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ABSTRACT

Robert Stea. ECOLOGICAL SANITATION: Technical Issues on the Adequacy of On-Site Storage and Treatment and of Human Waste.

(under the direction of Dr. Mark Sobsey, Dr. Douglas Crawford-Brown, and Dr. Christine Moe)

A recent development in the water and sanitation sector is the concept of ecological sanitation (Eco-sanitation, or "Eco-San"); that is, the on-site storage and treatment of human fecal waste. The goal of this type of sanitation is to provide the user with a hygienic means of waste disposal, as well as a safe, stable, and useful end product. This paper examines the efficacy of such systems; namely, the type of treatment provided and the extent of pathogen destruction. Mathematical models of pathogen die-off data from experimental studies are used to estimate the hygienic quality of human fecal material under conditions normally found in Eco-San systems.

A review of the literature shows major gaps in the data available to model the Eco-San systems. Lack of field data on the Eco-San process results in an incomplete description of the operating conditions. The scarcity of data on the kinetics of pathogen destruction at low temperatures also adds uncertainty to the assessment. Also, much of the available kinetic data is from studies that are carried out under conditions not necessarily encountered in Eco-San. Extrapolation of pathogen destruction from the kinetic models developed under different test conditions show inconsistent results. The use of the EPA *Part 503 Biosolids Rule* pathogen reduction model also is not appropriate as a guide to determining treatment efficiency. More research and data on the survival of pathogens at lower temperature ranges is needed to determine the exact nature of Eco-San process efficiency. Existing data is used to develop a simplified model for the prediction of pathogen destruction. Recommendations are made to develop indicators of the efficacy of Eco-San treatment. The conclusions include a discussion on the way to operate double-vault latrines in dual-phase manner that will result in a safe, hygienic end product.

I. INTRODUCTION: BACKGROUND, SCOPE, AND OBJECTIVES

"Sanitation is more important than independence"
(Mahatma Gandhi)

Background

In many parts of the world the provision of water and sanitation is minimal. Governments in such areas may not have the capacity or resources to provide such services which are possible in more developed parts of the world. With regards to sanitation, both of these situations may exist simultaneously. Sanitation has received increased attention over the last several years as a component of urban infrastructure that has been traditionally overlooked. The sanitation situation in the world was described as 'a shameful scandal that is totally unacceptable' by Dr. Richard Jolly, Chairperson of the Water Supply and Sanitation Collaborative Council (WSSCC), at a recent WSSCC global forum in Manila in November 1997. He also stated that:

> "Despite all efforts during the International Drinking Water Supply and Sanitation Decade, more than 2,500 million people in the developing world do not have access hygienic means of personal sanitation. The result is a horrifying toll in death and debilitating disease. Most water supply and sanitation programs aim to improve health, but the focus has always been on providing clean water. It is only now being widely realized that the most effective way of reducing water and sanitation related diseases is safe excreta disposal. This calls for special approaches to motivate people to use latrines, that the latrines are suitable for local conditions, and that people are willing to pay for, to construct and to manage them."

The surge in urban populations is creating a sanitary crisis of unprecedented proportions. Many have sought solutions to the unique set of problems caused by the sanitary needs of large urban and peri-urban environments, especially in developing countries. It is obvious that new approaches to sanitation be considered in order to alleviate the current crisis. The two basic approaches, as shown in Figure 1.1 below, are proving to be inadequate in

providing adequate sanitation to the unserved poor. These two basic types of systems are usually referred to as the "Flush-Discharge" system, and the "Drop-Store" system. In the Flush-Discharge system, a relatively large amount of water is used as a carrier for a much smaller amount of waste. In the Drop-Store systems, open space and adequate soil and groundwater levels are needed to ensure the minimum of environmental impacts. There are obvious disadvantages to both systems. In Flush-Discharge, large amounts of water that could otherwise be used as a potable water resource are necessary for the system to operate. In locations with scant water supplies, this type of system is inadequate. Also, the large amounts of wastewater created by such systems are difficult and costly to deal with. The Drop-Store system can present difficulties if located in surroundings with dense populations, inadequate soil, high groundwater, or periodic flooding.

Figure 1.1 – Schematics of the "Flush-Discharge" and "Drop-Store" systems

Over the last several years many have criticized these traditional approaches to waste treatment as a means to providing to those in densely populated urban and peri-urban areas. The infrastructure necessary to provide "flush-discharge" systems is not within the scope of most local governments. The land requirements and the risks of groundwater pollution for "drop-store" systems have also proved to be high. The need for a new, appropriate method of sanitation provision for these areas has never been more obvious.

The "flush-discharge" system has also received criticism because it is a type of sanitation that is not sustainable from the perspectives of water usage and waste management. The reason is that human waste should remain in what is considered to be a cycle, or a balance, of organic matter. The removal of waste from this "natural ecological cycle" breaks the flow of organic material, from food production back to replenishing the soil. This loop is broken

when wastes and wastewater are taken out for treatment, but are not returned. The ecological balance of waste can be illustrated as a closed loop, as shown in Figure 1.2. The use of more ecologically sound systems should allow for the reuse of organic waste without interrupting the cycle. In this case, fecal material is no longer considered a waste but as a valuable resource.

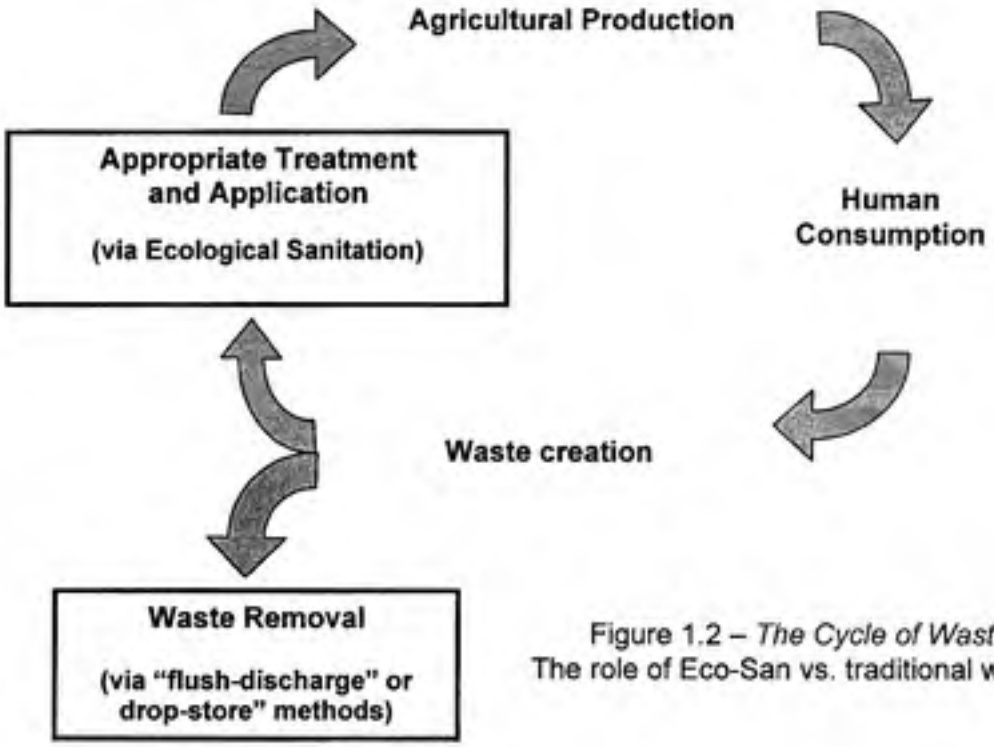


Figure 1.2 – *The Cycle of Waste Reuse*:
The role of Eco-San vs. traditional waste removal

An idea that has received increased attention during the last decade and is being promoted among international agencies is the concept of "Ecological Sanitation". An ecological sanitation system is a domestic ablution facility in which the collection, treatment, and stabilization of the solid waste all takes place on site. This would provide hygienic removal and storage of the waste, as well as the prospect of providing a useful end product that could be used as a soil amendment. The role that ecological sanitation can have in the illustrated scheme is to provide a barrier of appropriate treatment. This ensures that the survival and spread of pathogens is halted before the application to agricultural land.

The concept of reuse of human waste as an agricultural amendment is obviously not new. In the classic work entitled "Farmers of Forty Centuries" (King, 1911), much discussion is

devoted to the fact that several Asian societies practice human excrement reuse. King stated that:

> "One of the most remarkable agricultural practices adopted by any civilized people is the centuries-long and well nigh universal conservation and utilization of all human waste in China, Korea, and Japan, turning it into marvelous account in the maintenance of soil fertility and in the production of food."

McGarry (1976) reviewed historic and recent trends in the reuse of human waste in China, where this "closed loop" approach has been used for several thousand years. McGarry reported that the Chinese government estimated that one-third of all fertilizer for agricultural purposes come from human feces. He cites the practice of composting and storage as types of treatment commonly used to prepare the night soil for spreading, neither of which had been fully standardized. However, McGarry also found that over half of the individuals examined were infected with hookworm (Ascaris), and concluded that more appropriate treatment would be necessary to ensure that fecal related diseases were not spread by this practice.

Strauss and Blumenthal have described excreta as a "precious resource" in their comprehensive work in the utilization of human wastes in agriculture (Strauss and Blumenthal, 1990) as is illustrated in Table 1.1.

Table 1.1 – Nutrient values of organic fertilizers (from Strauss and Blumenthal, 1990)

	Nutrient Content as % of dry matter[1]		
	N_{total}	P_2O_5	K_20
Human Excreta	10.4 – 13.1	2.7 – 5.1	2.1 – 3.5
Cattle Manure	0.3 – 1.9	0.1 – 0.7	0.3 – 1.2
Pig Manure	4 – 6	3 – 4	2.5 – 3
Chicken Manure	6	5	2.7
Plant residues	1 – 11	0.5 – 2.8	1.11 - 11

1. Figures are taken from miscellaneous sources and relate to widely varying conditions.

It is obvious from Table 1.1 that the human excreta is actually not a "waste" but actually a resource. It is expected that the end product from ecological sanitation systems would be a valuable resource. Eco-San may be the alternative approach to sanitation that meets the criteria for sustainable systems. In order to be a viable sanitation option, Eco-San must provide adequate treatment to produce a microbially safe, nutrient-rich, and stable soil amendment. However, there are many unresolved issues with regards to the quality of treatment provided by different type of ecological sanitation systems. The following sections will attempt to investigate a basis for an analysis of the treatment provided using pertinent information from the available literature.

Scope

Sanitation is only part of a larger scheme to provide a healthy environment. Blumenthal et al (1988) described four elements essential to protect health with regards to the reuse of human waste. They listed the following steps as means to interrupt the potential transmission routes of excreted pathogens and reduce the risk of pathogens from fecal material:

- Step One: Appropriate treatment of waste material
- Step Two: Control of human exposure to the waste
- Step Three: The choice of methods of application of the wastes to crops
- Step Four: Restrictions on the crops grown for consumption.

Waste treatment is only the first in several lines of defense to reduce the health risks from the reuse of solids from ecological sanitation systems. The other methods of disease control are also critical in the overall development of programs involving fecal reuse. This paper will focus only on Step One, the appropriate treatment of the waste material at the source.

There are also many available treatment methods that have been proven to be effective in providing a safe end product. Most of these methods require conditions and operational parameters that are beyond the scope of the criteria set out in the previous section; namely, simplicity, cost, and sustainability. This paper will examine only those types of systems that meet these criteria.

Objectives

This paper will attempt to evaluate technical aspects of the treatment provided by ecological sanitation. The objectives are to:

1. identify and examine the quantifiable measures of effective ecological sanitation treatment

2. evaluate models based on previous studies of related waste treatment systems to identify the determinants of effective ecological sanitation

3. identify data requirements and research needs to evaluate the role of ecological sanitation as an effective and viable sanitation alternative

The goal of this paper is to provide a framework from which further investigation and research can be carried out to provide a more complete understanding of Eco-San.

II. DEFINING ECOLOGICAL SANITATION

A. Defining Characteristics of Eco-San vs. other Types of Sanitation

B. A Classification of Eco-San Systems

C. Description of various Systems worldwide

2.A Defining Characteristics of Eco-San *vs.* Other Types of Sanitation

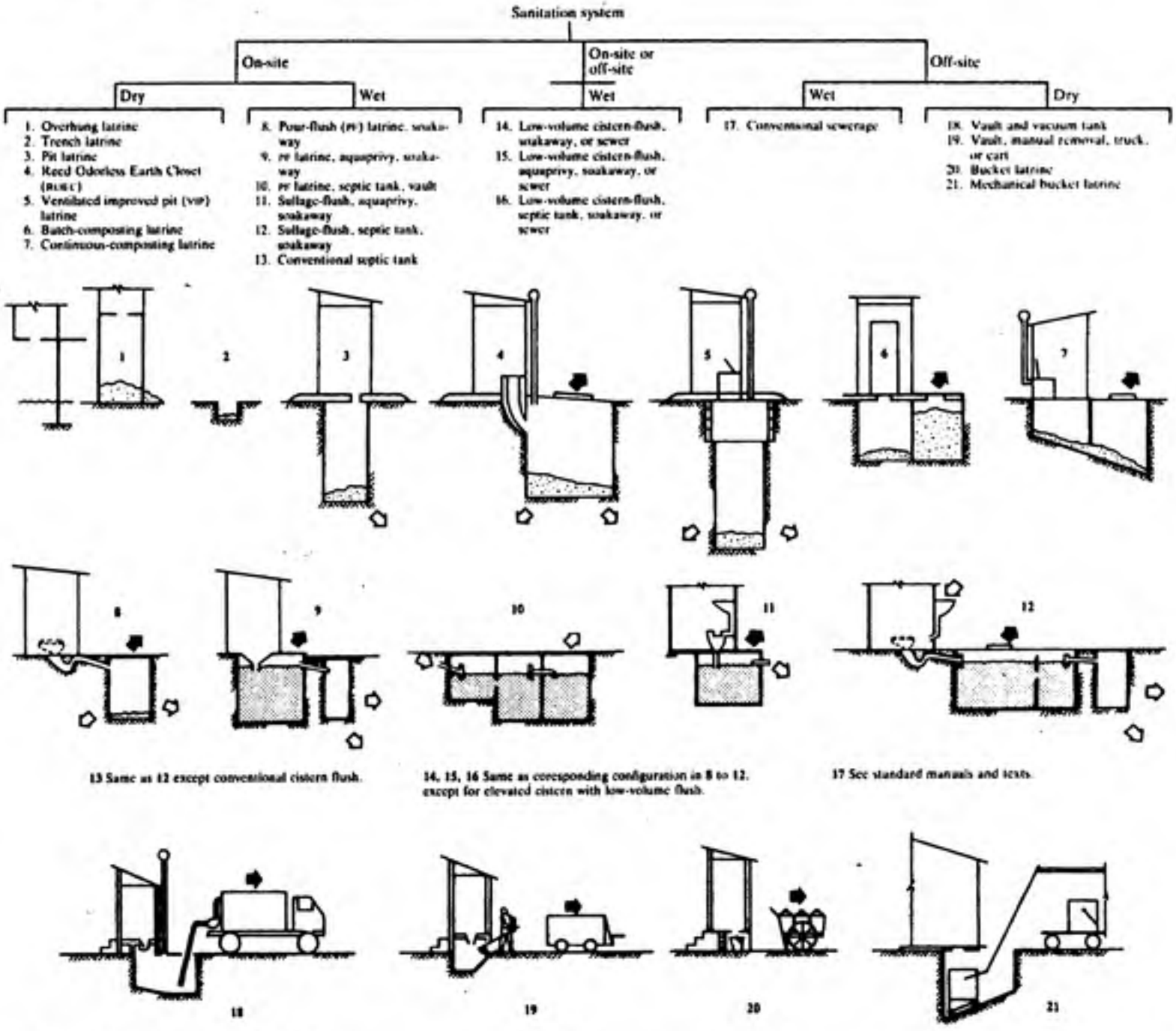
There are many types of on-site sanitation systems used around the world. Much work has been done in the last few decades to understand what types of on-site sanitation systems exist, and which types of systems could better serve those who do not receive "first world" amenities. Figure 2.1, developed by the World Bank, attempts to classify generic types of sanitation systems based on location and type of treatment (Kalbermatten, 1982).

Figure 2.1 reveals the widespread acceptance of the belief that sanitary conditions are made "more acceptable by removing unpleasant or undesired features" (Webster's Collegiate Dictionary, 1977). In most cases this is simply accomplished by removal of the fecal material itself. The majority of systems illustrated show that human excrement is either buried, or stored until it is removed from site. If the burial does not take place on-site, it is usually at a location distant from the homeowner or community. Fecal material that is left untreated in the ground is basically stored until it can be removed and treated elsewhere.

One exception to the above definition is referred to in Figure 2.1 as a "composting toilet" (see Figure 2.1, types 6 and 7). The basis for composting toilets is that human waste can be stored, treated, and made available for reuse immediately on-site. This principle would allow for the sanitizing of the fecal material, rendering it harmless with regards to possible pathogenic contamination. It would also provide the user with an agricultural amendment that would be safe, nutrient rich, and conveniently located for use in the immediate area. This type of sanitation would be an alternative to the widely accepted method of off-site storage and treatment.

In recent years, this idea has evolved from one particular system to a whole new approach of addressing the sanitary needs of the unserved poor. This approach, being promoted as an alternative to the more traditional methods of waste and wastewater treatment, is termed

Figure 2-1. *Generic Classification of Sanitation Systems*



◊, Movement of liquids; ♦, movement of solids.

Source: The World Bank, *Water Supply and Waste Disposal*, Poverty and Basic Needs Series (Washington, D.C.: September 1980).

ecological sanitation (or "Eco-San"). Eco-San is simply a form of on-site excreta storage, treatment, and reuse in a manner that accomplishes the removal of the undesired features of the excreta without eliminating the useful parts of it. The "Eco" prefix is meant to imply a method that is both ecologically sound and economically feasible (Winblad, 1997). The ecological soundness aspect refers to placing sanitation back in the ecological "cycle" of balances involving man and nature. The economic feasibility implies the ability to do it within the means available of the communities using such systems.

Eco-San has arisen from the concept of "sustainable development" in sanitation systems. This means that a community should be able to manage a system that can be developed locally, sustained indefinitely, and not irreversibly remove scarce natural resources. It has been noted that in the past hygiene was the overriding factor in developing sanitation systems such as conventional flush and discharge sewage systems, but that such systems are unsustainable in the developing world due to the other constraints. Some of the requirements that define such sustainable sanitation systems include (SEPA, 1995):

- *Ecological* – must not exceed the self-regenerative capacity of the ecosystem
- *Health* – minimizes the risks to pathogen exposure
- *Nuisance* – odors be kept below level where they impede proper use of the latrine
- *Operational* – simple enough to be maintained by the user.
- *Cost* – compatible with the income level of the society.

Eco-San is based on several principles:

1. Human fecal matter is part of a larger cycle of man's balance with nature. It should therefore not be taken out of the cycle but instead returned to complete it.
2. The provision of water-borne sewerage systems may not be available to the under-served people, due to the lack of resources as well as the inability of governments to provide such infrastructure.
3. On-site treatment can be utilized to provide a product that will be free of pathogenic organisms and suitable for reuse.
4. Sanitation should have a minimal impact on the environment and be based upon fundamental ecological principles of zero pollution, water conservation, and recycling (Winblad, 1997).

Important aspects of Eco-San are that treatment should be simple, natural, economical, sustainable, mechanically or chemically independent, and appropriate with the norms and customs of the people served. It must also provide an end product that is readily available for reuse. This end product (commonly referred to as *biosolids*) will provide the means to complete this balance between humans and their natural environment. Eco-San systems, in theory, may provide the type of treatment that meets all of the above criteria. Other advantages of Eco-San over other types of sanitation may also include (NSFC, 1998):

- the decreased need of water for flushing compared with conventional systems
- reducing the quantity and strength of wastewater
- adaptable to remote sites
- low power consumption
- self-containment, eliminating the need of transportation for treatment and disposal
- accepting kitchen wastes, thus reducing household garbage
- diversion of waste from a being source of pollution to a valuable resource
- the affordability of such systems to the user compared with conventional systems

These defining characteristics make Eco-San an "appropriate" type of sanitation system for developing nations.

2.B A Classification of Ecological Sanitation Systems

The simplest way to classify Eco-San systems is by the type of treatment employed. The two basic methods of treatment are based on *dehydration* and *composting*. Dehydration systems (sometimes referred to as "safe storage" systems) are sanitation systems in which the vault or pit has contents with moisture levels brought down below 25%. Urine diversion, ventilation, heat, and the addition of other dry materials are typical methods of control used to achieve this level. This moisture level is used as a rule of thumb to ensure that pathogen destruction is taking place. Composting systems are based on the fact that the energy generated by the decomposition of organic matter collected by the system will itself produce enough heat to cause pathogen destruction. Thermophilic composting units are supposedly designed to produce heat of at least 49°C for a time long enough to expose all of the contents of the system to sanitizing conditions.

The next level of classification is based upon the type of process used to achieve dehydrating or composting conditions. The two major processes used to achieve such conditions are referred to as "continuous" and "discontinuous" (batch). The continuous system is receiving incoming fecal material at the top end, while treated material is removed from the system at the bottom end. This continual process allows for the uninterrupted maintenance and operation of the system, details of which will be discussed later. Batch treatment, on the other hand, allows the solids to accumulate in the reception chamber, after which time it is sealed for a prescribed time until it is opened for biosolids removal

There are several other aspects that may be considered useful in the classification of Eco-San systems. One is the presence (or absence) of urine in the composting chamber, commonly referred to as either "wet" or "dry" (alternatively "mix" or "no mix") systems. Other differences are due to variations in the structure of the reaction chamber, the gaseous inlet/outlet of the vault, as well as the types and amounts of amendments used to aid the reaction process. It is difficult to define an exact "type" of Eco-San due to the wide range of operating parameters found in such systems. However, the design criteria given above can be used to classify different systems into six types. Each type is a broad range but will generally describe the system by function and process design. These types can then be used for the sake of comparison and analysis. The six types are shown below in Table 2.1 as follows:

Table 2.1 – Classification of Eco-Sanitation systems by process design

Category	Description
(1) Dehydrating Batch Wet	Solids are collected and stored in a pit or vault directly below the seat. Once the vault is full, the entry is usually filled with earth and sealed. The solids are left to dehydrate from several months to a year. Moisture is passively controlled by filtration/soaking through the underlying ground, or will be evaporated in the case of hot/dry climates.
(2) Dehydrating Batch Dry	Same as (1) above, except the moisture levels are controlled by prevention of urine and other washing liquids from entering the reaction chamber by diversion, by adding dry materials periodically to the chamber, or by allowing ventilation to drive off the moisture. Some systems may even have heating elements (solar or electric) that promote dehydration in the solids storage area.
(3) Composting Batch Wet	Solids are collected and stored together with any liquid waste, which may include urine as well as gray-water from anal cleansing and other household uses. Usually designed for use up to a year, after which chamber is sealed and allowed to compost. There can also be two pits that are used alternatively, allowing the wastes to in one vault to compost while the other is being used. This is the simplest form of composting toilets.
(4) Composting Batch Dry	As type (3) above, except the liquid wastes are allowed to drain from the unit and prevent high moisture levels that would inhibit the composting process from reaching appropriate temperatures; currently the most popular model being tested.
(5) Composting Continuous Wet	Used without interruption as the waste is removed periodically from the bottom of the pile after undergoing composting; while newly introduced fecal material is added to the top. No provision is made for liquid wastes to be removed or separated.
(6) Composting Continuous Dry	Same as the type (5) above, except for the fact that liquid wastes are either diverted (as in the case with urine separation), are dessicated by forced aeration of the system, or they are allowed to be drained from the composting unit.

2.C Description of Various Systems Worldwide

There are many different types of ecological sanitation systems being tested and used around the world. Some work has been done to identify and classify actual systems that are being used. A synthesis of past findings and recent developments would prove useful in developing a current list of systems that are known to be functional and worthy of consideration.

A comprehensive review of existing and proposed composting latrines was conducted by the International Development Reference Center and summarized in a report to the World Health Organization by the International Reference Centre for Wastes Disposal (Winblad, 1977), resulting in a report describing and illustrating twenty-five different systems. A World Bank state-of-the-art review of low-cost technology options for sanitation (Rybczynski et. al, 1982) contains a section on "Composting Privies" which lists twenty-eight references regarding on-site composting systems. A recent report by Swedish International Development Agency (1998) lists several other variations of composting toilets as well as systems based on dehydration. Another useful report was a study done on the effectiveness and user acceptance of composting toilets in New Zealand (Davison et al., 1997), a country where rural conditions have led to a greater interest in such systems. Most other references are found in development agency reports or as unpublished material, with little or no quantitative data.

Table 2.2 is a summary of the different types of toilet systems described in the reports. The table is by no means exhaustive, since modifications suited to local needs and environments would allow for a much greater list than is presented below. Table 2.2 is simply a synopsis of the most common systems being used and studied around the world.

Table 2.2 – A list of Eco-San toilets used worldwide

Type	Classification[A]	Description
Single Vault	1	Simple pit privy, anaerobic, slow and malodorous
Double Vault	1	Two adjacent single-vault latrines with common wall /superstructure
ROEC	1	Pit privy with vent, anaerobic
Gopuri	1	Double vault without floor, raised above ground; with vent pipe
Arrhenius	1	Excreta and organic refuse storage with air intake at bottom
Ladakh dehydrating	1	Excreta and urine combined with soil, then pushed into vault
Joansuu	2	Simple pit with urine diversion to mix with organic refuse
Western Pacific	2	Simple pit with urine diversion; fitted with wooden stirring mechanism
Ekologen	2	Toilet structure with plastic receptacle, left to dehydrate once full
Vietnam Open	2	Raised single/double vault, air intakes around the base; ashes added
Vietnam Closed/ LASF	2	As previous, with closed bottom; with urine diversion at slab level
Solar Double vault	2	Raised double vault with solar heating but without urine diversion
Tecpan	2	Raised, enclosed vault; with urine diversion and solar heating
Biopot	2	As a Gopuri, with a filter bed for urine at base
Kern	2	Double vault with sloping floor, used with flush water
Yemeni long drop	2	Multi-storied sanitation; feces is dropped to street level, urine diverted
Snurr-toa	2	Double vault in which the chamber below is moved mechanically
Farallones	3	Single vault with no urine diversion; compost mixed manually
Kanagawa	4	Double vault with urine diversion; user mixes compost manually
Sirdo-Seco	4	Prefabricated, double vault with baffle, solar
Carousel / RotaLoo	4	Manufactured, seat with container below, filled then rotated
Nature-loo	4	Manufactured, container ventilated once full
Wheelie Batch	4	Manufactured refuse bin compost chamber, aeration, urine diversion
CCD	4	Double vault with false floor and ventilation, organics added
Pickle Barrel Batch	4	Manufactured from pickle barrel, false floor, aeration, urine diversion
Dowmus Dry	6	Continuous flow system using worms to accelerate composting
Clivus Multrum	6	Manufactured, single vault with sloping floor
Humusdrum	6	Smaller version of Clivus
Sodertalje	6	Prototype of Humusdrum
Toa-Throne	6	Similar to Humusdrum, except that air enters through slots in floor
CADU type A	6	Simplified version of Clivus, with compost storage chamber at base
CADU type B / Minimus	6	Simplified version of above; without compost storage
Scanplan	6	Single closed vault with horizontal plates to collect feces
Shore	6	Single open vault with horizontal plates
Mulbank	6	Commercial dry unit with sloping floor, electric heating unit
Bioloo	6	As above, with heating unit for sterilization
Biolet	6	As above, with built in urine separation and filtration
Enviro-Loo	6	Grid system, agitator and paddles to break up fecal matter, aeration

A: The systems are classified according to functionality as described in Table 2.1 and signified by 1, 2, 3, 4, 5, or 6 depending on the type of treatment according to the number described in the table. Similar systems are grouped together under the same type to prevent duplication.

III. REVIEW OF TREATMENT PROCESSES

A. Treatment Objectives: Sterilization and Stabilization
B. Treatment Methods: Dehydration and Composting
C. Dehydration: Sterilization only
D. Composting: Sterilization and Stabilization
E. Current findings on Process Dynamics of existing Eco-San systems

3.A Treatment Objectives: Sterilization and Stabilization

It would be appropriate to begin a discussion on the types of treatment found in Eco-San systems with the topic of the objectives of treatment. The desired goal of Eco-San systems is to provide an end product that is largely free from pathogenic organisms, and is stable for use as an agricultural amendment. These two endpoints are commonly referred to as *sterilization* and *stabilization*. Both of these endpoints must be achieved in order for the end product to be of value to the user. Fecal material could undergo sterilization by simple storage for very long periods of time (years) without ever reaching full stabilization. The converse can also be true; a system that promotes stabilization may not always completely sterilize the product from pathogenic organisms.

Sterilization

Sterilization is the process that results in the destruction of pathogenic organisms found in human excrement. This process is of foremost importance in all sanitation systems, not only Eco-San. (The types and amounts of pathogens that are found in human fecal described in Section 4.) In order for pathogen die-off to occur, the conditions that lead to their inactivation and destruction must be promoted. The major factors that play a role in creating these conditions are:

1. temperature
2. pH
3. moisture levels
4. microbial competition / inhibition / destruction
5. sunlight (if exposed).

These factors can be optimized in different systems to promote the destruction of all pathogenic organisms and ensure that the end product is safe for human handling.

Stabilization

Stabilization is defined as the process by which microbes oxidize organic matter to a more refractory form. A stabilized end product has much of its complex organic molecules broken down into simpler forms and has a much lower energy potential with regards to further biological activity. In systems where the final product is not stabilized, the substrate retains its complex organic structure and energy.

The stability of treated fecal material is largely a function of the time allowed for biodegredation to take place. Processes that maintain long periods of microbial activity greatly reduce the fraction of complex organics remaining to be metabolized. As the process continues the remaining fraction of non-degradable organics, commonly referred to as humus, becomes larger. Highly engineered, large scale composting operations allow for a phase of treatment called "maturation" in which the end product is allowed to cure for an extended period, ensuring that microbial activity has proceeded to an adequate degree. In theory, stabilization could continue until all of the organics have been oxidized to H_2O and CO_2. This endpoint, however, is not achieved because of the limitations of the process. In this case the end product would have no value as a soil amendment.

Stabilization is important for several reasons. First, *pathogen regrowth* can occur in systems that provide an unstable end product. In well-designed composting processes, regrowth is a highly undesirable result of incomplete composting. Yanko (1987) has reviewed several studies showing that sterilized, but unstable, sludge supported *Salmonella* regrowth to high levels. Another consideration of non-stabilized compost is the presence of metabolic end products that can actually be harmful to plants. Zucconi (1981) noted that continued decomposition of immature compost, even at low rates of reaction, could cause imbalances in the nitrogen levels of the soil to which it is added. Composts with high C/N ratios will deplete the naturally occuring nitrogen in soil necessary for plant growth, while composts with low C/N ratios will release ammonia to phytotoxic levels. The final concern about

immature compost is the "nuisance potential", or how much post-process decomposition will lead to unwanted odors after treatment.

The level of stabilization necessary for the "adequate" quality of biosolids is difficult to quantify. There are several methods by which compost can be judged as reaching a satisfactory level of stabilization. Haug (1993) listed several, including:

1. decline in the temperature at the end of batch composting or curing
2. a low level of autoheating in the final product
3. organic content of the compost as measured by volatile solids content, COD, carbon content, ash content, or C/N ratio
4. oxygen uptake rate
5. the effect on seed germination and plant growth
6. the presence of particular constituents such as nitrate and the absence of others such as ammonia, sulfides, organic acids, and starch
7. lack of attraction of insects or lack of development of insect larvae in the final product
8. characteristic changes in odor during composting and odor producing potential of the final product upon rewetting
9. rise in the re-dox potential
10. experience of the operator

These parameters can provide a framework for guidelines to evaluate levels of stabilization. For example, if an Eco-San user notices that the pile of solids tends to warm up after undergoing the full extent of treatment, this would be an indication that biological activity is still taking place. S/he would then realize that the product is not fully stabilized and would require further treatment.

The importance of stabilization and the issue of the regrowth of Salmonella in the composting process are major concerns to the EPA. The *40 CFR Part 503* rules contain guidelines for the testing of treated sludge "at the last practical monitoring point before the sewage sludge is applied to the land or placed on a surface disposal site" (EPA, 1992). In this case, the detection of the number of fecal coliforms is used by the EPA as an "indicator" for the possible presence of Salmonella. This would indicate if the sludge had been adequately stabilized to prevent pathogen regrowth. According to the EPA (1992):

> "The fecal coliform requirement is based on experimental work by Yanko (1987) which shows that this level of fecal coliform correlates with a very low level of salmonellae detection in composted sludge (EPA, 1992). Anecdotal reports suggest that some composting facilities may have difficulty meeting this requirement even when salmonellae are never detected. This might be expected under several circumstances. For example, even severe thermal treatment of sewage sludge during composting can totally eliminate salmonellae yet leave residual coliforms. If the product has been poorly composted and thus is a good source of food, fecal coliforms may have regrown after the compost has cooled down from thermophilic temperatures. Under conditions favorable for regrowth, the fecal coliforms can regrow to levels higher than 1000 MPN per gram. For this reason, all the Part 503 Class A alternatives allow for the use of a test to determine that the *Salmonella* sp. are below detectable limits."

Proper design and operation of composting systems should provide a stable end product ensures that reinfection and recontamination does not occur. There would be no value in providing a process that sterilizes a product, only to allow the possibility of future contamination. The fecal material should be allowed to metabolize to the extent where the complex organics are oxidized to simpler metabolic by-products, metabolic by-products are decomposed even further to simpler forms, and the nuisance potential is reduced to a minimum. Stabilization should not be thought of a process whereby the final product is H_2O and CO_2, a claim made by many bioengineered systems. The value of compost as a soil amendment is in a large part dependent on its organic constituents. Stabilization can simply be considered sufficient if the end product does not exhibit further microbial activity that could interfere with the compost storage or reuse.

3.B Types of Treatment: Dehydration and Composting

The biological, chemical, and physical processes that take place within on-site sanitation systems are very complex. A glance at Table 2.2 will provide one with an appreciation for the variations of only this one type of sanitation, and does not include the other on- and off-site systems. In order to simplify the description of the processes involved, we shall use the aforementioned definitions of the general *types* of systems as models. As previously mentioned, Eco-San processes can be classified as six different basic types:

Table 3.1 – Types of Eco-San processes

(1)	(2)	(3)	(4)	(5)	(6)
Dehydrating Batch Wet	Dehydrating Batch Dry	Composting Batch Wet	Composting Batch Dry	Composting Continuous Wet	Composting Continuous Dry

One should notice from this table that there is no defined "Dehydrating, Continuous" system. This is because the dehydrating systems are typically enclosed once full, hence any treatment that has taken place during use is of minor significance compared to the long-term treatment during storage.

To simplify the description of the treatment found in such systems, the two most common systems from Table 2.2 will be used, namely number (2), the "Dehydrating Batch Dry" (or Dehydrating for short); and number (6), the "Composting Continuous Dry" (or Composting). An outline of the major factors that describe and define the treatment of fecal material will be presented. The following sections summarize the parameters that define the two different treatment processes (Dehydrating and Composting) found in Eco-San systems.

3.C Dehydration: Sterilization Only

Dehydration of fecal material is the simplest form of on-site treatment. The main two process parameters in the dehydration of human waste in Eco-San systems are *moisture level* and *time*. Dehydration occurs passively in systems, but it can be actively induced by an increase in heat or airflow, by liquids (urine) diversion, or simply by extended holding times. In Eco-San systems that rely on dehydration, biological activity does not contribute to the sanitizing process and therefore issues such as airspace, nutrient balance, and substrate biodegradability will have little or no effect on the process. Very high pH levels, over 11, could promote sterilization (for example, by lime addition), but will not be discussed as a typical Eco-San treatment method.

The dehydration process may not lead to the metabolic breakdown of the fecal matter and leaves an unstable end product (the importance of which is to be discussed later). Dehydration itself can be a valuable tool in providing a pathogen free end product, but is only a step in providing a suitable end product for agricultural reuse, which is the goal of Eco-San. Therefore, the process of dehydration should be viewed as only a part of the overall treatment process of fecal waste.

Moisture level reduction

Dehydration is usually defined as the reduction of moisture to below 25% of the total weight of the composting mixture. The reduction of moisture levels in the waste ensures that any biological activity in the system is no longer possible. These low moisture levels also create an environment that is unfavorable to the survival of the microbes already present in the system, leading to the destruction of pathogens in the waste. The level of moisture within an Eco-San system is obviously not uniform. The older fecal material will more than likely be drier than material deposited afterwards. In any case, it is assumed that the time factor will be long enough to ensure that drying out takes place throughout the pile. Feachem (1983) surveyed several studies containing data on on-site sanitation and surmised that the reduction in the level of moisture that can be obtained with such systems may reach down to 25 percent. Others predict that an actual figure may be higher, probably between 25 to 50 percent.

The level of moisture is dependent on other factors, such as the length of residence time of the process, the environmental moisture levels, average ambient temperatures, soil conditions, and the like. Given the usual one year residence time, Eco-San systems will only reach the moisture levels necessary for pathogen destruction probably only in very dry areas which have relatively high year-round ambient temperature. It would be advisable to consider the climatic conditions of an area first before recommending that dehydrating Eco-San units are used.

Relevant information on the effects of dehydration on pathogen survival can be found in literature pertaining to sludge drying beds. Although these studies were conducted under conditions that would rarely be found in Eco-San systems, the results can be useful in determining trends may be similar to on-site dehydrating toilets. Some of the studies conducted have shown a wide variety of moisture levels to which sludge can be dried. These levels are normally dependent on the thickness of sludge layers applied to the drying bed. For example, Hurst (1978) conducted tests to determine the moisture level of sun-dried sludge in Texas and showed that the lowest level of moisture reached after three months to be only 41 percent. His study did not mention of the depth of layers used, however, and it is possible that they were relatively thick. On the other hand, Murray (1960) studied sun-dried sludge in South Africa and observed a moisture level reduction down to 10% after two months, with sludge layers of about 2 inches thick. Other studies using methods to further dessicate sludge down to much lower moisture levels have been conducted, and will be discussed in the section on *Ascaris* survival in Chapter IV.

The ratio of surface area to volume is critical in moisture removal. A large surface area relative to the volume of sludge would ensure that the moisture could evaporate and leave the system. In the case of Eco-San systems, which usually have about a one cubic meter vault chamber, this ratio is much smaller and leaves one to estimate that a very long time is needed to dry the fecal material to desired levels. In addition, sludge that is treated on drying beds is exposed to sunlight, wind, and temperatures that greatly facilitate dessication. Human fecal material would not be exposed to these conditions unless they were removed from the treatment vault and laid out in the open.

The particle size of the dehydrating material is also a consideration for the time necessary for dehydration. Since moisture removal from within a particle is a direct function of the

temperature, the rate at which the temperature can be increased inside the particle is critical. The clumping of solids plays a large role in the moisture retention capacity of sanitation systems, since it increases the time necessary for heat transfer throughout the particles. Table 3.2 shows the estimated heat transfer times into hypothetical spherical compost particles in order for the center of the mass to reach 90 percent of the level of heat at the surface of the particle.

Table 3.2 – Heat transfer related to particle size (adapted from Haug, 1993)

Particle Radius (cm)	Time to Reach 90% of Surface Temperature (h)
1	0.1
10	10
20	40
50	250
100	1000

This illustrates the importance of providing large surface area and small particle size to ensure that dehydration occurs uniformly throughout the vault. The implications are that a simple Eco-San system based on dehydration should still be mixed in order to ensure the drying of fecal material.

Time

The time necessary for the destruction of pathogens by dehydration is not very well defined. It would be ideal to retain human fecal material for the longest possible duration to ensure that there is absolutely no pathogen survival. Depending on the conditions and the pathogens of concern, this may take over a decade. Some pathogens of interest have shown to be extremely resistant to environmental pressures, even under harsh conditions. *Ascaris*, the hardiest pathogen of the enteric disease causing organisms, has been shown to survive for years in sludge storage systems. *Ascaris* will survive longer in moist and cool climates than it will in drier, warmer environments. Once placed on the soil *Ascaris* may survive longer and will continue to be infective. Krasnonos (1978) showed that *Ascaris* could survive up to 15 years in soil. Therefore, it is important to ensure that all of the pathogens have been destroyed before the fecal material is removed from the vault.

3.D Composting: Sterilization and Stabilization

Composting can be defined as the "*the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free from pathogens and plant seeds, and can be beneficially applied to land*" (Haug, 1993). As mentioned previously, the composting process is a combination of many simultaneous biological, chemical, and physical processes. In order to define the process, the major factors involved in composting will be highlighted and discussed. These factors will then be discussed in light of conditions expected in Eco-San systems to determine if composting is actually occuring.

Another aspect of the waste treatment process is the physical and chemical condition of the substrate acting as the basis of the composting process. The five main items of this category *are temperature, moisture, free airspace, pH, nutrient balance, aeration,* and *substrate biodegradability*.

Temperature

Temperature levels reached by composting systems are the *result* of the composting process. Temperature levels reached by well-designed composting systems can reach well over 60 °C. If a system is not operating properly, the temperature levels will drop dramatically and will not be sustained over 45 °C for long. Once microbial activity has slowed down or stopped, the composting pile will then cool to the surrounding temperatures. Thus temperature itself is not a parameter that can be designed into the process. It is rather the result of the extent of the composting process taking place and the retention properties of the pile to keep the heat generated.

Moisture

Moisture is essential to maintain the biological activity necessary for decomposition to take place. Gouleke (1977) has recommended moisture contents as percentages of the total weight, as shown in Table 3.C.2. It becomes obvious that a theoretical moisture level of 100% would be ideal, since moisture would not be a limiting factor. However, in that case

the process would not produce a dry end product, and is only usually limited to situations in which the liquid slurry is land applied. (Autothermal, thermophilic aerobic digestion processes are commercially available and are referred to as "liquid composting".) High moisture levels also can cause packing and reduced void space, preventing proper air movement through the material necessary for aerobic activity.

In the case of ecological sanitation where semi-solid material is desired as an end product, the moisture content would have to be much less than 100% as shown in the table. In this case it is simply estimated that 50% levels would be appropriate.

Table 3.3 –Moisture contents for various materials commonly used as bulking agents

Type of Waste	Moisture content (% of weight)
Theoretical	100
Straw	75-85
Wood (sawdust, small chips)	75-90
Rice Hulls	75-85
Municipal Refuse	55-65
Manures	55-65
Digested or Raw Sludge	55-60
Wet Wastes (grass, garbage)	50-55

A study by Senn (1971) demonstrated that high moisture levels in the composting of dairy manures had a distinct effect on the temperatures achieved during the process. At 66% moisture the temperature during the process did not rise above 55 °C, but at a reduction to 61% moisture the temperature rose to 75 °C. In a test run at 60% moisture, the temperature quickly rose above 75 °C and remained for several days. It was concluded that the higher moisture content impeded the composting process because the excess wetness caused packing and reduced free airspace, preventing proper air movement necessary for biological activity.

It is assumed that these moisture levels must be maintained in Eco-San systems for the material to undergo the composting process. Any drop in moisture below the 50 percent will result in the reduction of biological activity. It is estimated that if moisture levels fall between 25% and 35% the system will no longer be considered as composting but rather will fall into the realm of dehydrating. Because of this the moisture can be maintained at these higher

levels by providing a "wet" system (see previous chapter). One concern however, with regards to the artificial increase in moisture, is the possibility of the reduction in the composting process due to other parameters, such as thermal losses or lack of air space. Promoting "wet" conditions only, without ensuring that the other all other conditions are met for composting, would allow for the prolonged survival of unwanted pathogens within the composting chamber.

Free Air Space

Free air space (commonly referred to as FAS) is also an important consideration in the operation of a composting process. FAS is defined as the voids that allow for air movement within the composting matrix (see Figure 3.1 *to be inserted*). In wet substrates, the FAS is reasonably assumed to be zero. In semi-wet/dry systems, FAS is available but only as a function of other parameters, such as time, structural properties of the compost, as well as the amounts and types of additional material used in the process. The matrix of these systems can be amended with bulking amendments to add structure to the system. The results will be to increase the FAS leading to increased aerobic microbial activity, which is essential to the composting process.

In the case of highly engineered composting systems, the types and amounts of bulking amendments are of great concern. The design of the system is dependent on the ratio of bulking agent to composting substrate. In the case of wood chips (a common bulking agent) the moisture capacity as well as the degradability of the chips must be factored in the design as part of the larger system. Wood chips is the bulking agent of choice due to their capacity to absorb moisture from the wet substrate, and thus increase the FAS, without reducing the level of moisture in the system. In such systems an FAS of approximately 30% is recommended for proper composting conditions (Haug, 1997)

In the case of Eco-San systems, most processes are designed to be relatively dry with a minimum of bulking agent addition. Commonly used bulking agents are ashes, dried grass, hay, or burned paper. These bulking agents do more to act as a carbon source than as a structural amendment providing increased FAS. It is therefore expected that the FAS, as a percentage of the total volume of the system, will not reach proportions encountered in engineered systems. In cases where no bulking agent used, the system may not have the

moisture retaining capacity necessary to reach high temperatures caused by microbial activity. This will act to set a limit on the extent of decomposition in such Eco-San systems.

Another consideration for FAS creation with bulking agent is the requirement for thorough mixing. The bulking agent should be evenly distributed throughout the composting matrix to ensure that aerobic conditions are met in the whole system, and not only in isolated pockets within the pile. In the case of poorly mixed systems, biological activity in the pile will occur for a limited time, and only in the layers that receive the amendments. Also, once the amendment is added, further mixing may be needed at a later time to allow for the continuation of oxygen supply to the pile. Eco-San systems that attempt to employ bulking agent additives are generally not well mixed and therefore cannot ensure that the whole pile is undergoing the composting process evenly.

pH

The pH of any composting system is a critical parameter in controlling biological activity. At either extreme, where both hydrogen ion (H+) and hydroxide ion (OH-) are high, levels will be toxic to microorganisms at high concentrations. Municipal sludges are notoriously variable in their range of pH due to natural processes as well as conditioning processes. In engineered composting systems, the natural tendency is for both high and low pH values to be brought into the neutral range of between 6 and 8. This buffering capacity is due to the fact that both a weak acid (CO_2) and a weak base (NH_3) are by-products of microbial activity within the system. CO_2 results from the decomposition of organic matter and will neutralize high pH conditions. NH_3 is formed from the breakdown of proteins and will buffer acidic conditions.

In most natural composting processes, a sag in the pH value is experienced during the first phases of batch systems. This is from the increase of CO_2 and organic acid production. Values as low as 4.5 can be observed at times. The pH value soon afterwards will tend to rise after this, however, due to the further decomposition of these acids. Also, the rise of temperatures and the formation of NH_3 from the decomposition of proteins will tend to neutralize the acids and take the pH value even higher, leading to a near neutral pH value in the later stages of the process. Studies have been conducted to elucidate the effect of this pH sage on the composting process. McGaughey and Gotaas (1955) attempted to reduce

this affect by the addition of calcium carbonate. Their conclusion was that it did little to alter the process kinetics and was an unnecessary consideration in the overall system dynamics.

In general, a neutral pH in Eco-San systems will ensure the optimum conditions for biological activity. Any large variations could be neutralized by the addition of buffering media. Because the composting process itself is self-neutralizing, it is usually not an important parameter to modify or control.

Nutrient Balance

In systems that require thermophilic temperatures to achieve pathogen destruction desired for the sanitary reuse of the composting material, a nutrient balance must be maintained during the process. The most important parameter defining nutrient balances is the carbon to nitrogen ratio. The C/N ratio is fundamental in describing these balances because carbon makes up the largest fraction of organic molecules in the cells, and nitrogen is important in cellular synthesis. Table 3.3 shows a summary by Kayhanian and Tchabanoglous (1992) for approximate C/N ratio for several substrates encountered in Eco-San systems.

Table 3.4 – C/N ratios for composting substrates (Kayhanian and Tchabanoglous, 1992)

Material	C/N Ratio
Night soil	6 -10
Urine	0.8
Cow Manure	18
Poultry Manure	15
Horse Manure	25
Grass clippings	12 – 15
Food wastes	15.6
Yard wastes	22.8
Mixed wastes	59.9
Straw (wheat)	128 - 150
Sawdust	200 - 500
Mixed Paper	227

In order for Eco-San systems to be effective, this ratio should be kept relatively constant. Since the C/N ratio of fecal material itself is in the range of 6 - 10, the addition of a bulking agent may be necessary to increase the amount of carbonaceous material in the system.

Some of the bulking agents shown in Table 3.4 have a much higher C/N ratio, which could be used to raise the overall nutrient balance of an amended night soil mixture.

One other consideration for C/N ratios is that these nutrients must be readily available for uptake and use by the microbes. In the case of macromolecules that contain carbon but are not degradable, the actual ratio would be lower. Nitrogen is usually associated with microbial protein molecules or ammonia, and therefore is assumed to be readily available in most systems. Thus it is important to define the type and biodegradability of the carbon source present in the composting system. In order to highlight this, Table 3.4 shows the difference in total vs. available carbon of types of substrates in different composting systems, taken from Kayhanian (1992). This will have an impact on the choice of amendment used as a carbon source to alter the C/N ratio.

Table 3.5 – Available vs. total C/N ratios in various composting systems

Component	C/N (Total Carbon)	C/N (Available Carbon)
Food wastes	15.6	12.4
Mixed paper	227	143.1
Yard wastes	22.8	14.5
Mixed wastes	59.9	34.4

Eco-San systems can be designed to operate with the use of an amendment. Some of the amendments are in the form of anal cleansing material, such as paper. Others such as ashes, soil, lime, wood shavings, twigs, or kitchen scraps are often added as well to act as an odor deterrent. All of these add to the C/N ratio and assist in the composting process. However, the amounts of carbonaceous material must not exceed the optimal levels, because this may lead to excessive drying of the system and stop the composting process.

Aeration Requirements

The amount of air made available to aerobic compost systems is another limiting factor in the process dynamics. The purpose for having air during the composting process is to supply oxygen for the biological activity, to remove excess moisture from the composting mass, and to remove heat to control the process temperatures. Because these are such fundamental aspects, aeration is a critical parameter in the process design of composting

systems. As discussed previously, in systems based on dehydration, aeration is mainly a consideration for moisture and heat removal.

The amount of air necessary for biological activity is based on the type of substrates and extent of biodegradation taking place within the system. A stoichiometric analysis of the amounts of air necessary for sludge digestion can be developed, using a typical composition of human sewage sludge as $C_{10}H_{19}O_3N$ and assuming that all nitrogen is in the form of ammonia. The oxygen demand is determined to be approximately 8.5 liters of air per gram of sludge. This is only a relative figure and the *rate* of airflow of course depends on the type of treatment and the residence time of the fecal material in the system.

Once the requirements for air quantities have been determined, the rates of air supply can be determined based on the residency time of the composting process. In batch processes, the length of residence time is considered to be the period that the fecal material is present in the chamber. In continuous processes, the time of residence is considerably shorter and is directly proportional to the time the fecal material is under the conditions that define the process. The amount of air that is present for biological activity is also responsible for moisture and heat removal. The more air present, the lower the levels of moisture and heat, which are also two important parameters for biological activity. Thus, a delicate balance must exist among these variables.

Air flow and moisture removal are inversely proportional; the higher the amount of air passing through the system, the lower the levels of moisture available within the substrate. The removal of moisture not only depends on the rate of flow, but also on the specific humidity and temperature of the air present in the processing chamber. However, if the difference between the inlet and outlet is greater than approximately 25°C, then the relative humidity of the inlet air will not be an important consideration on the overall moisture removal of the system. This means that drying can occur even in areas of high relative humidity, as long as the temperatures of the process run high enough. This can be an important consideration for composting toilets, because they are best suited in dry climates and not in areas of high humidity.

Heat is also transferred out of the system by the flow of air. Temperatures in thermophilic composting processes of engineered systems are actually controlled by varying the flow of

air into the system. In many cases the amount of air used in temperature control is greater than that used in promoting biological activity or moisture removal, especially in systems with relatively dry substrates. Large-scale composting processes produce more heat than is actually needed to ensure the viability of the biological processes and thus require heat removal. In on-site composting systems, however, the amount of heat produced by the composting process is a limiting factor and must be contained to promote the continuation of the process. Therefore airflow requirements for odor removal and biological activity must be carefully balanced to avoid excess heat removal.

Some work has been done on heat losses experienced during the operation of dry, batch composting toilets as a function of the flow of air. Chapman (1995) determined that evaporative cooling caused by the airflow needed to remove odors actually removes more heat than the composting process is able to produce. The conclusion was that airflow was the greatest factor in heat removal and in fact removed even more heat from the system than the system produced (the extra heat was absorbed in the from the surrounding environment). They recommended that airflow be regulated in order to prevent these heat losses. However, this may be hard to reconcile with the fact that the flow of air is the means by which odor removal is achieved. A low airflow will result in a greater amount of odor present in the system by promoting anaerobic conditions and increasing the concentration of odor producing chemicals.

Substrate Biodegradability

In most biologically active systems, the type and degradability of the substrate is important in the process design. The biodegradability of the incoming fecal material for composting systems will determine the quantity of heat energy available for the process, the mass balance of air supply and incoming substrate, and the oxygen demand based on metabolic requirements.

Many studies have been done to characterize human waste in terms of its chemical components. Feachem (1983) adapted the chemical composition from Gotaas as shown in Table 3.6. The C/N ratio in fecal material is in the region of 8, whereas that of urine is around 1.

Table 3.6 - Approximate chemical composition of human waste as percent of dry weight (adapted from Feachem, 1983).

Constituent	Feces	Urine
Calcium	4.5	4.5-6.0
Carbon	44-55	11-17
Nitrogen	5.0-7.0	15-19
Organic matter	88-97	65-85
Phosphorus (P2O5)	3.0 –5.4	2.5-5.0
Potassium (K2O)	1.0-2.5	3.0-4.5

Once the amount of carbonaceous material is determined, the next step is to determine the degradability of the material. Klein (1972) conducted studies on the degradability of the organic portions of composting substrates and found that the percent of substrate available for decomposition tended to be around 60%. Gouleke (1973) determined that the degradability of the total organic fraction of refuse is approximately 50%. The most extensive study carried out by Chandler et al (1980) determined the percent of volatile solid degradability of 14 substrates, including elephant, chicken, and cow manure and found that they were mostly in the range of 50% (except for chicken and pig waste which tended more towards 70%). Primary digested municipal sludge without amendments has shown to have between a 33% to 56% biodegradable fraction of its organic substrates (Horvath, 1978). In general, it is assumed that the fractional portion of organics that is readily available for decomposition in the composting process will be around 50%.

3.E Current Findings on Process Dynamics of Existing Eco-San Systems

This section is an attempt to summarize findings on treatment parameters from dehydrating and composting Eco-San latrines. These findings can then be compared with the requirements for appropriate treatment to determine if conditions support the desired process. Table 3.7 is a summary of the requirements of treatment parameters for dehydration and composting Eco-San systems to provide an end product that is relatively stable and pathogen free, as discussed in the previous sections.

Table 3.7 – Summary of requirements for dehydrating and composting Eco-San systems

Process Requirement	Defining Characteristic	Dehydrating (D)	Composting (C)
Size	vault / pile volume	N/A	large to prevent heat loss
Temperature	°C	greater at higher °C	can reach 60 °C
Moisture	% moisture by weight	below 30%	between 30% and 80%
free airspace	FAS	N/A	must be around 30%
pH	pH	N/A	between 6 and 8
Nutrients	C/N	N/A	between 15 to 30
Aeration Requirement	air supply	N/A	rates and amounts critical
Biodegradability	volatility (%)	N/A	ideally > 50% biodegradable
Mixing	agitation	N/A	necessary
Particle size	thickness	N/A	ideally < 0.1 cm
Product Stability	complete breakdown	end product not stable	stable if maintained

Note: N/A implies the stated requirement is not necessary for the type of process described.

There is little actual field data on treatment parameters for Eco-San systems. Much data comes in the form of unpublished material and incomplete studies. Also, methods of classifying systems differ and make it difficult to compare the test results. The following table is a collection of available test results that provide some data of interest. It has been taken from a wide range of reports and studies. Some are opinions by "experts" who have reviewed results and have made assessments of the outcome. This does not represent a complete set of data. Rather, it is meant to give an overview of findings from the field. Some of the above parameters, including FAS and particle size, have not been found in any studies and therefore have been omitted from the table.

Table 3.8 – Summary of results of operational parameters from tests on Eco-San systems

TYPE	°C	% moisture	pH	C/N	O_2 required	Amend-ments	Volatlity	Mixing	Source
IDEAL	45-60	40-60	7	30/1	yes	yes	50	yes	
IDEAL	25	<5-10	7	N/A	yes	N/A	unk	yes	
unknown	15-30	30-40	9.6	unk	unk	unk	unk	unk	Esrey (1996)
Clivus	21-31	30-82	7.2	unk	yes	unk	unk	unk	Cook (1981)
Bin	30-62	27-67	7.4	unk	no	unk	unk	unk	Cook (1981)
Clivus	8-26	66	7.3	unk	unk	unk	52	unk	Enferadi (1982)
Toa	10-26	68	7.3	unk	unk	unk	72	unk	Enferadi
Vault	5-32	55	6.3	unk	unk	unk	68	unk	Enferadi
Drum	7-28	66	7.6	unk	unk	unk	75	unk	Enferadi
Mullbank	15-48	72	7.3	unk	unk	unk	76	unk	Enferadi
Bioloo	14-40	73	8.7	unk	unk	unk	69	unk	Enferadi
Clivus	13	74	unk	unk	yes	yes	unk	unk	NSF (1982)
Carousel	19	49	unk	unk	yes	yes	unk	unk	NSF (1981)
EnviroLoo	15	unk	unk	unk	yes	unk	unk	yes	Banner (1997)

Note: "unk" implies that the source did not mention the parameter of concern. N/A signifies that the parameter is not essential for the type of system.

Several trends become clear from the above table. Temperatures obtained in composting systems are not reaching thermophilic levels proposed. This indicates that the composting process is taking place either in a very limited manner or is not occurring at all. Another rather surprising conclusion is there is no data on the C/N ratio for these systems. The following is a summary of the above mentioned studies from the landmark report by M. Strauss and U. Blumenthal "Use of Human Wastes in Agriculture and Aquaculture" (1990):

"Data collection seem to indicate the following:

- Within the range of humidities occuring in the DAFF latrine vaults (average of 34-44% water content for the lower and upper strata in the well-operated latrines), there is no correlation between the humidity and the egg viability.
- During the storage of the fecal material in the latrine vaults, average egg viability values do not drop below 30%, even if the storage period is about one year. However, from the few observations made so far for the "abono", i.e., the fecal material removed from the vaults, it appears that the viability drops rather rapidly upon removal of the fecal material from the vault. This might be due to the reported practice of many of the users to sun-dry the material before filling it into bags for the transport to the fields.
- A speculative inference from these observations is that a one-year storage period is not sufficient to achieve very low or zero egg viability at the average temperatures of 17 – 20° C. Neither does the humidity prevailing in the vaults, which is low relative to the other types of latrines, affect the egg viability. However, the sun drying of the abono may possibly lead to a further reduction of the humidity such that the dryness of the material may enhance die-off. This

> would be in agreement with information found in the literature on *Ascaris* egg die-off, which reveals that the water content of the fecal material must drop to approximately 5% or below for the dryness of the material to become a relevant factor for egg die-off."

The above observations conclude that the operating temperature of the system is the most important factor with regards to system efficiency. This is reported to be around 20°C for most of the process.

In a field evaluation of composting toilet systems by the U. S. Department of Agriculture (Cook, 1981), results from a two year study on the die-off of coliforms in on-site systems were published. This report compared the efficiency of 33 composting units, 26 of which were composting units and 7 that were dehydration units. The composting units were expected to reach temperatures of 50 – 65 °C for several hours, whereas the continuous unit was only expected to remain at ambient temperatures and allowed curing for up to 2 years. The actual result shows that the temperatures reached by the continuous composting units averaged 26°C, which is presumably close to the average ambient temperature. The moisture levels were mostly between 30% and 80% by weight of the total mass, and the pH varied between 6.5 and 7.5 in the composting pile. (The results of the study showed that none of the units achieved any reduction in total or fecal coliforms. The method of testing is questionable, however, since there was probably fresh fecal material mixed throughout the system periodically, causing recontamination of the composted material.) The results do show, however, that adequate temperatures for "composting" are not reached in such systems. In fact, the dehydration systems that were also tested alongside the composting units actually reached higher temperatures with anaerobic activity than the continuous composting units with presumably aerobic activity.

Most of the data indicates that most Eco-San systems will operate at relatively low temperature ranges. These results support the conclusion made by Feachem (1983) that it is very likely for toilets designed as "thermophilic composters" will in actuality act as "mesophilic dehydrating" units. The adequateness of treatment of human fecal matter under these operating conditions is to be addressed in the following chapter.

IV. REVIEW OF PATHOGENS

4.A Pathogenic Organisms in Human Excreta

The pathogenic organisms that are present in human excreta have been well documented. Several comprehensive reports describe and classify these organisms based on type, infection, and illness. The works of Fradkin et al (1985), Feachem et al (1983), Kowal (1982) and many others provide complete surveys of microorganisms of concern in sanitation systems and waste reuse. Sections 4.A.1 through 4.A.5 of this paper will to summarize this information arranged as human excreted viruses, bacteria, protozoa, and helminths, as well as fungi commonly found in such waste treatment systems.

Pathogenic Viruses

Viruses are the smallest pathogenic organisms excreted in human feces, and are less than 1um in size. Enteric viruses can be present in numbers up to 10^{11} per gram of feces from and infected host. The virus particles cannot multiply outside of the their host, but may survive for a period of several weeks given favorable conditions. A study of human viruses in water, wastewater and soil found that excreted viruses have reached concentrations of 10^5 per liter of raw sewage (WHO, 1979), and can be between 10^2 – 10^4 in sludge after the primary treatment of wastewater (EPA, 1985).

According to Bitton (1980), viruses may account for approximately twice as many gastrointestinal infections than bacteria. Enteric viruses are primarily transmitted from person to person by the fecal-oral route. The transmission can occur by direct personal contact or contact with contaminated surfaces, by ingestion of contaminated food or water, or possibly via an airborne route. Viruses are associated with diarrheal diseases, including the caliciviruses, adenoviruses, astrovirus, hepatitis A and E viruses, and the rotaviruses. Polioviruses are unique in that they are the major permanently crippling diseases of infectious origin. Hepatitis A virus occurs endemically in many parts of the world and is also

spread via the fecal-oral route. Table 4.1 lists the commonly found pathogenic viral agents in human excreta.

Table 4.1 - Common viral pathogens excreted in human feces

Species	Symptoms or Disease
Adenovirus	respiratory and eye infections, acute gastroenteritis (GI)
Astroviruses	acute GI
Caliciviruses	acute GI
Coronaviruses	respiratory tract (UR) illness, possibly GI
Enteroviruses	
Polioviruses	poliomyelitis, meningitis, fever, paralysis
Coxsackieviruses (A, B)	numerous conditions
Echoviruses	numerous conditions
other enteroviruses	encephalitis, hemorrhagic conjunctivitis
Hepatitis A Virus (HAV)	infectious hepatitis
Enteric non-A, non B (HEV)	infectious hepatitis
Parvoviruses	gastroenteritis, anemia, hydrops fetalis, others
Reoviruses	possibly fever, rash, mild GI and UR
Rotaviruses	acute GI, vomiting, diarrhea

Pathogenic Bacteria

The feces of a healthy, uninfected person normally contains many different bacteria in numbers reaching 10^{11} per gram. These bacteria include the Enterobacteria (*E. coli*), Enterococci, Lactobacilli, Clostridia, Bacteriodes, Bifidobacteria, and Eubacteria to name a few. Other normal enteric bacteria exist in healthy individuals and will be present in the fecal material, but are not responsible for causing disease. There are other bacteria that are normally absent from the intestines of a healthy individual, but can enter a host by ingestion via the fecal-oral route or other means (eyes, lungs). These bacteria will then proliferate in the intestines of the infected person, and the feces passed will contain a high number of the pathogenic bacteria that can in turn infect others. Table 4.2 lists the most common of these pathogenic bacteria and associated diseases. Diarrhea or diarrhea-like symptoms are the illnesses usually associated with bacterial related diseases.

Table 4.2 – Common bacterial pathogens excreted in human feces

Species	Symptom or Disease
Campylobacter jejuni	gastroenteritis
Escherichia coli (pathogenic strains, and other)	gastroenteritis
Leptospira spp.	leptospirosis (Weil's disease)
Salmonella paratyphi A, B, C	paratyphoid fever
Salmonella typhi	typhoid fever
Salmonella spp. (other)	salmonellosis
Shigella spp.	shigellosis
Vibrio cholerae	cholera
Yersinia spp.	Yersiniosis

Pathogenic Protozoa

There are several species of protozoa associated with enteric infection and disease. The most common illness associated with such infections is diarrhea or dysentery. These organisms are usually ingested in cyst form, which then excyst and proceed to infect the individual. The inactive, robust cyst form of these protozoa provide a high degree of survivability in the environment, leading to a prevalence of the organisms in water and waste related disease outbreaks. *Giardia lamblia* is the most prevalent parasite in humans in the US. A report identifies *G. lamblia* as the cause for over 20 percent of the determinable waterborne disease outbreaks (Yates and Yates, 1988).

Table 4.3 – Common pathogenic protozoa excreted in human feces

Organism	Disease
Balantidium coli	balantidiasis
Cryptosporidium parvuum	cryptosporidiosis
Dientamoeba fragilis	amebiasis
Entamoeba histolytica	amebic dysentery
Giardia lamblia	giardiasis
Isospora spp.	Coccidiosis

Pathogenic Helminths

The presence of these worms as a pathogenic infestation in humans is a worldwide phenomenon in developing countries. Prevalence is directly associated with low economic status and high contamination of the immediate environment (Headlee, 1933). In the US, the incidence of helminth infections decreased dramatically over the last century due to improvements in public sanitary conditions. Developing nations that use wastewater and sludge as agricultural amendments are particularly prone to increasing the risk of contacting helminth eggs or larvae.

Pathogenic helminths include a variety of worms: nematodes (roundworms), cestodes (tapeworms), trematodes (flukes), and many others. Some of the helminths commonly found in animals can also infect humans through the handling of animal waste.

The epidemiology of helminths is quite different from that of the types of pathogenic organism previously discussed, and even among the classes of helminths themselves there is considerable difference in the means and types of infections in humans. A generalization that can be made, however, about helminth infections is that they can be quantitatively measured in terms of the number of organisms present in the host. This is usually described as the "intensity of burden" of worm infection. Another general feature of this class is that the organism goes through a complex life cycle, in which the host (humans in this case) provides the appropriate reservoir for helminth growth upon infection. There are many variations in the means by which helminths are transmitted, spread, and ingested or penetrate humans. Transmission can be simply through the fecal-oral route or can be more complex, involving different development stages of their life cycle in the environment requiring one or two intermediate hosts along their passage from one human host to the next.

Table 4.4 - Pathogenic helminths excreted in human feces

Type	Common Name	Associated Disease
Nematodes (Roundworms)		
Ancylostoma duodenale	Hookworm	Ancylostomiasis
Ascaris spp.	Roundworm	Ascariasis
Echinococcus spp.		hydatid disease
Enterobius vermicularis	Pinworm	Enterobiosis
Necator americanus	Hookworm	Hookworm
Strongyloides stercoralis	Threadworm	skin inflammation
Toxacara spp.		visceral larva migrans
Trichuris trichuria	Whipworm	trichuriasis
Cestodes (Tapeworms)		
Diphyllobothrium latum	Fish tapeworm	anemia, diarrhea, obstruction
Hymenolepis nana	Dwarf tapeworm	Hymenolepiasis
Taenia spp.	Beef/pork tapeworm	taeniasis, cysticercosis
Trematodes (Flukes)		
Chlonorchis sinensis	Chinese liver fluke	Chlororchiasis
Opisthorchis spp.	Cat liver fluke	Opisthorchiasis
Schistosoma spp.	Schistosome	bilharziasis, liver cirrhosis
Paragonimus westermani	Lung fluke	blood coughing
Fasciola hepatica	Sheep liver fluke	Fascioliasis
Fasciolapsis buski	Giant intestinal fluke	Fasciolopsiasis
Other		
Gastrodiscoides hominis		Gastrodiscoidiasis
Heterophyes heterophyes		Heterophysiasis
Metagonimus yokogawi		metagonimiasis

Pathogenic Fungi

Fungi are ubiquitous in nature and are found in most waste and wastewater water systems. They are eucaryotic and thrive in dark, moist locations. Their presence in such systems has been studied, and it has been noted that even in properly treated compost recontamination with fungi is highly likely (Fradkin, 1989). The pathogenic fungus that is of interest in

composting systems is *Aspergillus*. It is ubiquitous in sludge treatment systems and can have a somewhat serious effect from ingestion or inhalation. *Aspergillus* has been reported as causing respiratory infections of workers at waste and wastewater treatment facilities (Burge and Marsh, 1978).

Table 4.5 – Common pathogenic fungi in composting systems

Organism	**Associated Disease**
Aspergillus fumigatus	respiratory infections, otomycosis
Candida albicans	Candidiasis
Cryptococcus neoformans	subacute chronic meningitis
Epidermophyton spp.	Ringworm and athlete's foot
Trichophyton spp.	Ringworm and athlete's foot
Trichosporon spp.	infection of hair follicles
Philophora spp.	Deep tissue infections

4.B Selection of Representative Pathogens for Eco-San Assessment

The presence of pathogenic organisms is highly variable in sanitation systems. The factors influencing their presence are dependent on the characteristics of the population and include incidence of infection within a community, seasonal and climactic variations, population densities, as well as the ratio of children to adults.

The first issue to resolve with regards to representative pathogen selection is to choose which classes of organisms pose the greatest threat to human health. Some of the classes contain organisms known to be more of a health risk than others are. The relative risks of pathogens and the selection of representative organisms have been considered in the literature. The exhaustive review of information on pathogen survival by Feachem (1983) led to the conclusion that helminths would be adequate as indicators of compost quality, with bacteria and viruses as secondary indicators, as stated in the following:

> "*Ascaris* eggs are the most hardy of all excreted pathogens considered in this book. The time-temperature requirements for complete inactivation are more stringent than for other pathogens, with the exception of enteroviruses at short retention times. For this reason, and because viruses are technically difficult to enumerate in compost samples, *Ascaris* eggs make an excellent indicator of compost quality. *Ascaris* egg standards for compost have been adopted in China and Vietnam. Where facilities are excellent, a combined enterovirus-*Salmonella*-*Ascaris* standard is appropriate. Where laboratory facilities are more limited, a *Salmonella*-*Ascaris* or fecal streptococci-*Ascaris* standard should be adopted. Where laboratory facilities are poor, an *Ascaris* standard alone will prove adequate".

The authoritative work on health aspects of wastewater and excreta use in agriculture and aquaculture, known as the Engelberg Report, attempts to provide a framework from which operational criteria and health risks can be drawn. The report was the result of a meeting of experts in Engelberg, Switzerland in July 1985 concerning the development of appropriate guidelines for such systems. The report presents a summary of relative health risks from pathogens in untreated excreta and wastewater from an epidemiological basis of health effects. They also based their conclusions on theoretical considerations of factors concerning the transmission of the pathogens in the overall scheme of waste and wastewater reuse. The summary is shown in Table 4.6. According to the table, the organisms posing the greatest risk to human health are from the helminths, then secondly from bacteria, and finally from viruses. The model compares the incidence of disease but

not the excess morbidity or mortality associated with the increase of infections. Nonetheless, it provides a useful index to estimate the importance of the presence of pathogens in the end product from on-site sanitation systems.

Other attempts to define parameters in the selection for representative organisms have been made and provide a useful basis for comparison. The EPA in their risk assessment model for land application of sewage sludge (EPA, 1989) uses the same three classes as above (helminths, bacteria and viruses) from which to choose representative organisms. Although the EPA model is designed to describe wastewater and sludge from waterborne sewerage, the same methodology in the selection of pathogens can be used for on-site sanitation systems, since the health risks posed by the organisms themselves are the same.

Table 4.6 – Relative health risks from use of untreated excreta and wastewater (from the *Engelberg Report*, 1985)

Class of Pathogen	**Relative excess frequency of infection or disease associated with wastewater or excreta use in agriculture**
Intestinal nematodes: *Ascaris* *Trichuris* *Ancylostoma* *Necator*	High
Bacterial Infections: diarrhea (e.g. cholera) typhoid	Medium
Viral Infections: diarrhea hepatitis A	Low
Trematodes / Cestodes: schistosomiasis clonorchiasis taeniasis	From high to nil, depending upon the particular excreta use practice and local circumstances

The EPA model is based on the selection of representative organisms according to the following criteria:

1. The pathogen is known to be present in municipal sludge
2. The pathogen is known to cause human disease
3. More data is available for the representative pathogen than for others in the same microbial group

4. Survivability of the species is typical of others in the group
5. Minimum infective dose is known
6. The pathogen survives outside the human host
7. The infective routes (ingestion, inhalation, or skin contact) are known.

With all of the aforementioned considerations, the model of representative pathogen selection will be based on three of the classes of organisms as follows, in order of importance: helminthes, bacteria, and viruses. These three classes will be examined more closely in an attempt to select representative species.

Helminths

The helminths are the most studied class of organisms with regards of appropriate representative properties for the assessment of compost quality. As a whole, helminths are generally hardy organisms and are also involved in complex life cycles. The three that are most commonly considered as candidates for representation are *Ascaris*, *Necator*, and *Ancylostoma*. In terms of representation, *Ascaris* has been universally accepted as the appropriate candidate of a representative organism for helminthes. The main feature of *Ascaris* is the persistence of its eggs in the environment. *Ascaris* worm eggs are found in most parts of the world and besides their longevity in the environment are difficult to eliminate by waste and wastewater treatment processes. The suitability of *Ascaris* is also highlighted by the plethora of information concerning its identification, occurrence, epidemiological characteristics, and its resistance to environmental and treatment conditions.

Ascariasis is one of the most prevalent helminth infections. Some estimate that about one billion people harbor this worm (Crompton, 1989); while others suggest the prevalence is as high as 1.3 billion (Peters, 1978). The fatality rate is about 0.02 percent of those infected but the main concern of ascariasis is the effect on the quality of life of those infected. The presence of worms in individuals, especially children, causes discomfort, malnutrition, vitamin deficiencies, nausea, abdominal pain, vomiting, and digestive disorders. In cases of high intensities of infection, ascariasis can cause bowel obstruction. The migration of adult worms to internal organs such as the liver, gall bladder or appendix can lead to death. In rare cases, extremely high burdens of *Ascaris* worms have caused perforations of the

intestines of those infected, leading to death. Because helminth infections generally do not produce host immunity, the infected individual is prone to repeated reinfection by the larval forms of the worms excreted in the feces. The persistence of infection is longer than for most other pathogens also. Adult worms can live up to 1 year in the intestines, and in the case of mature female worms, eggs will continue to be passed in the feces throughout the life of the organism.

It is estimated that the daily global contamination of the soil by *A. lumbricoides* eggs, the roundworm specific to humans, is on the order of 10^{15} eggs per day (Pawlowski, 1982). Once in the human host, the potential for reproduction by the female worm is extremely high. Studies by Sinniah (1987) on the fecundity of female worms showed an average of 240,000 eggs per day per female worm. The average number of organisms likely to be excreted by an infected individual is more on the order of 10^4 per gram of fecal material (Feachem, 1983). The fact that these large numbers of eggs are being shed in fecal material leads to the widespread occurrence of the disease because it is estimated that one single egg could cause infection in an individual. Also, once infected, *Ascaris* can reinfect a human host several times.

The hookworm *Necator americanus* and *Ancylostoma duodenale*, are also two worms with worldwide public health importance. Much work has been done to elucidate their life cycle and survival outside of human hosts. It is estimated that there may be over 700 million cases of hookworm worldwide (Feachem, 1983), highlighting the spread of the organisms. Hookworm eggs are carried in fecal material from adult worms in the human host. The eggs will hatch into larvae under in favorable conditions (cool, moist soil) and can remain infective for up to 3 months. Many studies have been conducted on the survivability of *N. americanus* and *A. duodenale* in the environment and have shown that they are reasonably resistant to the environmental pressures of heat and drying, though less than *Ascaris*. General trends indicate that one week of storage time at 35 °C is necessary to ensure 100% egg and larvae destruction. At temperatures of 25 °C, a longer storage time is needed, possibly three to six months.

Bacteria

Bacteria that are commonly proposed as possible representative candidates are *C. perfringens, P. aeruginosa,* and Bifidobacteria.. *C. perfringens* could be a suitable candidate because it is a spore forming anaerobe and is found in fecally contaminated environmental samples. It is pathogenic in nature and causes gas gangrene and food poisoning. It is generally more persistent in the environment than both fecal coliforms and streptococci because of its ability to form endospores under adverse conditions. However, this ability has also caused many to discount *C. perfringens* as a suitable indicator, due to the fact its persistence allows for the continued presence of this organism in the environment. This leads to the conclusion that the presence of this organism may not necessarily reflect the true degree of pathogenic contamination.

In addition to the above, *Shigella* and *Campylobacter* are species worth considering in the search of a representative species of bacterial survival. The roles they have in the cause of human illness have been well documented. However, *Campylobacter* survival in the environment or in waste treatment systems has not been studied as well. The persistence of *Shigella* has also been studied less than *Salmonella* has; studies that have been done show that *Shigella* has less chances of survival once excreted. *Shigella* survival is severely curtailed by the activity of large populations of other naturally occurring bacteria in feces, by higher temperatures, low moisture levels, and by lower pH values (Hutchinson 1956, McGarry and Stainforth 1978). Thus, while *Shigella* is important in water-related environmental issues, it may not be a good candidate as representative bacteria for waste treatment systems.

The EPA has chosen *Salmonella* as a suitable candidate. *Salmonella* survivability in the environment as well as its impact on human health has been thoroughly studied. *Salmonella* bacteria are also capable of infecting animals and being spread via contact with animal feces or ingestion of contaminated animal products. In general, most of the types of *Salmonella* cause acute gastroenteritis with diarrhea. Some serotypes, however, namely *S. typhi*, and *S. paratyphi* (A and B) invade tissue and produce septicemia and fever. Other serotypes (*S. paratyphi* C, *S. enteritidis, S. sendai, S. dublin, S. typhimurium, and S. cholerae suis*) cause pus-producing focal lesions of internal organs. Most other types of

Salmonella cause acute gastroenteritis or asymptomatic infections. *Salmonella* are motile, nonsporulating, noncapsulate rods; and are facultative-anaerobes.

The epidemiology of *Salmonella* related illnesses have been studied since the last century, starting with William Budd (1873). He suspected that the spread of disease of "infective agents" excreted in feces was passed on by contamination of food or health related workers or by contaminated food and drink. These bacteria are excreted in very high numbers in the feces of infected individuals, sometimes up to 10^{10} *Salmonella* per gram of fecal material. Table 4.7 illustrates the findings of several studies of the numbers of bacteria excreted by human carriers. Thompson (1954, 1955) showed asymptomic carriers of *Salmonella* also shed high numbers of organisms during infection.

Table 4.7 – Typical numbers of *Salmonella* excreted by human host during infection

Serotype	Numbers Excreted	Study
S. typhi	10^{11}	Merselis (1964)
S. typhi	$4.5x10^{7}$	Thomson (1954)
S. paratyphi B	$1.2x10^{10}$	Thomson (1955)

Although the minimum infective dose for enteric bacteria in general has been found to be between 10^{2} – 10^{6}, the number of *Salmonella* needed to produce clinical symptoms is relatively higher. Roughly 10^{5} to 10^{9} organisms will result in apparent illness, with a median infective dose of 10^{7} (Hornick et. al, 1970). Feachem reports the average number of *Salmonella* being excreted from an infected individual as 10^{6} organisms per gram of feces. It has also been shown that as few as 1.2×10^{4} *S. anatum* could produce infection and cause a temporary carrier state in some individuals (McCullough et. al, 1953). Other studies have examined the infective dose for individuals with compromised states of health, along with animal studies. As few as 10^{3} *Salmonella* have been reported as being sufficient to produce an infection in human hosts (D'Aoust and Pivnick, 1976).

Viruses

The EPA chose the enteroviruses as the representative species for use in their risk assessments, with a focus on the echoviruses and polioviruses. These viruses have been the subjects of many studies, and their responses to environmental factors have been well characterized. The reliance on the reasoning of enteroviuses representing all viruses can be brought into question, because they may not represent a "worst case" scenario with regards to survivability in the environment.

Studies conducted by Burge et al (1981) determined the relative time for the reduction of pathogens in composting systems. The comparisons also included a review of reduction tests on other various pathogenic organisms. Their results indicate that bacteriophage f2 was much more heat sensitive than all of the other viruses tested (HAV was not included in the study). The next closest was the poliovirus 1. The authors suggest several reasons for longer survival: multiple reactivation (damaged genomes complementing each other to produce infective particles), aggregation of particles, or the presence of heat resistant strains. Another study by Ward et al (1976) showed that the inactivation of picornaviruses, including polioviruses, is accelerated by the presence of NH_3. Their tests concluded that the viruses were inactivated only in anaerobically digested sludge and not in raw sludge. They inferred that anaerobically digested sludge, especially with pH at 8 or above, is naturally virucidal to picornaviruses, especially to poliovirus 1 since ammonia is produced as a byproduct of microbial activity. The effect of ammonia was shown to dramatically decrease the infectivities of other strains of enteroviruses, including coxsackieviruses and echoviruses. Reoviruses were shown to be insensitive to ammonia under the test conditions evaluated. The authors suggest that reoviruses be used as an indicator of viral disinfection in wastewater. These findings are pertinent to on-site sanitation systems, since treatment processes are often under anaerobic conditions.

Another study by Sobsey et al. (1986) compared the time necessary for inactivation for poliovirus, Echovirus and HAV in different environmental conditions at constant temperatures. HAV was shown to require roughly twice as much time for inactivation than poliovirus, Echovirus required less time than HAV but more than for polioviruses. HAV is also known to have greater persistence in the environment due to its increased resistance to heat inactivation and inactivation at low pH levels relative to other viruses. Because of this,

HAV could be considered a greater potential health threat to humans due its ability to survive longer in the environment. A similar study by Nasser (1993) to determine the comparative survival of *E.coli*, F^+ bacteriophages, HAV, and polioviruses suggested F^+ bacteriophages, followed by HAV, persist for longer periods than the pathogenic viruses and that their die-off is not influenced by the same environmental factors present in natural sources. Contrary to these studies, however, were the findings of Ahmed (1995) who observed that the thermal resistance of F^+ coliphages was comparable to pathogenic bacteria, and actually less than polioviruses in the storage of dewatered biosolids.

In light of these findings, HAV or F^+ coliphages may be a better choice for a representative organism in determining viral inactivation of ecological sanitation systems. The reduction in number of these organisms will ensure that other viral pathogens have also been destroyed. The only drawback for the use of these as representative pathogens is the amount of data available with regards to their survival under different environmental conditions. The fact that the EPA has used the enteroviruses has come into question in the light of this because it is a large and heterogeneous group. The reaction of different enteroviruses to environmental pressures can also vary, depending on the particular species in question. However, several studies have been done which give useful data for the determination of enteroviruses in Eco-San systems. Thus, for comparing pathogen inactivation models, the enteroviruses will be looked at more closely.

The enteroviruses are a group containing 3 types of polioviruses, 24 type of Coxsackievirus A, 6 types of Coxsackievirus B, 34 types of echoviruses, and several other more recent enteroviruses not included in the aforementioned categories. Adenoviruses and reoviruses are also very similar and are sometimes associated with the enteroviruses. The most important type, the polioviruses, have been shown much attention in the past due to the fact that it causes the major permanently crippling disease of infectious origin. The other enteroviruses cause a range of illnesses such as respiratory disease, meningitis, fever, rash, diarrhea, and other. More severe cases of infection can lead to the spread of the virus to other organs or the central nervous system. The minimal infectious dose of these viruses varies. It is possible that a single laboratory host infectious unit (IU) of some of the types may infect an individual. According to Fradkin (1985), a more likely scenario is a larger IU that would cause infection. Fradkin hypothesized that an infectious dose of between 5 to 30 infectious units could infect about 50 percent of the population. The other factors that

influence the size of the IU causing infection are virus type, individual physical health, physiological condition, diet, immunity, and enzymatic effects in the digestive system. Because healthy individuals do not normally excrete enteroviruses for prolonged periods, the amount of enteroviruses that is being excreted into any local environment varies widely. Feachem (1983) estimates the average of enteroviruses present in the feces of an infected individual can be greater than 10^6 per gram.

With regards to the reduction of these organisms in fecal material, the following values adapted from Feachem (1983) can be used as the typical initial concentrations of pathogens to determine the extent of die of in Eco-San systems:

Table 4.8 – Expected Concentration of Selected Pathogens in Fecal Material of a Tropical Community of 50,000 people in a Developing Country (adapted from Feachem, 1983).

Pathogen	Av. No. of organisms in feces	Concentration per liter of municipal sewage
Viruses		
Enteroviruses	10^6 per gram	5000
HAV		
Bacteria		
Salmonella	10^6 per gram	7000
Helminths		
Ascaris	10^4 per gram	600

The final concentration of pathogens in the biosolids from Eco-San are based on the Class A pathogen requirements from the EPA *Part 503 Biosolids Rule*. This will be used as a model for the case of Eco-San, because the requirements of providing an end product that does not pose a health threat to the individual user are the same. The EPA goal for the final quality of Class A biosolids as the reduction of pathogen densities to below detectable limits per unit biosolids mass as follows:

Enteric Viruses: less than 1 per 4 grams of total solids sewage sludge
Salmonella sp.: less than 3 per 4 grams of total solids sewage sludge
Viable helminth ova: less than 1 per 4 grams of total solids sewage sludge.

In summary, the following pathogens will be used to represent their respective categories in an analysis of organism survival rates and their potential for impact on public health from the use of treated fecal material are shown in Table 4.9.

Table 4.9 – Summary of representative pathogens of interest regarding the use of fecal material treated via Eco-San

Class	Pathogen	Risk[1]	Initial Concentration (organisms/gram)	Final Concentration (organisms/gram)
Helminth	*Ascaris* spp.	High	10^4 or less	< 1 per 4 grams
Bacteria	Salmonellae	Medium	10^6	< 3 per 4 grams
Viruses	Enteroviruses	Low	10^6	< 1 per 4 grams

1. Risk is defined as the liklihood of disease, based on probability of contact and infective dose.

This information will be used in the following sections to determine if the treatment expected in Eco-San systems is adequate to provide an end product which will have the reduction of pathogens outlined in Table 4.9.

V. PATHOGEN SURVIVAL DURING TREATMENT

A. Models of pathogen die-off during Eco-San treatment
B. Survival of Helminths
C. Survival of Bacteria
D. Survival of Viruses
E. Discussion

5.A Models of Pathogen Die-Off in Eco-San Treatment

The data regarding the survival of pathogens mentioned in the previous section can be examined to establish trends of pathogen survival in treated excreta from Eco-San systems. These trends can be useful in the prediction of the efficiency of different types of systems, as well as the quality of end product from various conditions. Several approaches can be used to model these trends. The most common model is the kinetic model, based on changes in concentration of organisms over a period of time as a function of the process parameters. Another model frequently used for such systems is the "threshold" time/temperature model. This model is based on the use of data from studies that determine the time and conditions necessary for potentially complete destruction of pathogens. The result is a guideline of operation for the minimum of time and temperature necessary to ensure appropriate end product quality. The final model for the sake of comparison is simply based on the EPA's version of the Part 503 Biosolids Rule.

There are other types of models that may be useful in relating the variables of interest in Eco-San. One type found in several of the earlier studies attempted to relate the die-off of pathogens under certain conditions as a function of time by using algebraic formula. This approach only results in an equation relating die-off and time for each specific set of temperature and moisture level. Thus, a large set of equations would be needed to describe the wide range of conditions experienced for any waste treatment systems. Also, within kinetic modeling there are variations as to whether the relationship can be first, second, or higher order. However, these types are not as commonly employed as the three types mentioned previously. Therefore, this paper will focus on the more familiar forms of modeling pathogen die-off.

Kinetic Models

Pathogen survival is usually described in terms of the number of organisms destroyed as a function of time. Data on pathogen concentration as a function of time and other operating parameters can be used to develop kinetic models. These models can in turn be used to interpolate or extrapolate the inactivation rates at different operating conditions, and provide a basis for the comparison of different modes of operation.

Kinetic models are based on the "order" of the decay as a function of time and temperature. First order relationships imply that the die-off rate of organisms is directly proportional to time. Second order relationships signify that this rate is to the order of the square of the time involved. There are several other variations that can be used to describe survival data more reliably, such as multi-hit kinetics and high-initial death rates. Variations in such relationships are beyond the scope of this paper. Therefore it will be assumed that first order kinetic equations are adequate to describe pathogen survival and this model will be applied to the available data.

The mathematical relationship describing the first order relationship between time and pathogen concentration is of the general form:

$$dn/dt = -\mathbf{k}(n)$$

where n = number of viable organisms
$\mathbf{k}$ = thermal inactivation coefficient, (in $\log_{10}$[no. of organisms] / day)
dn/dt = the change of the number of organisms with respect to time.

The thermal inactivation coefficient, **k**, is in units of the logarithm of the number of organisms which have died as a function of time ($\log_{10}$[no. of organisms] / day). If **k** is constant, then integration yields the concentration of organisms after a specified time *t* as:

$$n_t = n_o e^{(-kt)}$$

where n_t = the concentration of oganisms after time t, and
n_o = the initial concentration of organisms.

If the equation above is rearranged by taking the log of both sides, rearranging and converting to base 10 logs we find the following:

$$t = [\ln(n_o / n_t)] / \mathbf{k}$$
or
$$t = 2.303\,[\log(n_o / n_t)] / \mathbf{k}$$

Conversely, one can determine **k** if the concentration of organisms is known at the beginning of the process, and is also known after a specified time t as:

$$\mathbf{k} = [\ln(n_o / n_t)] / t$$
or
$$\mathbf{k} = 2.303\,[\log(n_o / n_t)] / t$$

The above set of equations will be used below in the development of a set of results for the sake of the comparison of different die-off models for each representative pathogen when heat inactivation data are available. For experiments in which concentrations are known at the beginning and the end of the process, the k values will be determined and compared.

Based on this model and the information found in the previous sections, the extent of pathogen reduction necessary for adequate biosolid production in Eco-San systems is summarized in Table 5.1.

Table 5.1 – Summary of Pathogen Log Reduction necessary in Eco-San systems to produce a safe, hygeinic end product

Pathogen	**Initial Concentration**	**Final Concentration**	**Log Reduction** ($\log_{10}$[no. of organisms] / day)
Enteroviruses	10^6 / gram	1 / 4grams	6.60
Salmonella	10^6 / gram	3 / 4grams	6.12
Ascaris	10^4 / gram	1 / 4grams	4.60

"Threshold" Time/Temperature Models

The previous section focused on the extent of pathogen die-off under varying conditions based on kinetic analyses. An opposte approach is to determine the types of conditions necessary for "complete" pathogen destruction. Complete destruction is defined as the state of inviability of an organism. This approach can be labeled as "threshold" time/temperature modeling, because it estimates the time and temperature necessary to reach the threshold of adequate die-off. The length of time necessary for complete destruction can be plotted against the given temperature of the process. In order for this type of model to be adequate, a large body of data is needed to ensure that all possible conditions are accounted for. However, using information from a wide variety of studies greatly decreases the accuracy of die-off estimates.

To examine the general trends of representative pathogen die-off in mesophilic systems, a figure was prepared from the bibliographic summary of information from "Sanitation and Disease" by Feachem (1983). Each data point represents information from the referenced studies on the length of time necessary for the respective pathogens to be rendered inviable. This set of data is a compilation of results from various studies carried out under widely different test conditions.

The approach taken by most of the studies done on such systems is to provide a conservative view by presenting a lower boundary of safety. The assumption is that combinations of time and temperature over this limit will then ensure that there will be complete pathogen destruction. Figure 5.1 indicates that temperatures in excess of 45°C, maintained for at least a year, would be adequate to ensure that complete pathogen destruction is met. The question that arises from this, however, is the exact nature of the temperature profile of Eco-San treatment over one year. If temperatures are up to 45°C for only a short time, and then maintained at 20°C for the remainder of the year, it is likely that only a small percentage of pathogens would be destroyed compared to the destruction at a sustained temperature of 45°C. Environmental conditions vary diurnally as well as seasonally and are rarely constant in most geographic regions.

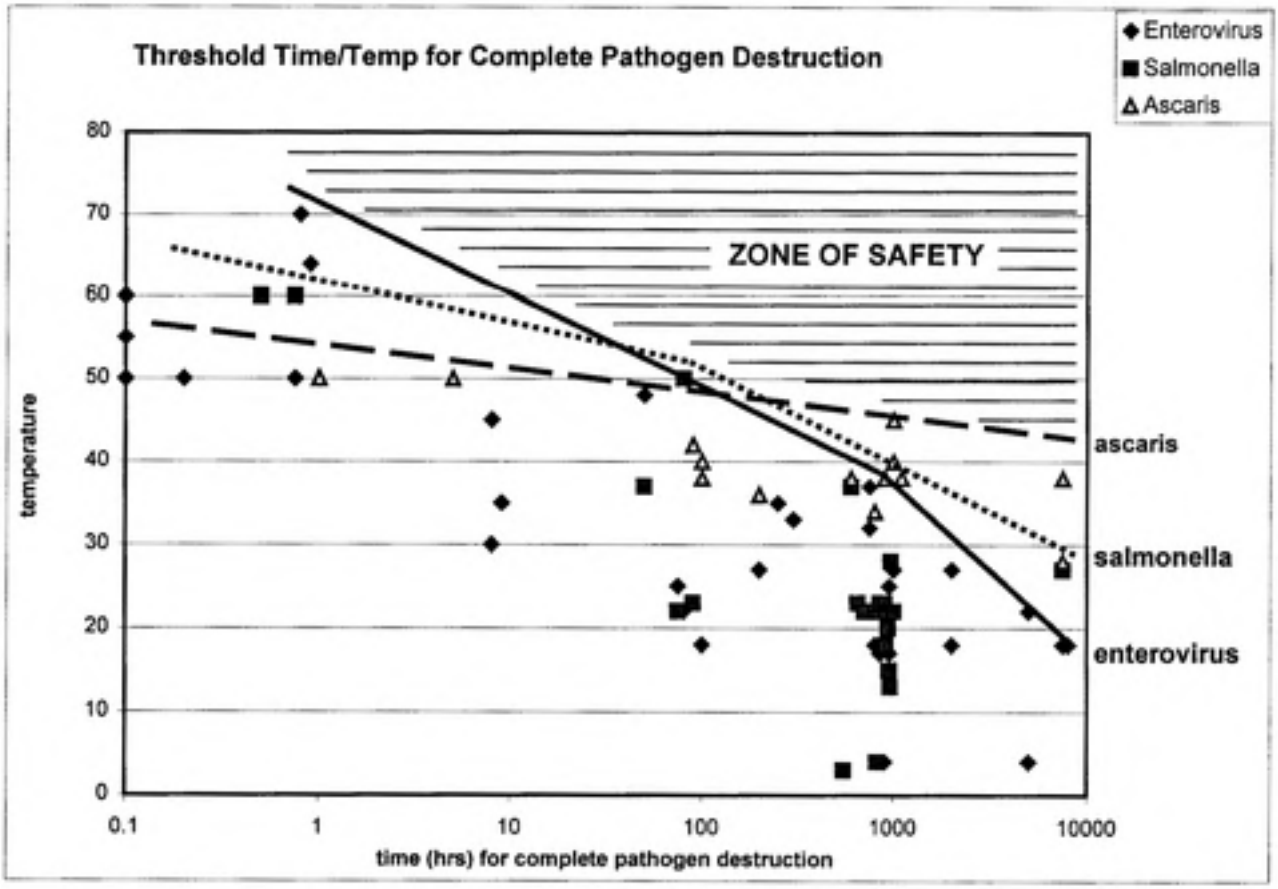


Figure 5.1 – Threshold Time/Temperature Survival of Pathogens (adapted from Feachem, 1983)

EPA Pathogen Reduction Model (503 Biosolids Rule)

The EPA has developed an extensive set of guidelines and regulations concerning the quality of biosolids for reuse. The Part 503 Regulation in the Federal Register Vol. 58, No. 32 (commonly referred to as the 503 Rules) contains the text summarizing the rules for biosolids quality and the methods and processes approved to achieve appropriate levels of pathogen reduction. Much of the rules deal with chemical contaminants, sampling, analysis, and liabilities of biosolid reuse. However, Appendix B, Subpart D of the 503 Rules focuses on pathogen reduction and vector attraction reduction requirements. Much discussion and debate exists concerning the accuracy and appropriateness of the EPA model and resulting pathogen risk assessment of biosolids reuse. Such discussion is beyond the scope of this paper and will not be discussed herewith. The results and guidelines developed by the EPA will be used as a model and compared with the previous descriptions of pathogen die-off.

The pathogen reduction rules developed by the EPA define two classes of reusable sludge:

1. Class A: pathogens are reduced to below detectable levels, and
2. Class B: pathogens are reduced to levels that are unlikely to pose a threat to public health and the environment under specific use conditions.

Class A biosolids have no site restrictions for reuse. Class B biosolids and sludge, on the other hand, are restricted to sites with minimal potential for animal and human contact for a period of time following land application until environmental factors have further reduced the pathogen levels. As mentioned in the previous sections, the final quality of Class A biosolids as the reduction of pathogen densities to below detectable limits, which are:

Enteric Viruses:	less than 1 per 4 grams of total solids sewage sludge
Salmonella sp.:	less than 3 per 4 grams of total solids sewage sludge
Viable helminth ova:	less than 1 per 4 grams of total solids sewage sludge.

Once this reduction has been met, the presence of fecal coliform or *Salmonellae* is to be monitored to detect regrowth. The rule specifies that the density of fecal coliforms in the residuals to less than 1000 MPN per gram of total solids (by dry weight). Another way to achieve compliance is to demonstrate that the density of Salmonella sp. bacteria in the sludge be less than 3 per 4 grams of total solids (dry weight).

To provide the guidelines for appropriate sludge reuse, the EPA has developed a generalized model for the die-off of pathogens in biosolids. This model provides a basis to determine the quality of biosolids with regards to pathogen content. A time-temperature relationship was established to meet certain criteria for biosolids quality according to the percent solids contained in the sludge. The relationship between temperature and time for sludges containing greater than 7 percent solids (applicable to eco-sanitation systems) is defined as:

$$\textbf{time} = (1.31 \times 10^{8}) * 10^{-0.14(\text{temp})}$$

Where: *time* = the length of time for complete pathogen destruction, and
temp = operating temperature in °C.

The equation that is used to describe the relationship between time and temperature to ensure pathogen destruction when the percent of solids in the sludge is less than 7% is:

$$\text{time} = (5.01 \times 10^{7}) * 10^{-0.14(\text{temp})}$$

The appropriateness of applying this model to estimate pathogen destruction in Eco-San systems can be examined by constructing a table of the time necessary for complete pathogen die-off at different temperatures. Table 5.2 includes typical operating temperatures and resulting times necessary to meet the EPA restrictions for Class A biosolids.

Table 5.2 – Estimates of time/temp requirements for pathogen destruction to produce Class-A biosolids based on the *EPA 503 Rules* model.

Temp (C)	Days	Years
45	66.0	0.2
40	330.8	0.9
35	1658.0	4.5
30	8309.7	22.8
25	41647.2	114.1

A graphical representation of this time-temperature relationship is shown in Figure 5.2. It is obvious from the graph that this model is not adequate to describe and determine the pathogen die-off that is taking place in Eco-San systems. A conservative estimate of an operating temperature of about 25°C would need to be maintained for almost 120 years in order to ensure, by EPA standards, that the waste is ready for reuse. According to this model, the Eco-San process is deficient in its capacity to reduce the levels of pathogens within the expected length of time for treatment.

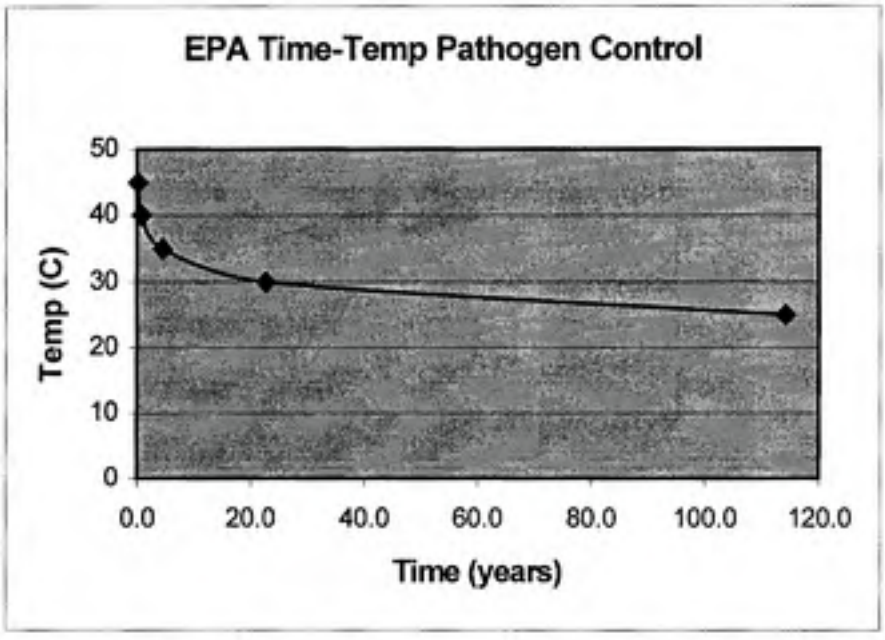


Figure 5.2 – Graphical representation of the time and temperature requirements of the EPA *503 Rules* pathogen reduction model to produce Class A Biosolids

5B. Survival of Helminths

Many studies have been done to determine the survival of *Ascaris* species in various aspects of wastewater and waste treatment processes. Because of the hardiness of *Ascaris* in the environment, there has been great interest in finding the limits of *Ascaris* survival as a means to ensure all pathogens have been destroyed. *Ascaris* left untreated can survive for years in the right conditions. Kirpichnikov (1963) reported the survival time for *Ascaris* as being 7 years in subsurface soil treated with sewage. The longest recorded survival time was from a study done by Krasnonos (1978) in Samarkand, Russia. He showed that 0.3% of eggs left in soil still had mobile larvae, and that 0.04% of were invasive to guinea pigs after 14 years in that environment. It is expected, however, that *Ascaris* will die off much more rapidly in biologically active systems with elevated temperatures.

Early qualitative reporting gives some indication of the requirements for *Ascaris* destruction in waste and wastewater systems. Some of the conclusions of these studies reveal certain contradictions, due to the differences in the methods used to recover *Ascaris* ova for viability counts, as well as variability in the composting systems used. Steer and Windt (1977) attempted to summarize historical findings in light of modern viability testing procedures. They reported differences in recovery results were possible when replicating historical tests with modern methods of testing the viability of ova. Nonetheless the information is useful in establish patterns of helminth survival.

Most studies found that helminth die-off was mostly a function of moisture level, time, and temperature. Studies to show the extent to which *Ascaris* die off is influenced by any other factors (without thermophilic temperatures) indicate that extreme conditions are necessary to lead to complete helminth destruction. For example, levels reaching a pH of 12.5 for several weeks are necessary for egg death at ambient temperatures (Schuh, 1985). Ghiglietti (1995) showed that a wide range of pH did not have any effect on *Ascaris* death at less than mesophilic temperatures (22°C), and had a minor effect at slightly higher temperatures (30°C). Since these extreme conditions will be rare in on-site composting systems, the issues of time, temperature, and moisture level will remain the focus of the discussion.

For time and temperature, several findings from field reports shed light on *Ascaris* die-off trends. A report from the Kanagawa (Japan) Prefecture (1951) states that maturation tanks operated for 80 to 90 days at ambient temperatures (between 3°C and 30°C) destroy only 25 to 70% of *Ascaris* eggs. It was speculated in the same report that prolonging the retention time in the maturation tank of the digestion process to 200 days would result in a 95 to 100% reduction in viable eggs. A set of experiments done in Naupara, India by Bhashkaran (1957) led researches to conclude that composting nightsoil for at least 10 days at temperatures above 45°C would lead to a hygienic end product. The results from this study can be set out in tabular form as follows and the decay rate determined, an analysis of which will be done in the next section.

Table 5.3 – Ascaris survival (log reduction) in nightsoil composting heaps (adapted from Bhashkaran, et al.)

Pit[1]	n_o[2]	35°C				25 °C				25 °C			
		days	n_t[3]	Moist[4]	$\ln(n_o/n_t)/t$[5]	days	n_t	Moist	$\ln(n_o/n_t)/t$	days	n_t	Moist	$\ln(n_o/n_t)/t$
1	1500	60	600	29	0.015	30	80	33	0.067	60	60	33	0.00
2	3000	60	500	32	0.030	30	40	35	0.084	60	40	35	0.00
3	2000	30	100	12	0.100	60	40	8	0.015	30	20	13	0.02
4	1600	60	60	17	0.055	30	40	13	0.014			5	0.12
5	3200	60	80	27	0.061	30	20	18	0.046	30	1	8	0.10
6	2500	60	60	21	0.062	30	1	8	0.136	30	1	8	0.00
7	1900	60	100	26	0.049	30	1	28	0.154	30	1	4	0.00
8	300	60	120	28	0.015	30	40	15	0.037	30	1		

Notes:
1. The experiments were conducted in pits used to compost fecal material
2. Number or organisms per gram of composted material was measured before composting
3. Concentration of organisms was measured after the number of days specified in the table.
4. Percent moisture level was determined in each pit after the number of days shown.
5. The log reduction was determined by using the given information

In other studies, Shulze (1969) found only a 10 percent reduction in viability of *Ascaris* eggs after 7 months of storage in sewage sludge maintained less than 20°C. Stern (1977) determined that there was no reduction in viability of eggs stored in sludge for 6 months at about 10°C. Veerannan (1977) found a 50% reduction in the viability of *Ascaris* eggs when stored up to one year, but the length of time necessary to ensure complete destruction was over 3 years. More recently, Schwartzbrod (1987) found that 4 years was necessary for the complete destruction of all *Ascaris* eggs stored in wastewater sludge at mesophilic temperatures. Related studies regarding *Ascaris* survival in sludge amended soil also provide information regarding temperature and moisture dependence on survival times.

Gaspard (1997) attempted to quantify the risks posed by the reuse of urban sludge on agricultural lands by determining the survival times of *Ascaris* eggs in sludge amended soils. He found that eggs stored at 4°C remained viable for over 2 years, while those kept between 20-30°C showed a survival time of less than a year.

Many laboratory studies have been done to understand *Ascaris* survival. The work of Cram (1943) was important in establishing the effects of sludge digestion and supplemental treatment on *Ascaris* eggs in mesophilic operating conditions. Several studies were conducted to develop a quantitative description of *Ascaris* survival in several different modes of sludge digestion. A small Imhoff tank was used as a reaction vessel, and the inflow of sewage was inoculated with eggs and cysts of intestinal parasites. Their findings showed that 10 percent of *A. lumbricoides* eggs were still viable after 6 months in digesting sludge, and at least several eggs were viable up to one year of processing. Cram states that the fluctuation of temperature between 20°C and 30°C did not appear to affect the results. Table 5.4 attempts to summarize some of the data relevant to on-site systems from the study. This table is presented here to highlight the fact that incomplete destruction of helminth eggs will result from systems in which mild environmental conditions exist.

Table 5.4 – Time/Temperature Relationship for *Ascaris* ova in digested sludge by age (days) and average percent viability (from Cram, 1943)

	Age (days)								
Temp	**1-40**	**40-60**	**60-80**	**80-100**	**100-120**	**120-140**	**140-160**	**160-180**	**180-200**
20 ° C	-	-	-	2	8	44	20	13	8
20 ° C	-	41	43	27	27	38	-	-	-
30 ° C	-	-	42	12	2	4	0	-	-

Reyes (1963) studied the effect of aerobic and anaerobic digestion on eggs of *Ascaris* in night soil. The study was based on quantitative assessment of viability and infectivity of ascarid eggs before, during, and after the destructive processes of sludge digestion in both aerobic and anaerobic conditions. Their findings led them to conclude that to ensure complete egg destruction in aerobic systems the minimum temperature is to be maintained at 45°C and that oxygen starvation in strictly anaerobic systems accelerated egg death.

They also found that at low temperatures and moderate conditions (25-35°C) helminth eggs remained viable for considerable periods of time.

Feachem et al. (1983) cites numerous studies that can be used to develop an understanding of Ascaris behavior in on-site systems. In all Feachem reviewed the results of 195 distinct studies on *Ascaris* survival. The findings from quantitative studies were summarized in tabular form and conclusions drawn (mentioned below). One conclusion made by the authors was that "temperatures of over 45°C must be reached, and preferably over 50°C. The practical way of achieving this is aerobic thermophilic composting of sludge or night soil mixed with organic refuse" (Feachem et. al, 1983).

A very relevant study by Ahmed (1995) determined the mean decay rates for selected organisms incubated in dewatered biosolids at various temperatures, including *S. typhimurium*, *Y. enterocolitica*, Bacteriophage f2, Poliovirus, and *A. suum* eggs. Ahmed found that there was no significant difference between the destruction of pathogens under aerobic or anaerobic conditions at all temperature studies. Moisture levels within the biosolid systems were maintained between 45 to 60%, to ensure that the moisture was not a limiting factor for biological activity. The pH remained between 5 and 8 and was determined to not effect the results. The results obtained for the decay rates at different temperatures are shown below in Table 5.5.

Table 5.5 – Mean decay rates for pathogens in stored biosolids at different temperatures (from Ahmed, 1995)

	Decay rate (k) in log reductions/day at the given temperature (°C)			
Organism	**50°C**	**35°C**	**20°C**	**5°C**
S. typhimurium	1.133	0.443	0.157	0.050
Y. enterocolitica	1.101	0.398	0.129	0.037
Bacteriophage f2	1.543	0.490	0.138	0.034
Poliovirus	0.813	0.276	0.084	0.022
Ascaris suum	0.211	0.043	0.008	0.001

Moisture level also plays a major role in *Ascaris* survival. Experiments by Mottram (1949) and Hogg (1950) showed that air-drying digested sludge accelerated Ascaris die-off. He found that reduction of the moisture content of sludge to below 6% was the only satisfactory means to provide complete destruction. Cram (1944) also had similar findings in

experiments to determine the level of dessication alone necessary for *Ascaris* destruction. He determined that ova were extremely resistant to drying; sludge dried to between 6% and 12 % still contained viable helminth ova. Sludge dried to moisture levels below 4% was found to be free of viable helminth ova.

Several studies have been done to describe the effect that dehydration has on *Ascaris* survival with relation to differences in temperature. One of the apparent observations from these studies is that at any given temperature, a lower moisture level will accelerate the destruction of *Ascaris* eggs. At decreased moisture levels (less than 25%, perhaps) the dehydration process may override the composting factor and will cause die-off to occur at a much sooner time than predicted by simply a time-temperature relationship. Work done in Australia (Safton, 1993) on the survival of human intestinal parasites in composting toilet systems attempted to determine their concentration in the final product of seven different composting toilets. Most of the work was done with relatively hardy organisms (*Blastocystis hominis, Entamoeba coli, Endolimax nana, Giardia lamblia,* others) compared to *Ascaris*. The units studied were of a continuous nature and it was estimated that the transit period for incoming fecal material to reach the bottom of the system was 18 months. During the sixteen months of testing samples were taken and system efficiency was determined. It was noted that the average temperature of the systems throughout the operation was between 18°C and 24°C. The units receiving moisture (urine) was compared to drier units (no urine addition) and the wetness of the final product was commented on; in both cases the author stated that "harsh environmental conditions" and not temperature was the likely cause of pathogen destruction. The discussion that follows implies that the reduction in moisture level was primary factor responsible for the destruction of the pathogens.

Because *Ascaris* forms environmentally resistant ova, it would seem likely that moist heat is more effective at the destruction of the pathogen than dry heat would be. However, the temperature range of Eco-San systems are well below the thermophilic temperatures usually found in pasteurizing systems which employ moist heat. It is therefore unlikely that this trend holds in mesophilic systems.

Table 5.6 is a summary of the available Ascaris die-off data, with the aim of relating the inactivation kinetic variable to time, temperature, and moisture level. Several other data

points from well-established die-off studies done under thermophilic temperatures are also included:

Table 5.6 – A Summary of kinetic data of *Ascaris* die-off (from various studies)

°C	% moisture	k (log_{10}[no. of organisms] / day)	pH	(an)aerobic
5	50	0.001	7	anaerobic
20	50	0.008	7	anaerobic
25	5	0.012	n/a	n/a
25	8	0.015	n/a	n/a
25	8	0.136	n/a	n/a
25	13	0.014	n/a	n/a
25	15	0.037	n/a	n/a
25	18	0.046	n/a	n/a
25	28	0.154	n/a	n/a
25	33	0.067	n/a	n/a
25	33	0.067	n/a	n/a
25	35	0.084	n/a	n/a
30	50	0.043	7	anaerobic
35	12	0.1	n/a	n/a
35	17	0.055	n/a	n/a
35	21	0.062	n/a	n/a
35	26	0.049	n/a	n/a
35	27	0.061	n/a	n/a
35	28	0.015	n/a	n/a
35	29	0.015	n/a	n/a
35	32	0.03	n/a	n/a
50	50	0.211	7	anaerobic
56	50	>200	7	aerobic
60	50	>400	7	aerobic

One of the early works to model *Ascaris* survival was done by Sandia Laboratories. Brannen et al (1975) studied the survival of *Ascaris* at 55°C, 51°C, and 47°C in sludge and concluded that no destruction took place below 50°C. (This study actually formed the basis of the EPA minimum requirement of 50°C for the Part 503 Biosolids Rule.) Further studies were conducted to model the kinetics of heat inactivation of *Ascaris* eggs over time (Sandia Laboratories, 1977) at thermophilic temperatures, and the following relationship was developed:

$$\log (n_o/n_t) = 0.0109\ (t)\ e^{0.361(Tc-50)}$$

where n_o = initial *Ascaris* population in the treatment system,
n_t = the amount of *Ascaris* eggs after a specified time t.
t = time in days
T_c = temperature in °C.

The EPA has attempted to determine the survivability of *Ascaris* under different conditions from several different studies. Early studies determined that 10 to 16 months were required for the complete destruction of *Ascaris* at 25°C, but a much longer period, over 25 months, was required for sludge stored at 4°C. Reimers et al (1990) followed this work by attempting to model the kinetic die-off of *Ascaris* in anaerobic sludge via lagoon storage at 25°C. The test results reveal no clear indication of *Ascaris* die-off over time.

Table 5.7 – The kinetics of *Ascaris* die-off at 25°C (according to Reimers, 1990)

Length of Time	**3 months**	**6 months**	**9.3 months**	**12.2 months**
% Survival	100	33	74	98
k ($\log_{10}$[no. of organisms] / day)	0	0.002225	0.004829	0.010691

A summary of the number of days necessary for a 4-log reduction in the concentration of *Ascaris* eggs according to a first order kinetic model, using averaged **k** values derived from each respective study, is shown in Table 5.8.

Table 5.8 – Comparison of time necessary for Ascaris die-off at different temperatures, from various studies.

	No. of ***days*** required for *Ascaris* destruction (4 log reduction) according to:		
Temperature	**Sandia Labs**	**Ahmed**	**Reimers**
5°C	many	9212	1129 (4°C)
20°C	1.8×10^7	1152	861 (25°C)
35°C	82,437	214	
50°C	365	44	

At 20°C, the least amount of time necessary is predicted as 861 days, or about 2.5 years. The longest number of days from the above table is 50,000 years. In any case, there is a wide range of outcomes predicted in the models presented.

The general trend of pathogen destruction with regards to time and temperature using kinetic models can be estimated by using the summary information presented in the Table 5.6. The trends that can be seen are that k for *Ascaris* increases as temperature increases, but also increases as the moisture levels decreases within the system. This would imply that at very low moisture levels (below 25%), ambient or mesophilic temperatures are not the driving force behind pathogen destruction, but rather that conditions caused by low moisture are responsible for the accelerated die-off. Figure 5.3 is a graphical presentation of the above information.

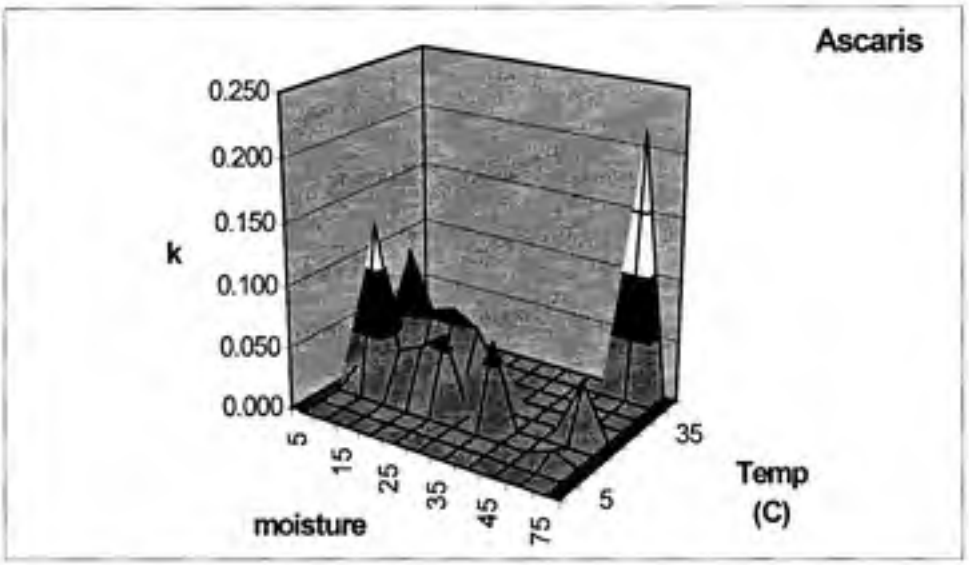


Figure 5.3 – *Ascaris* survival as a function of temperature and moisture

Figure 5.3 illustrates that at high temperatures as well as at low moisture levels, the kinetic die-off increases. There is not enough data to predict **k** at all points, but it appears that the highest **k** values would be reached at both low moisture and high temperatures. The next level of **k** values would be at low moisture and low temperatures, and also at high temperatures and high moisture levels. The lowest set of **k** values would probably be seen at conditions of low temperatures and high moisture levels.

Using these figures, the time requirements for *Ascaris* destruction at the range of temperatures and moisture levels expected in Eco-San systems is summarized in the following table.

Table 5.9 – Summary of time requirements for *Ascaris* destruction using kinetic modeling during various operating conditions expected in Eco-San systems

Pathogen	Temp (°C)	% Moisture	Log Reduction	average k	Time (days)
Ascaris	10-20	75	4.60	no data	-
		50	4.60	0.001	10,594
		25	4.60	no data	-
	20-30	75	4.60	no data	-
		50	4.60	0.008	3,086
		25	4.60	0.057	433
	30-40	75	4.60	no data	-
		50	4.60	0.043	574
		25	4.60	0.072	343
	40-50	75	4.60	-	
		50	4.60	0.211	50
		25	4.60	-	
	50-60	75	4.60	-	
		50	4.60	>100	1
		25	4.60	-	

Table 5.9 confirms the assumption that pathogen die-off accelerates with increasing temperature. There is also an indication that within the mesophilic temperature ranges, the rate of die-off also increases as the moisture levels are decreased. More data is needed to confirm this assumption, especially at the lower temperature ranges. This may have implications for the design and operation of Eco-San systems, which will be discussed in the next chapter.

The threshold model simply allows one to read off the graph illustrated in Figure 5.1 for a range of temperatures expected in Eco-San latrines. The major shortcoming of this type of model is the inability to include the other parameters, such as moisture levels, in the determination of the time necessary for pathogen destruction. The model is also inadequate for the lower range of temperatures that may be found, especially in the range of 10°C to 25°C. In Table 5.10, figures that are out of the range of values of the graph are signified by a "greater than" sign (except in the case of *Ascaris*, which is denoted as undefined).

Table 5.10 - Summary of time requirements for *Ascaris* destruction using threshold modeling during various temperatures expected in Eco-San systems

Pathogen	Temperature Range (°C)	Days required for *Ascaris* destruction
	10 – 20	undefined
	20 – 30	undefined
Ascaris	30 – 40	>>365
	40 - 50	83
	50 - 60	>1

According to the EPA pathogen reduction model discussed in the previous section, one equation can be used to determine the length of time necessary to ensure that all pathogens have been destroyed, regardless of type and initial concentration. This equation is based solely on temperature and like the threshold model does not take other operational parameters into consideration. As discussed above, this model is not particularly suited to describe the destruction of pathogens in systems such as the Eco-San latrines, but is included for the sake of comparison. The average value of each temperature range is used to determine the length of time in the equation above. This model gives time requirements that are summarized in Table 5.11.

Table 5.11 - Summary of time requirements for *Ascaris* destruction using the EPA pathogen reduction model during various temperatures expected in Eco-San systems

Temperature Range (°C)	**Average Value (°C)**	**Time (days) for Complete Die-Off**
10 – 20	15	1,046,130
20 – 30	25	41,647
30 - 40	35	1658
40 - 50	45	66
50 – 60	55	2

A side by side comparison of the three models with regards to the time necessary for *Ascaris* destruction in conditions typical in Eco-San systems is summarized in Table 5.12.

Table 5.12 - Time necessary for *Ascaris* destruction in Eco-San systems: a comparison of die-off models

			TYPE OF MODEL		
Pathogen	**Temp (°C)**	**% Moisture**	**KINETIC**	**THRESHOLD**	**EPA**
			Time (days)	Time (days)	Time (days)
Ascaris	10-20	75	-	**undefined**	**1,046,130**
		50	**10,594**		
		25	-		
	20-30	75	-	**undefined**	**41,647**
		50	**3,086**		
		25	**433**		
	30-40	75	-	**>>365**	**1658**
		50	**574**		
		25	**343**		
	40-50	75	-	83	66
		50	50		
		25	-		
	50-60	75	-	1	2
		50	1		
		25	-		

Table 5.12 illustrates that a comparison of these three models shows a wide disparity with regards to *Ascaris* die-off, especially in the lower temperature ranges. The kinetic modeling provides the least number of days, whereas the EPA die-off model gives the longest time period necessary for the reduction of pathogens to the levels specified previously. The models appear to converge at the higher temperatures. More data is needed in the lower temperature ranges to accurately describe the rate of die-off of *Ascaris*. Also, the models used in this comparison also may not be adequate to describe the nature of *Ascaris* destruction in the mesophilic temperature range.

5C. Survival of Bacteria

Salmonella has been an extensively studied organism with regards to its fate in the environment and can be found in several comprehensive reviews on the subject (Feachem, 1983; Ahmed, 1997; others). With regards to on-site sanitation systems, there are several important considerations concerning the mechanisms at work which lead to *Salmonella* destruction which will be distilled and discussed from the above reviews.

Time-temperature relationships have been established to give the relative length of time necessary at any given temperature to ensure complete *Salmonella* death. Feachem (1983) summarized several findings for this time and temperature relationship in graphical form and deduced that at 60°C it would take 1 hour for complete pathogen destruction. In the same way, a temperature of 50°C would take 1 day, and 45°C would take a week for lethal conditions for *Salmonella*. The more relevant set of data, however, for the circumstances found on-site concern temperatures found in the mesophilic range. The results from such tests indicate that pathogen destruction depends more on the effects of length of storage rather than temperature.

Feachem states that the *Salmonella* content expected in the final product of composting latrines operating anaerobically at ambient temperatures is expected reach zero sometime after two to three months. In the types of on-site composting toilets referred to in his summary, storage is somewhat limited due to the size of the units. Most were the Vietnamese type batch-operated double-vault latrines, in which the chambers are about half the size of typical double-vault latrines and are full after 4-6 months of operation. In these cases the systems should reach temperatures of about 50°C if all of the proper operating conditions are met. However, Feachem suggests in an interesting note that:

> "..the so-called composting latrines usually operate under anaerobic and ambient temperature conditions similar to pit and pour-flush latrines. The waste product from such latrines may, however, be of inferior quality due to the relatively short retention time – a few months only compared with one year or more in dry alternating-pit latrines and pour-flush latrines with twin leaching pits.." (Feachem, 1983).

In the data reported by Feachem, the results are prefaced as:

> "Samples of compost from Vietnamese double-vault composting toilets (retention time 6–7 weeks) have been found not to contain *Salmonella* (Nimpuno, personal

communication). These results must be treated with caution, however, because they may result from studies of toilets operating under controlled, experimental conditions. To eliminate salmonellae, all parts of the composting mass have to be brought to a warm enough temperature for a long enough time. This generally requires the presence of a carbon source (refuse, straw, or woodchips), careful moisture control, and a supply of oxygen throughout the mass provided by turning or forced aeration (p. 278)."

The data from the study conducted by Ahmed (1995) mentioned in the previous section can also be used to develop a time-temperature profile of *Salmonella* destruction. According to these results, a compost pile at 20°C would require about 7 days to achieve a 1 log, or 10 fold, reduction in *Salmonella*. In another study by Pike (1988) to determine the survival of *Salmonella* in stored digested sludge, the die-off kinetics were also determined at two different temperatures representing mesophilic and thermophilic conditions. The data obtained are summarized in Table 5.13.

Table 5.13 – *Salmonella* Die-off in stored biosolids (from Ahmed) and digested sludge (Pike)

	Stored Biosolids	Digested Sludge
Temp(°C)	k ($\log_{10}$[no. of organisms] / day)	k ($\log_{10}$[no. of organisms] / day)
5°C	0.050	-
20°C	0.157	0.9
35°C	0.443	-
50°C	1.133	3.4

With regards to dehydration, several experiments have shown that severe drying will accelerate *Salmonella* die-off. Stokes (1945) did several experiments on the survival of *Salmonella* in digested sludges that were dried on sludge drying beds during summer months in England. He inoculated sludge at 5.8 percent solids with 2.5×10^9 *S. paratyphi* B per 100 milliliters and found that after drying for 27 days and reaching 36 percent solids content, they were still detectable, but not after 41 days and reaching 43 percent solids. In a similar experiment done during colder months with *S. typhimurium*, 180 days of drying did not completely destroy all pathogens, even though the solids content of the sludge had reached 86 percent. In another set of experiments on the survival of salmonellae in a thermophilic biogas plant (Plym-Forshell, 1995), moist conditions were kept level at a constant temperature and resulted in pathogen destruction in less than 42 days. The author

concluded that *Salmonella* is more sensitive to moist heat. This may be due to the fact that the elevated moisture levels ensure that the entire system has reached the desired temperature. In drier systems, the composting pile may not reach required temperatures to ensure pathogen destruction. Pike (1981) conducted survival studies under varying conditions of temperature, moisture and exposure to sunlight. The findings showed that in general, with moisture levels below 60%, the time necessary for pathogen destruction was less than two months. However, one interesting note was that in the winter months, *Salmonella* was found to survive up to nine months, even with less than 15% moisture levels. One may conclude that temperature plays a stronger role in pathogen death that does moisture. In any case, there is sufficient evidence from other studies to show that if the length of time of storage in such systems is at least one year, the process will be adequate to ensure that any *Salmonella* present in the unit will be destroyed.

In another study on the effect of moisture levels on *salmonella* survival, Yeager and Ward (1981) determined that in order for long term storage to be effective the moisture levels should be maintained between 10 to 50 percent. They studied survival at 21°C during anaerobic storage, in which different levels of dewatering was accomplished by varying degrees of evaporation. The following table is an adaptation of their results, in a form relating percent solids changes to the inactivation kinetic rate.

Table 5.14 – Kinetic results of *Salmonella* Survival (from Yeager and Ward)

Temp (°C)	% Solids	k ($\log_{10}$[no. of organisms] / day)
21	5	0.016
21	30	0.088
21	86	0.107
21	97	0.008

This information shows that extreme dryness (greater than 95%) actually promotes the longevity of *Salmonella* survival. Extreme wetness (less than 5% solids) also tends to reduce the destruction of *Salmonella* over time. The trends from this data imply that as the moisture increases, the inactivation of bacteria also increases.

Again, as discussed in Chapter 3, the seemingly more important consideration for *Salmonella* is not the amount of die-off during the process, but the reinfection of the

pathogen after the process has taken place. The regrowth of *Salmonella* has been recognized as one of the major problems in the acceptance of biosolids in the U.S. Several studies have been conducted to elucidate the nature and occurrence of this regrowth. Skanavis and Yanko (1994) analyzed various soil conditioners derived from composted biosolids and found that the average total fecal coliform concentrations in four products to be higher than concentrations in the compost itself. *Salmonella* sp. were detected in the compost-based products and not in the biosolids compost or the bulking agent. Their data suggests that the nutrient value of the post-composted material contributed to the regrowth of Salmonella. This makes a strong case for the importance of proper composting to bring about the stabilization of the final product.

Table 5.15 – A summary of Kinetic data of *Salmonella* Die-Off, from various studies

Temp(°C)	moisture	k (log_{10}[no. of organisms] / day)	pH	(an)aerobic
5	50	0.05	n/a	both
20	50	0.157	n/a	both
21	3	0.008	n/a	anaerobic
21	14	0.107	n/a	anaerobic
21	70	0.088	n/a	anaerobic
21	95	0.016	n/a	anaerobic
35	n/a	0.9	n/a	n/a
35	50	0.443	n/a	both
48	n/a	3.400	n/a	n/a
50	50	1.133	n/a	both
55	50	>200	7	aerobic
60	50	>400	7	aerobic

The data from several of the kinetic studies mentioned in the previous section can also be used as a basis for the comparison of the determination of the time necessary for the destruction of *Salmonella* in Eco-San systems. Table 5.16 shows data from the various studies on the basis of the number of days for 6-log_{10} *Salmonella* reduction. The following table is a summary of the findings.

Table 5.16 – Comparison of *Salmonella* die-off in different temperature ranges, from various studies

	No. of ***days*** required for complete *Salmonella* destruction according to:		
Temperature	**Pike**	**Ahmed**	**Others**
5°C	undefined	120	undefined
20°C	undefined	38	>180
35°C	17	14	41
50°C	6	5	<7

From the summary of data presented in the previous sections on *Salmonella* survival, a matrix can be developed to examine the effects that temperature and moisture levels have with regards the die-off to within the system. This data can then be plotted in the same manner as *Ascaris* to determine the die-off trends. The trends are expected to follow the same patterns as before; namely, the higher the temperature and the lower the moisture that the die-off of *Salmonella* would increase. Ward and Yeager (1981) found that *Salmonella* survival was that lower moisture levels actually promoted the survival of *Salmonella*. However, this trend is expected to occur in thermophilic systems since it is well known that moist heat is much more effective in the destruction of microbes than is dry heat. Another factor that may also have relevance to the relationship of moisture content to die-of is the dependence of the uniformity of the heat profile on the moisture levels. In wet systems, the heat will be much more evenly distributed throughout the processing chamber than in dry systems. Dry systems may experience "pockets" of higher temperatures, with the other areas of the matrix remaining at mesophilic or lower temperatures. This may produce results leading to the conclusion that dryness may actually promote the preservation of *Salmonella*. In actuality the lack of moisture is preventing the heat from reaching the dry parts of the system. The graphical representation of Salmonella survival data is shown as follows in Figure 5.4.

It is obvious that more information is needed that relates both moisture levels and temperature on the survival of *Salmonella*. Most studies that are concerned with elevated temperature levels indicate that about 50°C brings about a very rapid increase in Salmonella die-off, well within the time frame that is afforded by Eco-San systems. Further studies on

the effects of decreased moisture levels at various temperatures are needed to better define the relationship between moisture content and *Salmonella* die-off.

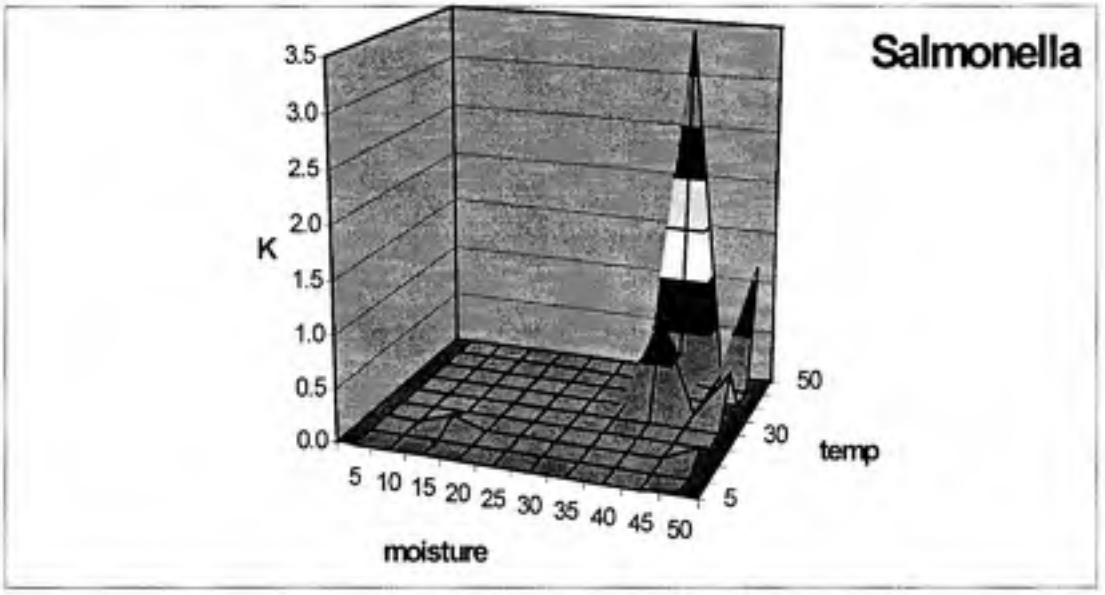


Figure 5.4 – *Salmonella* survival as a function of temperature and moisture

Figure 5.4 illustrates that at high temperatures the rate of die-off increases. There is also a slight indication that lower moisture levels also increase the rate of die-off. Under ideal conditions of high temperature and low moisture levels, the value of **k** may be the highest relative to other possible conditions. The next level of **k** values would be at low moisture and low temperatures, and also at high temperatures and high moisture levels. The lowest set of **k** values would probably be seen at conditions of low temperatures and high moisture levels. Table 5.17 is a summary of the time, in days, required for the reduction of *Salmonella* to levels that have been specified previously. Each temperature range has been divided into a range of moisture levels also, in order to elucidate any dependence on moisture within a given temperature range.

Table 5.17 – Summary of time requirements for *Salmonella* destruction using kinetic modeling during various operating conditions expected in Eco-San systems

Pathogen	Temperature	Moisture	Log Reduction	average k	Time (days)
Salmonella	10-20	75	6.12	no data	-
		50	6.12	0.05	282
		25	6.12	no data	-
	20-30	75	6.12	0.06	235
		50	6.12	0.16	88
		25	6.12	0.11	128
	30-40	75	6.12	no data	-
		50	6.12	0.78	18
		25	6.12	no data	-
	40-50	75	6.12	-	
		50	6.12	1.133	12
		25	6.12	-	
	50-60	75	6.12	-	
		50	6.12	>250	1
		25	6.12	-	

The threshold model can also be used for the determination of the length of time necessary for the complete destruction of *Salmonella*. Again, the major shortcoming of this type of model is the inability to include the other parameters, such as moisture levels, in the determination of the time necessary for pathogen destruction. The model is also inadequate for the lower range of temperatures that may be found, especially below 25°C. In Table 5.19, figures that are out of the range of values of the threshold graph are signified by a "greater than" (>) sign.

Table 5.19 - Summary of time requirements for pathogen destruction using threshold modeling during various temperatures expected in Eco-San systems

Pathogen	Temperature Range (°C)	Time (days) for Complete Die-Off
	10 – 20	>>365
	20 – 30	>365
Salmonella	30 – 40	200
	40 - 50	29
	50 - 60	>1

The EPA pathogen reduction model also can be used to determine the length of time necessary to ensure that all pathogens have been destroyed, regardless of type and initial concentration. As discussed above, this model is not particularly suited to describe the destruction of pathogens in systems such as the Eco-San latrines, but is included for the sake of comparison. The average value of each temperature range is used to determine the length of time in the equation above. This model gives time requirements that are summarized in Table 5.20.

Table 5.20 - Summary of time requirements for *Salmonella* destruction using the EPA pathogen reduction model during various temperatures expected in Eco-San systems

Pathogen	Temperature Range (°C)	Average Value (°C)	Time (days) for Complete Die-Off
All	10 – 20	15	1,046,130
All	20 – 30	25	41,647
All	30 - 40	35	1658
All	40 - 50	45	66
All	50 – 60	55	2

A side by side comparison of the three models with regards to the time necessary for *Ascaris* destruction in conditions typical in Eco-San systems is found in Table 5.12.

Table 5.21 - Time necessary for *Salmonella* destruction in Eco-San systems: a comparison of die-off models

Pathogen	Temp (°C)	% Moisture	KINETIC	THRESHOLD	EPA
			Time (days)	Time (days)	Time (days)
Salmonella	10-20	75	-	>>365	1,046,130
		50	282		
		25	-		
	20-30	75	235	>365	41,647
		50	88		
		25	128		
	30-40	75	-	200	1658
		50	18		
		25	-		
	40-50	75	-	29	66
		50	12		
		25	-		
	50-60	75	-	1	2
		50	1		
		25	-		

Table 5.21 highlights the fact that a comparison of these three models shows a wide disparity with regards to *Salmonella* die-off, especially in the lower temperature ranges. The kinetic modeling provides the least number of days, whereas the EPA die-off model gives the longest time period necessary for the reduction of pathogens to the levels specified previously. The models appear to converge at the higher temperatures. The models used in this comparison also may not be adequate to define the process of *Salmonella* destruction in the mesophilic temperature range. For example, some of the data indicates that very low moisture levels may actually promote the longevity of *Salmonella* at mesophilic temperatures. In this case, a first order kinetic relationship will not adequately describe *Salmonella* die-off for kinetic modeling. Threshold modeling also will not reflect this, because moisture levels are not taken into consideration. More data is needed in the lower temperature ranges to accurately describe the rate of die-off of *Salmonella*.

5D. Survival of Viruses

Many studies have examined the extent of virus inactivation and concentration reduction in sewage. A few of the studies that relate more directly to stored sludge and biosolids in the mesophilic temperature range and have relevance to the subject of on-site sanitation will be discussed in this section. Some studies that concern viruses other than the enteroviruses, such as HAV and f2, also provide useful information that can be useful in the development of a model for pathogen destruction.

Pesaro et al (1995) conducted a study by on the inactivation of animal viruses and coliphages in nonaerated liquid and semiliquid animal wastes. The authors concluded that at low temperatures, such as the combination of higher pH and ammonia. The percent solids were not mentioned, but inferred from descriptions that the dry systems were approximately 75% solids, and the wet systems were about 25% solid. The conclusion was that the addition of urine at higher pH levels caused the ammonia to be virucidal. Table 5.22 is a summary of results for f2 coliphage found from the study.

Table 5.22 – Inactivation of the f2 coliphage in animal wastes (from Pesaro, 1995)

wet/dry	type of manure	k (log_{10}[no. of organisms] / day)	temp (°C)	pH
wet	mixed	.141	19.2	-
wet	mixed	.045	10.1	-
dry	cattle	.106	15.9	8.7
dry	cattle	.029	16.2	6.9
dry	swine	.043	12.7	7.4
dry	mixed	.037	14.8	7.9

Deng and Cliver (1992) reported on the inactivation of poliovirus under anaerobic conditions in mixed human and swine waste and by bacteria from swine manure, and concluded that bacterial enzymes were responsible for variations in viral deactivation. Septic tank effluent (STE) and swine manure slurry (SMS) were both mixed to provide the composting matrix. Several variables were not defined, such as the percent solids in the mixture. From related studies, the percent solids level may be assumed to be approximately 25 percent. Table 5.23 is a summary of their findings for enteroviruses. The greatest inactivation occurred at higher temperatures.

Table 5.23 – Poliovirus inactivation in mixed wastes (from Deng and Cliver, 1992)

Ratio of STE and SMS	k (log_{10}[no.] / day)	temp(°C)	pH
1:4	. 0334	14.4	6.8
1:4	. 0535	20.8	6.9
1:4	.1478	25.0	7.2
1:4	.7950	37.0	7.2

Deng and Cliver (1995) also studied the survival of HAV in mixed human (STE) and animal wastes, including dairy cattle manure (DCMS) and swine manure (SMS). The authors did not specify the aerobic requirements, although it can be assumed that the systems were anaerobic since the study design did not include aeration of the mixture. The following is a table of the different types of mixtures tested and the following results were obtained at the given temperatures:

Table 5.24 – Kinetic data on the inactivation of HAV in mixed waste (from Deng and Cliver)

	k (log_{10}[no.] / day) for HAV in:		
Temp (°C)	STE + DCMS	STE + SMS	STE
5 °C	0.0289	0.0206	0.0171
22°C	0.0434	0.0583	0.0285
25°C	0.120	0.127	-
37°C	0.148	0.147	-

Note: STE denotes septic tank effluent; DCMS is dairy cattle manure sludge, and SMS signifies swine manure sludge

Mateu (1992) also studied enterobacterial and viral decay models for the anaerobic digestion of piggery waste. The volatile solids content of the manures averaged out to be 26.1g/l. The results for the f2 bacteriophage are as follows:

Table 5.25 – Enteroviral decay in animal waste (from Mateu, 1992)

Temperature	k(log_{10}[no.] / day)	Percent Moisture
4 °C	0.126	95
37°C	0.044	95

Studies that relate to the anaerobic digestion of sludge and virus inactivation can also be used to estimate the destruction of these pathogens in on-site composting systems. Ward (1976) as mentioned above in the previous section on virus representation concluded that ammonia is highly virucidal at pH values of 8 and above. This fact alone helps explain the short survival times generally found in completely anaerobic system such as those carried out by Berg and Metcalf (1978). Theirs was as series of studies done on the survival of enteroviruses at 35 °C in sludge digestion, showing that around 99 percent removal of viruses was accomplished in 20 days time. Other similar studies (Fenters, 1979; Eisenhardt, 1977 and others) seem to indicate that digestion at 35°C at 35 days ensures that the end product is virus free. The only question concerning these studies is the direct application of purely anaerobic systems to the type of environment found in on-site composting sytems.

With regards to aerobic digestion of sludge and enterovirus survival, Farrah (1986) determined the comparative survival rates in terms of the mean daily change of several types of virus concentrations relative to initial concentration and found in Table 5.26. The table illustrates the fact that poliovirus had the quickest die-off rate compared with other viruses.

Table 5.26 – Comparison of Virus Survival in Wastewater Sludges (from Farrah)

Virus	k (log_{10}[no.] / day)	Temp (°C)	% Moisture	O_2 (mg/l)
Poliovirus	0.77	28.9	98	6.2
Poliovirus	0.98	27.1	98	5.1
Echovirus	0.5	24.6	98	5.7
Coxsackievirus B	0.46	27.4	98	4.8
Rotavirus	0.43	28.0	98	5.8

In another set of tests by Scheurman and Farrah (1991) however, it was determined that the inactivation rate of viruses under aerobic conditions was found to be significantly higher than rates found under anaerobic conditions (0.77 log_{10}/day compared to 0.33 log_{10}/day). Their conclusion was that sludge source, detention time, or virus type did not significantly influence the rate of virus inactivation.

Another set of results that can be included in the development of a model for enterovirus destruction (particularly Poliovirus) is the data from Ahmed mentioned previously, as follows:

Table 5.27 – Enterovirus Die-Off rates in stored biosolids (from Ahmed, 1995)

Temperature:	50°C	35°C	20°C	5°C
k (log_{10}[no.] / day):	0.813	0.276	0.084	0.022

Scheuerman (1991) also determined the kinetic die-off of three enteroviruses during aerobic and anaerobic digestion of sewage sludge at various ranges of temperatures, and found inactivation rates:

Table 5.28 – Virus Inactivation rates in mesophilic sludge digestion (from Sheuerman, 1991)

	k (log_{10}[no.] / day) for:			
Temp	**Poliovirus**	**Echovirus**	**Coxsackie (B3)**	**Rotavirus SA-11**
3 –5 °C	0.21	0.18	-	0.44
25 –29 °C	0.51	0.50	0.46	0.43
31 – 34 °C	0.77	0.53	-	0.52

With regards to moisture level and virus destruction, Ward and Ashley (1977) studied the inactivation of enteric viruses in wastewater sludge through dewatering by evaporation. They determined that the increase in the percent solids had a dramatic effect on the rate of destruction, as illustrated in the following table of data obtained on the recovery in pfu/ml:

Table 5.29 – Enteric Virus destruction in dried sewage sludge (from Ward and Ashley, 1977)

°C	% solids	0 days	4 days	11 days	K(days^{-1})
4	5	$2.4x10^7$	$2.4x10^7$	$2.4x10^7$	0
21	5	$2.4x10^7$	$1.8x10^7$	$6.5x10^6$	0.119
21	12	$2.4x10^7$	$1.7x10^7$	$4.5x10^6$	0.152
21	20	$2.4x10^7$	$9.5x10^6$	$4.0x10^6$	0.163
21	30	$2.4x10^7$	$6.4x10^6$	$3.8x10^6$	0.168
21	58	$2.4x10^7$	$5.5x10^6$	$3.2x10^6$	0.183
21	65	$2.4x10^7$	$4.0x10^6$	$3.2x10^6$	0.183
21	83	$2.4x10^7$	$2.5x10^3$	$<2.5x10^2$	2.29
21	91	$2.4x10^7$	$1.0x10^3$	$<2.5x10^2$	2.52

Farrah (1986), in his study of pathogen survival, also determined the effect of evaporative drying on the recovery of poliovirus from aerobically digested sludge by exposing samples to air at room temperature. He obtained the following results:

Table 5.30 – Enteric Virus Die-off of aerobically digested sludge dehydration (from Farrah)

Days	% Solids	% Survival	Temperature	K ($days^{-1}$)
7	1.6	3.6	21°C	0.475
	1.6	0.4	21°C	0.789
	1.6	1.2	21°C	0.631
14	2.5	25.9	21°C	0.096
	3.0	13	21°C	0.146
21	6.7	1.6	21°C	0.197
	7.5	7.7	21°C	0.123
28	48.2	0.1	21°C	0.247

In terms of studies that relate the time necessary for complete die-off, Feachem (1983) reviewed an exhaustive set of studies on the survival of enteroviruses in different types of night soil and sludge treatment processes. His conclusion for the survival in pit latrines is:

> Little information is available, but it is probable that enteroviruses survive for several weeks in pit latrines. In warm climates, the pit contents should be free of enteroviruses if they are left for at least 3 months before digging out. A pit latrine may act as a source of viral groundwater pollution depending on the type of soil, groundwater levels, and the proximity of local wells.

It has been shown that pit latrines simply acting as storage of septage contain viable organisms. Francis (1953) was able to isolate polioviruses and coxsackieviruses from samples of fecal material from pit latrines in the U.S. and was shown to be associated with the isolation of polioviruses from flies in the vicinity of the latrines.

These data will be used in the next section to compare kinetic models of pathogen inactivation. The results will be reviewed as to their adequacy in estimating the pathogen die-off in Eco-San systems.

Table 5.31 – Summary of Kinetic die-off data of several types of viruses (from various studies)

Type	Temp	moisture	K(days^{-1})	pH	(an)aerobic
enteroviruses	4.0	95	0	n/a	n/a
enteroviruses	5.0	50	0.022	6.3	aerobic
enteroviruses	14.4	75	0.033	6.8	anaerobic
enteroviruses	20.0	50	0.084	6.3	aerobic
enteroviruses	20.8	75	0.054	6.9	anaerobic
enteroviruses	21.0	35	0.183	n/a	n/a
enteroviruses	21.0	42	0.183	n/a	n/a
enteroviruses	21.0	52	0.247	n/a	n/a
enteroviruses	21.0	70	0.168	n/a	n/a
enteroviruses	21.0	80	0.163	n/a	n/a
enteroviruses	21.0	88	0.152	n/a	n/a
enteroviruses	21.0	92	0.123	n/a	n/a
enteroviruses	21.0	93	0.197	n/a	n/a
enteroviruses	21.0	97	0.096	n/a	n/a
enteroviruses	21.0	97	0.146	n/a	n/a
enteroviruses	21.0	98	0.475	n/a	n/a
enteroviruses	21.0	98	0.789	n/a	n/a
enteroviruses	21.0	98	0.631	n/a	n/a
enteroviruses	24.6	98	0.500	n/a	aerobic
enteroviruses	25.0	75	0.148	7.2	anaerobic
enteroviruses	27.1	98	0.980	n/a	aerobic
enteroviruses	27.4	98	0.460	n/a	aerobic
enteroviruses	28.0	98	0.430	n/a	aerobic
enteroviruses	28.9	98	0.770	n/a	aerobic
enteroviruses	35.0	50	0.276	6.3	aerobic
enteroviruses	37.0	75	0.795	7.2	anaerobic
enteroviruses	50.0	50	0.813	6.3	aerobic
f2	4.0	95	0.126	7.5	anaerobic
f2	10.1	75	0.045	n/a	anaerobic
f2	12.7	25	0.043	7.4	anaerobic
f2	14.8	25	0.037	7.9	anaerobic
f2	15.9	25	0.106	8.7	anaerobic
f2	16.2	25	0.029	6.9	anaerobic
f2	19.2	75	0.141	n/a	anaerobic
f2	37.0	95	0.044	7.5	anaerobic
f2	50	50	1.54	7.0	aerobic
f2	55	50	12.4	7.0	aerobic
f2	60	50	70.5	7.0	aerobic
HAV	5.0	75	0.017	7.2	anaerobic
HAV	22.0	75	0.029	7.2	anaerobic
HAV	25.0	75	0.127	7.0	anaerobic
HAV	37.0	75	0.147	7.0	anaerobic

Based on three studies reported in the literature, the enterovirus die-off data in wastewater sludge for all temperature ranges can be summarized as shown in Table 5.32.

Table 5.32 – A comparison from three studies of Enterovirus die-off at different temperature ranges

	No. of ***days*** required for complete Enterovirus destruction according to:		
Temperature	**Ahmed**	**Scheuerman**	**Farrah**
5 -10°C	626	76	n/a
20 - 30°C	164	33	28
35 - 40°C	51	28	n/a
50°C	18	n/a	n/a

Figure 5.5 graphically represents the data that was presented in the previous section on enterovirus survival as a function of moisture and temperature.

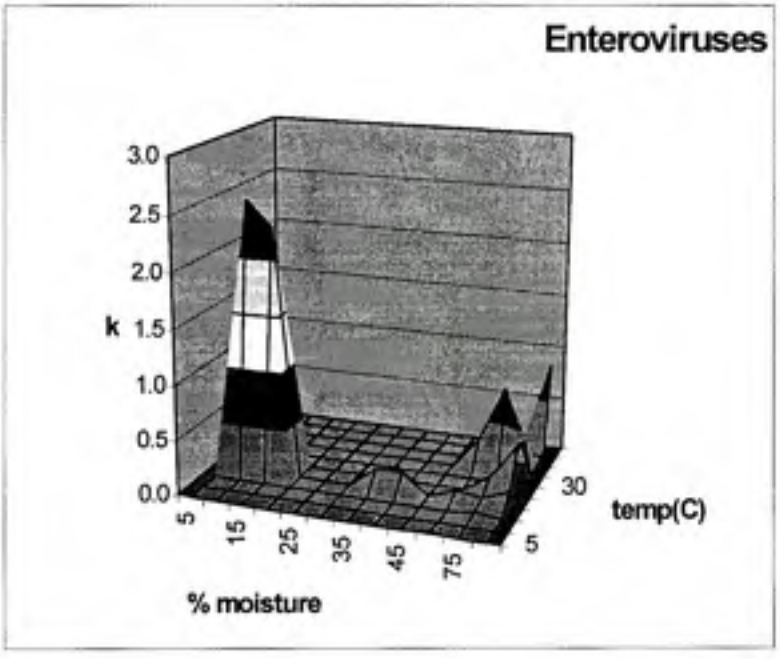


Figure 5.5 - Enterovirus Survival as a Function of Moisture and Temperature

The variation highlighted by the above table is expected, due to differences in operating conditions and test procedures. A trend apparent from Figure 5.5 is the fact that increased

temperatures dramatically decrease the number of days of virus survival. The simple form of modeling die-off as only a function of temperature may be overlooking the importance that moisture levels play in pathogen destruction. A review of the data indicates that differences in moisture levels do have an effect on the rate of survival of viruses.

One of the obvious trends in Figure 5.5 is the effect that very low levels of moisture have on enterovirus survival. At moisture levels below 20 percent, the moisture level becomes a dominant factor in raising the **k** value and accelerating die-off. At higher levels of moisture, the rate of survival seems not to be affected by the moisture level in the system.

A closer look at the effect that moisture levels have on the kinetics at a given temperature will allow one to appreciate the trends, as illustrated below:

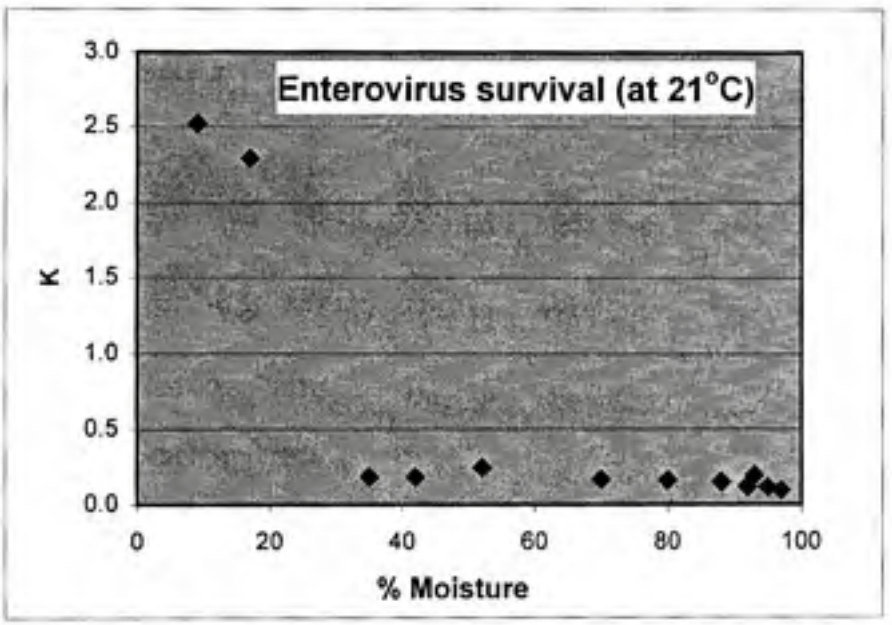


Figure 5.6 – Enterovirus Survival at a constant temperature (21°C), with varying moisture levels (from Ward et al.)

Other viruses have shown a greater degree of environmental resistance than enteroviruses. Table 5.33 shows the following data for HAV exists for different temperatures at approximately 75 percent moisture levels.

Table 5.33 – HAV survival with respect to temperature and moisture (Deng and Cliver, 1995)

	Temp	k	Moisture	pH	
HAV	5.0	0.017	75	7.2	anaerobic
HAV	22.0	0.029	75	7.2	anaerobic
HAV	25.0	0.127	75	7.0	anaerobic
HAV	37.0	0.147	75	7.0	anaerobic

This data is presented graphically, with the assumption of an exponential relationship. This experimental assumption fits the data poorly, and may miss an important consideration in the trend of HAV die-off between 20°C and 25 °C. The die-off between these two temperatures resembles a step-function, in which die-off suddenly increases within this range.

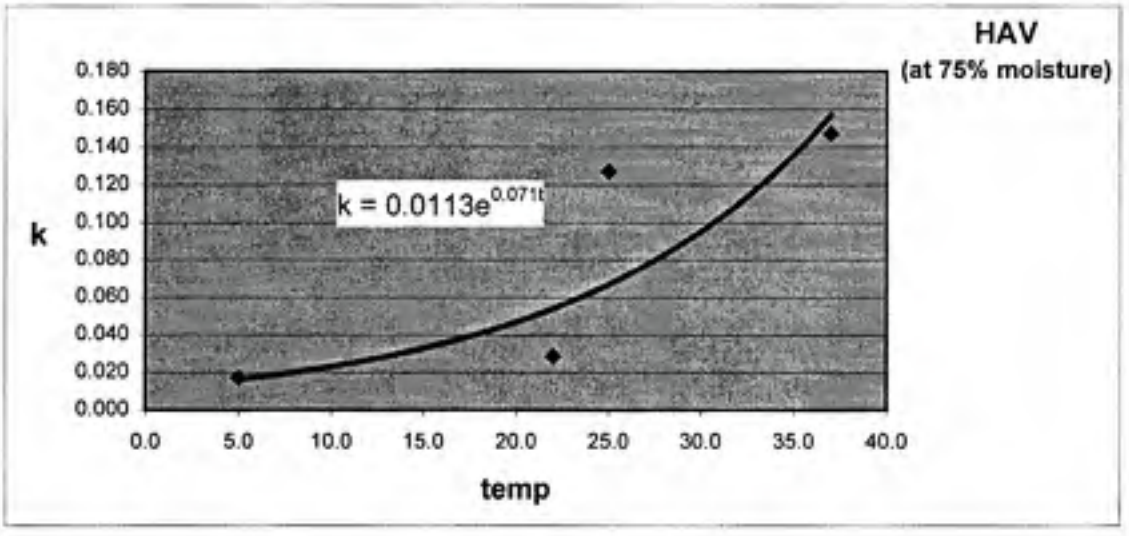


Figure 5.7 - Kinetic die-off **k** for HAV at 75% moisture levels

This can be used to estimate the time necessary for HAV reduction to acceptable levels at various temperatures. For example, at 20°C, the **k** value is about 0.045 ($\log_{10}$[no.of org.]/day), which implies that the amount of time necessary to bring about a 6 log reduction in numbers (assuming a concentration of about 10^6 in human feces) is:

$$t = (2.303) \times (6) / (.045) = 306 \text{ days}$$

It is obvious from this data that HAV shows a much greater environmental resistance that the enteroviruses do. Further studies on the survival of HAV under a greater variety of environmental conditions could provide data to quantify HAV survival more accurately, allowing it to be a possible candidate for a representative organism for viruses.

Another factor that may effect virus survival in Eco-San composting systems is the whether the process is aerobic or anaerobic. The following is a graph comparing data of enterovirus die-off at relatively high moisture levels (50% and 75%) and a range of temperatures for two types of systems, one which was operating at anaerobic conditions, and the other at aerobic conditions (Ward, 1977). It appears from the comparison that the die-off of enteroviruses is accelerated at anaerobic conditions relative to aerobic conditions. This is consistent with findings previously mentioned which indicate that anaerobic systems promote the formation of NH_3 which is virucidal at higher pH values. In waste treatment systems, the presence of urine will promote these conditions and thus will lead to an increase in virus inactivation.

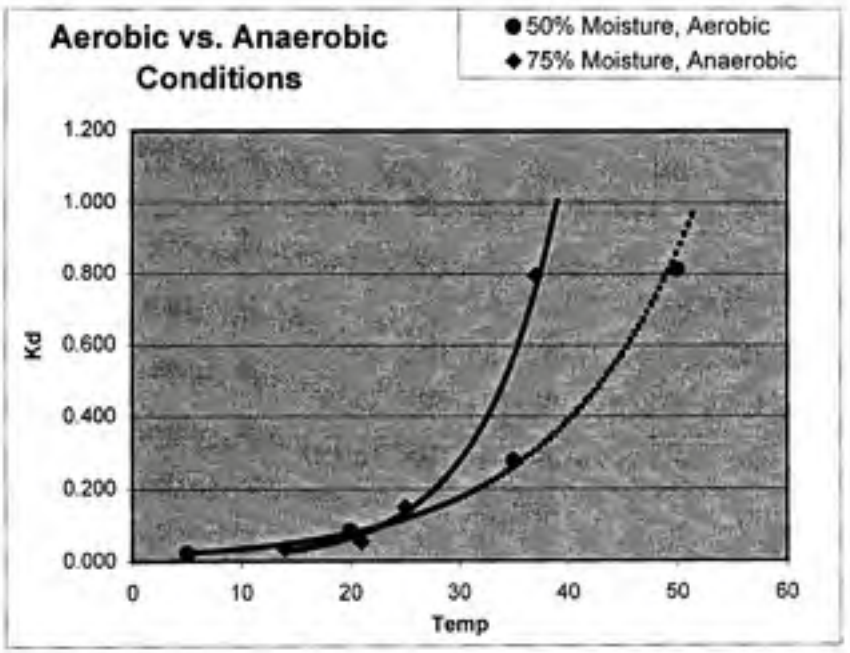


Figure 5.8 – Enterovirus survival in aerobic vs. anaerobic conditions (adapted from Ward, 1977)

Figures 5.5 through 5.8 illustrate that at high temperatures and at lower moisture leves, the rate of die-off increases. Under ideal conditions of high temperature and low moisture levels, the value of **k** may be the highest relative to other possible conditions. The next level of **k** values would be at low moisture and low temperatures, and also at high temperatures and high moisture levels. The lowest set of **k** values would probably be seen at conditions of low temperatures and high moisture levels. Table 5.34 is a summary of the time, in days, required for the reduction of enteroviruses to levels that have been specified previously. Each temperature range has been divided into a range of moisture levels also, in order to elucidate any dependence on moisture within a given temperature range.

Table 5.34 – Summary of time requirements for enterovirus destruction using kinetic modeling during various operating conditions expected in Eco-San systems

Pathogen	Temperature	Moisture	Log Reduction	average k	Time (days)
Enterovirus	10-20	75	6.60	0.03	460
		50	6.60	0.02	690
		25	6.60	no data	-
	20-30	75	6.60	0.21	73
		50	6.60	0.25	61
		25	6.60	1.66	10
	30-40	75	6.60	0.80	20
		50	6.60	0.30	19
		25	6.60	-	-
	40-50	75	6.60	-	
		50	6.60	0.81	18
		25	6.60	-	
	50-60	75	6.60	-	
		50	6.60	>20	1
		25	6.60	-	

The threshold model can also be used for the determination of the length of time necessary for the complete destruction of enteroviruses. Again, the major shortcoming of this type of model is the inability to include the other parameters, such as moisture levels, in the determination of the time necessary for pathogen destruction. The model is also inadequate for the lower range of temperatures that may be found, especially in the range of 10°C to 25°C. In Table 5.35, figures that are out of the range of values of the graph are signified by a "greater than" sign.

Table 5.35 - Summary of time requirements for enterovirus destruction using threshold modeling during various temperatures expected in Eco-San systems

Pathogen	Temperature Range (°C)	Time (days) for Complete Die-Off
	10 – 20	>365
	20 – 30	250
Enterovirus	30 - 40	100
	40 - 50	21
	50 - 60	>1

The EPA pathogen reduction model can also be used to determine the length of time necessary to ensure that enteroviruses have been destroyed. As discussed above, this model is not particularly suited to describe the destruction of pathogens in systems such as the Eco-San latrines, but is included for the sake of comparison. The average value of each temperature range is used to determine the length of time in the equation above. This model gives time requirements that are summarized in Table 5.36.

Table 5.36: Summary of time requirements for enterovirus destruction using the EPA pathogen reduction model during various temperatures expected in Eco-San systems

Temperature Range (°C)	Average Value (°C)	Time (days) for Complete Die-Off
10 – 20	15	1,046,130
20 – 30	25	41,647
30 - 40	35	1658
40 - 50	45	66
50 – 60	55	2

A side by side comparison of the three models with regards to the time necessary for enterovirus destruction in conditions typical in Eco-San systems is found in Table 5.12.

Table 5.37 - Time necessary for enterovirus destruction in Eco-San systems: a comparison of die-off models

Pathogen	Temp (°C)	% Moisture	Type of Model		
			KINETIC	THRESHOLD	EPA
			Time (days)	Time (days)	Time (days)
Enterovirus	10-20	75	460	>365	1,046,130
		50	690		
		25	-		
	20-30	75	73	250	41,647
		50	61		
		25	10		
	30-40	75	20	100	1658
		50	19		
		25	-		
	40-50	75	-	21	66
		50	18		
		25	-		
	50-60	75	-	1	2
		50	1		
		25	-		

The comparison of Table 5.37 shows that these three models provide a wide disparity with regards to enterovirus die-off. The discrepancies tend to increase in the lower temperature ranges. The kinetic modeling provides the least number of days, whereas the EPA die-off model gives the longest time period necessary for the reduction of pathogens to the levels specified previously. The models appear to converge at the higher temperatures. More data is needed in the lower temperature ranges to accurately describe the rate of die-off of enteroviruses.

5.D Comparison and Discussion

The previous sections of this report are an attempt to describe the pathogen reduction outcome of Eco-San systems using available and widely used methods currently employed for similar waste treatment systems. There are wide ranges of differences, not only among the different approaches in modeling pathogen die-off, but also among the data. These differences can be in the range of orders of magnitude apart from each other. The use of these models and data does not provide much certainty to the Eco-San user about the exact nature of pathogen destruction and end product quality in Eco-San systems.

The kinetic modeling of pathogen die-off, especially *Ascaris* die-off, shows a wide range of possibilities for retention time. Two of the three studies cited suggest that a period of two to three years of storage would be necessary to ensure Ascaris destruction at a temperature of about 25°C. Higher temperature ranges show shorter and less variable times necessary for die-off. The lack of experimental data at lower temperatures makes reliable predictions difficult. The assumption of first order kinetics may not adequately describe the relationship of die-off with temperature and moisture levels.

The use of "threshold" models also proves to be difficult because of the limitations of available data and the very conservative nature of the resulting relationship between time and temperature as predictions of die-off. The use of the compilation of many studies as illustrated in Figure 5-7 can be useful to the engineer in giving trends, but lacks the adequacy of a model useful for design and operation. The EPA model itself is not pathogen specific and has been designed for the worst case, but even when compared with Ascaris die-off data of other models, it is shown to be very conservative. The model indicates that at the expected temperature of 25°C, a storage period of 120 years would be necessary to reduce pathogens to acceptable levels. The results obtained when comparing length of time for complete pathogen destruction at 20°C differs from the results of the other models by four orders of magnitude.

In order to reliably model pathogen destruction at the conditions encountered in an Eco-San system, much more data must be gathered and analyzed. The survival of individual classes of pathogens must be studied at the range of conditions found in such systems, such as mesophilic temperatures and moisture levels of 50% or less.

To correlate the above findings with findings from field experiments, data based on various types of operating Eco-San latrines can be used. The following is synthesis of available information on operating conditions in Eco-San (based on Table 3.8 – Summary of Results from Recent Tests on Composting Eco-San Systems, and findings from LASF Latrines in El Salvador):

Table 5.38 – Summary of Operating Conditions found in field testing of Eco-San Systems

Source	Temp (°C)	% Moisture	pH	C:N Ratio	Aeration
Moe (1999)	15-30	5-50	6-12.2	n/a	n/a
Esrey (1996)	21-31	30-82	7.2	n/a	yes
Cook (1981)	30-62	27-67	7.4	n/a	no
Cook(1981)	8-26	66	7.3	n/a	n/a
Enferadi (1982)	10-26	68	7.3	n/a	n/a
Enferadi (1982)	5-32	55	6.3	n/a	n/a
Enferadi (1982)	7-28	66	7.6	n/a	n/a
Enferadi (1982)	15-48	72	7.3	n/a	n/a
Enferadi (1982)	14-40	73	8.7	n/a	n/a
NSF (1982)	13	74	n/a	n/a	yes
NSF (1981)	19	49	n/a	n/a	yes

Note: n/a signifies that the parameter was not measured in the study.

From the above we can estimate a range of temperatures and moisture levels that will most likely be found in Eco-San systems. Within these ranges we can then use the data from the models developed in the previous sections to estimate the time necessary for treatment in Eco-San systems to ensure pathogen destruction. The following table is a summary of the findings for Ascaris, the most environmentally resistant pathogen among the representative organisms.

Table 5.39 – The number of days necessary for *Ascaris* die-off in Eco-San systems from various studies, according to three types of models

			Number of days necessary for *ASCARIS* die-off according to the type of model:		
Source	**Temp (°C)**	**% Moisture**	**Kinetic**	**Threshold**	**EPA**
Moe (1999)	15-30	5-50	433	>>365	41,647
Esrey (1996)	21-31	30-82	574	>>365	1,658
Cook (1981)	30-62	27-67	50	83	66
Cook(1981)	8-26	66	10,594	>>365	1,046,130
Enferadi (1982)	10-26	68	10,594	>>365	1,046,130
Enferadi (1982)	5-32	55	3,086	>>365	41,647
Enferadi (1982)	7-28	66	10,594	>>365	1,046,130
Enferadi (1982)	15-48	72	?	>>365	1,658
Enferadi (1982)	14-40	73	?	>>365	41,647
NSF (1982)	13	74	?	>>365	1,046,130
NSF (1981)	19	49	10,594	>>365	1,046,130

The table highlights the fact that models determining the die-off of pathogens, in this case *Ascaris*, show a wide range of outcomes for pathogen reduction. Data concerning actual pathogen reduction from these systems would be useful to determine the accuracy of these models.

VI. Conclusions and Recommendations

Conclusions

Several conclusions can be made from the information presented in this paper concerning the relationship between pathogen survival and operational parameters of Eco-San systems. They are presented in terms of the objectives set out in the introduction as follows:

Objective 1: Identify and examine the quantifiable measures of effective ecological sanitation treatment.

Temperature levels are the first and most obvious quantifiable measure of Eco-San efficiency. However, because mesophilic levels are encountered for the greater part of the process in such systems, this may not be the sole cause of microbial destruction. Also, temperature itself is determined by all of the other factors discussed as important parameters of biological treatment, such as carbon content, air, pH, energy, volatile solids, etc. Therefore to measure these individual factors may be useful, but the role and interplay they all have in determining the extent of biodegredation and heat production is very complex. The measure of temperature may be sufficient as the overall indicator of a properly designed and operated system of a specific treatment process, such as composting. Increased temperatures for extended periods ensure that the stabilization process is taking place. Stabilization is important for the appropriate quality of the end product.

Moisture levels are the other primary measure of Eco-San efficiency in pathogen destruction. This is because Eco-San will not necessarily be a composting process, it could include periods of dehydration. During these dry periods, the lack of moisture will inhibit the biological processes responsible for elevated temperature levels in composting. The low moisture content itself will become the primary cause for pathogen destruction, as indicated in some of the data presented in this report. If both of these factors are optimized over time, the greatest amount of pathogen die-off will occur in the shortest time. For example, an increase in temperature for a period followed by a drying out period should maximize the potential for pathogen destruction.

Objective 2: Evaluate the application of information and models from related systems or studies to determine the effectiveness of ecological sanitation.

Kinetic models developed of data from studies can relate the decrease in pathogen concentration over time give a wide range of results. The reasons for this are in the variability of the testing conditions and processes. There may also be differences in measuring or defining "pathogen destruction. It is obvious that much more information is needed to conclusively describe pathogen destruction by this method. This type of modeling seems to be the most useful in describing the die-off of different pathogens under differing conditions.

Threshold time/temperature modeling is another approach to indicating trends and limits for complete pathogen destruction, but it also has limitations. Much of the data is from widely variable conditions and processes. Also, this model only provides one with a very conservative, worst case conclusion for the time required for pathogen destruction. Actual survival times may be much less, especially considering not all of the possible pathogens may be present. Hence, the residence time may be over-designed by orders of magnitudes.

The EPA *503 Rules* also prove to be inadequate for the modeling of pathogen survival in Eco-San systems. These rules are mainly for the description of pathogen destruction during conditions normally found in the PFRP processes used for municipal biosolids and not in conditions encountered in Eco-San systems. However, the *503 Rules* agree with the other models at the higher temperature ranges, and may be an appropriate model for active composting Eco-San systems that operate in the higher mesophilic to lower thermophilic range.

The evaluation of information and models from related systems and studies to determine the effectiveness of Eco-San is inconclusive and inconsistent. With regards to pathogen survival, there is a wide variation in the expected outcome of the microbiological quality of the final product. Also, systems may operate between the two operating regimes of dehydration and composting, and not necessarily within one exclusively, and lead to the conclusion that the extrapolation used in the aforementioned models is not appropriate. Much more research should be done in varying conditions to determine the exact nature of pathogen die-off.

Objective 3: Discuss the implications for further research requirements for the role ecological sanitation might have as an appropriate sanitation system.

The implications of the above information for further research and data requirements for Eco-San is that much more field data is needed for the appropriate analysis of the effectiveness of such systems. The majority of data used for the analysis in this paper is derived from laboratory results of limited experiments. There have been few attempts in the recent decades to quantify the performance of Eco-San systems. This has resulted in a scarcity of relevant data; thus the reliance on data only from similar or analagous treatment processes for other human wastes (sewage, biosolids, etc.).

A two-fold approach to the research and development of Eco-San with regards to their efficiency as waste treatment systems for pathogen destruction is needed. The first approach is to determine the operational parameters of the systems as they function in the field. Data can be collected with regards to the ambient temperature and moisture levels, as well as the temperature and moisture levels within the system itself. The second approach would be to establish the rate of die-off of pathogens from different regimes throughout the composting system. This would include sampling from the older material, as well as from the more recently deposited material. In this way, a profile can be developed that tracks the survival of pathogens throughout the system as a function of time.

These two approaches, namely the operational parameters and pathogen survival, can then be combined to determine the relationship between the operation and performance of Eco-San systems. This information can then be used to develop a quantitative assessment of the effectiveness of this type of sanitation systems. It can also be used to develop a predictive model to extrapolate the performance of different types of systems, based on their operating conditions and expected performance. This type of model would be useful in the situations where the determination of biosolids quality is not practical, but the measurement of temperature and moisture level is possible. Once these parameters are measured, the quality of end product can be predicted. The Eco-San user can then plan a program of treatment to ensure that the final product is adequate for beneficial reuse.

Recommendations

The previous analyses highlight the fact that much more research is needed on the exact nature of on-site treatment of human waste via ecological sanitation. The extent of pathogen destruction and product stability is highly variable depending on the conditions and systems. However, some generalizations can be made concerning the trends found in existing systems. These are useful in developing recommendations for ecological sanitation system development. The following is a list of findings based on the previous discussion.

1. **Monitoring of systems should be primarily based on temperature and moisture levels. The other secondary parameters (C/N, air, etc.) can be measured if possible.**

In recent attempts to define and describe the effectiveness of sanitation systems, the approach to determine the critical parameters is to follow as many parameters as possible during the treatment process. The technical level of testing and monitoring required for complicated analyses may not be possible in field studies of sanitation systems. Therefore a simpler approach is recommended to monitor the effectiveness of such systems.

The literature indicates that the two most important parameters of Eco-San treatment are temperature and moisture. Temperature is the overall indicator of the composting process, and moisture level is the measure of the extent of dehydration. These two parameters are the simplest way to measure the main regimes of treatment. The other secondary measures of treatment efficiency can be seen as components of these two major parameters. The levels of temperature sustainable in a composting latrine itself is a function of all the other factors, such as the carbon to nitrogen ratio, the air supply, the volatility of the pile, the energy balance, free air space, and others as described in the previous sections. If the requirements for all of these are met within the system, the temperature will reach its highest potential and will be sustained for the longest time possible. The level to which the temperature may reach otherwise depends on the extent that each parameter is developed in the system. For example, if all conditions are met for composting except for free air space, the temperature will not reach levels expected. In the case of Eco-San, the temperature is the appropriate measure for all of the other parameters, as well as the

primary cause of pathogen destruction in systems that rely on the composting treatment process.

The moisture level is the simplest measure for the extent of dehydration occuring during Eco-San treatment. The aim of the dehydration process is for the dryness of the pile to increase as a function of time. It is therefore important to determine the moisture levels throughout the pile and not only in the freshly deposited layers. The earlier material should be much drier and more disinfected than the more recent material. The moisture level itself can also depend on several other parameters such as temperature, airflow, and free air space. However, since it is the result of these other measures, it can be used as the overall indicator that the dehydration process is occuring.

2. The design of systems should take into consideration the two primary modes of operation; namely composting and dehydration.

Eco-San systems are currently designed to simply store fecal material. The main consideration in the design usually pertains to wetness removal. There are other important considerations that must be factored into the design of such systems.

The first issue to be addressed is whether the system is to be operated as a composting unit or a dehydrating unit. (Dehydration is obviously an easier and more feasible objective to achieve than composting. However, because dehydration only results in sterilization and not in stablization, it cannot be the end of treatment.) Once this is established, each different type of process has several requirements for optimal performance. The following is a simple table, or checklist, for the considerations in the design of these types of systems:

Table 7.1 – Considerations in the Design of Eco-San Systems

Type of Treatment:	Dehydrating	Composting
Mixing	May aid in drying pile	Necessary
Aeration	Necessary	Necessary
Nutrient Balance	not necessary	Necessary
Sunlight	Will accelerate drying	not necessary
Size of Reactor	large surface area required	Necessary

Several of the considerations above are not included in the design of many of the systems currently being used. It is advisable to consider the above and include appurtenances to accomplish the aspect of the process they are responsible for. It is recommended that the Eco-San system be designed and operated to initally run as a composting system to take advantage of the stabilization process. After the unit is full, it can then closed off and left to dehydrate, ensuring that the levels of pathogens has been reduced to safe levels. In case this step cannot take place, a phase of sun drying or the like would ensure that pathogen destruction has taken place to an adequate extent.

Another important aspect of Eco-San treatment is that although the dehydration and composting processes are exclusive of one another, it is possible that they can happen in the same system but only at different times. An Eco-San toilet may be designed to act as a composter for the duration of use by the owner even though some dehydration is taking place at the same time. Conversely, a system can be designed to operate as a dehydrating unit during, although active composting may be taking place as well. In fact, it is expected that the untrained user will end up with a type of hybrid system that is neither fully composting or fully dehydrating, but has both processes within the same vault.

3. The operation of systems should accomplish the two endpoints of treatment; namely stabilization and sterilization.

The operation of these types of systems should be performed in a manner that the two-fold goals of treatment are achieved: stabilization and sterilization. This type of treatment ensures that the end product is of the quality necessary for the reuse by the owner. If one goal is met without the other, the resulting biosolids will be of questionable quality and may be contaminated and pose adverse health risks for the user. Stabilization without sterilization results in a contaminated end product that needs the additional treatment for pathogen destruction. Sterilization without stabilization seems adequate in the short term, but produces an end product that is highly succeptible to reinfection and regrowth of pathogens once placed in the environment.

Stabilization and sterilization should be accomplished in some form of secondary treatment if the Eco-San system does not provide the full extent of treatment. Stabilization can be

accomplished after treatment in a batch process that would involve the collection of material from the latrine into a holding tank that can be operated in a thermophilic manner. Sterilization can be finalized by the exposure of the material to sunlight for a time after Eco-San treatment in order to destroy all surviving pathogenic organisms.

Eco-San toilet systems can work effectively as treatment units for human waste. Their use and operation must be done in a way that accomplishes all of the above objectives to ensure that the final product is safe and useful for the end user. Much more data is needed to correlate the operating conditions to pathogen reduction to fully determine their effectiveness.

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