pathogens (e.g. viruses and parasites) is very low and since some bacterial pathogens are capable of regrowth (Haug 1993), it is generally accepted that risk to public health from unrestricted compost use is sufficiently minimized only when pathogens cannot be detected in finished products (Epstein 1997; USEPA 1999).

Environmental agencies in North America have concluded, based on a significant body of previous work defining thermal inactivation rates for a wide variety of pathogens, that the pathogens of concern in compost feedstocks will be inactivated if they are exposed to sufficiently high temperatures for a sufficient amount of time (Clark et al. 1980; Déportes et al. 1998; USEPA 1999; CCME 2005). Thermal inactivation rates for the most heat resistant pathogens found in feedstock materials were used to define time-temperature criteria for composting operations. In the United States and Canada, a static pile or in-vessel composting system must maintain a temperature of at least 55°C for 3 days or longer, while a windrow should maintain the same temperature for at least 15 days with 5 turnings of the windrow during this time (USEPA 1999; CCME 2005). If these criteria are met by every particle of material being processed, it is expected that the health risk associated with pathogens in compost will be minimized.

Problems arise, however, in ensuring that the time-temperature criteria are actually met by all compost particles, as no adequate method exists for obtaining a time-temperature profile for the entire compost mass. Nor has a method been devised to measure profiles representative of a typical particle. Currently available methods of temperature monitoring include manual monitoring with long probes and automatic

monitoring with thermocouples connected to a logging device (usually a computer). A major drawback of both methods is that they are limited to measuring temperature at fixed, discrete locations and times. Because measurements are made at a limited number of fixed locations, it is possible that undetected low temperature zones exist within compost piles. Thus, any number of compost particles may pass through the process without experiencing the required time-temperature conditions, even in cases where available data indicate that satisfactory temperature conditions did exist.

Since the time-temperature criteria developed to ensure pathogen destruction apply to every particle of material processed, it is of interest to monitor the conditions that a particle of material actually encounters during the course of composting. Obtaining temperature profiles for a statistically significant number of "compost particles" should provide an idea of how well a composting system has performed in terms of achieving the required pathogen reduction conditions.

1.2. Research Goals

The first aim of this research was to determine whether composting processes meeting the required time and temperature conditions are consistently able to reduce enteric pathogens to non-detectable levels. To this end, an extensive literature review was carried out. Available literature reporting both time-temperature and pathogen survival data was reviewed. For composting systems reporting achievement of the required time-temperature criteria from the United States regulations (USEPA 1999) and Canadian guidelines (CCME 2005), it was reported whether or not any of the monitored pathogen species could be detected in finished products. Any pathogen survival in systems apparently meeting the time-temperature requirements would be cause for concern, and it would be necessary to evaluate the possible reasons for this survival.

The second goal of this research was to develop a method to model the temperature conditions that random particles of compost material encounter as they

undergo the composting process. A self-contained, battery powered temperature data logger was required to accomplish this goal. Important properties of this logger included a similar size and density to that of compost particles, robustness to the harsh environment of a composting system, and the ability to be incorporated into the compost feedstock and undergo the composting process in a manner similar to that of a random particle of material. These temperature loggers will be used in future studies to gather representative temperature data from various compost operations.

1.3. Principal Results and Conclusions

A literature review revealed that pathogens of all groups have occasionally been detected in finished composts which have apparently met the required time and temperature conditions. Several possible reasons for this pathogen survival were considered, including bacterial regrowth from below detection limits, insufficient time-temperature criteria, and the existence of undetected low-temperature zones.

It was hypothesized that the presence of non-uniform temperature distributions was the most likely reason for pathogen survival in seemingly properly operated composting systems. In order to investigate this possibility, a self-contained, battery-powered temperature data logger with an aluminum case was designed and prototypes built. The prototypes were tested to determine if they would behave as desired and how well they would stand up to the various impacts received during composting. It was found that, though the prototypes showed promise, modifications were necessary before finalizing the design. These modifications included making the device more impact-resistant and optimizing its density.

Once the design is finalized, it is recommended that these devices be used to compare data from random particles to data gathered using traditional temperature monitoring methods, as well as to the time-temperature criteria in guidelines and regulations. The language in the regulations, with regards to temperature monitoring

specifics, can then be evaluated based on the results; more detail in terms of temperature monitoring locations and frequency may be required.

1.4. Thesis Organization

As this thesis follows the University of Alberta's "paper" format, Chapters 2 and 3 are self-contained papers which have been submitted for publication in scientific journals.

Chapter 2 is a review of available literature examining the relationship between compost temperature and time characteristics and corresponding pathogen reduction in bench-, pilot-, and full-scale studies. The goal of this review was to gain insight into whether or not composting operations meeting current time-temperature regulations used in Canada and the United States consistently produce pathogen-free products.

Chapter 3 provides a justification for the design of a time-temperature probe, briefly describes the preliminary probe design, and discusses testing of the new probe. The preliminary design is evaluated and recommendations are made for its improvement.

Chapter 4 is an overview of the findings of this research project. Recommendations are made for future research.

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Chapter 2.

A Review of the Effectiveness of Current Time-Temperature Regulations on Pathogen Inactivation during Composting[1]

2.1. Introduction

One of the main goals of a composting process is to reduce pathogenic organisms to acceptable levels in order to minimize risk to public health and the environment (Hay 1996). For unrestricted compost use, it is generally accepted that risk is sufficiently minimized only when pathogens are not detectable in the finished product (USEPA 1999). Enteric organisms, including bacteria, viruses, protozoa, and helminths are of particular concern (Burge and Millner 1980) as they can present a hazard to both human health and the environment (de Bertoldi et al. 1988). Some enteric pathogens of concern, along with their potential health effects, are presented in Table 2-1. Several opportunistic fungal pathogens are also presented in Table 2-1, for the sake of completeness. However, fungi are not enteric in origin and produce adverse health effects via inhalation or skin contact rather than as a result of ingestion. Risk is thus much greater to compost facility workers, who are in close contact with airborne compost dust, than to the general public (Jager and Eckrich 1997; Hryhorczuk et al. 2001). Hence, fungi in compost are not considered in compost regulations in the United States (USEPA 1999) and will not be considered further in this paper.

During composting, pathogen reduction is accomplished to some degree by several processes, including competition between indigenous microorganisms and pathogens, antagonistic relationships between organisms, the action of antibiotics produced by certain fungi and actinomycetes, natural die-off in the compost environment (which is non-ideal for enteric pathogens), production of toxic by-

[1] *A version of this chapter has been accepted for publication: Wichuk and McCartney 2007. Journal of Environmental Engineering and Science.*

products such as gaseous ammonia, nutrient depletion, and thermal destruction (Burge et al. 1978a; Pereira-Neto et al. 1987; Haug 1993; Epstein 1997; Dumontet et al. 1999; Hogg et al. 2002). Because the degree to which pathogens are inactivated has not been determined for any of these processes aside from thermal destruction, the use of elevated temperatures is considered to be the most reliable method available for sanitizing compost (Vinnerås et al. 2003). Temperature is also the easiest, if not only, factor that a facility operator can measure and control during operation, so it is commonly specified by regulatory agencies as an appropriate means to induce pathogen destruction (Haug 1993).

The purpose of this literature review is to examine the correlation between compost temperatures and pathogen destruction in order to develop an understanding of whether or not the current guidelines and regulations regarding compost pathogen control, as they are written, are effective in ensuring production of a safe compost product. In other words, it was of interest to determine whether or not compliance with the temperature guidelines specified by regulatory agencies actually guarantees a pathogen-free end product. Data from existing laboratory-, pilot-, and full-scale studies were reviewed and evaluated.

2.1.1. Effect of Elevated Temperatures on Pathogens

For all pathogenic organisms, threshold temperatures exist above which the pathogen will no longer be viable. For viruses, thermal inactivation occurs as a result of damage to the viral structure. Specifically, surface proteins become denatured when exposed to high temperatures. Once this occurs the viruses are no longer infective because they are unable to bind to the host cell (Guardabassi et al. 2003). For the other pathogen groups, elevated temperatures are able to destroy cells as a result of the inactivation of cellular enzymes (Haug 1993). When organisms are exposed to temperatures higher than threshold for prolonged periods, enzymes

Table 2-1. Some pathogens found in compost feedstocks and associated diseases. *Adapted from Nell et al. (1983), de Bertoldi et al. (1988), Haug (1993), Epstein (1997), USEPA (1999), and Guardabassi (2003).*

Group	Organism	Associated diseases
Bacteria	*Arizona hinshawii*	Arizona infection
	Bacillus anthracis	Anthrax
	Bacillus cereus	Gastroenteritis
	Campylobacter jejuni	Gastroenteritis
	Clostridium botulinum	Botulism
	Clostridium perfringens	Gangrene, gastroenteritis
	Escherichia coli & other coliforms	Gastroenteritis, diarrhea and internal infections
	Leptospira icterohaemorrhagiae	Haemorrhagic jaundice
	Mycobacterium tuberculosis	Tuberculosis
	Pasteurella pseudotuberculosis	Pseudotuberculosis
	Pseudomonas aeruginosa	Gastroenteritis
	Salmonella (~1700 types)	Salmonellosis (food poisoning), gastroenteritis
	Salmonella typhi	Typhoid fever
	Shigella (4 species)	Shigellosis, bacteria/bacillary dysentery, gastroenteritis
	Streptococcus sp.	Gastroenteritis
	Vibrio cholerae	Cholera
	Yersinia sp.	Yersinosis, acute gastroenteritis (incl. diarrhea, abdominal pain)
Viruses	Adenovirus (31 types)	Conjectivitis, respiratory tract infections, gastroenteritis
	Astroviruses	Epidemic gastroenteritis
	Caliciviruses	Epidemic gastroenteritis
	Enteroviruses:	
	Coxsackie virus	Aseptic meningitis, gastroenteritis, hepatitis, fever, cold-like symptoms, etc.
	Echovirus	Aseptic meningitis, paralysis, encephalitis, fever, cold-like symptoms, diarrhea, hepatitis, etc
	Poliovirus	Poliomyelitis
	Hepatitis virus	Infectious hepatitis
	Norwalk and Norwalk-like viruses	Epidemic gastroenteritis with severe diarrhea
	Reovirus	Respiratory infections, gastroenteritis, diarrhea, common cold, hepatitis
	Rotavirus	Gastroenteritis, infant diarrhea, acute gastroenteritis with severe diarrhea
Protozoa	*Balantidium coli*	Balantiasis, diarrhea, and dysentery
	Cryptosporidium parvum	Gastroenteritis, cryptosporidiosis
	Dientamoeba fragilis	Dienamoeba infection
	Entamoeba histolytica	Amoebic dysentery, ameobiasis, acute enteritis

Table 2-1 (con't). Some pathogens found in compost feedstocks and associated diseases.

Group	Organism	Associated diseases
Protozoa (con't)	*Giardia intestinalis*	Giardiasis
	Giardia lamblia	Giardiasis (incl. diarrhea, cramps, weight loss)
	Isopora belli	Coccidiosis
	Naegleria fowleri	Meningoencephalitis
	Toxoplasma gondii	Toxoplasmosis
Nematodes (Helminth)	*Ancylostoma braziliense*	Cutaneous larva migrans (creeping eruption)
	Ancylostoma caninum	Cutaneous larva migrans
	Ancylostoma duodenale	Hookworm, Ancylostomiasis
	Ascaris lumbrioides	Ascariasis, digestive disturbances, abdominal pain, vomiting, restlessness, roundworm infestation
	Ascaris suum	May produce symptoms such as coughing, chest pain, and fever
	Enterobius vermicularis	Enterobiasis, pinworm infestation
	Necator americanus	Hookworm
	Strongyloides stercoralis	Strongyloidiasis
	Toxocara canis	Visceral larva migrans, fever, abdominal discomfort, muscle aches, neurological symptoms
	Toxocara cati	Visceral larva migrans
	Trichuris trichiura	Trichuriasis, abdominal pain, diarrhea, anemia, weight loss
Cestodes (Helminth)	*Diplylidium caninum*	Tapeworm infection
	Echinococcus granulosus	Unilocular echinococcosis (hydatid disease)
	Echinococcus multilocularis	Alveolar hydatid disease
	Hymenolepis nana	Taeniasis (tapeworm infection)
	Taenia saginata	Taeniasis, nervousness, insomnia, anorexia, abdominal pain, digestive disturbances
	Taenia solium	Taeniasis, nervousness, insomnia, anorexia, abdominal pain, digestive disturbances
Fungi	*Aspergillus fumigatus*	Lung mycosis, Aspergillosis
	Blastomyces dermatitides	Blastomycosis
	Candida sp.	Systemic and skin mycoses, Candidiasis
	Coccidiodes immitis	Coccidioidomycosis (San Joaquin fever)
	Epidemophyton sp.	Skin mycosis
	Histoplasma capsulatum	Histoplasmosis
	Micromonospora sp.	Farmer's lung
	Microsporum sp.	Skin mycosis
	Sporothrix schenkii	Sporotrichosis
	Trichosporon cutaneum	Skin mycosis
	Tricophyton sp.	Skin mycosis

become irreversibly inactivated. Since enzyme activity is necessary for cells to function, enzyme inactivation results in cellular inactivation.

The degree of thermal inactivation of pathogens is a function not only of temperature, but also of exposure time (de Bertoldi et al. 1988); the longer a population of organisms is exposed to a particular temperature, the greater the degree of destruction. Brannen et al. (1975) conducted a study of temperature effects on *Ascaris* ova in aqueous solution. They observed no change in ova viability after exposure to 47°C for two hours, whereas at 51°C viability was reduced by 99.5% in one hour and by 99.8 % in just 6 minutes at 55°C. Brannen's results also indicate that there is a very narrow range of temperatures over which pathogen inactivation ranges from negligible to extreme.

It should be emphasized that the ability to expose the entire bulk of the compost material to the required time-temperature conditions is as important as the time-temperature conditions themselves (Haug 1993), as pathogen survival could occur in low temperature zones. Significant temperature variations are seen throughout the compost mass in all types of large-scale systems. Pile temperatures depend on a number of factors, such as moisture content, substrate availability, C:N ratio, oxygen levels (which are affected by porosity and bulk density), wind speed, solar heating, ambient temperature, and humidity (Turner et al. 2005), and can vary with location in the pile. It is entirely possible that large temperature variations throughout the compost may lead to some areas experiencing temperatures low enough to prevent thermal pathogen inactivation even though other areas do achieve the required conditions (Hay 1996; Turner et al. 2005).

2.1.2. Time-Temperature Criteria for Compost Pathogen Reduction

The United States Environmental Protection Agency (USEPA) regulates biosolids composting in the United States. Two classes (A and B) of finished product are specified. Treated biosolids fit into Class B if pathogens are detectable but have

been reduced to levels that would not pose a significant threat to public health or the environment as long as exposure to the product is minimized (USEPA 1994). Site restrictions that prevent crop harvesting, animal grazing, and public access for a specified amount of time after application or disposal must be put in place for Class B products. Class A products are not restricted in use, and thus the regulations for this class are more stringent. The regulations for Class A were designed to produce treated biosolids products having no detectable pathogens. Composting at temperatures greater than 55°C for an extended period is specified as an acceptable option for reducing pathogens to below detection limits (USEPA 1999). Only Class A composts will be considered from here on in this report.

In Canada, guidelines for pathogen reduction during composting are set out by the Canadian Council of Ministers of the Environment (CCME). In terms of pathogen reduction requirements, compost produced following CCME guidelines must meet, with minor differences, nearly the same criteria as a USEPA Class A product (CCME 2005).

Time-temperature regulations and guidelines applicable to composting operations in the United States (for a Class A product) and Canada are presented in Table 2-2, and are essentially the same (aside from some additional comments about monitoring locations, as discussed below). A minimum temperature of 55°C should be maintained for a period of 3 consecutive days, unless windrow composting is employed. For windrows, temperatures greater than 55°C should be maintained for at least 15 days with a minimum of 5 turnings during the high-temperature period; this extended period is specified in order to ensure that all material gets mixed into the high-temperature core of the windrow for at least 3 consecutive days (USEPA 1999). It is imperative that these temperatures be maintained, aside from momentary changes such as may occur when a windrow is turned (Farrell 1993).

The USEPA gives more explicit details than does the CCME in terms of time-temperature conditions and monitoring. For example, the USEPA emphasizes that the above time-temperature criteria apply to every particle of material composted; thus it is important that temperature monitoring be representative of all areas in a compost

mass and that the temperature profile at each and every monitoring point (as opposed to the average of all monitoring points) meets the mandated time-temperature requirements. It is also recommended that temperature measurements be taken at multiple points at a range of depths throughout the composting medium, and that monitoring be done in areas of in-vessel and static pile systems where temperatures are typically lowest. For windrows it is suggested that turning should not occur until the core has been at 55°C for 3 days (USEPA 1999). No guidance is given in terms of exact numbers of locations to monitor, specific monitoring locations (aside from expected cool zones in static piles and in-vessel systems), or frequency of monitoring. The CCME has no specific requirements or recommendations at all for temperature measurements.

Table 2-2. Time-temperature criteria for compost pathogen reduction currently in place in North America. *Adapted from USEPA (1999) and CCME (2005).*

Technology	Time-temperature requirements	
	CCME guidelines	**USEPA Class A regulations**
Windrow	T ≥ 55°C for at least 15 days; during the high-temperature period, the windrow should be turned at least 5 times	T ≥ 55°C for 15 days or longer; during the >55°C period, there should be a minimum of 5 turnings of the windrow
Aerated Static Pile	T ≥ 55°C for 3 days	T ≥ 55°C for 3 days
In-vessel (reactor)	T ≥ 55°C for 3 days	T ≥ 55°C for 3 days

2.2. Pathogen Reduction as a Function of Compost Time-Temperature Conditions – Results from the Literature

Salter and Cuyler (2003) report that numerous studies have demonstrated the effectiveness of composting at temperatures greater than 55°C for several days. However, it would be premature to conclude, based on this statement, that all composting operations that appear to reach and maintain temperatures of 55°C for an

extended period will produce a safe end product. It should also be considered that, as Soares et al. (1995) point out, much of the research examining pathogen reduction during large-scale composting has focused on indicator organism reductions rather than on specific pathogens; few studies consider the effects of compost time-temperature conditions on a broad range of pathogens and indicators. Additionally, much of the pathogen reduction data in the literature are from laboratory or pilot-scale experiments. Conditions in the field are likely to differ from those in the lab, with factors such as clumping of solids, irregular temperature distribution, incomplete mixing, and/or poor process design and operation contributing to pathogen survival in large-scale operations (Soares et al. 1995; Hay 1996; Epstein 1997). Thus, laboratory or pilot-scale data may be insufficient to predict indicator and/or pathogen survival times accurately in full-scale composting facilities. Nell et al. (1983), for example, examined the inactivation of *Escherichia coli*, coliphage, *Salmonella* sp., and viable *Ascaris lumbricoides* ova in both pilot- and full-scale systems. In pilot-scale reactors, concentrations of all pathogens of interest declined to below detection limits within 8 days or less. During full-scale windrow composting, reduction of all organisms took significantly longer than during the pilot-scale experiments. More than two weeks were needed before *Salmonella* sp. was reduced to non-detectable levels. Coliphage reduction took at least 3 weeks, *E. coli* greater than 5 weeks, and *Ascaris* ova more than 6 weeks. Steer and Windt (1978) and Droffner and Brinton (1995) obtained similar results.

This paper focuses on literature examining the relationship between compost time-temperature conditions and pathogen reduction, since health concerns arise from pathogens, not indicator organisms. While laboratory-scale and pilot-scale studies are considered, the emphasis is on available full-scale studies.

2.2.1. Bacterial Pathogens

Pathogenic bacteria are frequently isolated in high numbers in compost feedstocks and sometimes in finished composts. According to the USEPA (1992), the bacteria of most concern are *Shigella* sp., *Salmonella* sp., and *Yersinia* sp., with salmonellae being the most often studied because they frequently occur in feedstock materials, they cause severe illness relatively often, and are easily and reliably quantified.

2.2.1.1. Salmonella

A number of studies have examined temperature effects on *Salmonella* sp. survival during composting. Some of these studies indicate that if the criterion of 55°C for 3 days (or 15 days for a windrow) is satisfied, salmonellae levels should be reduced to below the detection limit. For example, in a study by Pereira-Neto et al. (1986) of aerated static pile systems, temperatures were monitored every second day at three vertical positions along the pile centerline, and the pile was sampled and tested for salmonella (every few days) at the top, middle, and bottom of the pile along one edge. Salmonella concentrations along the edge at the middle and top tended to show an initial increase, but by day 7 in both trials (i.e. about 1 to 5 days above 55°C) these locations both had non-detectable salmonella levels. At the bottom centre of the pile, temperatures never reached 55°C; in one trial, salmonella levels at the bottom edge were reduced below detection limits within 7 days, while in the other trial salmonellae survived for up to 15 days. Tiquia et al. (1998) composted pig litter in windrows. Once per week samples from 5 locations were combined into a composite sample. Temperatures were monitored at a single location in the windrow once every four days, just prior to pile turning. At this location 55°C was reached within the first three to four days of composting and appeared to remain between 60 and 70°C for roughly four weeks. Coincident with this high temperature period was a decrease in salmonella levels to below the detection limits within the first two to three weeks of

composting. In other words, within 18 days or less at temperatures above 55°C, salmonellae could no longer be detected. Wiley and Westerberg (1969) inoculated sewage sludge with *Salmonella newport* and composted the sludge in a composting drum. Temperatures within the drum were maintained between 60 and 70°C, and within 25 hours of inoculation no salmonellae could be detected.

Other studies have shown salmonellae to be detectable for longer than the required amount of time, even when temperature monitoring indicates that the 55°C requirement has been met. For example, Hay (1996) presented the results of a survey of 72 composting facilities in the United States. More than half of the facilities monitoring for *Salmonella* sp. produced products still containing this organism, despite meeting the time-temperature criteria. In a pilot-scale reactor, Krogstad and Gudding (1975) inoculated *Salmonella typhimurium* into a mixture of municipal solid waste and biosolids. *S. typhimurium* was detected after 4 days of composting at 55°C, though it could not be detected after about 2 days at approximately 65°C. Droffner and Brinton (1995) used gene probes to study *Escherichia coli* and *Salmonella* sp. survival during composting at both laboratory- and full-scale. Both organisms survived in the full-scale system throughout the high temperature phase, when measured temperatures remained around 60°C for nearly 60 days, and did not become non-detectable until the temperature decreased again during curing. In bench-scale experiments, both organisms survived temperatures above 60°C for 9 days or more in food waste compost, while salmonellae survived for 5 days in the same temperature range in biosolids compost.

Still other studies have demonstrated salmonella regrowth from below detectable levels both during and after high-temperature periods meeting or exceeding the regulatory requirements. Regrowth indicates that either some organisms have survived composting or that recontamination has occurred. Déportes et al. (1998) monitored temperature and sampled for the presence of salmonella during windrow turning events (every 2 to 5 days). Four samples were taken for microbiological testing at each of three locations and combined into a composite sample. In one trial,

salmonella were eliminated within 12 days of composting even though some reported temperatures were below 55°C. However, in a second trial salmonella were detected during the low-temperature period subsequent to the thermophilic phase, despite levels dropping below detection limits when temperatures exceeded 55°C for at least 2 and as much as 20 days. Cekmecelioglu et al. (2005) studied the survival of *Salmonella* sp. during windrow composting in both summer and winter. In all trials the windrow was turned once per week. *Salmonella* sp. levels were monitored in weekly composite samples combined from two locations. During summer, windrow temperatures (reported every one to two days as an average of 6 measurements) from all trials remained above 55°C for a total of nine weeks or more. In the two trials reported, levels were reduced to below the detection limit even before monitored temperatures reached 55°C. However, regrowth was observed in one trial during the high temperature period, and over 15 additional days of high-temperature composting was required before this regrowth was eliminated. During winter, though 55°C was exceeded in all trials for at least 24 days, regrowth of *Salmonella* sp. was observed both during and after the high-temperature period. Salter and Cuyler (2003) monitored salmonellae levels weekly in four aerated static piles; testing was done on a composite of several subsamples. While *Salmonella* sp. initially decreased in number, periods of regrowth occasionally occurred. This regrowth took place during what appeared to be high temperature periods (i.e. >55°C), though the authors admit to the possibility that undetected cooler zones existed; temperatures were monitored only once per day at only four or six locations. Shuval et al. (1991) also observed *Salmonella* sp. regrowth in windrows during high-temperature periods, even after a rapid initial decrease to low concentrations. This pathogen was detected for the first 83 days of composting even though temperatures recorded at 9 different locations within the pile exceeded 55°C for several consecutive days within the first 40 days of the compost cycle. Windrows were only turned four times over the course of composting.

2.2.1.2. Escherichia coli

Both pathogenic and non-pathogenic strains of *Escherichia coli* can be present in fecally contaminated materials. The non-pathogenic strains are sometimes used as indicator organisms (Pereira-Neto et al. 1986; Déportes et al. 1998; Jones and Martin 2003), though they are not specified as such in most of the guidelines and regulations in North America (one exception is in Québec, where the CCME guidelines were not adopted by the provincial environment agency; here compost classification is partly based on *E. coli* levels (Hébert 2004; Ge et al. 2006)). Specifically, non-pathogenic strains may be used as a surrogate for pathogenic strains (Larney et al. 2003). Pathogenic *E. coli* tend to be present in fecal materials in much smaller quantities than are non-pathogenic varieties. Yanko (1988) found that toxigenic *E. coli* represented only a small proportion (an estimated 0.3%) of the total fecal coliform population. However, since in some samples pathogenic *E. coli* numbers were quite high, this organism could potentially pose a health risk.

Only three studies on pathogenic *E. coli* were located, and they give contrasting results as to the effectiveness of thermophilic composting in inactivating this organism. Jones and Martin (2003) cite a study in which 10^7 organisms per gram of *E. coli* O157:H7 was inoculated into a bench-scale manure composting system. After 48 hours of composting at only 45°C, this *E. coli* strain was not detected, though at 25°C no change in pathogen level was observed.

In contrast, in a laboratory-scale reactor study, Hess et al. (2004) monitored the inactivation of pathogenic *E. coli* O157:H7 as a function of compost temperature-time profiles. *E. coli* was inoculated into sample bags, which were then placed at the top and bottom of the reactor. Two bacterial cultures were used; one was a laboratory culture and the other was a naturally occurring culture obtained from infected cattle. Temperatures were monitored at two locations, corresponding to the depths of the sample bags, with a 6-minute frequency. At the bottom of the reactors, where the temperature peaked between 40 and 45°C, all but one sample remained positive for pathogenic *E. coli*. In higher temperature areas of the reactors, a larger degree of

inactivation was observed. Elimination of the naturally occurring pathogen, with no subsequent regrowth, was seen when temperatures exceeded 55°C for 3.3 days. The laboratory strain, however, required 58°C and 5.2 days for reduction to below the detection limit with no subsequent regrowth. Cekmecelioglu et al. (2005) also studied the survival of the same pathogenic strain of *E. coli* during windrow composting. In summer trials, (average) pile temperatures quickly surpassed the 55°C target and remained high for more than nine weeks. A rapid decrease in *E. coli* O157:H7 to non-detectable levels occurred within days of temperatures reaching 55°C. Regrowth was not observed beyond day 21; because testing for *E. coli* took place only once per week, it can be concluded only that this organism appeared to be eliminated within 25 days of >55°C temperatures. During the winter trials, though reported average pile temperatures exceeded 55°C for at least 24 days in all trials, *E. coli* levels fluctuated up and down significantly and were still detectable at the end of composting. In this study, temperatures were monitored at 3 depths at each of 2 locations, and bacteria were monitored in a composite sample taken from two locations.

Several studies also examined temperature effects on non-pathogenic *E. coli*, most of which demonstrated rapid inactivation even at temperatures below 55°C. Lafond et al. (2002) composted duck excreta and wood shavings in an enclosed hall. Temperatures were monitored continuously in five locations and the average temperature reported. In one trial the average temperature exceeded 55°C for approximately 10 consecutive days, while in a second trial the average temperature peaked between 45 and 55°C. In both trials, however, *E. coli*, monitored at two locations in the centre of the pile, was reduced rapidly to non-detectable levels and did not experience regrowth. Larney et al. (2003) studied the effects of windrow composting on levels of non-pathogenic *E. coli* in order to model the behaviour of pathogenic *E. coli* strains. Temperature was monitored every 20 minutes at three depths at each of three locations in each pile and reported as an average value. Samples of compost were taken prior to turning at similar locations to the temperature monitoring points and analyzed for *E. coli*. In one trial, *E. coli* was detectable for

more than 3 weeks with average temperatures over 55°C; the windrow was turned at least 7 times during this period. However, in another trial reduction to non-detectable levels occurred within a few days at these temperatures though the windrow was turned only 2 or 3 times prior to *E. coli* reduction. In two trials the following year, *E. coli* levels dropped below the detection limit before average temperatures even reached 55°C. Pereira-Neto et al. (1986) found that even though the bottom of an aerated static pile remained below 55°C, levels of *E. coli* at all sample locations, including the pile base, declined from over 10^7 organisms per gram to below the detection limit of 10^2 organisms per gram. Turner (2002) conducted a bench-scale study of the inactivation of laboratory *E. coli* inoculated into sterilized materials with different moisture contents and different chemical compositions. With incubation at 55°C, *E. coli* was consistently reduced to below detection limits within 2 hours. At 50°C *E. coli* was able, in some cases, to persist beyond the 72-hour run-time of the experiment.

A comparison of studies on non-pathogenic and pathogenic *E. coli* indicates that pathogenic strains may be the more heat-resistant ones, and thus non-pathogenic *E. coli* may be poor indicators.

2.2.1.3. Other Bacteria

Many bacterial pathogens aside from *E. coli* and salmonellae can be present in fecally contaminated compost feedstock materials (see Table 2-1). Though information on the survival of most other pathogenic bacteria is sparse or non-existent, the thermal inactivation of a few of them has been studied.

Morgan and Macdonald (1969), for instance, observed that *Mycobacterium tuberculosis* was normally destroyed within 10 days of windrow composting when average temperatures were at least 60°C, though in one windrow it took up to 21 days to reduce this bacterium to non-detectable levels. Krogstad and Gudding (1975) examined the fate of *Serratia marcescens* at 10 locations during composting of a mixture of municipal solid waste and biosolids and found that it was not particularly

hardy. It survived composting for only about 24 hours at 45°C and only a few hours at temperatures greater than 45°C. Epstein (1997) cited the results of a study in which *Legionella* sp. were enumerated in finished composts, and concluded that composting at 43°C or greater would destroy this organism, since it survived for many months in potting mixes kept at temperatures below 35°C, but was eliminated at temperatures above 43°C. Christensen et al. (2002) placed inoculated sample bags containing temperature data loggers at 12 locations in four facilities. In two windrow systems, both turned weekly, CCME (2005) and USEPA (1999) time-temperature criteria were satisfied at most of the measurement locations. Direct process monitoring showed varying degrees of *Enterococcus* reduction at the different monitoring points. In particular, it was seen that reductions were lower in the sections of the piles that did not meet the time-temperature criteria. However, *Enterococcus* was still detectable in some locations maintaining 55°C temperatures for an extended period. In two in-vessel facilities also studied, *Enterococcus* could not be detected by direct process monitoring, even in a zone which only remained at 55°C for 34 hours.

Some bacteria, such as *Bacillus* and *Clostridium,* produce resistant endospores which can survive for extended periods under a variety of environmental conditions. *Bacillus cereus*, in one study, was detected after composting for 7 days at temperatures below about 70°C, but could not be detected if temperatures above 70°C persisted for a period of 2 to 3 days (Krogstad and Gudding 1975). Clostridial spores can survive at temperatures of 100°C for close to two hours in slightly acidic conditions; therefore it is possible, though there are no known studies, that spores of *Clostridium botulinum* and *C. perfringens* can survive composting conditions that inactivate other bacteria (Jones and Martin 2003). Feachem et al. (1983) echo this sentiment, stating that spore-forming bacteria such as *C. perfringens* are capable of surviving temperature conditions which inactivate the majority of fecally excreted pathogens. It is unlikely that bacterial endospores would be removed from compost via thermal destruction with the regulated time-temperature criteria.

2.2.2. Viruses

Viruses that may be present in compost, as summarized in Table 2-1, include several subclasses of enteroviruses as well as other viruses of enteric origin. In total more than 130 types of enteric viruses may be present in fecally contaminated materials (Yanko 1988; Guardabassi et al. 2003). Viral pathogens have low infective doses, with some evidence showing that as little as one plaque forming unit (PFU) can cause infection. Their inactivation during composting is largely due to exposure to elevated temperatures (Haug 1993; Guardabassi et al. 2003).

According to Guardabassi et al. (2003), the viruses of major importance in composting systems, such as adenoviruses, astroviruses, caliciviruses, enteroviruses, hepatitis A (HAV) and E (HEV) viruses, and rotaviruses, all lack an envelope, which renders them more thermally tolerant than their enveloped counterparts. Hepatitis A virus appears to be the most thermotolerant of the human enteric viruses, and evidence indicates that conditions similar to those aimed for during composting (60°C for 10 hours) are capable of inactivating all viruses of concern, including HAV (Guardabassi et al. 2003). Time-temperature effects on enterovirus, reovirus, and adenovirus survival during sewage sludge composting were considered by Feachem et al. (1983), who examined the literature and concluded that exposure to 30°C for 3 months, 40°C for 2 weeks, 50°C for 1 day, or 60°C for 2 hours would be sufficient to inactivate these viruses.

Viruses were enumerated during the course of composting or heating in a number of studies. Monteith et al. (1986) seeded cattle manure with heat resistant bovine enterovirus and parvovirus. Laboratory scale experiments were carried out to simulate the internal temperatures experienced during composting. The operating temperature was set to 30°C on the first day, rose to 45 °C on the second day, and finally increased to and maintained at 60°C from day 3 on. Viruses were enumerated after 28 days of "composting" (with 25 of these days at 60°C) and neither inoculated strain could be detected. Wiley and Westerberg (1969) inoculated a laboratory culture of poliovirus type 1 into a drum where sewage sludge was being composted at

temperatures of 60 to 70 °C. One hour after inoculation the sludge mixture was sampled and viruses could no longer be detected. Hirotani et al. (1988) emulated the decrease in coliphage during composting by maintaining aerated pig feces at different temperatures (10, 30, 40, and 60°C). At the lowest three temperatures, coliphage was still detectable at the end of the 23 day experiment. At 60°C, however, coliphage density decreased from a starting value of 2.5 x 10^6 PFU g^{-1} to below the detection limits by the time the first monitoring event took place (on day 5). Senne et al. (1994) found that even temperatures lower than 55°C were sufficient to inactivate some viruses. The effect of pilot-scale bin composting of chicken carcasses on the survival of highly pathogenic avian influenza (HPAI) and the adenovirus that causes egg-drop syndrome-76 (EDS-76) was studied. Temperature was monitored daily at five locations in each of two layers of compost. Bags of chicken carcasses inoculated with one of the two viruses were placed around the edges and at the center of the bin. After 10 days of composting, during which time the upper layer exceeded 55°C for 3 consecutive days and the lower layer remained below 41°C, HPAI virus was not detected in any of 20 samples and only one was positive for adenovirus of EDS-76. After turning and composting for a second 10-day period, neither HPAI nor adenovirus of EDS-76 was detected in any sample despite the fact that the measured temperature in the lower layer of the composter again did not exceed 43°C.

None of the above studies conclusively show virus survival beyond the required time-temperature conditions. However, Strauch (1983) reported that ECBO-virus (a bovine enterovirus (Yilmaz and Kaleta 2003)) survived in a reactor system with a retention time of 19 days despite a peak temperature of 82°C, while ascaris eggs were inactivated. The author hypothesized that there were temperature variations throughout the compost. Guardabassi et al. (2003) note that some animal enteric viruses such as parvovirus can take up to 8 days to be inactivated by composting at 55°C, though it was not mentioned if this was applicable to windrows or to static pile or in-vessel systems. In a windrow system inactivation of viruses in 8 days would fall

within the time-temperature requirements, while in the other types of composting systems, which only require 3 days at 55°C, this result would be cause for concern.

2.2.3. Parasites

Two types of parasites can be present in compost feedstocks: the single-celled protozoans and the helminths, or worms. Although the adult forms of these parasites are sensitive to adverse conditions, the cysts and oocysts of some protozoa and the ova of helminths can survive harsh environmental conditions and may pose a significant threat to human health (Burge et al. 1978a; Gaspard et al. 1997). These resistant forms are passed to the external environment through the feces of host organisms (Little 1980). Table 2-1 includes some parasites of concern in composting.

Burge et al. (1978a) cite several studies showing that composting at 60 to 70°C should destroy even the resistant forms of protozoa and helminths. Most subsequent studies, as detailed in the following sections, agree with these results and indicate that parasites will be destroyed if the time-temperature criteria set out in North American guidelines and regulations (e.g. USEPA 1999; CCME 2005) are met. However, a number of others show parasite survival even when temperatures exceed 55°C for several days.

2.2.3.1. Protozoa

Fecally contaminated feedstock materials often contain pathogenic protozoa of varieties including *Giardia lamblia*, *Entamoeba histolytica*, and others (Yanko 1988; USEPA 1992; Rimhanen-Finne et al. 2004). It is generally assumed that protozoan cysts and oocysts are easily destroyed by minimal treatment or even by environmental factors such as drying. As a result, though very few studies have actually examined temperature effects on protozoan survival during composting, it is a common belief that these parasites are not of concern in finished composts because

they should easily be reduced to below detection limits if USEPA Class A time-temperature requirements are satisfied (Kowal 1985; USEPA 1992; USEPA 1999; Larney et al. 2003).

Hu et al. (1996) found that *Giardia* cysts were still present in significant numbers at the end of composting in several small-scale trials, though a distinction between viable and non-viable cysts was not made (the authors assumed that intact cysts have the potential to be infective). It should be noted that none of these trials met the required Class A time-temperature regulations and only two of the trials actually achieved temperatures of greater than 55°C at any time. The authors speculated that *Giardia* cysts would have been destroyed if the composting process had been properly operated.

It is not universally accepted that these organisms are unlikely to present a hazard in finished compost products. Haug (1993) indicates that the protozoan *E. histolytica* may in fact be one of the more thermotolerant of the fecal pathogens. Additionally, protozoan parasites have an extremely low infective dose; a single protozoan cyst has been observed to cause infection (Kowal 1985; Haug 1993; USEPA 1999), so survival of even a single cyst is cause for concern.

A few studies have demonstrated that there is potential for protozoan survival during composting. Jones and Martin (2003) reported that in one study *Giardia* cysts were found to be present (though viability was unknown) after composting at 52 to 53°C, whereas the protozoans *Entamoeba hystolitica* and *Endolimax nana* and even some helminths had completely disintegrated after several days under the same conditions. Rimhanen-Finne et al. (2004) evaluated *Cryptosporidium* oocyst and *Giardia* cyst levels after 10 weeks and 30 weeks of windrow composting. After 10 weeks, 37.5% of the samples analyzed contained *Cryptosporidium* oocysts and 44% still contained *Giardia* cysts. After 30 weeks, though these levels were reduced, *Cryptosporidium* were still detected in 10% of samples and *Giardia* in 35%. Neither cyst/oocyst viability nor temperature was monitored in this study, however. Though neither of these studies directly correlates protozoan viability with compost temperature or proves their survival in systems meeting Class A time-temperature

conditions, the results are indicative of the possibility that protozoa are not as easily destroyed as is often implied.

At present only one study is known to have taken into account both cyst/oocyst viability and compost temperature. Van Herk et al. (2004) studied the effects of full-scale windrow composting on the viability of *Giardia* cysts and *Cryptosporidium* oocysts. Sample bags inoculated with *Giardia* and *Cryptosporidium* were placed in the windrow at several lateral locations. During one year, each lateral location had sample bags at 3 depths and 3 horizontal locations, while the following year all sample bags were placed right in the centre of the windrows. Temperatures of 55°C or more (monitored every 20 minutes and averaged daily for 27 locations) were maintained for more than 30 days during all trials. While in some of the trials all cysts and oocysts were rendered non-viable within 12 days at 55°C, in one trial up to 26 days was required before levels fell below detection limits (during this trial the windrow was turned approximately once every two weeks during the high-temperature period) . In view of these results, the authors recommended that windrow composting should proceed for a period of at least 56 days, which correlated to 26 days at temperatures above 55°C, to ensure complete destruction of protozoan parasites. This suggested time is longer than the 15 days required in USEPA (1999) regulations and CCME (2005) guidelines.

2.2.3.2. Helminths

Helminth ova are of particular concern in compost for a number of reasons. First, they are frequently isolated in feedstocks of fecal origin and can be present in relatively high numbers (Little 1980; Rubin 1996). Second, they are very resistant to a variety of chemical and physical agents (Little 1980; USEPA 1992; Haug 1993). This is especially true at temperatures below 50°C, and attempts to correlate indicator organism reduction to helminth levels in this temperature range over-predict helminth reduction (Rubin 1996). The persistence of helminth ova is illustrated by the fact that *Ascaris*, *Trichuris*, and *Toxocara* ova have been reported to remain viable in soil for

several years, with one study reporting *Ascaris* infectivity even after 15 years in soil (Little 1980). Third, helminths, like protozoa and viruses, have a very low infective dose; ingestion of a single egg poses a significant health risk. For these reasons, their reduction to below detection limits is desired (Little 1980; Haug 1993; Rubin 1996).

Ascaris ova are generally considered to be the most heat-resistant of all the fecal pathogens, aside from enteroviruses at short retention times (Burge et al. 1980; Feachem et al. 1983; Reimers et al. 1986). It is thus assumed that time-temperature conditions capable of inactivating *Ascaris* should be sufficient to inactivate other enteric pathogens (Haug 1993), and USEPA (1999) and CCME (2005) time-temperature criteria are presumed to be sufficient to ensure helminth elimination. According to Burge et al. (1980), the time for one order of magnitude reduction in *Ascaris* population at 55°C or greater in compost is small enough that its destruction is essentially guaranteed in properly composted materials for the levels commonly observed in fecally contaminated feedstocks.

The results of a number of studies support the conclusion that *Ascaris* ova will be reduced to non-detectable levels if composting achieves 55°C or more for 3 days (or 15 days in a windrow system). For example, Haug (1993) cited a study in which *Ascaris lumbricoides*, *Trichuris trichuria*, and hookworm ova were found, with few exceptions, to lose viability within the first 7 to 10 days of windrow composting. This was true despite the fact that the windrows from which the samples were taken did not consistently achieve the desired time-temperature conditions of 55°C for 15 days. Similarly, in a bioreactor experiment *Ascaris* eggs were reduced to non-detectable levels even when the reactor malfunctioned and the peak temperature remained between 49 and 53°C (though salmonella survived these conditions) (Strauch 1983). Wiley and Westerberg (1969) recovered viable ova one hour after inoculating *Ascaris lumbricoides* ova into a bin composter containing sewage sludge at 60 to 70°C, but found that all viability was lost within 4 hours. After 50 hours of composting, no traces of ova could be isolated. At a municipal solid waste composting facility (windrow), Déportes et al. (1998) monitored for *Ascaris* ova at three locations and four sampling points each during turning event (every 2 to 5 days). Temperature was

monitored at the same time, at a 50cm depth, at each of the three sampling locations. *Ascaris* ova became undetectable within 27 days, during which time the minimum recorded temperature appeared to exceed 55°C for at least 8 but less than 21 days (there was up to an 8 day gap in reported temperature data). Gaspard et al. (1997) examined the viability of helminth eggs in the end products of composts which had undergone a 4 to 7 week aeration period followed by 3 months of curing. Three out of the seven composts tested contained viable helminth eggs. Temperature data was not provided, but the authors implied that composting at temperatures less than 40 to 50°C led to inefficient destruction of helminth ova.

Other results imply that helminth ova can sometimes survive in what appear to be properly operated systems. Steer and Windt (1978) called into question the applicability of results from small-scale studies, saying that in smaller systems temperatures would be more uniform and easier to control than in full-scale systems. This means that laboratory scale studies would suggest shorter inactivation times for helminths than may be necessary in full-scale systems. To this end, they studied the inactivation of *Ascaris* in laboratory-scale, pilot-scale, and full-scale systems. In the lab-scale experiment, no viable ova were detected after incubation of inoculated domestic refuse at 50°C for 5 days. In the pilot plant, *Ascaris* survived for six days, during at least one of which the temperature exceeded 60°C and three of which exceeded 50°C. In the full-scale windrow experiments, with weekly turnings, measured temperatures appeared to exceed 55°C for over 30 consecutive days before viable *Ascaris* ova could no longer be detected. The authors thus recommended a windrow composting period of at least 70 days, during which time temperatures should exceed 65°C, to provide sufficient probability of *Ascaris* ova inactivation. They cited insufficient mixing, low moisture content, and irregular temperature distribution as possible reasons for the inability of some processes to achieve helminth-free products.

Helminth ova reduction has, on occasion, been observed at temperatures much lower than 55°C. Tharaldsen and Helle (1989) found that the viability of *Ascaris* eggs

was reduced after 2 weeks at 37°C and all eggs were completely destroyed after 31 days at this temperature. It should be noted that in this study the feedstock material was actually a slurry of liquid manure, so thermal conduction would have been better than in a dryer material. In another study, small-scale composting of tannery effluent, cow manure, and wheat straw took place during the winter, and measured temperatures never exceeded 40°C. Viable helminth ova were detected initially, but could not be found in the finished compost; in other words, inactivation took place despite low temperatures. However, the authors hypothesized that the presence of ammonia in this compost may have affected pathogen survival (Contreras-Ramos et al. 2004). In a study to determine if eggs of *Ascaridia galli* (a surrogate for the human pathogen *Ascaris lumbricoides*) could be destroyed in the lower temperatures found in the outer portions of a pile, Meekings et al. (1996) found that while there was ova destruction at 30°C in compost samples, viability was not lost at the same temperature in distilled water or compost filtrate. They concluded that the temperature was too low to have had any significant effect on ova viability, and that microbial activity within the compost could have been responsible for this destruction. Though there are other potential mechanisms aside from thermal destruction for helminth removal, as mentioned previously these mechanisms are not guaranteed to consistently produce pathogen-free products; thermal destruction is the most reliable approach (Vinnerås et al. 2003).

2.3. Potential Explanations for Pathogen Survival

It is generally accepted that the time-temperature criteria for composting specified in the United States regulations (USEPA 1999) and Canadian guidelines (CCME 2005) are sufficient, as-is, to ensure complete inactivation of all important groups of pathogens. Though a large body of work does support this conclusion, a disconcerting number of studies have found that one or more pathogens remained viable even in composting systems that appeared to achieve conditions of 55°C or

greater for at least 3 days (or 15 days for windrow systems). As previously discussed, a number of pathogenic bacteria, viruses, viable protozoan cysts and oocysts, and viable helminth ova have all been detected in the products of seemingly properly operated composting systems. All three types of composting systems have been affected, but based on this literature review it seems that pathogen survival occurs most often in windrows. There are several potential explanations for this apparent discrepancy between expected and actual pathogen reductions.

2.3.1. Regrowth

Recontamination of the compost pile from external sources and/or regrowth from undetectable levels is one potential explanation for bacterial pathogen presence beyond the high-temperature phase (Haug 1993; Gerba et al. 1995; Epstein 1997; Dumontet et al. 1999). Regrowth is a problem only for certain bacterial pathogens such as *Salmonella* sp. and *E. coli* which, unlike other bacterial species, viruses, protozoa, and helminths, do not require a host organism in order to reproduce (Haug 1993; Rubin 1996; Jones and Martin 2003). Regrowth is a potential problem even in composts that have been properly treated to reduce pathogenic bacteria to very low levels (Brandon et al. 1977).

Regrowth is less likely to occur in high-temperature areas of a compost heap than in cool spots. Shuval et al. (1991) observed *Salmonella* sp. regrowth in the cool exterior of windrows. Others (Haug 1993; Christensen et al. 2002) have observed regrowth during the lower-temperature stabilization phase following the high-temperature stage. Russ and Yanko (1981) observed regrowth of salmonellae from undetectable levels even after the compost had been stored in a desiccated state for approximately one year. In a large-scale composting experiment, Turner (2002) observed that *E. coli* concentrations actually increased from their initial levels when composting was carried out at mesophilic temperatures (i.e. <45°C). Turner thus concluded that care should be taken in controlling conditions so that bacterial

pathogen growth is not induced. Thus, low-temperature zones within compost are a concern not only because pathogens may not be sufficiently reduced, but also because conditions may be favourable for bacterial pathogen growth.

The regrowth phenomenon cannot explain the presence of viruses, protozoa, or helminths in finished composts.

2.3.2. Time-Temperature Criteria

Another possible reason, applicable for all groups of pathogens, for the frequent disparity between the expected and achieved levels of pathogen reduction in systems apparently meeting time-temperature regulations is that, despite the indications of previous research, the current time-temperature criteria are not actually sufficient to ensure inactivation of all pathogens. The fact that some bench-scale experiments, which should provide more uniform temperatures and better temperature control than is possible in full-scale systems, show that it takes longer than 3 days at 55°C to achieve sufficient pathogen inactivation (e.g. Droffner and Brinton 1995) suggests that this is a possibility. Droffner and Brinton postulated that their results were indicative of the difficulty in reliably correlating time-temperature and pathogen destruction and suggested that the removal mechanisms for bacterial pathogens may be more complex than simply time-temperature.

Additionally, it may be of interest to consider the relative locations of pathogen sampling and temperature monitoring points. In one of two studies in which temperature was monitored near sampling points, meeting the time-temperature conditions in the regulations was sufficient to remove a naturally-occurring strain of *E. coli*, but not an inoculated laboratory strain (Van Herk et al. 2004). In the other study (Christensen et al. 2002), *Enterococcus* was sometimes detectable at temperature monitoring points which had exceeded 55°C for the required amount of time. These results again imply that perhaps the time-temperature conditions in the guidelines and regulations are not sufficient. It should be noted, however, that the

applicability of the time-temperature guidelines is rarely questioned, as they were based on a solid body of work examining the thermal inactivation of pathogens.

An additional factor to be considered when dealing with windrow systems is pile turning. The requirement for windrow systems that 55°C should be maintained for a period of 15 days, during which the pile should be turned 5 times (USEPA 1999; CCME 2005), was specified on the assumption that 5 turnings are required to move all material into the high-temperature core for 3 consecutive days. It is interesting to note that of the studies in which pathogen survival was seen in windrows for longer than 15 days, all those reporting turning schedules (i.e. Steer and Windt 1978; Shuval et al. 1991; Larney et al. 2003; Van Herk et al 2004; Cekmecelioglu et al 2005) had not turned the pile 5 times within the first 15 days at or above 55°C. In the Steer and Windt (1978) study, for example, pathogens could not be detected after 30 days at 55°C, which corresponded to 4 or 5 turns of the windrow, whereas at 15 days this windrow had only been turned 2 or 3 times and viable Ascaris ova were still present. These results are indicative of the importance of exposing all material in the pile to lethal temperatures (Haug 1993); failure to do so, for example by inadequate turning of a windrow, may result in prolonged periods of pathogen survival.

2.3.3. Process Monitoring

Probably the most commonly cited explanation for pathogen survival during composting is that temperatures may not be uniform throughout the entire mass of compost. In other words, temperature monitoring and/or reporting may falsely give the impression that the time-temperature criteria have been met throughout the entire composting mass, though some zones may never have reached 55°C for the specified amount of time (Gerba et al. 1995; Guardabassi et al. 2003; Salter and Cuyler 2003). As pointed out previously, guidelines and regulations for composting do not have specific requirements for temperature monitoring events. Low-temperature zones may not be detected due to infrequent temperature monitoring events, limited spatial

temperature data, and/or the monitoring of average pile temperatures, and pathogen survival may occur in these zones. Burge et al. (1978b), for example, observed salmonellae survival in a lower corner of an aerated static pile, which experienced lower temperatures than the rest of the compost mass.

It is virtually impossible to obtain a temperature profile for an entire compost heap, or even a representative temperature profile, with available technologies. Instead, temperature measurements are made at fixed, discrete locations within the pile. Monitoring at only a few points may result in temperature variations being overlooked. That there may be temperature differences between different areas of a pile can be qualitatively observed during winter-time composting, when there may be layers of ice and/or snow on the outer surfaces of piles, while the pile interiors experience thermophilic temperatures (see Figure 2-1). For instance, McCartney and Eftoda (2005) observed layers of frozen material up to 0.9 m in thickness during winter windrow composting trials, though some locations in the pile experienced temperatures between 55 and 65°C. The authors expressed concern that such a situation may lead to a decreased ability to inactivate pathogens.

Windrow composting during wintertime is not a special case; significant temperature variations have been observed with location in all types of full-scale composting systems in all weather conditions. For example, Pereira-Neto et al. (1987) monitored temperatures at the top, middle, and bottom of a mixed refuse and sludge aerated static pile. The boundaries of the pile, especially at the bottom, were the coolest areas, and data showed a peak difference of more than 40°C between the highest and lowest temperatures at a single point in time. Levels of *E. coli* and fecal streptococci were highest in the cooler areas of the pile. Over a summer, Fernandes et al. (1994) monitored temperatures every 4 hours at 33 locations in aerated static piles constructed from mixtures of poultry manure, straw, and peat moss. In all trials it was seen that the bottom edges of the piles were cooler than the middle and upper zones. There was also temperature variation within the bottom zone itself; in one pile, the bottom corner never exceeded 33°C, while a location on the same edge of the pile, but away from the corner, peaked above 60°C. In another pile, the temperature at the

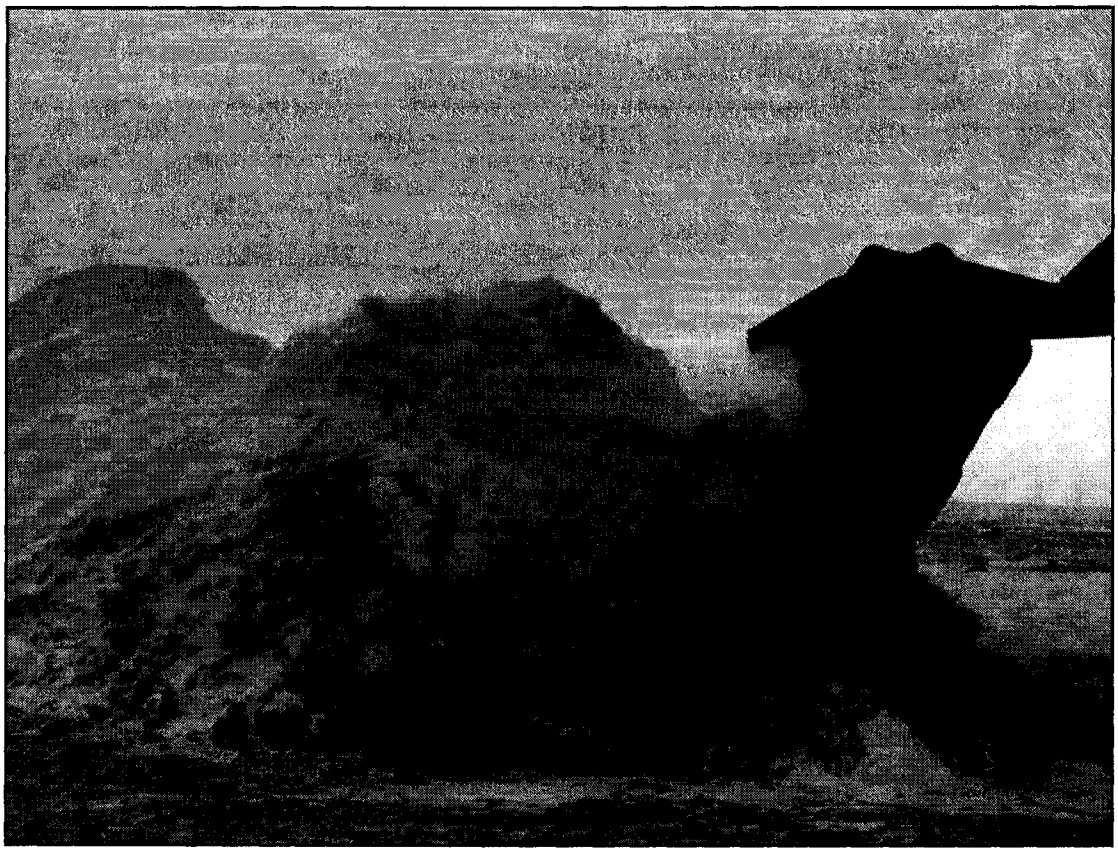

Figure 2-1. A City of Winnipeg windrow being turned during the winter of 2001/2002. Though the pile core peaked at temperatures between 55 and 65°C, snow and ice remained at the surface of the pile (courtesy of Daryl McCartney).

center of the pile bottom peaked at 44°C, while temperatures at the peripheries exceeded 55°C. In all trials, temperatures rose and fell at different rates and times at different locations, even when the monitoring locations were near each other. Bhamidimarri and Pandey (1996) also observed significant temperature differences between adjacent monitoring points while composting piggery wastes in a static pile. At one location (the centre of the pile at the bottom) temperature peaked at around 52°C, while at the same time the monitoring location directly above was at ~59°C and an adjacent lateral location was at ~68°C. A peak difference between the highest and lowest temperatures occurred on day 13, and was near 52°C. Strader and Bromhal (1997), who conducted a study on windrow temperature variation during late

springtime, reported differences of up to 20°C within the space of a few feet. Fischer et al. (1998), during the fall, manually monitored temperatures once per day at 30 locations in a turned (daily) garden waste windrow. Isotherms plotted for a cross-section of the windrow indicated that, while the core experienced temperatures of over 75°C, only 50% of the section was warmer than 50°C. Outer parts of the pile were coolest (below 30°C). Similarly, Christensen et al. (2002) observed a trend toward lower reductions in both *E. coli* and *Enterococcus* in lower-temperature zones of a mixed sewage sludge and yard waste windrow facility. Christensen et al. (2002) also studied two in-vessel composting facilities, one of which had significant temperature differences between the middle and lower zones, with the lower zones experiencing temperatures above 55°C for a significantly shorter amount of time than the middle of the compost. These experiments were conducted during March and April in Scandinavian countries. Vinnerås et al. (2003) conducted a pilot-scale experiment in which a mixture of fecal matter, food waste, and mature compost were composted in an insulated 90-L reactor. Two thermocouples were placed in the bin, one in the middle and one at the wall, and temperatures were recorded every 10 minutes. Temperatures remained above 55°C for more than twice as long in the middle as compared to at the edge of this reactor.

Not all studies reported temperature monitoring and pathogen sampling locations, but it is of interest to consider the relative positions of those that did. Of those studies where reported temperature and pathogen monitoring points differed (e.g. Pereira-Neto et al. 1986; Déportes et al. 1998; Tiquia et al. 1998; Lafond et al. 2002; Salter and Cuyler 2003; Cekmecelioglu et al. 2005), half showed pathogen survival or regrowth even when temperature monitoring showed that 55°C was achieved for more than 3 days (or 15 days in windrows). Van Herk et al. (2004) monitored temperature at similar locations to some pathogen sampling points, though there were many more sampling points than temperature monitoring points. They found that in some trials up to 26 days was required before no viable protozoan cysts or oocysts could be recovered from any sampling locations. It is possible that these

results occurred because compost samples for microbiological analysis were taken from undetected cooler temperature zones where pathogen survival was possible.

The frequency of temperature monitoring should also be considered. Compost temperatures are monitored over a wide range of frequencies, from minutes to days (Déportes et al. 1998; Tiquia et al. 1998; Hess et al. 2004; Van Herk et al. 2004). Since temperatures in compost fluctuate with time, in the short-term as well as the long-term (Pereira-Neto et al. 1987), two temperature measurements of 55°C or more taken days apart do not necessarily imply that the time-temperature criteria have been met. During the time between measurements the temperature could have decreased; for example, fluctuations of up to 15°C per day are not uncommon in windrows (Strader and Bromhal 1997).

Additionally, many authors report temperature data as an average of several measurements taken at a specific time, rather than reporting all temperature data from all measurement points (i.e. Déportes et al. 1998; Larney et al. 2003; Van Herk et al. 2004; Cekmecelioglu et al. 2005). In instances where averages are reported, it is unclear to the reader whether or not all monitored areas of the compost pile have actually experienced temperatures exceeding 55°C for the required amount of time. It should be emphasized that the time-temperature regulations apply to all particles of compost processed, and do not represent an average value.

For all of the above reasons, the use of discrete temperature measurements at fixed locations is not representative of the conditions that every particle of material experiences during composting; there is no guarantee that all areas of a compost pile have attained the required time-temperature conditions, even if measured or reported temperatures indicate that they do. As Salter and Cuyler (2003) admit, it is possible that undetected cooler zones exist within compost piles when temperatures are monitored infrequently at a limited number of locations. Pathogenic organisms remaining in or being mixed into low temperature pockets could survive the composting process.

2.4. Summary and Conclusions

In order to reduce human and environmental health risks due to pathogenic organisms to a negligible level in compost products, environmental organizations in North America have developed time-temperature criteria (e.g. USEPA 1999; CCME 2005). These criteria state that all particles of compost should maintain temperatures of 55°C or more for at least three days. It is generally expected that composting processes complying with these criteria will produce pathogen-free end products.

A literature review focusing on the correlation between compost time-temperature conditions and pathogen survival revealed that pathogens from the four major groups have been detected on occasion in the finished products of what appear to be properly operated processes (from the perspective of having met the regulated time-temperature conditions). It is possible that the current regulations are not adequate to ensure pathogen inactivation, though the applicability of the time-temperature criteria is not often questioned. It is also possible that commonly used methods of temperature monitoring and reporting can give the false impression that the regulations have been met when in reality they have not been. Because composting guidelines and regulations are not specific about temperature monitoring requirements, a wide variety of monitoring schemes are used in practice. Temperature monitoring points vary widely in both space and time, and may not be sufficient to ensure that cool zones do not exist within compost piles.

In the interest of ensuring the lowest possible risk due to pathogen contamination, it would be beneficial to attempt to clarify the reasons for the inability of some apparently properly operated composting operations to eliminate pathogenic organisms. This would likely involve a) attempting to define a temperature monitoring plan that would effectively provide temperature measurements representative of conditions in the entire pile, b) examining temperature distributions throughout all types of full-scale composting systems, and c) more thoroughly evaluating the relationship between compost pile temperatures and a wide range of pathogenic organisms in full-scale composting systems.

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Chapter 3.

DEVELOPMENT OF TIME-TEMPERATURE PROBES FOR TRACKING PATHOGEN INACTIVATION DURING COMPOSTING[2,3]

3.1. Introduction

Pathogen reduction during composting is thought to occur largely due to the elevated temperature conditions that exist within the compost mass in a properly operated system. Guidelines and regulations in the United States (USEPA 1999) and Canada (CCME 2005) indicate that enteric pathogen reduction to below detectable levels should be accomplished if all material in a static pile or in-vessel composter attains a temperature of 55°C for at least 3 days. For windrow systems, this requirement is slightly modified; temperatures should be maintained at 55°C for at least 15 days with at least five turnings of the windrow during the high-temperature period (USEPA 1999; CCME 2005).

A large body of work on pathogen reduction during composting indicates that if the above time-temperature conditions are met then enteric pathogen levels should be reduced to below detection limits. However, an extensive review of available literature by the authors revealed that pathogens are occasionally detected in the finished products of some systems appearing to meet the specified temperature conditions for the required amount of time (Wichuk and McCartney unpublished).

One commonly cited explanation for pathogen survival during composting is that temperatures are generally not consistent throughout large piles or reactors. Non-uniform temperature distributions have been observed in numerous studies of all three

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[2] *A version of this chapter has been accepted for publication: Wichuk and McCartney 2007. Proceedings of the US Composting Council's 15th Annual Conference, Jan 21-24, Orlando, FL.*

[3] *A version of this chapter has been submitted for publication: Wichuk and McCartney 2007. Compost Science and Utilization.*

types of composting processes (Lau et al. 1993; 1994; Déportes et al. 1998; Joshua et al. 1998; Bari and Koenig 2001; Avnimelech et al. 2004; Hess et al. 2004; Van Herk et al. 2004; Turner et al. 2005; Wichuk and McCartney unpublished). It is possible, for instance, that a pile core may experience temperatures 30°C or more above those in outer zones, which may remain near ambient temperatures (Stentiford 1996; Fischer et al. 1998). In fact, during the winter McCartney and Eftoda (2005) observed zones of frozen material up to 0.9 m thick in windrows, though other areas of the same piles remained at thermophilic temperatures. Even in late springtime differences of up to 20°C within the space of a few feet have been reported (Strader and Bromhal 1997).

Low-temperature zones within the compost mass likely contribute to the survival of pathogenic organisms through treatment (USEPA 1999). Since many pathogens have very low infective doses, ingestion or inhalation of only a few surviving organisms may result in considerable risk (Little 1980; Kowal 1985; Haug 1993; Rubin 1996; USEPA 1999). It is therefore important to ensure that all material is exposed to the lethal time-temperature conditions (Haug 1993). In fact, the USEPA regulations (USEPA 1999) specifically indicate that each and every particle of material being treated must meet the time-temperature requirements. However, specifications for actually monitoring temperatures are limited to the statement that measurements must be made at representative locations, and at multiple points at a number of depths in the compost heap (Hay 1996; USEPA 1999). Canadian composting guidelines do not mention any specific requirements for monitoring frequency or location (CCME 2005).

In order to determine whether more specific temperature monitoring requirements are needed to ensure that the entire mass of compost achieves the required temperature and time conditions, it is of interest to monitor the temperature conditions that random particles of material encounter as they undergo the composting process. Temperature profiles from a statistically significant number of compost particles should provide an idea of whether or not a composting system has actually achieved the required pathogen reduction conditions. Temperature

measurements obtained using traditional monitoring methods could be compared to those obtained using the new method in order to determine whether or not traditional measurements capture the temperature variations that occur within a compost pile.

Currently available monitoring methods are inadequate to accomplish this goal. This paper discusses the rationale for and development of a new temperature monitoring method capable of monitoring the environment of random particles of compost material.

3.2. Current Compost Temperature Monitoring Methods

Monitoring compost temperatures is not a straightforward process. Because temperature varies throughout the heap, careful planning must be done to ensure measurement of a representative temperature spectrum with a limited number of discrete temperature probes (Turner et al. 2005). In most previous studies of composting processes, temperature has been monitored periodically in fixed locations in compost piles or reactors. Generally, two types of temperature measuring devices have been used: long probe type thermometers, which must be inserted into the compost each time and at each location that a measurement is to be made (Turner et al. 2005), and thermocouples combined with data loggers, which can be set up and left in the compost mass (Fernandes et al. 1994).

One of the main downfalls of both of these methods is that they monitor temperature at predetermined, fixed locations within the compost mass. The USEPA regulations, however, state that the time-temperature requirements apply to every particle processed. The use of discrete measurements at fixed locations is not representative of "every particle" of material, and may result in temperature variations being overlooked (Salter and Cuyler 2003). Thus, even if measured data indicate that the required time-temperature conditions have been met at all points, there is no guarantee that all areas of the pile have satisfactorily met these conditions.

Turner et al. (2005) attempted to solve the problem of working with discrete measurements by monitoring compost heap temperatures using thermal imaging technology. However, this technique allows only for the monitoring of surface temperatures. The authors used a combination of the thermal imaging data and internal temperature data to create a mathematical model capable of inferring internal temperature data. They found that different modelling techniques were needed to model internal temperatures for different windrows (Turner et al. 2005), and thus this technique is not particularly practical.

Due to the shortcomings of currently available monitoring methods, a new method is required to obtain time-temperature profiles representative of a random compost particle.

3.3. Time-Temperature Probe Conception and Design

The best way to monitor the conditions that a random compost particle experiences during composting would be to randomly introduce into the process a self-contained device (temperature probe) free to move around as a particle of compost would during pile building, pile mixing, windrow turning, and other operations, as well as during material settling. Since such a device is not currently used in composting systems, its development was undertaken.

In addition to having the ability to mimic closely the behaviour of a lump of compost, this device must also be able to survive the harsh conditions encountered during composting and to be easily recoverable after testing is complete. The parameters and performance characteristics used in the probe design are presented in Table A-1 in Appendix A. The proposed device consists of an electronic circuit to monitor and record temperature, software to control the device and upload data, and a rugged case to protect the electronics from physical, chemical, and microbiological stresses.

In terms of creating a device that would behave similarly to a particle of compost, it was expected that the most important property of the device would be its density. The density of the probe should be such that it does not preferentially move up or down in the pile relative to the compost material as a result of agitation or settling. Since the probe was expected to be large relative to the majority of compost particles or lumps, it was speculated that probe movement would be random if the device density roughly corresponded to the wet bulk density of the compost (generally between 500 and 900 kg/m^3 (Agnew and Leonard 2003)). Minor departures of probe density from compost wet bulk density were not expected to have a major effect on probe movement within the pile. However, since the density of the device has the potential to affect its correct operation, and since it was unknown exactly how much of a departure from wet bulk density would be acceptable, it was decided that a range of densities should be tested before finalizing the probe design.

One of the initial steps in the design process was to determine whether any suitable device already existed. A number of temperature logging devices were already commercially available (see Appendix B), but were deemed unsuitable for one or more of the following reasons: a smaller than required temperature range (the required temperature range was at least -40 to 100°C), plastic casing unable to survive impacts sustained during composting, and/or a density much higher than compost wet bulk density. Therefore, a probe case and temperature logging circuitry were designed from scratch.

3.3.1. Preliminary Case Design

The temperature probe housing design was contracted out to a senior mechanical engineering design class. Their conceptual design solution consisted of a 76.2 mm long section of 16-gauge (ga.), 76.2 mm diameter aluminum tubing, capped on each end by a polypropylene cylinder. The end caps were to be fastened to the probe case sides by an assembly consisting of two 18-8 stainless steel machine

screws, fender washers, silicone sealing washers, and nylon locknuts. A moisture seal between the end caps and the aluminum tube would be provided by neoprene O-rings. Allowance for two square circuit boards was provided as a possible arrangement for the mounting of the temperature logging circuit. These boards would attach to the end cap insides with four screws each.

More detailed explanations, analyses, and drawings of the initial phase of temperature probe housing design can be found in a report by Alloway et al. (2005). It should be noted that modifications were made during testing in order to decrease the size of the housing.

3.3.2. Preliminary Electronics Design

The functional portion of the temperature logging circuitry was designed around a temperature data logging chip (Maxim Integrated Products/Dallas Semiconductor part number DS2422), which provided temperature sensing and recording capabilities and enough memory to log up to 8192 temperature data points (i.e. every 10 minutes for 8 weeks). Control software for the device was provided by the manufacturer. The other main component of the temperature logging circuit was a power supply supervisor. This component switches between a main and backup power supply when one of them fails, and was necessary because the DS2422 uses volatile memory, which means that it would lose data if power to the device was lost.

The requirement that the logger be self-contained necessitated the use of a long-life battery to provide power. It was determined that a high temperature lithium battery would be the best choice. A ½AA-sized battery was chosen to save board space and minimize probe mass.

A more detailed description of the circuit along with a circuit diagram and parts list is included in Appendix C.

3.4. Probe Test Methods

The temperature probe described above was designed, based on theoretical worst-case scenarios, to survive and function properly in a composting system. To ensure that this was the case and to optimize the design, the performance of the probe was evaluated in an actual composting system. Several parameters required testing. These included the strength of the case material, the effect of a probe's density on its ability to move randomly, the robustness of the circuitry to impacts, the temperature response time of the device, the ease of probe recovery, and the effect of exposure to a strong magnetic field. Detailed test procedures are presented in Appendix E.

All of the tests involving the probe housing used 90 mm lengths of 50.8 mm diameter round aluminum tubing (6061 grade). This size and grade were chosen because they were easy to obtain and because it was desired that the size of the temperature probe be reduced from the initial design specifications.

The performance of the developed device was also compared to that of a similar commercially available temperature logging device. The device chosen for comparison met most of the design criteria set out in Appendix A (Table A-1), but its density (approximately 1800 kg/m^3) was nearly double the specified design limit.

Unless otherwise noted, all of the following tests were done at the Edmonton Waste Management Centre of Excellence (EWMCE). Composting facilities at the EWMCE include a co-composter, Gore® composter, and a yard waste composting facility. At the co-composter, dewatered biosolids and pre-sorted municipal solid waste (MSW) are mixed together, pass through a 1.5 day mixing process, and are then composted in an aeration bay for 28 days before being moved to a cure site (Yee 2005; Yee 2006). The Gore® composter is an aerated static pile system for biosolids composting in which the Gore Cover® system is used to control odours and process parameters such as moisture (Fichtner et al. 2003) during the active phase of composting. Composting of source-separated yard waste is accomplished using turned windrows.

3.4.1. Case Strength

The conceptual design of the temperature sensor housing specified the use of 16-gauge aluminum tubing as the case walls. It was of some concern that this thickness may not be strong enough to withstand impacts such as being dropped onto a hard surface, being turned with a windrow turner, and being run over by heavy machinery (which could occur if a probe rolled out of a pile). Thus, testing was done to determine the response of a section of aluminum tubing to each of these three stresses. Two thicker gauges of aluminum tubing, 14 and 11, were tested along with the 16-ga. material.

A drop test was done to determine the impact of dropping the cases onto a hard surface, which would simulate the worst-case conditions that might occur during pile building. For this test, 30 pieces of aluminum tubing without end caps (10 of each gauge) were loaded into a front-end loader bucket. The bucket was raised to its maximum height and the probes dropped onto a compacted gravel surface.

The second test involved determining whether or not a probe (cased in 16-, 14-, or 11-ga. aluminum) could be expected to survive being driven over by a piece of heavy equipment. One section of each gauge of aluminum tubing (without end caps) was placed on the ground and driven over by a front-end loader.

A final test of material strength involved determining how well the probe housing would withstand the impacts of windrow turning. Sections of aluminum tubing were placed in a windrow at the cure site for the EWMCE's co-composter, and the windrow was turned using a Frontier Industrial Corporation, model F-18 windrow turner. This test was performed twice; for the first run 9 sections of 16-ga., 8 sections of 14-ga., and 10 sections of 11-ga. tubing were placed in the windrow, and for the second run 18 pieces of 16-ga., 16 pieces of 14-ga., and 54 sections of 11-ga. aluminum were used. Sections of each gauge were divided as evenly as possible between the top, middle, and bottom of the windrow.

After each test the probes were collected and the damage to each recorded. Additionally, during all tests where probes were placed in composts, damage to the aluminum housing due to chemical and biological stresses was noted.

3.4.2. Probe Density

As previously mentioned, it was hypothesized that density would be the most important factor affecting the ability of the probes to behave randomly during compost agitation and settling, and that the ideal density for a probe would be close to that of the wet bulk density of the compost material being monitored. Testing was done to confirm this theory and to determine how much, if any, difference between the probe density and compost bulk density would be acceptable. This experiment was conducted coincident with the windrow turner case strength test.

This test was conducted twice. In the first run, three densities were chosen for testing. The minimum density tested was 800 kg/m^3, roughly corresponding to the calculated density for a 16-ga. aluminum probe of 50.8 mm diameter and 90 mm length. The maximum density tested was 2300 kg/m^3. This was the approximate density calculated for an 11-ga. stainless steel tube (diameter 50.8 mm, length 90 mm); stainless steel was also being considered as housing material in case aluminum was not strong enough. The third density was the midpoint between the high and low densities: 1550 kg/m^3. Nine probes each of 800 kg/m^3 and 2300 kg/m^3 were built for this trial along with eight probes of 1550 kg/m^3. The densities were adjusted by partially filling the aluminum tube with nuts, bolts, and/or nails. Both ends were capped with 50.8 mm circles of 1.58 mm thick polycarbonate secured to the aluminum tubing using either electrical or duct tape. All probes were engraved with an identification number.

In order to account for the effects of initial location within the pile on probe movement, the probes were placed in three different locations, roughly at the top, middle, and bottom of a windrow at the co-composter cure site. One third of the

probes of each density being tested were placed at each height. All probes were placed in the same lateral position in order to minimize the search area after turning. The heights of the probes in each position were measured and recorded. The windrow was then turned once (Figure 3-1) and the probes recovered. This was accomplished by digging through the compost by hand, in order not to affect the location of the probes during their recovery. When a probe case was located, its final height was recorded.

The second run was carried out approximately 4 weeks after the first run, in the same windrow as the first trial. The procedure was similar, with the exception of the number of cases introduced, the method of securing the end caps to the aluminum tube, and the densities tested. For this trial, 27 cases of each of three densities were introduced into the windrow. The end caps were secured to the aluminum tubing using electrical tape only, as duct tape tended to tear during the first trial. The high density was changed to 1800 kg/m^3, roughly corresponding to the density of the commercial temperature logger. The low density was kept at 800 kg/m^3, and thus the midpoint was 1400 kg/m^3. The remainder of the procedure was the same as during the first trial, with one third of the probes of each density being placed at the top, middle, and bottom of the windrow, the windrow being turned, and the location of the probes after turning being recorded.

During the second run, the wet bulk density of the compost was tested, in order to have a point of comparison between probe and compost densities. Compost was collected from four locations (top, bottom, and two middle locations) in the windrow used for testing (after turning), in the same zone as the temperature probe cases were placed. These four samples were amalgamated in a 5-gallon bucket with a lid and stored for 10 days prior to analysis. The procedure used for the bulk density determination was a modification of TMECC Method 03.03-A/03.01-A (steps 10.3 to 10.5 only) (TMECC 2001).

Change in height data (i.e. the difference between initial and final heights) were analyzed using a two-factor analysis of variance (ANOVA), with density and initial height being the factors considered (see Appendix G for details). The effect of

Figure 3-1. Windrow being turned during probe density testing.

effect of density on probe movement was of major concern, but the initial height of the probes also needed to be considered because the starting position affected the possible directions (up or down) and magnitudes of the height change. The ANOVA analysis provided insight into whether probe density significantly affected the change in height of the probes after turning.

The cross-sectional dimensions of the windrow (see Figure 3-2) were measured to obtain an estimate of the pile volume. It should be noted that a windrow cannot be represented perfectly by simple geometric shapes, so these calculations are approximations. The width at the top was determined by measuring from the centerline to the point where the pile began to slope steeply downward. The width at the bottom was determined by measuring across the pile at the end of the windrow. The pile height was determined by measuring from the ground to a pole extended horizontally from the top of the pile. From these dimensions, it was possible to approximate the distance, d, above ground at which an equal volume of compost lay above and below. Since probes were initially placed in equal numbers at the top,

middle, and bottom of the pile, the corresponding change in height, Δd, to this volume midpoint should be the difference between this distance, d, and the half the pile height, h/2 (the mean initial location of the probes). It was postulated that random probe movement during windrow turning would be indicated by a mean change in height corresponding to the volume midpoint, since there would be a 50% chance that material would lay above or below this line. A t-test was used to evaluate this.

3.4.3. Robustness of Circuitry

It was also of prime importance that the temperature logging circuit inside the housing remain intact and functioning for the duration of the data-logging mission, regardless of the conditions encountered. Thus, during tests of density and housing material strength in the co-composter cure site windrow, some quick experiments were also done to examine the robustness of the electronics to severe impacts (as occur during windrow turning).

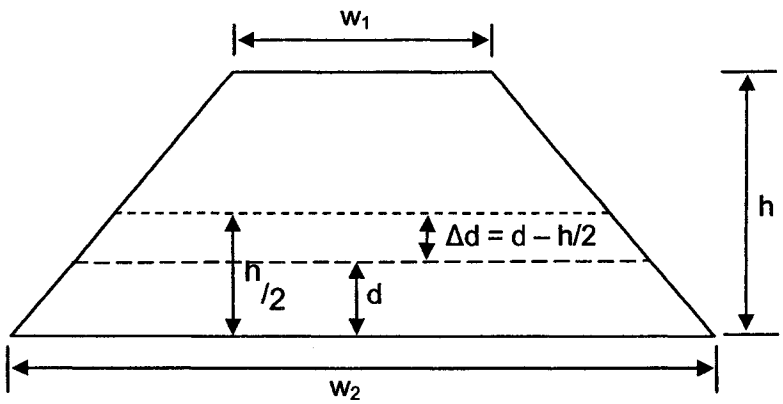

Figure 3-2. Approximate dimensions of a windrow cross-section. The volumes of material above and below "d" (compost volume midpoint) are approximately equal. Dimension "Δd" is used to compare "change in height" values to "d".

During the first run, an operating commercial temperature logger was introduced into the middle of the windrow, as was an operational DS2422-based temperature logging circuit with a single AA battery. The DS2422 circuit was enclosed in a section of aluminum tubing in such a way that minimal movement of the circuit board would occur inside the housing, and the tube was capped with a 50.8 mm diameter, 1.58 mm thick polycarbonate circle on each end. The windrow was turned, the circuits recovered, and the electronics examined for damage.

During the second windrow-turning trial, in addition to the two temperature logging circuits listed above, six cases containing ½AA sized lithium batteries soldered onto a circuit board were placed into the windrow at the bottom. Three of the cases contained tabbed batteries (Tadiran TL-5902/T) and the other three contained batteries with solder pins (Tadiran TL-5902/P). Again, the circuits were recovered after windrow turning and examined for damage.

3.4.4. Temperature Response Time

The response time of a temperature sensor is dependent on a number of factors, including the thermal conductivity of the sensor itself and of the materials (such as the case walls and air space) between the sensor and the temperature of interest. It was desired that the amount of time required for both the commercial and DS2422-based loggers to respond to a step change in-temperature be determined. An excessively long response time would be undesirable because temperature fluctuations of interest may be overlooked; three hours or less was set as the target (see Appendix A).

A two-point temperature calibration (at approximate temperatures of -10°C and 60°C) was done for each device, to ensure that both would provide the same data under equivalent conditions. The two-point calibration was completed as specified in the documentation for each device (Maxim/Dallas 2003; Madge Tech n.d.). After calibration, each device was set up to record temperature once every 60 seconds and

enclosed in its housing (the DS2422 circuit housing was as described in section 4.4.3, except that the end caps were 4.76 mm thick). The temperature response times of both devices were evaluated over temperature changes of approximately ±10°C, ±15°C, ±20°C, ±30°C, and ±40°C. These changes were achieved by moving the probes between a room temperature zone and a pre-heated lab oven. When the devices were moved from one temperature zone to another, they were allowed to equilibrate for a period of at least 2 hours (based on preliminary observations), to ensure that sufficient time had been allowed for the temperature readings to stabilize. The time required for a given temperature rise or fall was evaluated when the device had attained a temperature within 0.5°C of its peak or minimum temperature, respectively.

After all specified positive and negative temperature change cycles had been completed, temperature datasets were downloaded from each device and evaluated to determine the response time for each step change in temperature.

This test was performed at the University of Alberta, Department of Civil and Environmental Engineering.

3.4.5. Probe Recovery

It was desired that as close as possible to 100% of the probes introduced into a composting system be recovered so as not to lose collected data. Several probe detection and recovery methods were considered during the design phases (see Appendix E). Of those considered, visual recovery during screening and location by metal detection were considered the most viable options.

The efficiency of probe recovery during screening was tested by introducing 30 sections (six each of the following colors: gold, blue, yellow, orange, and unpainted) of aluminum tubing into a rotary drum screener along with a loader bucket of compost. The overs of the screen were scanned visually for the aluminum tubes and all those spotted were collected and counted. The different colour tubes were

evaluated for relative visibility levels. This test was repeated twice: once in the finished product of the Gore® composter and once in compost from the co-composter.

Two trials were also done to determine how easily the temperature probes could be located using metal detection. First, the ease of locating the aluminum sections with a relatively basic, low-cost hand-held metal detector (Garret Treasure Ace 100) was tested. The maximum depth that the aluminum probes could be sensed with the metal detector was determined by burying a piece of aluminum tubing in screened biosolids compost at a known location at a known depth, varying from 1 cm to 20 cm. The metal detector was set on its most sensitive setting and the compost was scanned. The depth at which the piece of aluminum could no longer be sensed was noted. It was also of interest to see how easy it would be to locate a stainless steel probe (in case the housing material was modified) and to see how the performance of an industrial detector would compare with the hobby model used in the first test. Thus, a magnetic "pin finder" (Schonstedt GA-52Cx Magnetic Locator) was used to locate magnetic stainless steel rods buried in a co-composter cure pile and also in a yard waste pile. A similar test to that done with the Garrett Treasure Ace was performed.

3.4.6. Effect of Magnetic Field on Data Memory

In some composting operations, magnetic separation is employed either at the front-end or during screening of the final product. Such operations use strong magnetic fields to separate out and capture ferrous materials. It is therefore possible that the temperature loggers may enter into a relatively strong magnetic field during their use. It was of interest to determine what effect, if any, a strong magnetic field would have on a device, as data loss or any change in functioning would be undesirable. The effect of magnetic fields is not a standard test for most semiconductor devices (TI Support 2005), and was therefore unknown.

An experiment was conducted on both the commercial device and the DS2422-based circuit. A temperature-logging session was started on each device, and

data collected for one day. The data were then downloaded and saved without stopping the data-logging missions or erasing data. The devices were then enclosed in their cases and put under the magnetic separation unit at the EWMCE's co-composter for two minutes (which exceeds the amount of time it would normally take for an object to pass under the magnet). The data stored in memory were downloaded from each device and compared to the data downloaded prior to magnet exposure. A second temperature-logging mission was started on both devices and the data from that mission examined to ensure that device functioning was not affected.

3.5. Probe Test Results

Relevant data and statistical analyses pertaining to the results of probe testing are presented in Appendices F and G.

3.5.1. Material Strength and Robustness

None of the 16, 14, or 11-gauge aluminum tubes suffered any damage, aside from paint chips, when they were dropped from a loader bucket onto a packed gravel surface. When driven over by a front-end loader the 14 and 16-ga. tubes were crushed, while the 11-ga. tube was compressed only slightly (Figure 3-3). It is important to note that this experiment was conducted without the recommended end caps in place, which may have made the cases stronger by providing structural support at the ends.

During the windrow-turning tests, aluminum sections of all gauges were dented by the turner's auger blades. Some of the most severe damage can be seen in Figure 3-4. While all gauges of aluminum were affected to some degree, the most acute damage occurred to the 16-ga. tubing and the least amount of severe denting occurred to the 11-ga. tubes. More and larger dents tended to occur at the ends of the tubes rather than in the middle. Again, it should be noted that having the

recommended end caps in place may have provided some additional structural support and hence reduced the severity of the denting at the tube ends.

Qualitative observations of damage sustained to the aluminum cases due to chemical and biological factors were also made during the windrow test. Some of the painted cases darkened in colour after only a few days in the cure pile. The gold cases began to show signs of corrosion or microbial degradation of the paint and aluminum after having been in compost for less than four days. One unpainted case was recovered during the second trial after spending nearly a month in the windrow; this case was severely pitted in numerous locations due to some combination of corrosion and microbial degradation. The housing of the commercial temperature logger, made from the same aluminum grade, but anodized, was not affected by chemical or microbiological stresses after the same amount of time (see Figure 3-5).

3.5.2. Probe Density

During the first trial, a significant amount of data was lost either because the probe housing was not recovered or because one or both ends of the case fell off, resulting in a significant density change. Out of 26 housings introduced to the windrow, only 20 were recovered. Of these, 9 had been broken during turning and suffered a change in density, leaving only 11 probes intact. Thus, only 11 probes provided useful information for data analysis. A two-factor ANOVA was performed on these 11 data points for change in height data. The results of the analysis indicated that, once the initial location of the probes was taken into account, there was not a significant difference in height changes due to different densities. However, since only a small amount of useful data was obtained during the first trial, no strong conclusions could be drawn regarding the affect of density on probe movement.

A second trial was performed because so many probes were lost or damaged during the first trial. Three times as many probe housings were used and the end caps better secured. During the second experiment 7 probes were not recovered and two

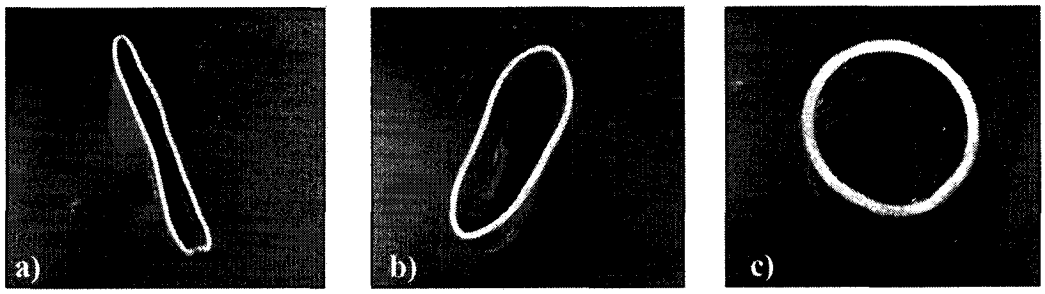

Figure 3-3. Typical damage to aluminum tubes driven over by a front-end loader. a) 16-ga. tube. b) 14-ga. tube. c) 11-ga. tube.

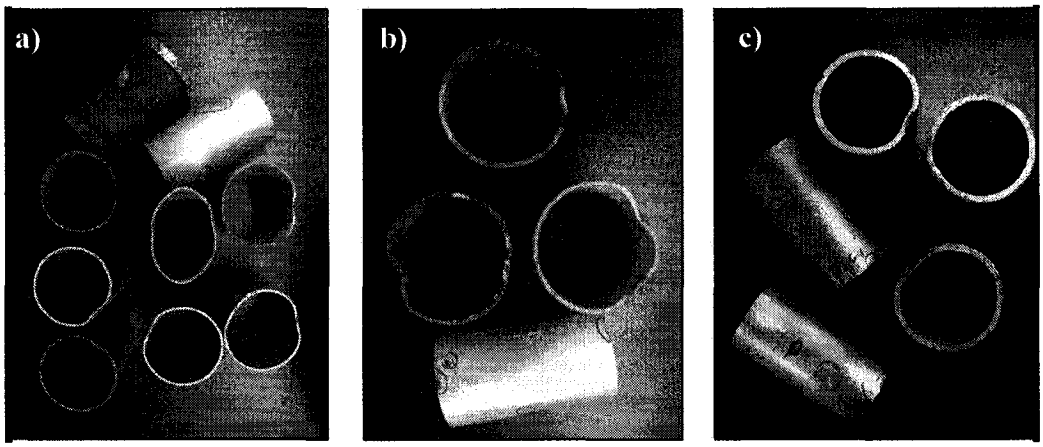

Figure 3-4. Examples of damage to aluminum tubes after windrow turning, including denting and deformation. a) 16 ga. tubes. b) 14-ga. tubes. c) 11-ga. tubes.

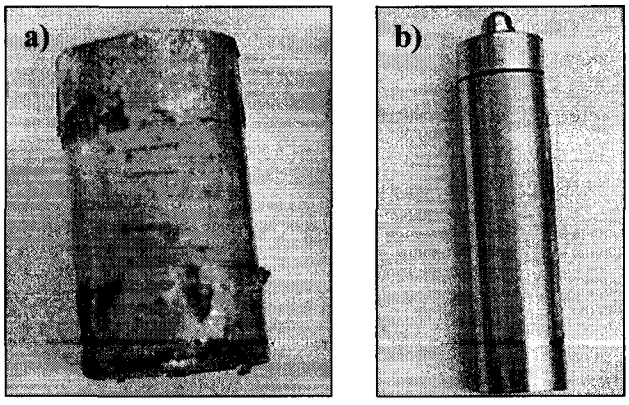

Figure 3-5. Chemical and microbiological degradation of aluminum housings recovered after four weeks in a compost cure pile (dark spots indicate areas of damage): a) unpainted, unanodized tube and b) anodized commercial logger case.

broke. However, the large amount of remaining data meant that a more meaningful analysis could be completed than was possible after the first trial.

The dimensions of a cross-section of the windrow were roughly measured (as in Section 3.4.2). The measured pile height, h, was 1.5 m. The width of the windrow at the top, w_1, was 1.2 m. The width at the bottom of the pile, w_2, was 5.5 m. From these dimensions, it was determined that there were approximately equal volumes of material above and below d = 0.53 m, which corresponded to a change in height, Δd, of -0.22 m. Compost bulk density during this trial was 446.9 ± 8.7 kg/m³.

From the average change in height data for each density, it appeared that there was a slight trend toward more downward probe movement as density increased. Interestingly, a best-fit line (linear regression) through the average change in height data crossed the volume midpoint (Δd = -0.22 m) at a density of 452 kg/m³, which is nearly the same as the compost bulk density. However, when the data were weighted to take into account the different numbers of probes that were lost from each height, the trend toward downward movement with increasing density was not as obvious (Figure 3-6) and the volume midpoint was crossed at a density of 246 kg/m³. Additionally, after accounting for the effects of initial probe location, an ANOVA analysis (95% confidence level) indicated no significant difference in change in height data between probes of different densities. In other words, the ANOVA results indicate that varying probe density from 800 kg/m³ to 2000 kg/m³ appeared not to affect probe movement significantly.

T-tests indicated that for all densities, neither the average nor the weighted average change in heights significantly differed from the compost volume midpoint (again with a 95% confidence level). This result, along with the ANOVA result that there was no significant difference in change of height between different densities, seems to indicate that there was random dispersion for probes with densities between 800 and 2000 kg/m³ during turning of a windrow with a bulk density near 450 kg/m³. However, analysis of the variability of the data (i.e. the standard deviation) revealed that 84 probes of each density would be required to fully capture all possible vertical movement of the probes, with a 95% confidence level (see Appendix G).

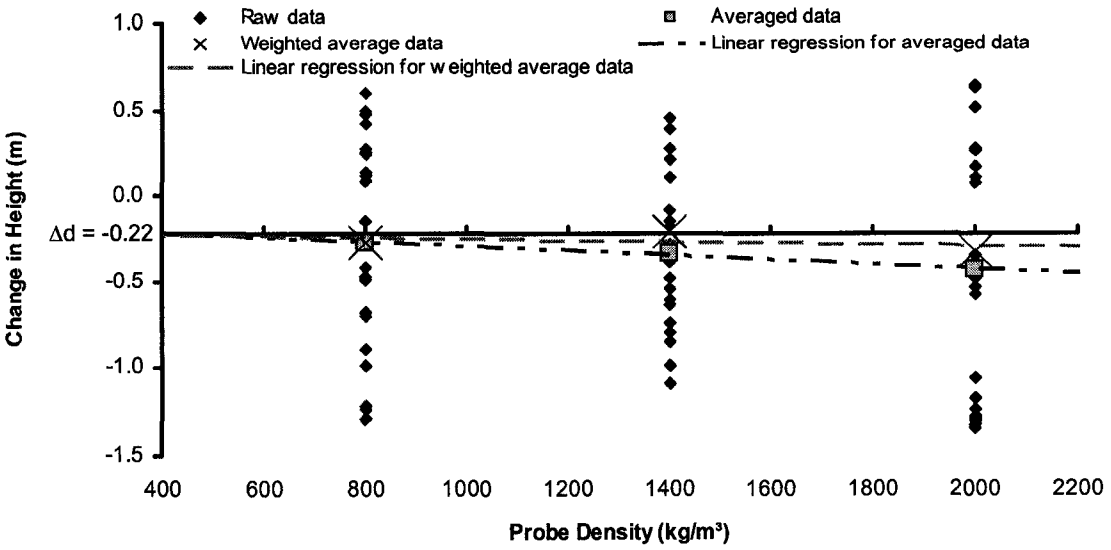

Figure 3-6. Plot of change in height data after windrow turning (raw, averaged, and weighted average) for probes of different densities.

3.5.3. Robustness of Circuitry

During the first trial, only the DS2422 device was recovered after windrow turning. All circuit components and solder contacts remained intact during windrow turning. However, one of the tabs tore off of the battery, so that power to the circuit was lost (see Figure 3-7). When the battery was replaced the circuit functioned properly; however, no data were retained.

During the second trial, several ½AA-sized batteries of both tabbed and solder pin varieties were tested in order to see if the battery problems encountered during initial testing would occur again, and to see if pins would be stronger than tabs. After turning, the commercial logger was recovered along with the DS2422 circuit, all three cases containing tabbed ½AA batteries, and one of the three cases containing batteries with solder pins. All of the soldered batteries had one or both tabs/pins broken. Again, the only apparent problem with the DS2422 circuit was the broken battery connection, and the device functioned normally when it was replaced.

The battery in the commercial temperature logging device was similar to the other ½AA batteries with pins that were tested, except that it was placed in a socket rather than being soldered directly into the circuit. Sometime during the three windrow turning activities experienced by the commercial logger (one during the initial trial, one during the second trial, and one between trials), one of the battery pins came out of its socket and the device lost power. Another main component of the circuit, a microcontroller, also popped out of its socket, and a diode was broken in half (see Figure 3-8). It was hypothesized that the diode broke because it was hit when the battery came out of its socket. All other components of the commercially available device were soldered onto the circuit board and survived three passes of the windrow turner. When all broken or loose parts were replaced, the logger resumed normal operation. Data memory was full to capacity (32767 readings). As temperatures were logged once per minute, data memory would have filled up in 22.7 days. Since turning events occurred every 14 days, damage to the device likely occurred during the third turning event.

3.5.4. Temperature Response Time

The results of the temperature response test are presented in Table 3-1. The commercial and DS2422-based temperature loggers had similar response times. The maximum amount of time needed for either device to respond to a step change in temperature was 81 minutes, which easily met the desired three-hour limit set on response time. Though the data shows an overall trend of longer response times for larger changes in temperature, the temperature probes are not expected to experience a step change in temperature much more than the largest change tested. Therefore, the temperature response times of both devices were deemed adequate.

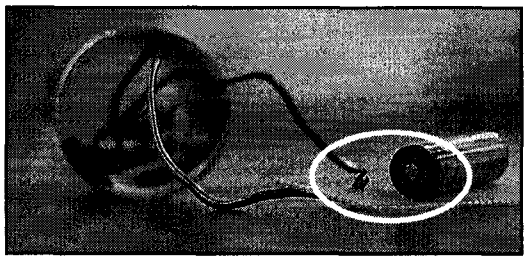

Figure 3-7. Damage to the DS2422-based temperature logging circuit after being turned once by a windrow turner. One of the battery tabs was torn off.

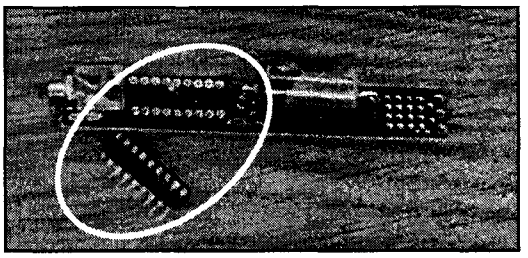

Figure 3-8. Damage to the internal circuitry of the commercial temperature logger after being turned three times with a windrow turner. One of the components popped out of its socket.

Table 3-1. Time required for each of the commercial and DS2422-based devices to respond to different changes in temperature.

Temperature Low (°C)	Temperature High (°C)	Temperature Differential (°C)	DS2422-based Logger		Commercial Temperature Logger	
			Rise Time (min.)	Fall Time (min.)	Rise Time (min.)	Fall Time (min.)
20.5	64.0	43.5	70	81	70	79
20.0	52.5	32.5	70	78	72	65
20.0	42.0	22.0	68	64	67	65
19.5	37.0	17.5	64	65	71	58
19.5	28.5	9.0	44	36	40	38

3.5.5. Probe Recovery

When various colours of aluminum tubing were screened with both biosolids and mixed biosolids/MSW compost, a person visually scanning the screen overs easily recovered 100% of the tubing. In the biosolids compost, all colours were equally easy to see. However, in the mixed compost the gold and unpainted cases tended to blend slightly more than the other colours with non-compostable materials (such as bits of coloured plastic, glass, and metal) in the product. Nonetheless, it

appeared that screening the probes out of finished compost would be a viable method of recovery.

The low-cost metal detector used to evaluate the recovery of aluminum probe cases performed quite poorly. A case placed at a known location could only be detected up to a depth of 15 cm. Numerous other objects were also picked up by the metal detector (even in screened biosolids compost). In fact, other objects were picked up with such frequency that an operator would be unable to determine whether the detector was signaling the presence of a probe or of some extraneous object. Reducing the sensitivity of the detector was not effective in reducing this interference. Additionally, with reduced sensitivity the maximum detection depth decreases.

The magnetic locator was also found to be ineffective for use in probe recovery. In the co-composter cure pile, a stainless steel bar was easily detected, but other objects in the pile were also picked up. As was the case with the metal detector used to locate aluminum tubing, it would be virtually impossible to distinguish between a stainless steel probe and other ferrous objects in the compost. The situation was even worse in the yard waste windrow, with the detector giving strong signals whether or not the stainless steel bars were in the pile.

3.5.6. Effect of Magnetic Field on Data Memory

After exposure to a magnetic field generated by a ferrous magnetic separation unit, temperature data collected by the DS2422 device and the commercial device was compared to that collected prior to the exposure, and was found to be the same. Data collection continued, unaffected, during and after subjection to a magnetic field. The devices also both operated normally when they were stopped and started again, indicating that a strong magnetic field had no effect on the operation of either device.

3.6. Discussion and Recommendations

Testing of the designed temperature logging device and a similar commercially available model revealed that, while both devices showed potential as far as performing their desired function, neither device was ideal. Improvements could be made to both devices in order to obtain a better fit between the specified parameters and the actual performance of the probes.

One of the most important features of the temperature probe was an ability for the devices to mimic the behaviour of random particles of compost during agitation and settling. The average position of a probe should tend toward the volume midpoint of a compost pile (i.e. there should be a random distribution of probes around the level at which there are equal volumes of compost in the top and bottom of the pile). Three probe densities were tested (800, 1400, and 2000 kg/m^3) in compost with a bulk density of approximately 450 kg/m^3. An ANOVA analysis indicated no significant differences between the different probe densities, and there were no statistically significant difference between the average change in height data and the volume midpoint for all probe densities. These results imply that random probe distribution was achieved. However, they were based on a single experiment; additional trials are recommended to confirm the results. It should also be noted that even though random distribution was observed during this trial, the same results may not be seen with probes of different sizes or in a pile with fresh feedstock materials. This is because during this test the probe size was significantly larger than the average pore size within the compost heap and thus the probes were easily held up by the compost matrix. If the probe size approaches the size of a compost pore, it will likely become easier for dense probes to move downward in the pile. Hence, if the probe dimensions are decreased such that they become similar to pore size, this test should be repeated.

Edge effects should also be considered in future trials to determine how well the probes are able to mimic random probe behaviour. Such effects may include an inability for a windrow turner to pick up a small probe sitting right at the ground

(though in this case the probe would be able to monitor conditions seen by a compost particle sitting at ground level). Also, since the probes are cylindrical, if they reach the edge of the pile there is a high probability that they will roll off the pile, whereas a compost particle may not. This is an undesirable situation, as valuable data could be lost. A possible way to prevent rolling would be to attach a counterweight or hook to the device.

It was also important to be able to recover all (or nearly all) of the probes introduced into the compost. Screening appeared to be a feasible method of probe recovery. However, it is recommended that additional screening tests be performed after probes have undergone a complete compost cycle, as it is possible that the compression of materials within a pile could cause compost to stick to the cases and thus make them difficult to see. The results reported in this paper refer to a screening test done immediately after adding cases to relatively dry compost. Two attempts at probe recovery by metal detection failed, partly because detection depth was small and partly because there was interference from extraneous objects in the compost pile. It is possible that a more expensive detector may perform better; some higher end detectors have visual displays which allow specific objects to be identified by signal/wave shape. These detectors are also able to penetrate deeper, though maximum depths of only a few feet are reported, which may still be too shallow (Catalano 2006). At this point, screening seems to be the most viable probe recovery method. Since neither device appeared to be affected at all by exposure to a strong magnetic field, it is not of concern if screening operations employ magnets to remove ferrous materials from the compost.

The temperature response times of both the commercial and DS2422-based temperature loggers were satisfactory; the response times were short enough that it is unlikely any significant variation in temperature (with time) would be overlooked. However, if major changes are made to the probe design, these tests should be repeated to confirm that the results are still adequate. Changes to the amount of air space inside the probe or changes to the materials used could potentially affect the amount of time required for the device to respond to a temperature change.

As far as the probe housing is concerned, the 16-gauge aluminum was not sturdy enough to survive relatively unscathed during activities such as windrow turning. It is recommended that a thicker gauge, such as 14 or 11, be used in the final design. The 11-gauge tubing did suffer some denting during turning, but the severity of the dents was small relative to those on the other two gauges. However, since 11-gauge adds extra mass to the probes 14-gauge might be a better choice since it survived reasonably well during high impact situations and would contribute less to increasing probe density. It should be noted that dent frequency and severity were greater at the ends of all gauges of aluminum tubes than in the middle. Severe denting at the tube ends is cause for concern, given the proposed design of the case (an aluminum tube with polypropylene end caps fitting inside the tube); it is possible that even minor dents at the tube ends may damage the seal between the end caps and the aluminum tube. This could lead to exposure of the electronic circuitry to moisture, compost, and/or contaminants; it is particularly important to prevent moisture from coming into contact with the lithium battery used, as this may present an explosion hazard. Had the suggested end caps been in place during testing, however, there may have been additional structural support and dent severity may have been reduced.

A brightly coloured case (i.e. blue, yellow, or orange) is recommended to increase visibility. Aluminum can be anodized different colours; this is advised, as anodizing seemed to be effective in preventing corrosion and would limit paint chipping and discoloration.

The most serious problem encountered during windrow turning experiments was that electronic components and batteries placed in sockets popped out of the sockets, and batteries soldered to the circuit board suffered broken pins or tabs. The ability of the device to function as desired was affected when power was lost and/or circuit components failed. The use of solder-mount chips rather than sockets would solve half the problem. However, another solution is needed for the problem of battery connection breakage.

It is hypothesized that the battery connections failed due to inertial force; when the probe case was accelerated or decelerated, the battery on the inside of the

case experienced a larger inertial force than did the other components of the circuit. In other words, when the case, and hence the circuit board, was stopped, the battery was able to keep moving and the solder tabs broke. This was a problem for the battery but not for other soldered parts because the battery was relatively heavy (for a given acceleration, force is directly proportional to mass) and because the battery was attached to the circuit board in only two places (at either end), while other parts were attached at several points along two edges. It is important to find a solution to the problem of battery breakage, as this causes power loss and hence data loss. The solution is probably as simple as finding a better way to secure the battery to the circuit board. One option would be to create a mould that would fit snugly around the circuit board and battery, preventing movement of the internal parts. Another option, suggested by the manufacturer of the commercial data logger, would be to wrap tape around the battery to keep it in place; electrical tape may be suitable for this purpose, as it was strong enough to hold end caps in place during windrow turning. The tape option may be preferable because the temperature response time may be increased by the mould material. Tape would also add less weight to the probe. Testing is recommended prior to finalizing the design.

Several of the initial design parameters were modified based on the above test results and additional observations during testing. Changes were made to the operational temperature range (changed to -40 to 85°C) and probe density (ideally less than 2000 kg/m^3) parameters, among others. It was also seen that the type of data memory used in the device was important. The design parameter modifications are presented in Table A-3 in Appendix A. Based on these modifications, the commercial device was deemed preferable over the conceptual design presented in this paper (Table A-4 in Appendix A presents a comparison between the two devices). The commercial device case, a bored out aluminum rod with a screw cap and O-ring on one end, was simpler, had a smaller part count, was easier to open and close, and was stronger at the cylinder ends because there were no joints between parts. Also, in the interest of data retention, the commercial logger circuitry, with non-volatile memory, is preferred to the DS2422-based circuit, which loses data when power to the circuit

is lost. The commercial device also has four times more memory capacity than the DS2422-based device. The impact of the smaller case size of the commercial device would have to be considered, though. Probe recovery would likely be unaffected, since the smallest dimension of the commercial temperature logger is 26 mm, so capture on a 1 in. (25.4 mm) or smaller screen would still be possible. These probes are also still large enough to be easily recovered visually in the screen overs. However, a decrease in case size may affect the ability of the probes to disperse randomly in compost, as they may more easily fit into pore space than the larger cases tested. If they do fit into the pore spaces they may have a tendency to move downward since their density is higher than that of the compost. As mentioned previously, testing should be done to determine the effect of a change in probe size on dispersion during compost agitation events.

3.7. Conclusion

A new method for monitoring temperatures in compost from the point of view of a random compost particle was desired. To this end, a self-contained temperature logging device was designed, built, tested, and compared with a similar commercially available device. Both devices showed potential, but required modifications to make the electronic circuitry more resistant to impacts. The commercial temperature logger, however, showed more promise than the new device because of several advantageous features. More testing is recommended to confirm the ability of the devices to mimic the behaviour of compost particles.

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Chapter 4.

GENERAL DISCUSSION AND CONCLUSIONS

4.1. Research Problem

Most environmental regulatory agencies specify a set of temperature and time conditions that must be met during composting in order to induce pathogen destruction (Haug 1993). In Canada (CCME 2005) and the United States (USEPA 1999), it is specified that temperatures of 55°C or higher must be achieved throughout a compost heap for several days in order to minimize the health risk associated with the presence of enteric pathogens. The specified time at 55°C is 3 days for an aerated static pile or in-vessel system, and 15 days for a windrow (which must be turned 5 times during the high-temperature period). It is important to note that these time-temperature conditions must be met by all particles of material being composted (USEPA 1999). Temperature monitoring frequency and location specifics are not provided in the CCME (2005) guidelines or USEPA (1999) regulations.

The first aim of this research was to determine, based on a literature review, whether or not composting systems meeting the pathogen reduction guidelines as specified by the USEPA and CCME were routinely found to be essentially pathogen-free (i.e. no pathogens detectable).

The second aim of this research was to design and test a new method capable of monitoring temperature conditions seen by random particles of material during composting, with the future goal of using these probes to gather temperature data representative of conditions seen by a typical particle of material.

4.2. Overview of Literature Review

A review of available literature providing both compost temperature and pathogen data showed that it is possible for enteric pathogens to survive composting even when the required time-temperature criteria appear to have been met. Despite many studies finding that pathogens could not be detected if the required time-temperature conditions were met, a significant number of researchers' results indicated that various pathogens were still present in compost after monitored temperatures exceeded 55°C for the required amount of time. All of the major enteric pathogen groups (i.e. bacteria, viruses, protozoa, and helminths) were detected in at least one study.

For instance, Krogstad and Gudding (1975) detected *Salmonella typhimurium* after 4 days of composting at 55°C in a pilot-scale reactor, and Droffner and Brinton (1995), using a gene-probe analysis, detected both *Escherichia coli* and *Salmonella* sp. in a full-scale composter even though temperatures remained near 60°C for nearly two months. Strauch (1983) reported ECBO-virus survival in a compost reactor even though temperatures peaked at 82°C. Van Herk et al. (2004) observed the survival of viable *Giardia* cysts and *Cryptosporidium* oocysts for up to 26 days at 55°C or more in windrows. In another full-scale windrow experiment, Steer and Windt (1978) could detect viable *Ascaris* ova until monitored temperatures exceeded 55°C for 30 consecutive days.

Several potential reasons for pathogen detection after the required time-temperature conditions have been met were theorized. One possibility is that recontamination of the pile and/or regrowth (from non-detectable levels or due to recontamination) could occur after the high-temperature phase, allowing pathogens to re-establish themselves in finished composts. It should be noted that the regrowth phenomenon is only applicable for those pathogenic bacteria capable of reproducing outside of a host organism (e.g. *Salmonella* sp. and *Escherichia coli*) (Haug 1993; Gerba et al. 1995; Epstein 1997; Dumontet et al. 1999). Regrowth of viruses, parasitic organisms, and other bacterial species is not possible within compost.

It is also possible that the current specifications for time and temperature conditions are not actually adequate. In a bench-scale experiment Droffner and Brinton (1995) found that significantly longer than 3 days at 60°C or more was required to reduce inoculated *E. coli B* and *Salmonella typhimurium Q* to below detection limits (using a sensitive gene probe detection method). Since their work was done on a small scale, they likely were able to achieve uniform temperatures and to measure them accurately, which calls into question the applicability of the time-temperature regulations. The authors postulated that their results are indicative of the difficulty in decisively correlating time-temperature and pathogen destruction, due to the development of heat-resistant strains of bacteria and to the complex nature of bacterial destruction mechanisms. However, the time-temperature guidelines used in North America were based on a large body of work examining the thermal inactivation of numerous pathogenic organisms, and are rarely called into question.

Since regrowth is only a possibility for certain bacterial species, and since parasite ova and viruses have also been found to survive in compost operations which have apparently met the required time-temperature conditions, it is likely that regrowth is not the only reason for pathogen contaminated compost products. Furthermore, assuming that the science upon which the North American regulations are based is sound, it is also likely that the time-temperature conditions specified are sufficient and that there is some other cause for pathogen survival.

The existence of temperature variations throughout compost masses is commonly given as a potential explanation for pathogen survival during composting. Low-temperature zones within a compost heap have been noted in numerous studies of windrow, aerated static pile, and in-vessel systems (e.g. Lau et al. 1993; Déportes et al. 1998; Van Herk et al. 2004; McCartney and Eftoda 2005; Turner et al. 2005). Temperature differentials of 30°C or more have been observed between the core and outer edges of piles (Stentiford 1996; Fischer et al. 1998). Thus, it is quite possible that some parts of a compost heap may never reach thermophilic temperatures, even when monitored locations (for example, in the heart of a pile) may have attained temperatures of 55°C or more for the specified amount of time. It was hypothesized

that the existence of non-uniform temperatures may be the most likely cause for pathogen survival in seemingly properly operated compost systems. It was recommended that testing be carried out to verify this possibility. The recommended first step was to develop a temperature monitoring plan to obtain temperature measurements representative of conditions throughout a compost pile. Once this monitoring method was developed, it could then be used to examine temperature distributions throughout all types of full-scale operations.

4.3. Overview of Probe Design

Monitoring temperature conditions seen by a statistically significant number of random compost particles was assumed to be a suitable method of approximating temperature conditions representative of the entire compost mass, providing an idea of whether or not a composting system has actually achieved the required pathogen reduction conditions. Monitoring conditions seen by compost particles is also particularly appropriate since USEPA regulations (USEPA 1999) emphasize that the time-temperature requirements set out must be met by all particles of material being composted.

A new method was necessary in order to monitor conditions seen by random particles of compost. One of the most important characteristics of this method was an ability for the temperature monitoring equipment to freely move around in a compost heap during settling and any type of agitation of the compost. Since currently used methods of temperature monitoring all involve probes placed at fixed locations, it was necessary to develop a new self-contained, rugged temperature data logger with size and density properties similar to that of compost particles. These devices would be able to be incorporated into compost piles randomly and undergo the composting process in a manner similar to a random compost particle.

An initial set of requirements was developed for the temperature data logger (see Table A-1 in Appendix A). A survey was done of commercial devices to

determine whether any suitable temperature loggers were available. None of the commercial devices met all of the required parameters, so design of a new device was undertaken. The preliminary design solution consisted of a battery-operated temperature logging circuit, with enough memory to store 8192 temperature readings, enclosed in an aluminum cylinder closed at both ends with polypropylene caps.

4.4. Discussion of Probe Test Results

To determine how well the preliminary probe design actually performed in a full-scale composting system, and to optimize the design, several tests were carried out. These included tests of case strength, the effect of density on probe movement, the ability of the electronic circuitry to survive repeated impacts, device temperature response time, efficiency of probe recovery, and magnetic field exposure effects. The commercial device with the best fit to the desired parameters listed in Table A-1 was also tested for the sake of comparison.

The main results of the tests performed, along with a brief discussion of the implications of these results, are presented in Table 4-1.

After the tests were completed, it was decided that the commercial temperature logging device performed satisfactorily and would, in fact, probably be preferable to the custom-designed probe. There were several reasons for this change from the initial hypothesis that no commercially available devices would satisfy the set of parameters needed for the temperature logger, all involving a change in design parameters based on the results of testing (see Tables A-1 through A-4 in Appendix A). In particular, it was seen that the upper limit for probe density could apparently be changed from 900 kg/m^3 to 2000 kg/m^3 without affecting the ability of the device to behave randomly during pile agitation. This new limit encompasses the density of the commercial temperature logger, which is around 1800 kg/m^3. It was also seen that the device should ideally use non-volatile memory to store temperature data, as there is potential for power loss to the devices which would cause temperature data stored in

Table 4-1. Main results of probe testing and implications of these results.

Test	Result	Implications
Material Strength	Probes of three gauges (16, 14, and 11) all survived being dropped from a raised loader bucket onto a hard surface.	The thicker the walls of the aluminum tube, the better it stood up to the various impacts it was subjected to. Thus, the 11-gauge tubing performed the best out of the three gauges tested.
	Pieces of 16- and 14-gauge aluminum tubing were flattened when driven over by a front-end loader, while an 11-gauge tube survived relatively unscathed.	
	All gauges of aluminum were dented by a windrow turner, though the 11-gauge tubes suffered the least amount of severe denting.	
	During windrow turning, dents occurred more frequently and tended to be larger at the ends of the tubes than in the middles.	Denting at the end of the tubes may cause the tight seal between the end caps and the aluminum tube to be lost, exposing the electronic circuitry to moisture, compost, and/or contaminants. However, the suggested end caps were not used during testing; having these end caps in place may have provided some structural support and reduced the severity of the dents at the tube ends.
	Some of the unanodized aluminum tubes (particularly the gold ones) placed in a cure pile began to show signs of corrosion and/or microbial degradation after a only a few days.	Anodizing the aluminum case appears to be very effective in preventing chemically- or biologically-induced deterioration. Thus, anodizing is strongly recommended if aluminum is chosen for the final probe case design.
	An unpainted, unanodized tube suffered severe pitting due to chemical or biological factors within 4 weeks in a cure pile.	
	The anodized aluminum commercial logger case, showed no signs of chemical or microbiological degradation after 4 weeks in a cure pile.	
Probe Density	The bulk density of the compost in the cure pile where the probe density tests took place was approximately 450 kg/m^3.	As desired, probes of 800, 1400, and 2000 kg/m^3 all appeared to be dispersed randomly in compost (bulk density ~450 kg/m^3) during windrow turning, with no significant differences between densities. This random dispersion implies that probes of the densities tested would be suitable for monitoring conditions seen by random compost particles. However, it is recommended that more testing be done to confirm these results. It should be noted that these results are only valid for the size of case tested (i.e. 52.8 mm diameter by 90 mm length), but may change if the size is altered significantly (particularly if it is decreased).
	There was not a statistically significant difference in "change in height" data between probes of 800, 1400, and 2000 kg/m^3 densities.	
	For probes of all three densities tested (800, 1400, and 2000 kg/m^3), there was no significant difference between the change in height corresponding to the volume midpoint of the compost pile and both the average and weighted average "change in height" values.	

Table 4-1 (con't). Main results of probe testing and implications of these results.

Test	Result	Implications
Robustness of Circuitry	When batteries of the tabbed or solder pin varieties were soldered to the circuit, at least one of the tabs or pins consistently broke during windrow turning.	Impacts encountered during turning mainly affected the power supply (i.e. the batteries) and parts in sockets. This is a serious problem because of the potential for loss of data. It is recommended that all parts be soldered into the circuit board, and that the battery is secured in place using some method in addition to soldering or a battery socket; such a method may be as simple as wrapping the battery and circuit board with strong tape, or could involve making a mould that slides snugly around the circuit and into the aluminum tube.
	The commercial temperature logger had the following circuitry problems during windrow turning: battery popped out of its socket, a microcontroller popped out of its socket, and a diode broke.	
	Devices all functioned normally when batteries and/or broken parts replaced.	
Temperature Response Time	The commercial temperature logger and the DS2422-based device had very similar temperature response times for step changes in temperature between 9 and 43.5°C.	Since it was previously decided that a temperature response time of less than three hours would be sufficient, and since an instantaneous change of more than 43.5°C is not likely to occur during composting, the temperature response times of both devices are satisfactory. However, if the size of the probe is increased, these tests should be repeated, as the additional air space or material changes may affect the response time.
	The longest response time, 81 minutes, was seen when there was a step change in ambient temperature (decrease) of 43.5°C.	
	Response times increased as the temperature differential was increased.	
Probe Recovery	A low-cost metal detector and a magnetic locator performed poorly in locating aluminum probes and stainless steel bars, respectively, as there was interference from other metals in the compost (in both yard waste and screened biosolids composts).	Screening appears to be a better method of probe recovery than does metal detection, since both metal detectors tested picked up strong signals from other metallic objects in compost. However, it is possible that a higher-end metal detector with a visual display may be more useful, though penetration depth may still be an issue. Screening tests should be repeated after probes have undergone an entire composting cycle, as compost may adhere to the cases making them difficult to recognize.
	30 aluminum tubes were easily recovered in the overs of a drum screener after being screened with a load of finished compost.	
	Gold and unpainted cases were slightly more difficult to see in municipal solid waste compost than were yellow, orange, and blue.	
Magnetic Field Exposure	Neither data integrity nor device operation of both the commercial and DS2422-based devices was affected by a 2- minute exposure to a strong magnetic field.	Since device operation was not affected by exposure to a strong magnetic field (of a longer-than-expected duration), these probes may be used in areas of composting plants employing magnetic separation units.

memory to be lost. The commercial device uses non-volatile memory, while the DS2422 does not. The commercial data logger also had more memory than the DS2422. The case design of the commercial device was superior to the design developed for the DS2422-based device because it was simpler, easier to open and close, and used fewer parts (3 separate pieces as opposed to 17 for the designed device). The commercial logger case was also stronger at the ends because both the main case and the cap were made from bored out aluminum rods and thus had more structural support at the ends due to the lack of joints.

4.5. Recommendations

The results of preliminary testing done on the compost temperature logging devices indicate that the commercial device is superior to the DS2422-based device that was designed for this project. However, further testing and improvements, as described below, are required prior to making a final recommendation regarding the temperature logging device and/or finalizing a design.

A method of better securing the batteries to the circuit boards is necessary; both types of devices tested experienced problems with power loss due to lost contact between the battery and the rest of the circuit. Two potential options for better securing the battery to prevent contact loss are 1) to wrap the battery and board with strong tape (electrical tape may suffice for this) and 2) to create a mould fitting around the battery and snugly into the aluminum tube. If the first option is adequate, it may be preferable as it will probably be cheaper, add less weight to the device, and should not affect the temperature response time. If a mould is necessary, the temperature response tests should be repeated.

If the DS2422-based device is chosen, it is recommended that the case be redesigned to be similar to the commercial device case. Rather than an aluminum tube capped at both ends by polypropylene cylinders held on by two bolt and nut assemblies, it would be preferable to create a case with as few parts and joints as

possible, as this should increase the robustness of the device to impacts. The commercial device case, for example, is made from a hollowed out aluminum rod with an aluminum screw cap on one end and a single O-ring to create a seal against moisture. The aluminum should be anodized to increase resistance to chemical and microbial stresses.

The effect of probe density on the randomness of probe movement/behaviour should be tested further because the hypothesis that random behaviour can be expected for probes of a density less than 2000 kg/m^3 was based on a single test. If the commercial device is chosen, this additional testing will be particularly important since the commercial device is smaller than the cases tested and may fit more easily into pore spaces between the compost particles. It is not expected that the slight decrease in the size of the commercial devices from those tested would have a significant effect on their ability to fit into pore spaces. However, if there was an effect, the probes would probably move preferentially downward in the pile since they are much denser than compost; this is undesirable.

Additionally, since the temperature loggers are meant to monitor conditions seen during active/thermophilic composting (i.e. the initial stage of the process), it is important to ensure that probe behaviour is random during this stage. Initial density testing was done in a compost cure pile, and provided useful information regarding probe behaviour in relatively dry materials as a function of compost bulk density and probe density. However, there are several general differences between the material in a fresh pile and cure pile which require consideration. Particles of material and hence void spaces tend to be larger in fresh compost; thus, it may be easier for the probes to move downward since the pore spaces are closer in size to the probe than in a cure pile. The moisture content of fresh material is generally higher than that in a cure pile, leading to increased cohesion between the compost and the probes, which may possibly act to minimize probe movement (especially downward). The higher moisture content also leads to a higher bulk density in fresh material, which could also counteract the tendency for heavy probes to move preferentially downward. It is not expected that there will be a significant difference in the results of the probe

density test from those that were seen in the compost cure pile, but testing should be done to confirm this hypothesis.

Additional tests should be done in newly constructed compost piles. The efficiency of probe recovery via screening may be affected by the increased cohesion between the compost and the probe case in fresh material with a high moisture content. It is possible that compost will stick to the cases making them difficult to visually recover during screening. Additionally, materials undergoing active composting will likely be more chemically and biologically active than materials in the curing stages, potentially putting a greater strain on the case material. Thus, the ability of anodized aluminum cases to stand up to these stresses should be determined.

A suitable method of introducing the temperature logging devices into compost, in a random fashion, must also be developed. One potential method would be to introduce the probes into a mixing truck along with the compost feedstock materials. The probes would then be mixed in prior to pile formation and presumably would end up in random locations in the pile (all probes could be introduced into a single mixer load or could be distributed between several loads). A mixer would potentially be a high-impact situation for the temperature probes, but presumably if they are able to withstand windrow turning they should be able to survive mixing as well.

A second potential system for adding probes to a compost heap avoids placing them directly in the mixer; this will avoid encountering a potentially unnecessary high impact situation. This method would involve placing the probes on the mixer conveyor belt during mixer discharge based on time. It should be determined whether all probes will be introduced with a single mixer load, or divided between several loads. The time required to empty a mixer should be determined and divided into small increments. Each temperature logger can then randomly be assigned a mixer load and a time increment during unloading of the mixer contents. The probe can then be placed on the conveyor belt at the appropriate time.

A third method, for operations that use loaders to mix materials rather than mixers, would be to determine the number of loader buckets required to build the pile

section of interest and then to randomly assign each temperature probe to a bucket load of feedstock material.

It is possible, due to the cylindrical shape of the probes, that there could be a problem with probes rolling off the piles during construction. Attaching some sort of tail may help prevent rolling. One option is to join two devices together with a length of rugged, non-biodegradable cable (such as fishing line). A second option would be to attach a counterweight with a piece of cable.

4.6. Suggestions for Future Research

Once the probe design is finalized and reliable methods developed to randomly introduce the probes into and recover them from compost piles, they can be used to gain further insights into the sanitation potential of different types of compost systems.

One expected research use for the probes is to determine how well current methods actually work to guarantee that the required time-temperature conditions are met. This could be accomplished by comparing temperature data from each device (as compared to average temperatures) with data obtained using conventional temperature monitoring methods. Temperature data obtained from the data loggers will be representative of the conditions seen by random particles of compost. In order for time-temperature requirements to be met, all probes must give evidence that 55°C was maintained for 3 days or more. This is because all particles of compost must see these conditions in order for effective sanitation to have taken place (USEPA 1999). If standard monitoring methods show that the compost has met the required time-temperature conditions and the data from all probes consistently indicates the same, then current methods are probably sufficient to achieve the desired pathogen reduction goals. However, if even one of the probes shows that 55°C has not been met for 3 consecutive days when conventional monitoring shows that time-temperature requirements have been met, then there may be problems with the regulations that

need to be examined. Possibilities include insufficient guidance in the guidelines and regulations as to temperature monitoring location and frequency.

A second use for the probes would be to evaluate the time-temperature criteria themselves. This could be accomplished by comparing temperature probe data with random samples of finished compost tested for a variety of pathogens. One potential method for obtaining random samples of compost for pathogen testing would be to attach bags of compost to the temperature probes with short pieces of cable. Pathogen destruction could then be correlated to the temperature data from the probes. If all probes show that 55°C or more has been attained for at least 3 days and pathogens are consistently non-detectable in random samples, then the temperature-time criteria in guidelines and regulations are likely adequate. If all probes show the time-temperature requirements have been met but pathogens are detected in random samples, then these criteria should be re-evaluated. A comparison between pathogen destruction by temperature effects and by other effects, such as antagonistic relationships between organisms, could also be made by attaching both permeable and impermeable bags.

Both of the above research questions require that a statistically significant number of temperature probes be used in the investigations. It is hypothesized that if a statistically sufficient number of the new temperature logging devices are incorporated into a single pile, data representative of time-temperature conditions seen by typical random compost particles should be obtained. It should be noted that in order to determine an appropriate number of devices to use, information about the temperature variability in a compost heap is necessary (Barcelona 1988; Holcombe 1988; Keith 1991). Preliminary testing may be required to estimate this variability. The point in time with the largest temperature variations should be considered; this is probably when the core of the pile is at its peak temperature. The efficiency of probe recovery (i.e. the percentage of the introduced probes that are reasonably expected to be recovered) and the degree of vertical probe dispersion should also be taken into account when determining the number of probes necessary to obtain data representative of typical compost particles. The degree of probe dispersion is

important because it will affect the number of probes required to ensure that data is collected over the entire vertical profile of the pile. Holcombe (1988) and Keith et al. (1996) provide equations for determining an applicable sample size.

4.7. Conclusion

A literature review revealed that enteric pathogens of all types (i.e. bacteria, viruses, protozoa, and helminths) sometimes survive thermophilic composting even when the criteria set out for pathogen reduction have apparently been achieved. It was determined that research should be done into the reasons for this pathogen survival; potential reasons include inadequate temperature monitoring methods and/or insufficient time-temperature criteria. Since pathogen reduction criteria, based on time and temperature conditions, apply to every particle of material processed (USEPA 1999), a new method capable of monitoring temperatures representative of random compost particles was desired for use in future studies. These devices must be able to survive the harsh conditions encountered during composting, as well as be able to mimic the behaviour of a random compost particle during settling and pile agitation.

A temperature logging device was developed and a number of parameters tested at a composting facility. A commercial temperature logger was purchased for the sake of comparison and was also put through a series of tests. It was seen that, with some improvements, either device would probably perform as desired. The main improvement necessary for both devices is a better setup for battery mounting, as high-impact situations tended to cause power loss. However, after preliminary testing the commercial temperature logger appeared to have several advantages over the DS2422-based device, including a superior case design, larger data memory, and, most importantly, the ability to retain collected data in the event of battery failure.

Once their design is optimized, these temperature loggers can be used in future studies to gather temperature data representative of conditions seen by random

compost particles. This data can then be examined and compared with the pathogen reduction criteria in compost guidelines and regulations, as well as with data gathered using more common temperature measurement methods and pathogen survival data. The language in the guidelines and regulations, with regards to temperature monitoring specifics, could then be evaluated based on the results.

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Appendix A.

COMPOST TEMPERATURE LOGGER DESIGN SPECIFICATIONS

A temperature monitoring device capable of monitoring conditions seen by random compost particles was required. It was determined that this compost temperature logging device ("probe") should consist of a temperature monitoring circuit enclosed in a rugged, sealed case. The initial specifications for the device are presented in Table A-1.

Table A-2 presents a comparison between a commercial temperature logging device (with the best fit to the specifications – see Appendix B) and a specially-designed device (DS2422-based device) in terms of their fit to the device specifications presented in Table A-1. It was determined that the DS2422-based device better satisfied the original design specifications than did the commercial device.

However, after preliminary testing of the devices for ease of recovery, ruggedness of the case and circuitry, the effect of density on probe movement, temperature response time, and magnetic field effects, some of the device specifications were changed. The modified specifications are presented in Table A-3 and a comparison between the commercial and designed devices in terms of the new specifications is presented in Table A-4. The commercial device was preferable to the DS2422-based device based on the modified specifications.

Table A-1. Initial design specifications for compost temperature probe.

Parameter	Constraints	Reason for constraints
Power supply	Battery	Device must be self-contained so that it is able to move freely when compost is moved, turned, or settles.
Operational (battery) life	2 months or greater	Device operational lifetime must encompass at least an entire thermophilic phase in order to capture a full temperature rise and fall cycle.
Temperature measurement frequency	On the order of minutes to hours.	The measurement frequency should be on the order of several hours or less in order to capture as much temporal temperature change as possible.
Data acquisition	Enough memory to record temperature and time data for at least 2 months.	There should be enough memory to record temperatures for at least the thermophilic phase of composting. Real-time data is not required because the devices are being developed to gain a better understanding of conditions that compost particles encounter; they are not meant to replace traditional temperature monitoring methods.
Operational temperature range	-40 to 100°C	The low temperature extreme of -40°C is based on the lowest temperature the probe would be likely to encounter if it rolled out of a pile during the winter. At the other extreme, the device must withstand the maximum temperatures within the pile core during the high-temperature phase of composting. Data from the biosolids composting operation at the EWMCE, where testing of the devices will be done, revealed peak temperatures of 96°C, though temperatures above the mid 80s (°C) are relatively rare (Yee 2005b). Ideally the device should function up to a temperature of 100°C.
Size	Larger than 19 mm in two dimensions and smaller than 80 mm in all dimensions	Probes should be larger than 19 mm (¾ in.) so that they can be captured on a screen of that size. In order to prevent the probes from becoming unwieldy, an upper limit of 80 mm was imposed. This limit was based on the size of the screen at the front end of the EWMCE's co-composter (Yee 2005a) and thus represents the largest particle size likely to be encountered.
Shape	Angular shape.	An angular shape would increase the friction angle and prevent rolling.
Probe recovery	Close to 100% of devices should be recovered.	Since data is stored, devices must be recovered in order to obtain the recorded temperature data.

Table A-1 (con't). Initial design specifications for compost temperature probe.

Parameter	Constraints	Reason for constraints
Density	500 to 900 kg/m^3	The density of the probe should be such that it does not preferentially move up or down in the pile relative to the compost material as a result of agitation or settling. The probe will probably be large relative to the majority of compost particles or lumps, so if its density roughly corresponds to that of the compost wet bulk density it is assumed that probe movement should be random. According to Agnew and Leonard (2003), the wet bulk density of compost mixtures generally ranges from approximately 500 to 900 kg/m^3.
Strength	Must survive physical, chemical, and biological conditions encountered when composting.	Physical conditions likely to be encountered include impacts sustained during windrow turning (often done using a windrow turner with a rapidly turning drum/auger) and pile building (which could involve material being dropped onto a hard surface from a height of up to 4.6 m (Scott 2005)). Both the case and the electronic circuitry must survive these impacts. Chemical compounds produced during composting include ammonia and weak organic acids (Haug 1993; Pichtel 2005). The case material must be unaffected by such compounds. Also, since composting is an active microbiological process, the case material must be non-biodegradable. Moisture may affect the temperature logging circuitry, so the device design must also provide a moisture seal for the electronics.
Temperature accuracy	±1.0°C or better over the range from 45 to 60°C.	Brannen *et al.* (1975) found that *Ascaris* ova inactivation varied from negligible at 47°C to extreme (99.8% destruction in 6 minutes) at 55°C. Therefore, the accuracy of temperature measurements should be much better than ±4°C (half of the 8°C change in the Brannen *et al.* experiment, since a reading of 51°C with an accuracy of ±4°C could be on either extreme of the *Ascaris* destruction test). An accuracy of ±1°C should be sufficient and easily achievable.
Temperature response time	3 hours or better	Pile turning frequency was considered when specifying response times, since the most rapid change in temperature that a temperature probe (or compost particle) would experience would probably occur during turning of the material. The compost would not be turned more often than once per day (Yee 2006), so a response time of three hours or less should be sufficient to capture any major temperature changes.
Cost	Less than $100 (CDN)	Because a large number of these devices are to be used at once, it is important to keep costs low.

Table A-2. Comparison between devices in terms of ability to meet initial design specifications. (1 = meets constraint; 0 = does not meet constraint; ½ = probably meets constraint or could be adjusted to meet constraint; ? = ability of device to meet constraint is unclear). Constraints are weighted on a scale of 1 (least important) to 5 (most important).

Parameter	Constraints	Weight	Constraints Met?		Preferred Device
			DS2422-based Device	Commercial Device	
Power supply	Battery	2	1	1	Either
Operational (battery) life	2 months or greater	2	1	1	Either
Temperature measurement frequency	User adjustable, on the order of minutes to hours.	1	1	1	Either
Data acquisition	Enough memory to record temperature and time data for at least 2 months.	2	1	1	Commercial (more memory)
Operational temperature range	-40 to 100°C	4	0	0	Neither
Size	Larger than 19 mm in two dimensions and smaller than 80 mm in all dimensions	2	½	0	DS2422 (size can be adjusted)
Shape	Angular shape.	2	0	0	Neither
Density	500 to 900 kg/m^3	5	½	0	DS2422 (density can be adjusted)
Strength	Must survive physical, chemical, and biological conditions encountered when composting.	5	?	?	Undetermined (testing required)
Temperature accuracy	±1.0°C or better over the range from 45 to 60°C.	3	½	½	Either (can be calibrated to increase accuracy)
Temperature response time	3 hours or better	3	?	?	Undetermined (testing required)
Probe recovery	Close to 100% of devices should be recovered.	4	?	?	Undetermined (testing required)
Cost	Less than $100 (CDN)	2	½	0	DS2422 (*probably* cheaper)
OVERALL			**13**	**8.5**	**DS2422**

Table A-3. Final design specifications for compost temperature probe.

Parameter	Constraints	Reason for constraints
Power supply	Battery	Device must be self-contained so that it is able to move freely when compost is moved, turned, or settles.
Operational (battery) life	2 months or greater	Device operational lifetime must encompass at least an entire thermophilic phase in order to capture a full temperature rise and fall cycle.
Temperature measurement frequency	User adjustable, on the order of minutes to hours.	The measurement frequency should be on the order of several hours or less in order to capture as much temporal temperature change as possible.
Data acquisition	Enough memory to record temperature and time data for at least 2 months.	There should be enough memory to record temperatures for at least the thermophilic phase of composting. Real-time data is not required because the devices are being developed to gain a better understanding of conditions that compost particles encounter; they are not meant to replace traditional temperature monitoring methods.
†Data memory	Non-volatile memory.	Since data is stored in memory and is not accessible until the devices are recovered, it is important that collected data be retained in the event that the device stops functioning (for example, because of power loss).
†Operational temperature range	-40 to 85°C	The low temperature extreme of -40°C is based on the lowest temperature the probe would be likely to encounter if it rolled out of a pile during the winter. At the other extreme, the device must withstand the maximum temperatures within the pile core during the high-temperature phase of composting. Data from the biosolids composting operation at the EWMCE, where testing of the devices will be done, revealed peak temperatures of 96°C, though temperatures above the mid 80s (°C) are relatively rare (Yee 2005b). Data from the biosolids composting operation at the EWMCE, where testing of the devices will be done, revealed peak temperatures of 96°C, though temperatures above the mid 80s (°C) are relatively rare (Yee 2005b). Ideally the device should function up to a temperature of 100°C, but testing revealed that all components used in the tested devices (even those rated to 85°C) could withstand temperatures near 100°C.
†Size	Larger than 19 mm in all dimensions, but not prohibitively large.	Probes should be larger than 19 mm (¾ in.) so that they can be captured on a screen of that size. Probe size may be adjusted in order to adjust probe density. However, the probes should not become excessively large (less than 80mm in all dimensions would be ideal).
†Shape	Compromise between an angular shape and a spherical shape.	A spherical shape would increase the strength of the case, but the device could potentially roll down the pile sides easily. An angular shape would increase the friction angle and prevent rolling.

Table A-3 (con't). Final design specifications for compost temperature probe.

Parameter	Constraints	Reason for constraints
†Density	Less than 2000 kg/m³	The density of the probe should be such that it does not preferentially move up or down in the pile as a result of agitation or settling. Preliminary testing revealed that, for cylindrical probes of 2 in. (50.8 mm) diameter and 90 mm length, there was no significant difference in probe movement between probes of densities ranging from 800 to 2000 kg/m³. Probe movement appeared to be random for all tested densities.
Strength	Must survive physical, chemical, and biological conditions encountered when composting.	Physical conditions likely to be encountered include impacts sustained during windrow turning (often done using a windrow turner with a rapidly turning drum/auger) and pile building (which could involve material being dropped onto a hard surface from a height of up to 4.6 m (Scott 2005)). Both the case and the electronic circuitry must survive these impacts. Chemical compounds produced during composting include ammonia and weak organic acids (Haug 1993; Pichtel 2005). The case material must be unaffected by such compounds. Also, since composting is an active microbiological process, the case material must be non-biodegradable. Moisture may affect the temperature logging circuitry, so the device design must also provide a moisture seal for the electronics.
Temperature accuracy	±1.0°C or better over the range from 45 to 60°C.	Brannen et al (1975) found that *Ascaris* ova inactivation varied from negligible at 47°C to extreme (99.8% destruction in 6 minutes) at 55°C. Therefore, the accuracy of temperature measurements should be much better than ±4°C (half of the 8°C change in the Brannen *et al.* experiment, since a reading of 51°C with an accuracy of ±4°C could be on either extreme of the *Ascaris* destruction test). An accuracy of ±1°C should be sufficient and easily achievable.
Temperature response time	3 hours or better	Pile turning frequency was considered when specifying response times, since the most rapid change in temperature that a temperature probe (or compost particle) would experience would probably occur during turning of the material. The compost would not be turned more often than once per day (Yee 2006), so a response time of three hours or less should be sufficient to capture any major temperature changes.
Probe recovery	Close to 100% of devices should be recovered.	Since data is stored, devices must be recovered in order to obtain the recorded temperature data.
†Cost	As low as possible, while still meeting all other constraints.	Because a large number of these devices are to be used at once, it is important to keep costs low.

†Criteria changed from initial design parameters, based on test results.

Table A-4. Final design specifications – comparison between tested devices. (1 = meets constraint; 0 = does not meet constraint; ½ or ¾ = partially meets constraint or could be adjusted to meet constraint). Constraints are weighted on a scale of 1 (least important) to 5 (most important).

Parameter	Constraints	Weight	Constraints Met?		Preferred Device
			DS2422-based Device	Commercial Device	
Power supply	Battery	2	1	1	Either
Operational (battery) life	2 months or greater	2	1	1	Either
Temperature measurement frequency	User adjustable, on the order of minutes to hours.	1	1	1	Either
Data acquisition	Enough memory to record temperature and time data for at least 2 months.	2	1	1	Commercial (more memory)
†Data memory	Non-volatile memory.	4	0	1	Commercial
†Operational temperature range	-40 to 85°C	4	1	1	Either
†Size	Larger than 19 mm in all dimensions, but not prohibitively large.	2	1	1	Either
†Shape	Compromise between an angular shape and a spherical shape.	2	½	½	Either
†Density	Less than 2000 kg/m³	5	1	1	Either
Strength	Must survive physical, chemical, and biological conditions encountered when composting.	5	½	¾	Commercial (better case deign)
Temperature accuracy	±1.0°C or better over the range from 45 to 60°C.	3	½	½	Either
Temperature response time	3 hours or better	3	1	1	Either
Probe recovery	Close to 100% of devices should be recovered.	4	½	½	Either
†Cost	As low as possible, while still meeting all other constraints.	2	1	¾	DS2422 is *probably* cheaper
OVERALL			**30**	**34.75**	**Commercial**

†Criteria changed from initial design parameters, based on test results.

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Appendix B

COMMERCIALLY AVAILABLE TEMPERATURE LOGGING DEVICES

Table B-1. Comparison of commercially available self-contained temperature data loggers (as of April 12, 2006).

Manufacturer	Part No.	Temp. Range and Accuracy	Case Material	Memory capacity	Battery	Shape and Size	Mass, M (g) and Density, ρ (kg/m³)	Comments	Price (not including software)
Madge Tech	Temp 1000	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	Aluminum	32767 readings	3.6V lithium. Typical life 1 year @ 25°C, 1 min intervals. User replaceable.	Cylinder: Ø26 mm x 110 mm length	M = 110 ρ = 1883	Waterproof temperature logger. Digital calibration through software. Data is date and time stamped.	Thermo-kinetics (CDN) $264
	Temp 1000SS	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	Stainless Steel	32767 readings	3.6V lithium. Typical life 1 year @ 25°C, 1 min intervals. User replaceable.	Cylinder: Ø26 mm x 110 mm length	M = 230 ρ = 3938	Waterproof temperature logger. Digital calibration through software. Data is date and time stamped.	Thermo-kinetics (CDN) $329
	Temp 100	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	ABS Plastic	32767 readings	3.6V lithium. Typical life 1 year. User replaceable.	Box: 35 x 56 x 16 mm	M = 23 ρ = 733	Pushbutton start/stop temp. recorder. Digital calibration through software. Data is stored even if battery becomes discharged.	Thermo-kinetics (CDN) $147
	Temp 101	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	ABS Plastic	32767 readings	3.6V lithium. Typical life 1 year. User replaceable.	Box: 35 x 56 x 16 mm	M = 22 ρ = 701	Miniature temperature recorder. Digital calibration through software. Data is stored even if battery becomes discharged.	Thermo-kinetics (CDN) ~$110
	Temp 110	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	ABS Plastic	32767 readings	3.6V lithium. Typical life 10 years @ 25°C, 15 min intervals. User replaceable.	Box: 20 x 42 x 58 mm	M = 30 ρ = 616	Miniature temp recorder w/ 10 yr battery life. Digital calibration through software. Data is stored even if battery becomes discharged.	Thermo-kinetics (CDN) $264
	PR Temp 1000	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	Stainless Steel	21845 temp. readings	3.6V lithium. Typical life 1 year @ 25°C. User replaceable	Cylinder: Ø32 mm x 163 mm length	M = 340 ρ = 2594	Rugged, submersible temperature and pressure recorder.	Thermo-kinetics (CDN) $849

Table B-1 (con't). Comparison of commercially available self-contained temperature data loggers (as of April 12, 2006).

Manufacturer	Part No.	Temp. Range and Accuracy	Case Material	Memory capacity	Battery	Shape and Size	Mass, M (g) and Density, ρ (kg/m³)	Comments	Price (not including software)
Madge Tech	RH Temp 1000	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	Stainless Steel	21845 temp. readings	3.6V lithium. Typical life 1 year @ 25°C. User replaceable	Cylinder: ∅26mm x 138mm length	M = 285 ρ = 3890	Rugged, submersible temperature and humidity recorder.	Thermo-kinetics (CDN) $524
	PRH Temp 110	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	ABS Plastic	13107 temp. readings	3.6V lithium. Typical life 1 year @ 25°C. User replaceable	Box: 41 x 59 x 22 mm	M = 60 ρ = 1127	Miniature temperature, pressure, and humidity recorder.	Thermo-kinetics (CDN) $524
	Micro Temp	-40 to 80°C; ±0.5°C typ. over 0 to 50°C	Stainless Steel	32767 temp. readings	3.0V lithium. Typical life 1 year @ 25°C, 1 min intervals. User replaceable	Cylinder: ∅18mm x 66 mm length	M = 50 ρ = 2977	Miniature submersible temperature recorder	Thermo-kinetics (CDN) $229 @ 1 ($206.10 @ 30)
Onset Computer	HOBO U12-015	-40 to 125°C; ±0.5°C typ. over -20 to 80°C	Stainless Steel	43000 readings	3 yr. typ., continuous op. with 60min./day at 125°C.	Cylinder: ∅17.5 mm x 106 mm length	M = 72 ρ = 2946	Battery is factory replaceable only. 2200 psi max pressure rating.	(USD) $249 $75 or $100 replacement battery
Log Tag	TRIX-8	-40 to 85°C; ±0.8°C max. over -40 to 80°C	Plastic	8000 readings	3.6V lithium. Typical life 1 year @ 25°C, 1 min intervals. User replaceable.	86 x 54.5 x 8.6 mm	M = 35 ρ = 868	Card type temperature recorder (same shape/size as credit card)	(USD) $33 10-pack $300 Starter kit $69
ACR	ACRSB	-10 to 85°C; ±1.5°C max. over 45 to 70°C	Stainless Steel and Plastic	2048 readings	3.0V lithium. Typical life 10 years.	Button: ∅17mm x 6 mm height	M = 4 ρ = 2937	Miniature-sized smart button data logger.	(USD) $39 Starter kit $65
	NTL-101	-40 to 85°C; ±0.2°C typ. over 0 to 70°C	Stainless Steel	up to 244800 readings	3.6 V lithium. Typical life 10 years.	Cylinder: ∅18mm x 127 mm length	M = 112 ρ = 3466	Nautilus 85 data logger. Single-channel, waterproof data logger. Robust, waterproof casing.	(USD) $299
Lascar	EL-USB-1	-35 to 80°C; ±1°C	Plastic	16382 readings	3.6 V lithium battery. Typical life 1 year.	Cylinder: ∅26mm x 98 mm length	unknown	Temperature logger with USB interface; USB interface cap not sealed or secured.	(USD) $59 incl. software.
Dickson	HT100	-40 to 125°C; ±1°C	Stainless Steel	7936 sample points	unknown	Cylinder: ∅18mm x 94 mm length	M = 72 ρ = 3195	Stainless steel temperature data logger with waterproof case.	(USD) $310

Appendix C

TEMPERATURE LOGGING CIRCUIT

The temperature logging circuit, shown in Figure C-1 (parts list in Table C-1), is based around the DS2422 Temperature Datalogger (U3), available from Maxim Integrated Products/Dallas Semiconductor. This device is a fully functioning datalogger on a chip, complete with 8 kilobytes (kB) of on-chip data memory (meaning that it can record up to 8192 temperature measurements), and a real-time clock. It records temperatures in the range -40 to 85°C, and testing showed that the device still functions normally after exposure to temperatures near 96°C. The device also has a high accuracy after calibration (up to ±0.75°C over its entire operating range). This chip provides the temperature sensing and recording capabilities to the temperature logging circuit, and comes with software to control the device and upload recorded data to a computer. An external 32.768 kHz crystal (X1) provides timing for the internal clock on the DS2422 so that the timing of temperature measurements is accurate. CON1 is a 2-pin connector used to connect the temperature probe to a computer for data upload.

Power is supplied to the circuit from two ½AA size 3.6V lithium batteries (Vmain and Vbackup). The small ½AA size was chosen to save board space and minimize probe mass. Lithium batteries were chosen because they are available with suitable maximum operating temperatures, whereas other chemistries do not. As mentioned in Appendix A, all circuit components must be capable of operating up to temperatures of at least 85°C. However, since temperatures greater than 85°C are sometimes seen during the thermophilic phase of composting (Yee 2005), testing was done to determine what effect temperatures near 100°C would have on a battery rated to 85°C. It was found that the batteries sustained no damage and were still operational when tested at temperatures up to 104.1°C (± 1.7°C). Thus, it was determined that a long-life lithium battery rated to 85°C would be adequate for use in the temperature probe being designed. The batteries are soldered into the circuit board to provide anchoring, and thus must have solder pins. The authors recommend using part number TL-5902/P from Tadiran Batteries Ltd.

A power switch (SW) is included to turn the device off and on. A backup battery supervisor (Texas Instruments TPS3619-33, U1) is required to switch the power supply to the circuit from the main battery to the backup battery when the main battery fails. This component was incorporated into the design to minimize the chances that power to the device would be lost. It was necessary because data memory on the DS2422 is volatile (in other words, data is lost during power failures).

An ESD (electrostatic discharge) protection diode (Maxim/Dallas DS9503P, U2) is used between the device power supply and the power supply pin on the DS2422. This chip prevents damage to the DS2422 in case of a power supply spike.

Two LEDs (LED1 and LED2) are included in the circuit to indicate whether the device is operating from the main or backup battery. If the LED1 is lit, the device is operating from the backup supply and the main battery should be replaced. If LED2 is lit, the device is operating from the main battery. If both LEDs are off, this indicates that either the power switch is turned off or there is a broken connection somewhere between the batteries and the backup battery supervisor (U1).

All components of the temperature logging circuit have a specified operating temperature range of at least -40 to 85°C.

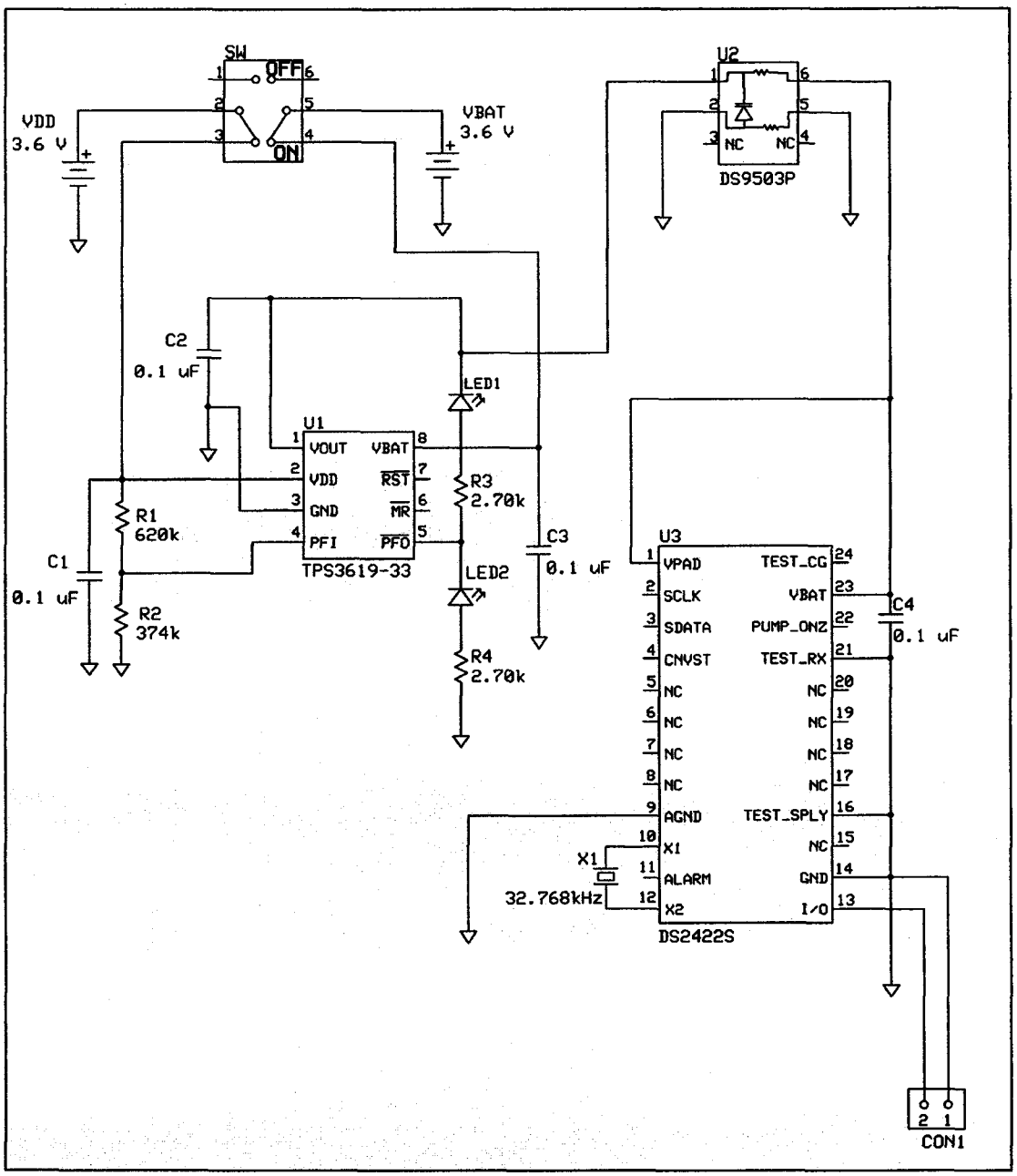

Figure C-1. DS2422-based temperature logger circuit diagram.

Table C-1. DS2422-based temperature logger circuit components.

Part ID	Manufacturer and Part Number	Part Description	Distributor	Price Break	Price (USD)	Price (CDN)*
C1, C2, C3, C4	Panasonic ECJ-2VB1E104K	0.1µF ceramic surface mount capacitor, 25V X7R, 0805	Digikey (PCC1828CT)	10	N/A†	0^{08}
				100		**0^{06}**
CON1	Hirose DF3DZ-2P-2V(20)	2 position connector header, SM, no boss, tin, 2mm pitch, vertical, DF3 series	Digikey (HR2072)	1	N/A	0^{89}
				25		**0^{73}**
				100		0^{53}
LED1, LED2	OSRAM LO T67K-L1M-24-Z	Orange LED, 28mcd @ 2mA, 120°, SM	Digikey (475-1178-1)	1	N/A	0^{21}
				25		**0^{18}**
R1	Rohm MCR18EZHF620K	620 kΩ resistor, SM, 1%, 1206 size	Digikey (RHM620KFCT)	10	N/A	0^{10}
				50		**0^{06}**
R2	Rohm MCR18EZHF374K	374 kΩ resistor, SM, 1%, 1206 size	Digikey (RHM374KFCT)	10	N/A	0^{10}
				50		**0^{06}**
R3	Rohm MCR18EZHF2.70K	2.70 kΩ resistor, SM, 1%, 1206 size	Digikey (RHM2.70KFCT)	10	N/A	0^{10}
				50		**0^{06}**
SW	Copal Electronics CAS-220TB	SM slide switch, gullwing, vertical, DPDT, -40 to 85°C	Digikey (CAS220GCT)	**10**	N/A	**4^{57}**
				100		3^{30}
U1	Texas Instruments TPS3619-33	Backup battery supervisor; when main power supply fails, switches to backup battery.	Digikey (296-12141-5)	1	N/A	3^{00}
				25		**2^{40}**
				100		1^{86}
U2	Maxim / Dallas DS9503P	ESD protection diode with resistors.	Digikey (DS9503P+)	1	N/A	1^{34}
				25		**1^{02}**
				50		0^{73}
U3	Maxim / Dallas DS2422S	Temperature / datalogger with 8kB datalog memory.	Maxim	1-24	$48^{00}	$52^{77}
				25-99	$40^{75}	**$44^{80}**
			Avnet	31	$48^{90}	$53^{76}
Vbackup, Vmain	Tadiran TL-5902/T	1/2AA with tabs, -55 to 85°C lithium battery (3.6V), main supply, 1200 mAh	Digikey (439-1006)	1	N/A	$7^{25}
				10		$6^{71}
				50		**$6^{35}**
X1	Citizen CM200S32.768KDZB-UT	32.768kHz crystal, operates -40 to 85°C, storage -55 to 125°C, 6pF load capacitance, SM	Digikey (300-8317-1)	1	N/A	1^{06}
				10		**0^{91}**
				50		0^{68}

*Where applicable, prices converted to CDN on June 2/06 and June 7/06.
†N/A = not applicable

In addition to the above parts, a connector is also needed to interface the temperature probe to a computer for set-up and for downloading data. Only one cable is necessary for use with all of the probes. The parts required for this cable are listed in Table C-2, and include a USB to 1-wire converter, available from Maxim Integrated Products/Dallas Semiconductor, used to convert the data to a form recognized by the control software (also available from Maxim/Dallas). A connection diagram is shown in Figure C-2.

Table C-2. Components required for cable between DS2422 temperature logging circuit and computer.

Part ID	Manufacturer and Part Number	Part Description	Distributor	Price Break	Price (USD)	Price each (CDN)**
CON2	DF3-2S-2C	2 position crimp socket, 2mm pitch, DF3 series	Digikey (H2083)	1	N/A†	0^{28}
WIRE	H2BXT-10110-B4	Socket single end interconnect wire for Hirose DF3 connectors	Digikey (H2BXT-10110-B4)	10 (minimum order)	N/A	0^{72}
USB / 1-WIRE	DS9490R	USB to 1-wire converter	Maxim (DS9490R)	1	28^{04}	31^{36}
CABLE	N/A	RJ11 cable (cut in half)	Active Electronics	1	N/A	3^{99}
					Total cost for one cable = $42.83	

**Where applicable, prices converted to CDN on June 22/06.
†N/A = not applicable.

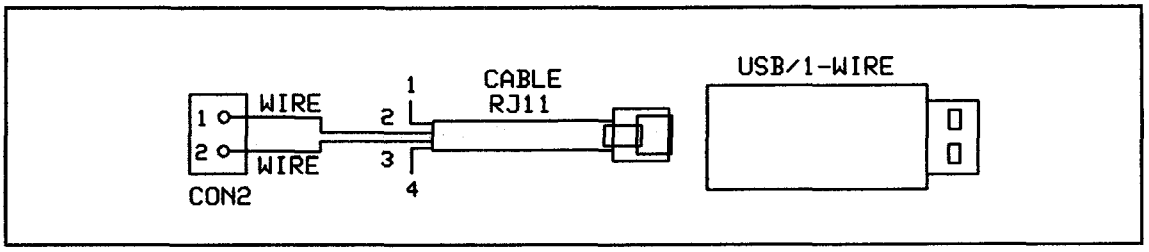

Figure C-2. Cable used to connect between temperature logging circuit and computer.

References

Yee, A. 2005. Personal communication. Edmonton Waste Management Centre of Excellence (EWMCE). Edmonton, AB

Appendix D

OPTIONS CONSIDERED FOR RECOVERY OF PROBES FROM COMPOST

Several potential methods exist for locating and recovering the temperature logging devices from a compost pile after testing is complete. A summary and evaluation of methods considered is presented in Table D-1.

Table D-1. Comparison of potential temperature probe recovery options.

Recovery Option	Description	Pros	Cons
Radio Frequency Detection	A radio frequency transmitter could be added to the probe's electronics and a receiver used to detect the strength of the signal and hence pinpoint the location of the probe.	• should be relatively easy to narrow in on the location of a probe within a compost pile • may allow for future modifications of the device with the ability to transmit data via a wireless connection in real-time.	• would require additional battery power (a review of several RF transmitting chips revealed that transmitters typically require 0.5 to 54 mA while operating, which at the very least doubles the current requirement) • complicates electronics design, which would necessitate extra design time. • requires the labour-intensive and time-consuming task of digging through compost to recover multiple probes
Metal Detector	If the probe case was made of metal, it may be possible to detect the probe location within the pile using a metal detector.	• metal detection is a fairly simple solution • requires no additional materials or design time for the probe • some metal detectors can estimate the depth of an object	• requires the purchase of a metal detector (which can be quite expensive for high-end types) • would require locating probes in the pile (since other metals such as on a conveyor belt or heavy equipment would interfere with detection), and hence would require digging • most metal detectors can only locate objects within a few feet of a surface, which may be a problem in a large compost pile. Even a high-end type such as the Geonics EM61 has an absolute maximum depth of ~5 ft (1.5m) (Catalano 2006). • requires the labour-intensive and time-consuming task of digging through compost to recover multiple probes

Table D-1 (con't). Comparison of potential temperature probe recovery options.

Recovery Option	Description	Pros	Cons
Eddy Current Separation	Eddy current / electrostatic separation could potentially be used to separate non-ferrous metals, such as aluminum, out of the compost.	• method would both locate *and* remove probes with minimal physical labour • does not require any additional parts to be added to the probes, provided they are manufactured from a suitable metal • does not require digging through a compost heap to locate probes	• adds an extra step to the process • may be difficult to arrange the movement of large volumes of compost to separation equipment • not all composting operations may have access to the required equipment
Radioactivity Detection	If a piece of radioactive material is included inside the temperature probe, it should be possible to pinpoint the probe's location using a radiation detector. This radioactive material should be gamma ray emitting, such as ^{60}Co or ^{137}Cs because gamma rays travel further through most materials better than beta or alpha radiation.	• should not interfere with the operation of the temperature logger • should make it relatively easy to narrow in on the location of a probe within a compost pile • could screen for probes while compost is on a conveyor (conveyor materials would not interfere with detection), which would make them easier to recover than having to dig for them	• requires the addition of extra materials to the probes • require permitting to use radioactive material • all facility staff dealing directly with compost would have to be trained in radiation safety • if the probe case were to break open, radioactive material could be leaked into the compost or the environment • inadvertent contact with the radioactive source could potentially be harmful • requires extra safety precautions • according to the Radiation Safety Officer at the University of Alberta, a backup method of probe recovery would be required if radioisotopes were used, as it is not allowable to have radioactive material, no matter how small the amount, unaccounted for (Schumaker 2006). • requires the labour-intensive and time-consuming task of digging through compost to recover multiple probes

Table D-1 (con't). Comparison of potential temperature probe recovery options.

Recovery Option	Description	Pros	Cons
Capture on a Screen (With or Without a "Tail" Attached to the Probe)	If the probes are larger than the screen used to separate oversized particles out of a finished compost product (typically smaller than 1 in. (25.4 mm)), then the probes would be captured in the overs of that screen. An operator would then simply have to watch the overs for probes and remove them manually. Adding a "tail" (i.e. a flag attached by a piece of chain, wire, or rope) may make the probes easier to spot.	• simple and straightforward method • does not require an extra operation, as most facilities screen finished compost as standard operating procedure • does not require an operator to "locate and dig" for probes (i.e. minimal physical labour involved) • does not require additional parts to be added to the probes • addition of a "tail" may make it easier for the probes to be seen • "tail" may prevent probes from rolling down the sides of a compost pile during turning events • does not require digging through a compost heap to locate probes	• need to have a person available to watch the screen overs for as long as it takes to screen a pile • if compost sticks to the temperature probes, they may be difficult to detect visually • "tail" may cause probes to become tangled • "tail may get tangled in mixing, turning, or screening equipment
Magnetic Separation	It would likely be possible, if the probes were manufactured from a ferrous (magnetic) material, to locate and remove the probes from compost if the compost was passed under magnetic separation equipment	• method would both locate *and* remove probes, with minimal physical labour • does not require any additional parts to be added to the probes, provided they are manufactured from magnetic material • does not require digging through a compost heap to locate probes	• adds an extra step to the process • may be difficult to arrange the movement of large volumes of compost to magnetic separation equipment • not all composting operations may have access to magnetic separation equipment • requires the case to be made from a ferrous material, which may be prohibitively heavy • the effect of a magnetic field on data memory is unknown (TI Support 2005). This should be tested.

References

Catalano, M. 2006. Personal communication. Geonics Limited. Mississauga, ON

Schumaker, C. 2006. Personal communication. Radiation Safety Officer; Office of Environmental Health and Safety; University of Alberta. Edmonton, AB

TI Support. 2005. Personal communication. Texas Instruments Semiconductor Technical Support.

Appendix E

EXPERIMENTAL PROCEDURES

E.1. Case Strength

E.1.1. Background and Motivation

The conceptual design for the temperature sensor housing specified that the housing walls should be manufactured from 16 gauge aluminum tubing. There was some concern that this gauge may not be thick enough to withstand some of the impacts that may potentially be received during a composting cycle. Thus, two thicker gauges of aluminum were also considered, and the purpose of this test was to determine the response of different gauges of aluminum to various impacts that may be encountered during composting. These impacts included being dropped from a loader bucket onto a hard surface, being driven over by a piece of heavy machinery, and being impacted by a windrow turner blade.

It was deemed unnecessary to have end caps manufactured for this series of tests (to save time and money). While a lack of end caps may lead to more severe damage to the aluminum tube ends in high impact situations than would otherwise be expected, it should be noted that the purpose of this test was simply to determine what, if any, difference there is between different gauges of aluminum in response to specified impacts that may be encountered. Thus, the degree of damage to one gauge of aluminum as compared to the others was of greatest importance. In any case, it should be valid to ignore any damage to the ends of the tube and to just note the damage that occurs to the middle section.

The grade of aluminum chosen for testing (6061) is rated as having "good" resistance to corrosion (McMaster-Carr 2006), but should be tested in a composting environment. Observations should therefore also be made of the extent of damage to the probe cases due to chemical and microbiological factors. Ideally, the aluminum cases should be left in compost for an extended period of time, since the degree of corrosion will be affected by the length of exposure.

E.1.2. Procedures

For all tests it is assumed that the dimensions of the probe will not have a significant effect on probe robustness as compared to the gauge of the material; thus, a single aluminum tube diameter and length should be chosen. Aluminum tubing (unanodized 6061 gauge aluminum) with a diameter of 2.00 in. (50.8mm) and length of 90 mm may be appropriate. Several probe gauges (for example, 11, 14, and 16) should be tested. A commercial device, with a case made from anodized 6061 gauge aluminum, can also be tested. The test procedures are as follows:

A. Drop test.
    1. Place several probe cases (an equal number of each gauge to be tested) in an empty front-end loader bucket.
    2. Raise the bucket to its maximum height and drop cases onto composting pad.
    3. Recover all probe cases.
    4. Note the damage to each case.

B. Windrow turner test. (This test can be performed at the same time as the probe density tests.)
    1. Place several probe cases (with ID numbers) of each gauge to be tested (preferably equal numbers of each gauge) in a small section of a windrow.
    2. Pass over cases with a windrow turner.
    3. Recover all cases; this can be accomplished by digging with a hand shovel through the section of the pile where the probes were initially placed, or by skimming off a 10-20 cm layer of material with a front-end loader and passing this material through a screen.
    4. Note the damage to each probe case.

C. Heavy machinery test.

1. Place one probe case of each gauge on the composting pad.
2. Drive over cases with a front-end loader.
3. Recover cases.
4. Note the damage to each case.

D. Microbiological/chemical damage test. (This test may be performed coincident with another test – for example during the probe density test.)

1. Insert several sections of aluminum tubing (i.e. probe cases) into a compost pile.
2. Leave cases in compost for a predetermined amount of time (e.g. several days to several weeks)
3. Recover aluminum sections/cases.
4. Note damage to each case; damage to look for includes corrosion/pitting.

E.2. Probe Density

E.2.1. Background and Motivation

Because the ultimate goal of this project was to create a temperature probe which will record temperatures representative of those seen by a random particle of compost, it was important that the movement of the probes through the composting process be random. It was believed that if the density of a probe fell within a suitable range, then its movement would be random.

Compost bulk densities (wet) generally fall in the range of 500 to 900 kg/m^3. Since the temperature probe will likely be large compared to the particles in a compost pile, it was assumed that a probe density close to the compost wet bulk density would allow the probes to move randomly as desired. However, it was unknown just how much of a disparity between the compost and probe densities

would be possible before probe movement would be significantly affected. It was important to find out how high the probe density could be made without affecting the randomness of probe movement, as 1) it was found during the design stages that the probes had to be larger than initially desired in order to get their density within the range of 500 to 900 kg/m^3, 2) if aluminum turned out to be unsuitable as a case material, the next option being considered was stainless steel, which is much heavier than aluminum, and 3) the commercial temperature logger chosen for testing had a density near 1880 kg/m^3 (Madge Tech 2006) and it was of interest to determine if this logger could be used for the desired application.

This experiment involves mixing probes with a known density and known starting location into compost and determining how they are affected by mixing. Because this experiment is time-consuming and labour-intensive (because the location of the probes must be determined during recovery), and because of the potential for loss of probes, a large number of probes should be used during a single test. All probes should have the same dimensions in order to cancel the effect of probe shape/size. A potential output value is change in probe location (i.e. depth or height) in a compost pile, and ANOVA and t-tests can be used to analyze the results. This method assumes that the degree of randomness of probe movement is not significantly affected by mixing method.

Three potential probe densities are:

- **2000 kg/m^3**: This is the approximate density of the commercial temperature data logger (according to the spec sheet ~1880 kg/m^2), rounded up slightly. It is also a reasonable density for a probe case made of stainless steel.
- **800 kg/m^3**: This is the approximate density of a 63.5 mm (2.5 in.) diameter probe with a 90 mm case made from 14 gauge 6061 aluminum, which was arbitrarily imposed as a desired maximum probe size. Thus, this is theoretically the lowest density achievable without making the probes prohibitively large.
- **1400 kg/m^3**: This density falls halfway between the minimum and maximum densities to be tested.

E.2.2. Procedures

The test procedure is as follows:

1. Select the densities to be tested.
2. Provide ID numbers for each probe housing.
3. Adjust the probe densities to the desired values by placing dense material (i.e. wire, nuts and bolts, nails, etc) inside the cases (all cases should be the same size). Ensure that an equal number of probes are adjusted to each desired density.
4. Secure the ends of the probe cases so no material will be lost.
5. Place 1/3 of the probes of each density at the bottom of a windrow section about to be turned. Place 1/3 of the probes of each density directly above the bottom cases at the middle of the pile (vertically). Place the remaining 1/3 of the probes of each density on the top surface of the pile, again directly above the other cases. Record the starting locations of each probe.
6. Pass over the probes with a windrow turner.
7. Locate all probes in the pile. Since the positions of the probes in the pile is the output, it is important not to affect the final location of a probe significantly during recovery. One possible recovery method would be to dig through the pile manually. Another method would be to skim 10-20 cm deep layers of compost off the pile with a loader and remove the probes on a screen.
8. Note the final location of each recovered probe.
9. Collect a sample of the compost in which the probes were placed in order to estimate the (wet) bulk density of the material.
10. Use TMECC Method 03.03-A/03.01-A, steps 10.3 to 10.5 only, to determine the compost bulk density.
11. Analyze the change in height data of the probes of each density.

E.3. Robustness of Circuitry

E.3.1. Background and Motivation

Since the temperature probes log temperatures, and data are not recoverable until the probe is recovered, it is important that the temperature logging circuit function properly and retain data for the entire duration that the probe is in the compost. This means that the circuitry must be capable of withstanding the impacts potentially encountered during composting.

It was seen during tests of probe case strength (see section E.1.) that the most severe impacts occurred during windrow turning. Thus, it was desired that the effect of windrow turning on the electronic circuitry be examined.

After preliminary testing it was seen that the battery was the circuit component that was most likely to be affected by impacts received during windrow turning. Thus, further testing was done to determine the frequency of battery damage and to compare the survival of batteries with tabbed and solder pin contacts.

E.3.2. Procedures

The test procedures are as follows:

A. Operating circuits.

1. Start a temperature-logging mission on devices to be tested (including the commercial device and the DS2422-based device)
2. Enclose operating temperature logging circuits in their cases.
3. Place devices in a windrow.
4. Pass over devices with a windrow turner.
5. Recover devices.
6. Determine if devices are still operating normally.

B. Batteries.

1. Solder an equal number of batteries of the tabbed and solder pin varieties to separated circuit boards.
2. Enclose each circuit board inside an aluminum case.
3. Place the batteries/cases inside a windrow.
4. Pass over the cases with a windrow turner.
5. Recover all batteries/cases.
6. Examine batteries for damage.

E.4. Temperature Response Time

E.4.1. Background and Motivation

The response time of a temperature sensor is dependent on a number of factors, including the thermal conductivity of the sensor itself and of the materials (such as a case and air space) between the sensor and the temperature of interest. Because the sensor does not respond instantaneously to a change in the temperature of the surrounding material, it is important to determine the time it does take for the sensor to respond to a step change in "ambient" temperature. If the response time is too long, temperature fluctuations of interest may be missed.

The commercial temperature logger and the DS2422-based circuits are both enclosed in aluminum cases, and have some air space between the case wall and the temperature sensor. Because air is a good insulator, this air space may significantly slow down the response time of the temperature sensors to a change in environmental/ambient temperature.

At the Edmonton Waste Management Centre, the most frequent turning of compost material occurs in the co-composter aeration bay. This material is turned once per day at most. So, as long as the temperature response time is significantly shorter than 24 hours, these devices should be satisfactory as-is.

E.4.2. Procedures

A. Device Calibration

The devices should be calibrated in order to ensure an accurate temperature reading. This calibration will be done with the cases removed, so as to ensure that the sensor calibration is not affected by the lag in response caused by the air inside the case.

A two-point calibration should be done for each device. The low temperature will be room temperature (near -10°C), and the high temperature will be near 60°C. These two temperatures are specified in the calibration procedure for the DS2422, and can also be used for the Temp1000 calibration.

The procedure for device calibration is as follows:

1. Remove electronics of both the DS2422-based device and the commercial temperature logger from their respective cases.
2. Assemble a thermocouple temperature probe and a mercury thermometer.
3. Install the appropriate software for the DS2422 and commercial devices on a computer in the vicinity of an oven and a freezer (a laptop would be ideal).
4. Set the freezer temperature near -10°C.
5. Heat oven to a temperature near 60°C.
6. Connect DS2422 and commercial devices to the computer and run the appropriate software. Set up devices to monitor temperature.
7. While the devices are still connected to the computer, place them inside the -10°C freezer. Also place the thermocouple inside of the freezer. Close the freezer door as tight as is possible with the cables hanging out.
8. After 30 minutes, make a note of the freezer temperature (should be near -10°C) as measured by each of: a) the thermocouple probe, b) the

commercial, and c) the DS2422. Open the freezer door and, as quickly as possible, note the temperature of the mercury thermometer.

9. Leave devices connected to the computer, and place them in the 60°C oven. Also insert the thermocouple temperature probe and mercury thermometer into the oven.
10. After 30 minutes, make a note of the oven temperature as measured by each of: a) the thermocouple probe, b) the Temp1000, c) the DS2422, and d) the mercury thermometer.
11. Follow the instructions for the commercial device and the DS2422 (in Application Note 2810 – DS2422 Trim Procedure and Software Correction available from www.maxim-ic.com) to input the previously recorded values and calibrate the devices. For the "actual temperature" readings, use the temperature measured with the mercury thermometer, as it will likely be more accurate than that of the thermocouple.

B. Temperature Response Time

The temperature response of the device will be evaluated over a temperature change of approximately ±10°C, ±15°C, ±20°C, ±30°C, and ± 40°C. Smaller increments than 10°C will be difficult to evaluate because it is difficult to adjust the oven temperature below 30°C. All temperature ranges will be evaluated between room temperature (approximately 20°C) and some higher temperature (in the oven).

The procedure for determining temperature response times is as follows:

1. Set up each device (commercial device and DS2422) to record temperature once every 60 seconds, and start a temperature logging mission.
2. Place each device in its case.
3. Heat oven to 30°C (±5°C).

4. Leave devices at room temperature for at least 120 minutes, in order to give them sufficient time to attain a stable temperature.
5. Place devices in the 30°C oven. Open and close the oven door as quickly as possible to prevent excessive heat loss. Leave devices at 30°C for at least 120 minutes, in order to give them sufficient time to reach a stable temperature.
6. Remove devices from the oven into room temperature environment. Leave devices at room temperature for at least 120 minutes, in order to allow sufficient time for them to reach a stable temperature.
7. Repeat steps 3.3 to 3.6 for oven temperatures of 35°C, 40°C, 50°C, and 60°C (all temperatures with an acceptable error of ±5°C).
8. Download recorded temperature data and determine the amount of time required for each device to respond to the step changes in temperature tested.

E.5. Probe Recovery

E.5.1. Background and Motivation

Since temperature data collected by the probes is stored in memory and cannot be obtained until the probes are recaptured, it is important that 100% (or very close to 100%) of the probes introduced into a compost system can be retrieved at the end of the process. Thus, testing must be done to determine what fraction of the probes introduced can be recovered using various means.

Two potentially viable options were considered for probe recovery. The first method considered was visual recovery of the probes during compost screening; the probes should be large enough to be captured in the "overs" of the screen, and then removed from the overs by a spotter. It was recommended that several case colors be

tested to determine which color is easiest to see. The second potential method for locating the probes at the end of an experiment would be to use metal detection to pinpoint their locations in a compost pile and then dig them out. Digging for probes will probably be labour-intensive and time-consuming, so some combination of the two methods may be beneficial, particularly if it is difficult to recover probes based on observation alone.

E.5.2. Procedures

The procedure for testing the recovery of probes by screening is as follows:

1. Paint $^1/_5$ of the probes to be tested bright orange, $^1/_5$ bright blue, $^1/_5$ bright yellow, and $^1/_5$ gold. Leave the remaining $^1/_5$ unpainted.
2. Place all probes in compost ready to be screened.
3. Let probes sit in the compost for several days, if possible, so that conditions possible during actual probe use, such as discoloration of the cases by organic matter or clumping of compost onto the cases, will occur during this test. If there is a time constraint, skip this step.
4. Screen compost and probes on a 25.4 mm (1 in.) or smaller screen.
5. Watch for probe cases on the "overs" conveyor of the compost screener. Recover all cases seen. Note the relative ease with which each color probe can be seen.
6. Determine what fraction of probes was recovered, both of the total amount and of each color.

The procedure for testing the recovery of probes by metal detection is as follows:

1. Adjust the sensitivity of a metal detector so that it can detect a probe case with minimal interference from other objects.
2. Bury a probe case at a known depth in compost. Start with a depth of 5 to 10 cm.

3. Scan the compost with the metal detector to determine if the probe case can be detected.
4. Note whether or not the probe could be detected at the current depth.
5. If the probe was detected, increase its depth by 1 to 5 cm and repeat steps 3 to 5.
6. Note the maximum depth at which the probe can be detected using a metal detector.
7. Make a note of interference from other metallic objects in the vicinity.

E.6. Effect of Magnetic Field on Data Memory

E.6.1. Background and Motivation

At large solid waste processing facilities, including composting facilities, there are often systems set up to separate various materials out of the waste stream. These systems can include magnetic separation for the removal of ferrous materials. At the Edmonton Waste Management Centre, such a magnetic separation system is in place at the front end of the co-composter (after the digesters and 80 mm primary screen), and also on the star screen used to screen the final product from the Gore composter. It is therefore possible that the temperature loggers may come into a fairly strong magnetic field during the course of their use in either of these two composting systems. Because these devices are storing temperature data, it is important that this data not be lost or altered by exposure to a magnetic field. Therefore, testing was recommended to determine whether or not the commercial and DS2422-based temperature loggers would be affected by exposure to a strong magnetic field. This exposure may affect the data recorded in memory, and/or the correct operation of the device.

This test was carried out at the EWMCE. The devices were placed under the strongest magnet that they might encounter during the composting process (i.e. the magnet prior to the aeration bay at the co-composter). Since the material passes under the magnet on a conveyor belt, in practice the exposure time to the magnetic field will be fairly short. To be conservative, the probes were placed under the magnet for 2 minutes.

E.6.2. Procedures

The procedure is as follows:

1. Start a temperature logging mission on both the commercial temperature logger and DS2422-based device at least one day prior to placing the devices in a magnetic field. For the sake of consistency, set up the devices to log temperature once every minute. Place devices in their cases.
2. Obtain a known temperature profile. For example, both operating devices could be placed in a 50°C oven for 4 hours, after which time they could be removed from the oven and cooled to room temperature overnight.
3. Download and save the temperature data recorded to date from each device. Do not stop the temperature logging missions.
4. Place both the DS2422-based and commercial temperature loggers (in their respective cases) under the co-composter magnet for 2 minutes. The devices should be placed on the conveyor belt which passes under the magnet. Place the devices on the top of any material on the conveyor. If the conveyor is moving during this test, then prevent the devices from moving out of the magnetic field by recapturing and replacing them under the magnet.
5. After 2 minutes under the magnets, remove both devices.
6. Download data from both devices and compare to the original data.
7. Stop the mission and attempt to restart a new mission, as per step 1.
8. Repeat step 2 and examine data to see if it makes sense.

E.7. Response of Lithium Batteries to Elevated Temperatures

E.7.1. Background and Motivation

In order to monitor temperature conditions within a composting mass, a stand-alone, battery-operated temperature probe is required. All electronics used in this application must be capable of operating up to or above the peak temperature which may be seen in a compost pile. Normally, compost temperatures peak between 50 and 80°C. However, on occasion 80°C can be exceeded in compost piles, and, in rare cases, temperatures can even exceed 85°C. At the Edmonton composting facility, where initial testing is to be done with the finished probes, peak temperatures of 96°C have been recorded.

Since the temperature probe circuitry is to be battery-powered, the batteries chosen must be capable of operating over the range of temperatures experienced in composting environments. After some research, it was determined that lithium is the only battery chemistry able to operate at elevated temperatures. Lithium batteries capable rated at -40 to 85°C are quite readily available and reasonably priced. Lithium batteries with an operating temperature range of -40 to 125°C are manufactured, but these are difficult to acquire and very expensive.

In the interests of saving time and money, and because incidences of compost temperatures exceeding 85°C are rare, it was desirable to use the batteries rated at -40 to 85°C. However, it was desired that the response of the batteries to temperatures exceeding the rated operating range be tested. It would be acceptable if the batteries simply ceased to function when heated above 85°C. However, the possibility existed that the batteries could fail in a more severe manner, possibly leaking or exploding, which could affect the integrity of the temperature probe circuitry and could potentially be a health concern should someone come into contact with electrolyte residues. For this reason, tests were conducted to determine the response of lithium batteries rated to a maximum of 85°C when ambient temperatures approached 100°C.

E.7.2. Procedures

This experiment should take place in a well-ventilated area. During this experiment, the laboratory should be evacuated and signage posted indicating that there is an explosion and noxious fume hazard in the room. Proper safety precautions should be taken when handling the batteries and when entering the room. For instance, an approved acid gas mask should be worn when entering the room after exposing the batteries to high temperatures. As an extra precaution the oven used should be placed in an operating, closed fume hood during this experiment. All gas cylinders should be removed from the laboratory and flammable materials removed from the vicinity of the fume hood. A plumbed eyewash and emergency shower should be accessible within 10 seconds of the experimental proceedings. An Alberta #1 first aid kit should be available at all times.

The procedure for testing the batteries is as follows:

1. Prior to the experiment, contact the appropriate authority (at the University, this is the Communications Control Centre (492-4855)) to notify them about proposed experiment and to ensure that the ventilation system for the room will be operational for the duration of the procedure. The authority must be made aware of any fire hazards.
2. Assemble personal protective equipment (PPE) (P100 respirator with acid gas cartridges, PVC or nitrile gloves of 15 mils (0.015 in.) or thicker, disposable Tyvex coveralls and safety goggles or face shield), spill kit (spill pillows or absorbent mixture, non-sparking dustpan and brush, disposal container, pH paper, mop, bucket), Alberta #1 First Aid Kit and other equipment required for the procedure. Affix signage to door indicating explosion hazard. Ensure that the laboratory door remains locked.

3. Remove any flammable and combustible materials from the immediate vicinity of the experiment, and ensure that gas cylinders are removed from the lab.
4. Move oven into fume hood.
5. Connect batteries to a 720 Ω resistor in order to simulate worst-case (highest current draw) operating conditions.
6. Place each battery circuit in a separate explosion-proof container (a 100 mL alumina ceramic crucible with non-screw lid is appropriate for this purpose).
7. Heat oven to a temperature between 96 and100°C.
8. Place crucibles/circuits in oven. Close but do not latch the door, so that if an explosion occurs the door can swing open and absorb some of the shock.
9. Fully close sash on fume hood.
10. Leave contents in oven for 7 hours. During the first two hours, remain in the vicinity of (but not inside) the lab in order to monitor for incidence of any adverse conditions (fire, explosions, etc). Thereafter, until the experiment is complete, check the lab every 30 minutes. (Note that the lab should not be entered unless personal protective clothing is worn.)
11. After 7 hours, turn off oven. Wear all appropriate PPE when entering room (i.e. respirator, gloves, coveralls, and eye/face protection).
12. Allow batteries to cool for 1 hour.
13. Don appropriate PPE and remove batteries from oven.
14. Examine batteries for signs of damage or leakage.
15. Dispose of batteries in rigid, acid-resistant container, label as to contents and send for disposal as hazardous waste following the appropriate procedures.

In case of a spill, contain using spill pillows or dike around the spill with an absorbent. The absorbent mixture should contain a mild neutralizing agent such as

sodium carbonate (Na_2CO_3) or a 1:1 mixture of soda ash and slaked lime. Carefully cover the spill area with spill absorbent or spill pillows, starting at the outside and working inward. Sweep up the residue using spark-proof tools and place the residue in an approved container (acid resistant), and labelled clearly. Send residues for disposal as hazardous waste, flowing appropriate procedures. Check the pH of the spill area. It if is less than pH 6, neutralize with a dilute solution of sodium carbonate. Mop the affected area using detergent and water. Dispose of this water to the sanitary sewer. Remove and bag personal protective equipment for cleaning or disposal.

In case of fire, evacuate the room, close (but DO NOT lock) the door behind you and activate the fire alarm. Leave the building immediately and contact the appropriate authority (at the University of Alberta this is the Communications Control Centre (492-5555)). Meet emergency responders and provide information on the nature, extent and exact location of the fire. No attempt should be made to extinguish the fire without appropriate personal protective equipment (i.e. self-contained breathing apparatus).

References

Madge Tech. 2006. Temp1000 Rugged Temperature Recorder (Specifications) [online]. Available from http://www.madgetech.com/pdf_files/data_sheets/temp1000_ds.pdf [cited Oct 3 2006].

McMaster-Carr. 2006. About Aluminum Tubing Materials [online]. Available from http://www.mcmaster.com/param/html/tubing/aluminummaterials.htm [cited Dec 7 2006].

Appendix F

EXPERIMENTAL DATA AND OBSERVATIONS

F.1. Case Strength

During the drop test (from a raised loader bucket onto a compacted gravel surface) conducted on May 19 2006, the following observations were made:

- no denting or cracking was observed on any aluminum tubes of gauges 16, 14, and 11.
- some paint chipped off of the aluminum tubes

During the test, conducted on May 19 2006, to determine the impact on aluminum tubing of being driven over by heavy machinery, the following observations were made:

- the thicker the aluminum tubing, the smaller the amount of compression suffered by the tube
- the 11 gauge (thickest) tubing cross-section was still essentially round after being driven over, though it suffered a few scratches
- the 14-gauge tubing was crushed to less than half of its original diameter
- the 16-gauge tubing (thinnest) was completely flattened, and one side split open

Windrow turner tests for material strength were performed twice: once on July 18 2006 and once on August 15 2006. The total numbers of dents of different sizes in the three aluminum gauges tested are presented in Tables F-1 and F-2.

During both windrow turner tests, the following observations were made regarding chemical and biological stresses to aluminum cases:

- paint color tended to darken after only a few days in compost; gold and yellow paints were most affected
- an unpainted, unanodized aluminum tube showed pitting in numerous locations (which appeared to be due to corrosion or microbiological activity, as opposed to physical impacts) after spending about 4 weeks in a compost cure pile
- an unpainted, anodized aluminum case from a commercial temperature logger (same aluminum grade as other sections of aluminum tubing tested) showed no signs of chemical or microbiological degradation.

Table F-1. Data from material strength tests (windrow turner) of July 18, 2006. The number of impacts on the device ends was determined by evaluating whether or not the end caps were pushed in. The dent severity was evaluated as follows: a small dent is one that does not penetrate all the way through the case wall; a medium dent which can be detected on the inside of the case wall; a severe dent is one that appears prominently on the inside of the case wall. The total number of impacts is a minimum value, reflecting only those impacts that caused damage to the probe case.

	Probe ID	Initial Height (m)	No. of Impacts on End Caps	Total No. of Dents	No. of Severe Dents	No. of Medium Dents	No. of Small Dents	Total No. of Impacts
Low Density (~800 kg/m³)	16-01	0.79	0	0	0	0	0	0
	16-02	0.15	2	0	0	0	0	2
	16-03	1.25	0	0	0	0	0	0
	16-04	0.15	2	3	0	2-ends	1-end	5
	16-05	1.25	0	0	0	0	0	0
	16-06	0.79	0	0	0	0	0	0
	16-07	1.25	Not recovered					
	16-08	0.15	0	3	0	1-end 1-middle	1-end	3
	16-10	0.79	0	1	0	0	1-end	1
Middle Density (~1550 kg/m³)	11-02	0.79	0	1	0	0	1-end	1
	14-01	0.15	1	5	1-middle 2-ends	1-middle	1-middle	6
	14-03	1.25	Not recovered					
	14-04	1.25	0	0	0	0	0	0
	14-05	0.79	0	2	0	0	2 - ends	2
	14-07	1.25	Not recovered					
	14-08	0.15	1	2	1-end	1-end	0	3
	14-09	0.15	2	5	1-end	1-middle	3-ends	7
	14-10	0.79	0	1	0	1-middle	0	1
	Communication error	0.79	Not recovered					
High Density (~2300 kg/m³)	11-01	1.25	Not recovered					
	11-03	0.15	0	6	0	1-middle 1-end	1-middle 3-ends	6
	11-04	1.25	Not recovered					
	11-05	0.79	0	1	0	0	1-end	1
	11-06	1.25	Not recovered					
	11-07	0.15	0	7	1-middle	1-middle 2-ends	3-ends	7
	11-08	0.15	0	2	0	1-end	1-middle	2
	11-09	0.79	0	1	0	0	1-end	1
	11-10	0.79	0	2	0	0	2-end	2

Table F-2. Data from material strength tests (windrow turner) of August 15, 2006. The number of impacts on the device ends was determined by evaluating whether or not the end caps were pushed in. The dent severity was evaluated as follows: a small dent is one that does not penetrate all the way through the case wall; a medium dent which can be detected on the inside of the case wall; a severe dent is one that appears prominently on the inside of the case wall. The total number of impacts is a minimum value, reflecting only those impacts that caused damage to the probe case.

	Probe ID	Initial Height (m)	No. of Impacts on End Caps	No. of Dents	No. of Severe Dents	No. of Medium Dents	No. of Small Dents	Total No. of Impacts
Low Density (~800 kg/m³)	16-01	1.50	0	0	0	0	0	0
	16-02	1.50	0	1	0	0	1-end	1
	16-03	1.50	0	0	0	0	0	0
	16-04	0.75	1	0	0	0	0	1
	16-05	0.75	0	1	0	0	1-end	1
	16-06	0.75	0	1	1-end	0	0	1
	16-07 (driven over three times)	1.25	0	6	2-ends 2-middle	0	2-middle	6
	16-08	0.00	0	7	3-middle	2-end	2-middle	7
	16-10	0.00	1	3	3-ends	0	0	4
	16-11	1.50	0	0	0	0	0	0
	16-12	1.50	0	0	0	0	0	0
	16-13	1.50	0	0	0	0	0	0
	16-14	0.00	0	5	2-middle	1-middle	1-middle 1-end	5
	16-15	0.00	0	5	1-end 1-middle	2-ends	1-end	5
	16-16	0.00	1	3	2-ends	1-end	0	4
	16-17	0.00	1	4	0	2-ends	1-middle 2-end	5
	16-18	0.75	0	2	1-end	1-middle	0	2
	16-19	0.75	0	2	0	1-end	1-end	2
	16-20	0.75	0	0	0	0	0	0
	11-11	0.75	0	0	0	0	0	0
	11-12	0.75	0	2	0	0	1-middle 1-end	2
	11-13	0.00	0	2	0	1-end	1-end	2
	11-14	1.50	0	0	0	0	0	0
	11-15	1.50	0	0	0	0	0	0
	11-16	1.50	0	0	0	0	0	0
	11-17	0.75	0	1	0	1-end	0	1
	11-18	0.00	0	6	1-end	2-middle	1-end 2-middle	6
	11-19	0.00	0	7	0	2-middle	2-end 3-middle	7

Table F-2 (con't). Data from material strength tests of August 15, 2006.

	Probe ID	Initial Height (m)	No. of Impacts on End Caps	No. of Dents	No. of Severe Dents	No. of Medium Dents	No. of Small Dents	Total No. of Impacts
Middle Density (~1400 kg/m³)	14-01	1.50	0	0	0	0	0	0
	14-03	0.15	Turned three times; dents not counted					
	14-04	1.50	0	0	0	0	0	0
	14-05	0.75	0	1	0	0	1-end	1
	14-07	0.75	Turned three times; dents not counted					
	14-08	0.75	0	0	0	0	0	0
	14-09	0.00	Not recovered					
	14-10	0.00	2	2	1-end	1-end	0	4
	14-11	1.50	0	0	0	0	0	0
	14-12	1.50	0	0	0	0	0	0
	14-13	1.50	0	1	0	0	1-end	1
	14-14	0.75	0	0	0	0	0	0
	14-15	0.75	0	1	0	0	1-middle	1
	14-16	0.75	0	1	0	0	1-middle	1
	14-17	0.00	Not recovered					
	14-18	0.00	0	4	0	1-end	1-middle 2-end	4
	14-19	0.00	Not recovered					
	14-20	0.00	0	5	1-middle 1-end	1-end	1-middle 1-end	5
	11-20	1.50	0	0	0	0	0	0
	11-21	1.50	0	0	0	0	0	0
	11-22	1.50	0	0	0	0	0	0
	11-23	1.50	0	1	0	0	1-middle	1
	11-24	0.75	0	0	0	0	0	0
	11-25	0.75	0	1	0	0	1-end	1
	11-26	0.75	0	0	0	0	0	0
	11-27	0.75	0	1	0	1-end	0	1
	11-28	0.00	Not recovered					
	11-29	0.00	1	5	0	1-end	3-middle 1-end	6
	11-30	0.00	Not recovered					
Cases with Batteries	11-2	0.00	0	7	0	1-middle 1-end	3-middle 2-end	7
	11-52	0.00	0	6	0	2-ends	1-middle 3-ends	6
	11-53	0.00	0	4	0	1-end	1-middle 2-end	4
	11-54	0.00	0	4	0	1-end	3-ends	4
	11-55	0.00	0	7	1-end	2-ends	4-ends	7
	11-56	0.00	Not recovered					
	11-57	0.00	Not recovered					

Table F-2 (con't). Data from material strength tests of August 15, 2006.

	Probe ID	Initial Height (m)	No. of Impacts on End Caps	No. of Dents	No. of Severe Dents	No. of Medium Dents	No. of Small Dents	Total No. of Impacts
High Density (~2000 kg/m³)	11-01	1.25	Turned three times, dents not counted					
	11-03	1.50	0	0	0	0	0	0
	11-04	1.25	Turned three times, dents not counted					
	11-05	1.50	0	0	0	0	0	0
	11-06	1.25	Turned three times, dents not counted					
	11-07	0.75	0	2	0	1-end	1-middle	2
	11-08	0.75	0	2	0	0	1-middle 1-end	2
	11-09	0.00	0	6	0	0	4-middle 2-end	6
	11-10	0.00	0	5	0	1-end	2-middle 2-ends	5
	11-31	1.50	0	0	0	0	0	0
	11-32	1.50	0	0	0	0	0	0
	11-33	1.50	0	0	0	0	0	0
	11-34	1.50	0	0	0	0	0	0
	11-35	1.50	0	2	0	0	2-ends	2
	11-36	1.50	0	0	0	0	0	0
	11-37	1.50	0	0	0	0	0	0
	11-38	0.75	0	2	0	1-middle	1-middle	2
	11-39	0.75	0	1	0	0	1-end	1
	11-40	0.75	0	1	0	0	1-end	1
	11-41	0.75	0	2	0	1-end	1-end	2
	11-42	0.75	0	3	0	0	1-middle 2-end	3
	11-43	0.75	0	0	0	0	0	0
	11-44	0.75	0	3	0	0	3-ends	3
	11-45	0.00	1	6	0	2-ends	3-middle 1-end	7
	11-46	0.00	0	3	1-middle	0	1-middle 1-end	3
	11-47	0.00	1	10	0	1-middle 2-ends	3-middle 4-end	11
	11-48	0.00	Not recovered					
	11-49	1.25	Turned three times, dents not counted					
	11-50	0.00	0	5	1-middle	3-middle	1-end	5
	11-51	0.00	0	4	0	1-middle	3-ends	4
	Commercial	1.25	Turned three times, dents not counted					

F.2. Probe Density

The effect of probe density on probe movement during compost agitation was tested by placing probes of three densities at known locations in a windrow, turning the windrow using a windrow turner, and then locating the probes and noting their final locations. This test was performed twice: once on July 18 2006 and once on August 15 2006. The probe height data is presented Tables F-3 and F-4.

The probe cases were made from 50.8 mm diameter tubing with a length of 90 mm, for a probe volume of 1.824×10^{-4} m^3. Densities were determined by dividing the probe mass by the case volume.

The density of the commercial temperature logger is approximately 1880 kg/m^3 (determined from the specification sheet).

The approximate dimensions of the windrow were measured during the second set of tests. The same windrow was used for both sets of tests (see Figure F-1), so the dimensions should be similar. The windrow cross-sectional dimensions were as follows:

- height $\approx$ 1.5 m
- width at base $\approx$ 5.5 m
- width at top $\approx$ 1.2 m

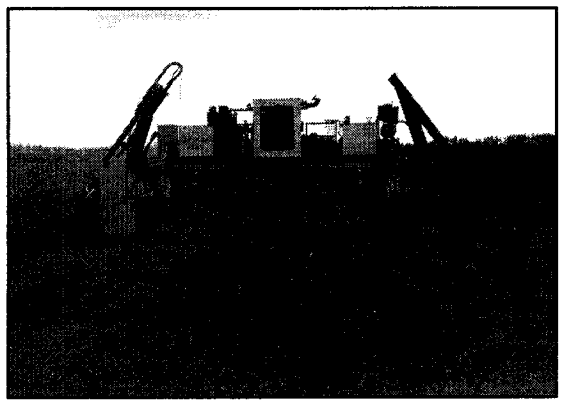

Figure F-1. Windrow in which probe density tests were conducted.

The density of compost in the co-composter cure windrow used during this test was determined to be approximately 447 kg/m^3.

Table F-3. Data from density tests (windrow turner) of July 18, 2006. The change in probe height was determined from the difference between the initial and final locations of each aluminum case; a positive "change in height" indicates that the probe case moved upward, while a negative value indicates downward movement.

	Probe ID	Initial Mass (g)	Final Mass (g)	Initial Height (m)	Final Height (m)	Change in Height (m)	Comments
Low Density (~800 kg/m³)	16-01	145.7	145.8	0.79	0.42	-0.37	
	16-02	145.6	148.4	0.15	0.18	0.03	
	16-03	145.7	146.2	1.25	0.51	-0.74	
	16-04	145.7	124.6	0.15	1.20	1.05	Density change during test
	16-05	145.6	145.8	1.25	0.43	-0.82	
	16-06	145.7	145.7	0.79	0.47	-0.32	
	16-07	145.6	Not recovered				
	16-08	146.1	146.1	0.15	1.40	1.25	
	16-10	146.4	146.6	0.79	1.20	0.41	
Middle Density (~1550 kg/m³)	11-02	168.3	168.4	0.79	0.53	-0.26	
	14-01	282.0	195.7	0.15	0.40	0.25	Density change during test
	14-03	282.8	Not recovered				
	14-04	282.8	283.0	1.25	0.42	-0.83	
	14-05	282.8	282.9	0.79	0.43	-0.36	
	14-07	282.7	Not recovered				
	14-08	283.5	109.8	0.15	0.14	-0.01	Density change during test
	14-09	282.7	254.1	0.15	1.25	1.10	Density change during test
	14-10	282.6	282.7	0.79	0.61	-0.18	
	Commercial device	N/A	Not recovered				
High Density (~2300 kg/m³)	11-01	419.8	Not recovered				
	11-03	420.1	121.2	0.15	0.18	0.03	Density change during test
	11-04	420.3	Not recovered				
	11-05	420.1	420.3	0.79	0.79	0.00	
	11-06	419.8	Not recovered				
	11-07	419.7	120.3	0.15	1.23	1.08	Density change during test
	11-08	419.7	126.0	0.15	0.18	0.03	Density change during test
	11-09	420.1	126.6	0.79	0.60	-0.19	Density change during test
	11-10	419.4	126.9	0.79	0.76	-0.03	Density change during test

Table F-4. Data from density tests (windrow turner) of August 15, 2006. The change in probe height was determined from the difference between the initial and final locations of each aluminum case; a positive "change in height" indicates that the probe case moved upward, while a negative value indicates downward movement.

	Probe ID	Initial Mass (g)	Final Mass (g)	Initial Height (m)	Final Height (m)	Change in Height (m)	Comments
Low Density (~800 kg/m³)	16-01	146.8	No change	1.50	0.21	-1.29	
	16-02	146.5	No change	1.50	0.28	-1.22	
	16-03	146.2	No change	1.50	0.26	-1.24	
	16-04	145.6	No change	0.75	0.26	-0.49	
	16-05	146.0	No change	0.75	0.61	-0.14	
	16-06	146.2	No change	0.75	0.99	0.24	
	[illegible]						
	16-10	146.0	No change	0.00	0.09	0.09	
	16-11	145.7	No change	1.50	0.51	-0.99	
	16-12	146.1	No change	1.50	0.82	-0.68	
	16-13	146.2	No change	1.50	1.24	-0.26	
	16-14	145.7	No change	0.00	0.09	0.09	
	16-15	146.1	No change	0.00	0.48	0.48	
	16-16	145.1	No change	0.00	0.50	0.50	
	16-17	145.3	No change	0.00	0.14	0.14	
	16-18	145.7	No change	0.75	0.27	-0.48	
	16-19	145.6	No change	0.75	0.26	-0.49	
	16-20	145.3	No change	0.75	1.17	0.42	
	[illegible]						
	11-12	145.8	No change	0.75	0.27	-0.48	
	11-13	145.7	No change	0.00	0.60	0.60	
	11-14	145.7	No change	1.50	1.24	-0.26	
	11-15	146.8	No change	1.50	1.08	-0.42	
	11-16	145.5	No change	1.50	0.61	-0.89	
	11-17	145.6	No change	0.75	0.28	-0.47	
	11-18	145.9	No change	0.00	0.25	0.25	
	11-19	145.7	No change	0.00	0.12	0.12	

Table F-4 (con't). Data from density tests (windrow turner) of August 15, 2006.

	Probe ID	Initial Mass (g)	Final Mass (g)	Initial Height (m)	Final Height (m)	Change in Height (m)	Comments
Middle Density (~1400 kg/m³)	14-01	256.0	No change	1.50	0.65	-0.85	
	14-03	282.0	Not recovered.				
	14-04	255.2	No change	1.50	0.51	-0.99	
	14-05	256.1	No change	0.75	0.38	-0.37	
	14-07	282.3	Not recovered.				
	14-08	255.8	No change	0.75	0.57	-0.18	
	14-09	254.2	Not recovered.				
	14-10	255.2	No change	0.00	0.45	0.45	
	14-11	255.2	No change	1.50	0.70	-0.80	
	14-12	255.1	No change	1.50	0.89	-0.61	
	14-13	255.0	No change	1.50	0.76	-0.74	
	14-14	254.8	No change	0.75	0.44	-0.31	
	14-15	254.9	No change	0.75	0.60	-0.15	
	14-16	256.2	No change	0.75	0.47	-0.28	
	14-17	255.7	Not recovered.				
	14-18	254.4	No change	0.00	0.28	0.28	
	14-19	255.1	Not recovered.				
	14-20	254.8	No change	0.00	0.21	0.21	
	11-20	255.6	No change	1.50	0.41	-1.09	
	11-21	254.4	No change	1.50	0.86	-0.64	
	11-22	254.0	No change	1.50	0.96	-0.54	
	11-23	255.8	No change	1.50	1.18	-0.32	
	11-24	255.5	No change	0.75	0.67	-0.08	
	11-25	254.9	No change	0.75	0.36	-0.39	
	11-26	255.7	No change	0.75	0.27	-0.48	
	11-27	255.7	No change	0.75	0.86	0.11	
	11-28	254.2	Not recovered.				
	11-29	255.6	No change	0.00	0.39	0.39	
	11-30	255.6	Not recovered.				
Batteries	11-2	169.8	No change	0.00	0.14	0.14	
	11-52	143.5	No change	0.00	0.36	0.36	
	11-53	143.2	No change	0.00	1.17	1.17	
	11-54	143.4	No change	0.00	1.35	1.35	
	11-55	143.4	No change	0.00	1.02	1.02	
	11-56	140.5	Not recovered.				
	11-57	143.0	Not recovered.				

Table F-4 (con't). Data from density tests (windrow turner) of August 15, 2006.

	Probe ID	Initial Mass (g)	Final Mass (g)	Initial Height (m)	Final Height (m)	Change in Height (m)	Comments
High Density (~2000 kg/m³)	11-01	419.8	120.6	1.25	0.00		
	11-03	366.1	No change	1.50	0.20	-1.30	
	11-04	420.4	Not recovered				
	11-05	364.5	No change	1.50	0.33	-1.17	
	11-06	419.5	Not recovered				
	11-07	365.4	No change	0.75	0.27	-0.48	
	11-08	364.6	No change	0.75	0.27	-0.48	
	11-09	365.2	No change	0.00	0.27	0.27	
	11-10	365.9	No change	0.00	0.63	0.63	
	11-31	365.1	No change	1.50	0.21	-1.29	
	11-32	366.1	No change	1.50	0.26	-1.24	
	11-33	364.3	No change	1.50	0.44	-1.06	
	11-34	365.8	No change	1.50	0.22	-1.28	
	11-35	365.3	No change	1.50	0.18	-1.32	
	11-36	363.9	No change	1.50	0.16	-1.34	
	11-37	364.9	No change	1.50	0.92	-0.58	
	11-38	364.2	No change	0.75	1.27	0.52	
	11-39	364.6	No change	0.75	0.83	0.08	
	11-40	364.6	No change	0.75	0.41	-0.34	
	11-41	365.1	No change	0.75	1.39	0.64	
	11-42	364.1	No change	0.75	0.36	-0.39	
	11-43	363.9	No change	0.75	0.22	-0.53	
	11-44	363.8	No change	0.75	0.92	0.17	
	11-45	363.0	Not recovered				
	11-46	364.3	No change	0.00	0.26	0.26	
	11-47	364.0	Not recovered				
	11-48	365.8	Not recovered				
	11-49	364.3	Not recovered				
	11-50	364.6	No change	0.00	0.11	0.11	
	11-51	365.2	No change	0.00	0.28	0.28	
	11-52	364.3	Not recovered				

F.3. Robustness of Circuitry

Observations from an initial windrow turner test – July 18, 2006:

- Only two temperature logging circuits (the DS2422-based probe and the commercial temperature logger) were placed into the windrow during the first windrow turning test. The DS2422 circuit was recovered, but the commercial device was not.
- The tabbed lithium battery on the DS2422 temperature logging circuit had one of the battery tabs ripped off of it (the tab actually ripped; the solder did not fail).
- The 3.6V lithium battery was tested to see if it still worked. It was still functioning after that experiment. The no-load voltage was 3.71 V and the in-circuit voltage was 3.45 V, but with a load of 720 Ω (~5 mA @ 3.6 V) the voltage dropped rapidly from 2.36 V to below 2.0 V.
- The temperature sensing circuit was still functional after windrow turning.

Observations from a second windrow turner test – August 15, 2006:

- The DS2422 temperature logging circuit was placed into the windrow for this test. The commercial temperature logger was not located during the test in July 2006 and remained in the windrow during the current test.
- In addition to operating temperature logging circuits, 6 batteries (3 with tabs and 3 with pins) were soldered onto circuit boards (with cardboard end caps to prevent sideways movement), enclosed in 6 cases of 11-gauge aluminum, and put in the windrow. The purpose of this test was to determine if the tearing of the battery tabs during initial testing was a freak occurrence, and to see if pins would be stronger than tabs.

- The commercial temperature logging device was recovered, and it was seen that some damage had occurred to the circuit while it was in the windrow (turned 3 times); the microcontroller chip popped completely out of its socket, one side of the battery had come loose from its socket, and a diode was broken in half.
- When the commercial device was reassembled, it was found that data had been collected for most of the time the device had been in the windrow and, in fact, data memory was full. All temperature data recorded was still intact despite the problems with the circuit, and seemed to make sense. In other words, there was no indication that the temperature data had been affected in any way when the circuit broke.
- The commercial device circuit still functioned correctly as a temperature logger after all parts were replaced.
- The battery powering the DS2422 circuit had one of its tabs broken during windrow turning.
- The DS2422 circuit was intact aside from the battery. When the battery was reconnected, the circuit still functioned properly.
- The DS2422 circuit did not retain any data when the battery broke.
- All three tabbed battery assemblies were recovered, and one or both tabs had broken on all of them.
- One of the three battery assemblies using solder pins was recovered – both pins were broken.
- All batteries still functioned when connected to a 720 Ω load (i.e. ~5 mA @ 3.6 V)

F.4. Temperature Response Time

Table F-5. Time required for each of the commercial and DS2422-based devices to respond to different changes in temperature.

Temperature Low (°C)	Temperature High (°C)	Temperature Differential (°C)	DS2422-based Logger		Commercial Temperature Logger	
			Rise Time (min.)	Fall Time (min.)	Rise Time (min.)	Fall Time (min.)
20.5	64.0	43.5	70	81	70	79
20.0	52.5	32.5	70	78	72	65
20.0	42.0	22.0	68	64	67	65
19.5	37.0	17.5	64	65	71	58
19.5	28.5	9.0	44	36	40	38

F.5. Probe Recovery

During tests of probe recovery during screening, conducted on May 19 2006, the following observations were made:

- when probes were screened with finished biosolids compost (from the Gore® composter) all colors were easily detected visually and recovered from the screen "overs"; all probes were recovered.
- when probes were screened with mixed biosolids and MSW compost (from the co-composter) all probes were detected visually and recovered; the blue, orange, and yellow cases stood out more than the gold and unpainted cases.
- at both screening sites (Gore® and co-composter), a counter-weight (an orange-painted washer) was attached to each of four cases with a length of rope; these "flagged" cases were easy to spot, and the counter-weight prevented the cases from rolling down the "overs" pile. The flagged cases did not become tangled with each other or in the machinery.

During tests of aluminum case recovery with a metal detector, conducted on May 19 2006, the following observations were made:

- metal detector used was Garrett Treasure Ace 100
- in open air, on the detector's most sensitive setting, the aluminum probe case could only be detected to a height of ~11 cm.
- in screened biosolids compost (from the Gore® site), on the detector's most sensitive setting, an aluminum case could be detected to a maximum depth of 15 cm, with the metal detector situated right on the surface of the compost
- the metal detector picked up a lot of signals from the screened biosolids compost, making it difficult to determine whether the signals were due to the probe case or to other metallic objects in the compost

During tests of probe recovery (with magnetic stainless steel case) with a metal detector, conducted on July 18 2006, the following observations were made:

- metal detector used was Schonstedt GA-52Cx Magnetic Locator ("pin finder")
- magnetic stainless steel bars were used to simulate a stainless steel case
- in co-composter cure pile, pin finder detected stainless steel bars, but also picked up signals from other materials in the pile when the steel bars were removed from pile
- in a yard waste windrow, the pin finder gave strong signals whether or not steel bars were in the pile

F.6. Effect of Magnetic Field on Data Recovery

During tests to determine the effect of a strong magnet on stored temperature data and probe operation, conducted on Sept 12 2006, the following observations were made:

- exposure to a strong magnetic field for 2 minutes did not result in any change in the stored temperature data in either the commercial device or the DS2422-based device
- both devices continued to function normally after a 2-minute exposure to a strong magnetic field

Appendix G

CALCULATIONS AND STATISTICAL ANALYSIS OF EXPERIMENTAL DATA

G.1. Results of Statistical Analysis regarding Case Strength

The effect of probe gauge on the number of severe dents suffered by aluminum probe cases was examined by using two-way ANOVA analyses (factors are 1) initial location of the probe and 2) aluminum gauge) to determine whether or not there were significant differences between the number of severe dents for probes of different gauges. The ANOVA analysis was carried out using Sigma Stat; a brief summary of the results of the analyses using this program is presented below.

Two-way ANOVA – Material Strength Experiment of August 15 2006:

General Linear Model

Dependent Variable: No. of Severe Dents

Normality Test: Failed (P < 0.050)

Equal Variance Test: Failed (P < 0.050)

Source of Variation	DF	SS	MS	F	P
Initial Location	2	11.077	5.538	29.444	<0.001
Probe Gauge	2	5.403	2.701	14.362	<0.001
Initial Location x Probe Gauge	4	6.631	1.590	8.455	<0.001
Residual	70	13.167	0.188		
Total	78	32.937	0.422		

The difference in mean values among the different levels of Probe Gauge is greater than would be expected by chance after allowing for the effects of differences in Initial Location. There is a statistically significant difference (P = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor: **Probe Gauge**

Comparison	Diff. of Means	t	Unadjusted P	Critical Level	Significant?
16 ga vs. 11 ga	0.639	5.330	0.00000114	0.017	Yes
16 ga vs. 14 ga	0.389	2.422	0.0180	0.025	Yes
14 ga vs. 11 ga	0.250	1.802	0.0758	0.050	No

G.2. Calculation of Compost Density

Determination of true beaker volume at 1800 mL mark:

$T_{water} = 21.5°C$
$M_{beaker} = 142.6$ g
$m_{beaker + water} = 1899.9$ g
$\rho_{water(21.5°C)} = 0.99788$ g/mL

$$V_{true,1800mL} = \frac{M_{water}}{\rho_{water}} = \frac{M_{beaker+water} - M_{beaker}}{\rho_{water}} = \frac{1899.9g - 142.6g}{0.99788g/mL} = 1761mL = 1761cm^3$$

Determination of compost density:

$$\rho_{compost} = \frac{M_{compost}}{V_{true,1800mL}} = \frac{M_{compost}}{1761cm^3}$$

Table G-1. Calculation of wet bulk density of compost from the co-composter cure pile in which the probe density tests were conducted.

M_{beaker} (g)	$M_{beaker+compost}$ (g)	$M_{compost}$ (g)	$\rho_{compost}$ (g/cm³)	$\rho_{compost}$ (kg/m³)
142.6	945.7	803.1	0.4560	456.0
142.7	946.3	803.6	0.4563	456.3
142.6	927.2	784.6	0.4455	455.5
142.7	930.9	788.2	0.4476	447.6
142.7	910.1	767.4	0.4358	453.8
142.7	918.1	775.4	0.4403	440.3
			Average	**446.92**
			Standard Deviation	**7.53**

G.3. Calculation of Windrow Volume Midpoint

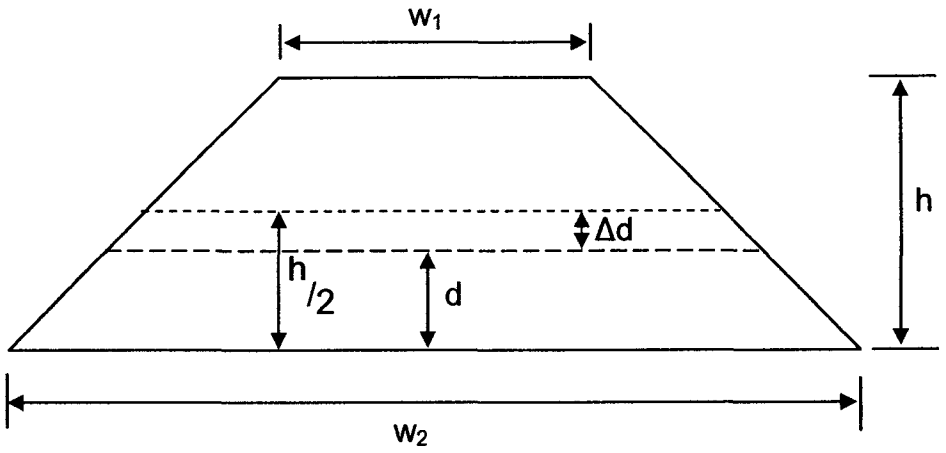

Figure G-1. Approximation of a windrow cross-section; dimension "d" is the distance from the windrow base to the level in the pile where the volume of material above and below this level is approximately equal.

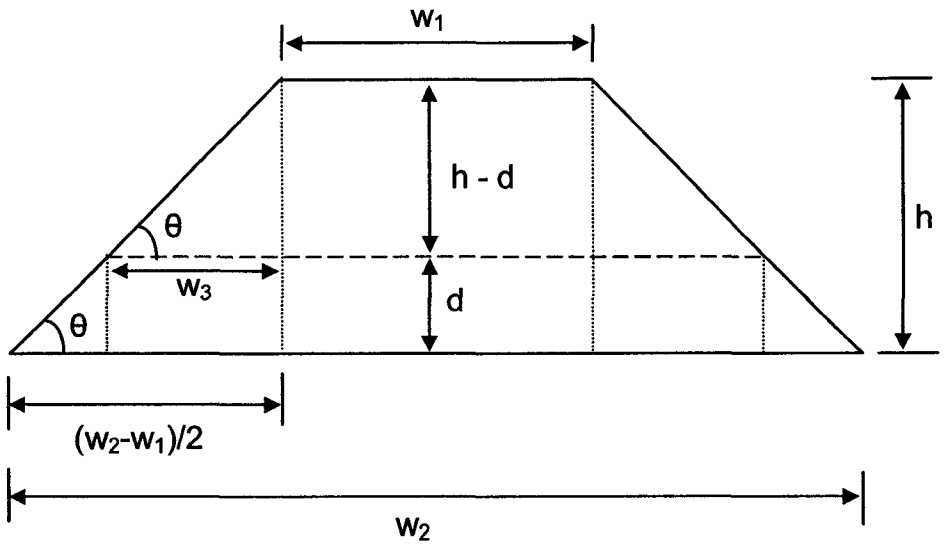

Figure G-2. Division of the windrow pile into simple geometric shapes in order to calculate approximate cross-sectional areas. It was assumed that the pile cross-section was roughly symmetric.

Table G-2. Approximate dimensions of the co-composter cure windrow in which the density tests were completed.

Dimension	Approximate Value
d	to be determined
h	1.5 m
w1	1.2 m
w2	5.5 m

In order to determine the cross-sectional areas (and hence volumes) above and below the "mid-line," it is necessary to put all unknowns in terms of h, d, w_1, and w_2.

$$\theta = \tan^{-1}\left(\frac{2h}{w_2 - w_1}\right) \qquad \text{and} \qquad w_3 = \frac{(h-d)}{\tan\theta}$$

Since $\tan(\tan^{-1} x) = x$;

$$\tan\theta = \tan\left(\tan^{-1}\left(\frac{2h}{w_2 - w_1}\right)\right) = \frac{2h}{w_2 - w_1} \qquad \text{and} \qquad w_3 = \frac{(h-d)\cdot(w_2 - w_1)}{2h}$$

Therefore,

$$A_{above\_line} = [w_1 \cdot (h-d)] + [w_3 \cdot (h-d)] = (w_1 + w_3)\cdot(h-d)$$

$$A_{above\_line} = \left[w_1 + \frac{(h-d)\cdot(w_2 - w_1)}{2h}\right]\cdot(h-d)$$

and

$$A_{below\_line} = [w_1 \cdot d] + 2\cdot[w_3 \cdot d] + \left[\left\{\frac{(w_2 - w_1)}{2} - w_3\right\}\cdot d\right] = \left(\frac{w_1}{2} + \frac{w_2}{2} + w_3\right)\cdot d$$

$$A_{below\_line} = \left(\frac{w_1}{2} + \frac{w_2}{2} + \frac{(h-d)\cdot(w_2 - w_1)}{2h}\right)\cdot d$$

At the point where the cross-sectional area of material above the line is equal to the cross-sectional area below the line,

$$V_{above\_line} = V_{below\_line} \qquad \text{and} \qquad A_{above\_line} = A_{below\_line}$$

$$\left[w_1 + \frac{(h-d)\cdot(w_2 - w_1)}{2h} \right] \cdot (h-d) = \left(\frac{w_1}{2} + \frac{w_2}{2} + \frac{(h-d)\cdot(w_2 - w_1)}{2h}\right) \cdot d$$

Expanding and grouping terms gives:

$$\frac{h^2(w_1 + w_2) - 2hdw_2 + d^2(w_2 - w_1)}{2h} = \frac{2hdw_2 + d^2(w_1 - w_2)}{2h}$$

from which the following quadratic equation is obtained:

$$2d^2(w_2 - w_1) - 4hdw_2 + h^2(w_1 + w_2) = 0$$

Substituting in the known dimensions (Table G-2) gives:

$$8.6d^2 - 33d + 15.075 = 0$$

Solving this quadratic gives the solution that d = 0.53 m.

The change in height corresponding to the volume midpoint should be equal to Δh = -0.22 m, since the probes were placed in equal numbers at the bottom (0 m), middle (0.75 m) and top (1.5 m) of the windrow:

$$\Delta h = (\text{volume\_midpoint}) - (\text{average\_starting\_height}) = 0.53\text{m} - 0.75\text{m} = -0.22\text{m}$$

G.4. Results of Statistical Analysis regarding Probe Density

The effect of probe density on the randomness of probe movement was examined by: 1) using two-way ANOVA analyses to determine whether or not there were significant differences between the change in height data for probes of different densities and 2) using t-tests to determine if the average change in height for probes of a specific density was significantly different from the volume midpoint of the windrow that the test were conducted in. The ANOVA analysis was carried out using Sigma Stat; a brief summary of the results of the analyses using this program is presented below. The t-tests were carried out in Microsoft Excel; these results are also summarized below.

Two-way ANOVA – Density Experiment of July 18 2006:

General Linear Model (No interactions)

Dependent Variable: Change in Height

Normality Test: Failed ($P < 0.050$)

Equal Variance Test: Passed ($P = 0.201$)

Source of Variation	DF	SS	MS	F	P
Initial Location	2	2.220	1.110	5.781	0.040
Density	2	0.0547	0.0273	0.142	0.870
Residual	6	1.152	0.192		
Total	10	3.703	0.370		

The difference in mean values among the different levels of Density is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Initial Location. There is not a statistically significant difference ($P = 0.870$).

Two-way ANOVA – Density Experiment of Aug 15 2006:

General Linear Model

Dependent Variable: Change in Height

Normality Test: Failed ($P < 0.050$)

Equal Variance Test: Passed ($P = 0.073$)

Source of Variation	DF	SS	MS	F	P
Initial Location	2	15.812	7.906	84.920	<0.001
Density	2	0.115	0.0574	0.616	0.543
Initial Location x Density	4	1.047	0.262	2.811	0.033
Residual	63	5.865	0.0931		
Total	71	23.578	0.332		

The difference in mean values among the different levels of Density is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Initial Location. There is not a statistically significant difference ($P = 0.543$).

The effect of different levels of Initial Location depends on what level of Density is present. There is a statistically significant interaction between Initial Location and Density. ($P = 0.033$)

T-test Example – Density Experiment of Aug 15 2006

Table G-3. Change in Height data for low density probes during density experiment conducted on August 15, 1006.

i	Density (kg/m^3)	Initial Height (m)	Change in Height (m)	Average for Each Initial Height (m)	Std. Dev. for Each Initial Height (m)
1	800	1.50	-1.29		
2	800	1.50	-1.24		
3	800	1.50	-1.22		
4	800	1.50	-0.89		
5	800	1.50	-0.68		
6	800	1.50	-0.42		
7	800	1.50	-0.26		
8	800	1.50	-0.26		
9	800	1.50	-0.99	-0.80556	0.41774
10	800	0.75	-0.70		
11	800	0.75	-0.49		
12	800	0.75	-0.49		
13	800	0.75	-0.48		
14	800	0.75	-0.48		
15	800	0.75	-0.47		
16	800	0.75	-0.14		
17	800	0.75	0.24		
18	800	0.75	0.42	-0.28778	0.38081
19	800	0.00	0.09		
20	800	0.00	0.09		
21	800	0.00	0.12		
22	800	0.00	0.14		
23	800	0.00	0.25		
24	800	0.00	0.28		
25	800	0.00	0.48		
26	800	0.00	0.50		
27	800	0.00	0.60	0.28333	0.19653
		average =	-0.27	-0.27000	
		std. dev =	0.56		0.59845

Check if average of all samples = -0.22 (equivalent to volume midpoint of windrow)

Null Hypothesis:	H_0: true average = -0.22
Alternative Hypothesis:	H_A: true average $\neq$ -0.22

Use t-test, since sample size is < 30.

t_o statistic (all data points) = 0.46
t_o statistic (averages) = 0.43

$t_{critical} = t_{alpha/2,df} = t_{0.025,26}$ (all data points) = 2.06
$t_{critical} = t_{alpha/2,df} = t_{0.025,23}$ (averages) = 2.07

Because $t_o < t_{critical}$ (for analysis with all data points and for analysis using averaged data, both with a 95% confidence interval)), the null hypothesis is accepted. Therefore, statistically it cannot be said that the mean change in height is different from -0.22 m.

Similar results were obtained for the middle (1400 kg/m^3) and high (2000 kg/m^3) probes.

G.5. Determination of Number of Samples Required to Capture Vertical Probe Dispersion

The testing done to determine the effect of probe density on vertical probe dispersion was done using an arbitrary number of probes, based simply on the amount of materials available. In order to capture all possible vertical probe movement in future tests, it is necessary to determine the number of probes which, statistically, will be able to capture this dispersion.

Keith et al. (1996) describe one method of determining the required number of samples for a specific environment, given the standard deviation of a previously studied sample set from that environment. They specify an iterative process, as follows:

first-pass equation: $$n = \left[z\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{SD}{E}\right) \right]^2$$

subsequent passes: $$n = \left[t\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{SD}{E}\right) \right]^2$$

where:

n = required number of samples for a specified confidence level

z = standard normal deviation from the z-distribution (using α for a two-sided distribution). For a 95% confidence level, z = 1.96.

α = significance level (1 – confidence level)

SD = standard deviation for a sample set

E = the tolerable error (absolute error) in the estimate of the mean

t = value of Student's t-distribution (using α for a two-sided distribution). The degrees of freedom used to obtain "t" is based on the number of samples calculated in the previous iteration.

The second equation (i.e. for "subsequent passes") should be repeated until the value of "n" stabilizes.

For subsequent probe density testing, the number of probes to be used can be determined from the standard deviation of previous trials. The most conservative estimate is obtained from the trial with the largest standard deviation, namely, the second trial in which 27 x 2000 kg/m^3 probes were tested. The standard deviation of the data obtained from this trial was 0.71 m. Setting a 95% confidence level and selecting a tolerable error of 10% of the windrow height of 1.5 m, the following parameters can be used to determine the required number of probes:

$z = 1.96$

$\alpha = 0.05$

$SD = 0.71$ m

$E = (0.1)(1.5\text{ m}) = 0.15$ m

first pass:

$$n = \left[z\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{SD}{E}\right)\right]^2$$

$$n = \left[1.96\left(1 - \frac{0.05}{2}\right) \cdot \left(\frac{0.71\text{m}}{0.15\text{m}}\right)\right]^2$$

$$n = 81$$

second pass:

$$n = \left[t_{\alpha/2,DF}\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{SD}{E}\right)\right]^2$$

$$n = \left[1.99\left(1 - \frac{0.05}{2}\right) \cdot \left(\frac{0.71\text{m}}{0.15\text{m}}\right)\right]^2$$

$$n = 84$$

third pass:

$$n = \left[t_{\alpha/2,DF}\left(1 - \frac{\alpha}{2}\right) \cdot \left(\frac{SD}{E}\right)\right]^2$$

$$n = \left[1.99\left(1 - \frac{0.05}{2}\right) \cdot \left(\frac{0.71\text{m}}{0.15\text{m}}\right)\right]^2$$

$$n = 84$$

Therefore, 84 probes should be enough to capture all possible vertical dispersion within a windrow, with a 95% confidence level.

References

Keith, L.H., Patton, G.L., Lewis, D.L., and Edwards, P.G. 1996. Determining What Kinds of Samples and How Many Samples to Analyze. *In* Principles of Environmental Sampling. Second Edition. *Edited by* L.H. Keith. American Chemical Society, Washington, DC. pp. 3-40.