**Historical Review of United States (US) Guidance and Regulations
For Sludge Disinfection and Stabilization including a Future Projection**

James E. Smith, Jr., DSc, BCEEM
Independent Consultant
5821 Marlborough Drive
Cincinnati, OH 45230
(513) 232-5629

ABSTRACT

This paper discusses the evolution of the current US sewage sludge disinfection and vector attraction reduction regulations including their bases, associated practices and the limitations of those practices. It further discusses the criteria employed in demonstrating equivalency of a process to a Process to Significantly Reduce Pathogens (PSRP) or a Process to Further Reduce Pathogens (PFRP). The US's current regulations are designed to protect human health by minimizing the contact of humans with pathogenic microorganisms likely present in fecal material. Two types of disinfection processes are typically employed. Processes like pasteurization are employed to reduce pathogens below their analytical detection limits, while processes like mesophilic anaerobic digestion are combined with public access and crop harvesting restrictions to insure adequate reduction of any pathogens present. An effort is made in the paper to discuss what future regulations for controlling pathogens in sludge and its attractiveness to vectors may look like.

KEYWORDS

Sludge, biosolids, disinfection, vector attraction reduction, stabilization, regulations.

INTRODUCTION

Utilities evaluating their present sludge/biosolids (treated sludge) management practices should, according to the Water Environment Federation (WEF, 2011), view their treatment plant as a manufacturing facility, and they should convey this view to their community. That facility produces high quality water, which can often be reused; potentially energy in the form of biogas and electric power contributing to the facility's self sufficiency; and a soil conditioner containing the fertilizing elements of nitrogen, phosphorus, potash, and other trace nutrients for use in agriculture. So as the utility may seek to improve its operation and make it sustainable for the next ten, fifteen or more years, it should not only consider immediate economics but should look at ways to reduce its energy consumption and recover more energy in its biosolids handling as well as how the environment may be affected and the community's interests. As of 2004 the United States was producing approximately 7 million tons of dry biosolids, of which approximately 55% was land applied, 28% was disposed to municipal solid waste landfills and 15% was incinerated (NEBRA, 2007). Such a large percentage of biosolids or treated sludge can be land applied because there is little public controversy and very strong public support.

Should a utility wish to beneficially use its sludge by applying it to land as shown in Figure 1, it will need to select processes for reducing pathogens and the vector attractiveness in its sludge, thus creating biosolids. It is useful in making such selections to know the origin of the US regulations and guidance.

HISTORICAL PERSPECTIVE, NEED FOR AND USE OF DISINFECTION

In the United States today approximately 17,000 treatment plants daily process 34 billion gallons of municipal wastewater containing feces and urine from both humans and animals that may contain

Figure 1. Land Application of Biosolids Cake

many disease-causing organisms. Disease causing organisms or pathogens from humans can enter a community's wastewater from patients at hospitals, or from any sick person or individual carrying the organisms. Animal wastes can enter the wastewater from farms, meat packing and processing facilities and from rats and other animals and/or vectors found in or around sewage or sewers. Table 1 shows the principal pathogens of concern in municipal wastewater and sewage sludge and associated disease/symptoms (USEPA, 2003). The causes of typhoid, gastroenteritis, cholera, hepatitis A, polio, giardiasis, hook worms, cryptosporidiosis, and amebiasis are shown. During the course of treating wastewater through primary (sedimentation) and secondary (typically with activated sludge) processes, the microorganisms present in sewage are reduced in number and become concentrated in the sewage sludge. The cleansed wastewater is very low in suspended matter and soluble materials with an oxygen demand. Prior to discharge the cleansed water is disinfected to reduce any remaining pathogens to a level where the water is safe for recreational purposes. If sludges are to be beneficially used, they are disinfected and stabilized to control their attractiveness to vectors.

The link between human health and what humans ingest, inhale, or come in contact with by some other means has, perhaps surprisingly, been known since the early ages. Figure 2 illustrates the concern with handling of fecal material and the opportunity for human infection and disease. Disposal and use of fecal material on land has occurred since the earliest times. In USA land application of biosolids has been practiced since modern wastewater treatment started or about 165 years ago (NCR, 1996). As an early example, municipal sludge from Alliance, Ohio, was used as a fertilizer in1907. During the same period, Baltimore, Maryland, used domestic septage in agricultural production. Early operations were carried for the most part with no reports of adverse impacts to heath or environment. Treatment was mainly for mass and/or volume reduction and odor control to facilitate its use and/or disposal. While the first recorded anaerobic digester was built by a leper colony in Bombay, India in 1859, US literature did not begin discussing the design and effectiveness of the anaerobic digestion process for reducing sludge mass and odor and producing a usable gas until the 1930s, and it said little about its ability to reduce concentrations of indicator and pathogenic microorganisms up into the 1970s (Schlenz, 1937; Fair and Moore, 1954). The same situation was found for aerobic digestion (Jaworski

et al. 1963). One public health text of the early 1900s suggested that residuals be treated by a process like anaerobic digestion before being used on food chain crops (Babbitt and Baumann, 1958). An examination of all the literature between 1930 and 1975 suggested that with anaerobic and aerobic digestion one could expect about a 40 % reduction in a sludge's volatile solids concentration and about a two log reduction in indicator organisms like fecal coliforms and a one log reduction in pathogenic organisms like *Salmonella* sp., enteric viruses and worms like *Ascaris* (USEPA, 1979).

Table 1. Major Pathogens Present in Raw Domestic Sludge

CLASS	EXAMPLES	DISEASE
Bacteria	*Shigella sp.*	Bacillary dysentery
	Salmonella sp.	Salmonellosis (gastroenteritis)
	Salmonella typhi	Typhoid fever
	Vibrio cholerae	Cholera
	Enteropathogenic-	
	Escherichia coli	A variety of gastroenteric diseases
	Yersinia sp.	Yersiniosos (gastroenteritis)
	Campylobacter jejuni	Campylobacteriosis (gastroenteritis)
Viruses	Hepatitis A	Infectious hepatitis
	Norwalk virus	Acute gastroenteritis
	Rotaviruses	Acute gastroenteritis
	Polioviruses	Poliomyelitis
	Coxsackie viruses	"flu-like" symptoms
	Echoviruses	"flu-like" symptoms
Protozoa	*Entamoeba histolytica*	Amebiasis (amoebic dysentery)
	Giardia lamblia	Giardiasis (gastroenteritis)
	Cryptosporidium sp.	Crytosporidiosis (gastroenteritis)
	Balantidium coli	Balantidiasis (gastroenteritis)
Helminths	*Ascaris sp.*	Ascariasis (roundworm infection)
	Taenia sp.	Taeniasis (tapeworm infection)
	Necator americanus	Ancylostomiasis (hookworm infection)
	Trichuris trichuria	Trichuriasis (whipworm infection)

Looking back to the early use of disinfection practices, we find two basic rules in 2000 B.C. which state that water must be exposed to sunlight and filtered with charcoal, and that impure water must be purified by boiling the water and then dipping a piece of copper into the water seven times, before filtering the water (Baker and Taras, 1981). Amazingly these rules show an awareness of the disinfection/germicidal benefits of stressors/processes like UV rays; filtration, charcoal, high temperature; and heavy metals for removal of contaminants/germs. In the nineteenth century the effect of disinfectants, such as chlorine, was discovered. One of the first known uses of chlorine was for water disinfection in 1850 after an outbreak of cholera in London (Christman, 1998). Chlorine was first used in the USA in 1908 as a chemical disinfectant for drinking water, and the powerful disinfectant attributes come from its ability to bond with and destroy the outer surfaces of bacteria and viruses (Christman, 1998). Chlorine oxidation of sludge is not practiced, however, because of the high concentrations of chlorinated organic compounds that are created (USEPA, 1979).
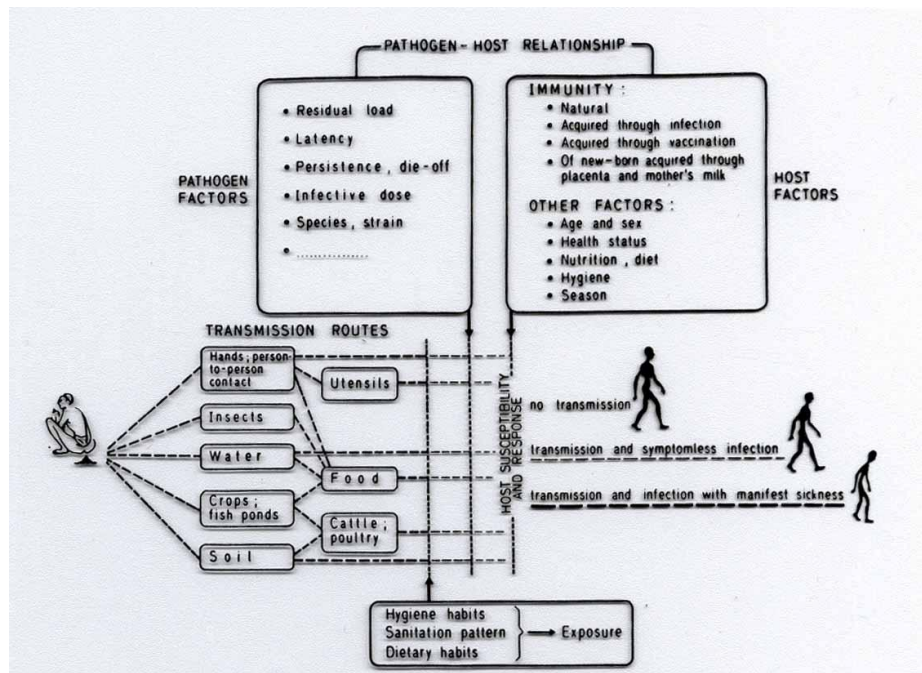
Figure 2. Routes of Infectious Microorganisms from Fecal Material to Humans

Alkaline treatment of wastes has been used effectively for centuries to control odors and eliminate the spread of infectious diseases. Essentially the process stops biological activity and makes the waste unattractive to vectors. Literature shows that ancient Egyptians utilized lime in their army latrines to destroy offensive odors. Lime was employed in the late 1800's for the physical-chemical treatment of water including its ability to clarify, control odors and kill bacteria. Lime sterilization was proposed in 1913 by a Dr. A. C. Houston of London, and its effectiveness was verified in the same year in Columbus & other cities in Ohio by *B. coli* tests showing 3 to 5 log reductions in 5 to 24 hours with CaO (Riehl, 1952). Grabow (1969) found when lime was added to maintain the pH level of humus tank effluent at 11.5 for 1 hour, all gram-negative bacteria were destroyed and the plate count was reduced by more than 99 percent. The only surviving microorganisms were spore formers. The U.S. Environmental Protection Agency's research laboratory in Cincinnati studied the disinfection effect of hydrated lime on liquid sludges at the laboratory, pilot scale and full scale during the early 1970's (Farrell et al., 1974). Raw sewage from the Lebanon, Ohio wastewater treatment plant was treated in one instance with aluminum sulfate ($Al_2(SO_4)_3$ and in another with ferric chloride ($FeCl_3$). Resulting sludges were dosed with lime to pH 11.5 to reduce the bacteria present. Results indicated complete removal of *Salmonella* sp. and *Pseudomonas aeruginosa*, and almost a 3-log removal of total aerobic bacteria. Additional pilot plant work was conducted for EPA by Battelle Northwest's Laboratories (USEPA, 1975). Bacterial counts were recorded before and after treatment of liquid mixed primary sludge and trickling filter humus to pH 12.2 for 30 minutes. Four or more logs of destruction of bacteria were accomplished. Poliovirus 1 was added to secondary effluent and this was then flocculated with dosages of hydrated lime to study the effects of pH on virus survival. Viruses fell below the detection limit at pH 11.20 (Berg et al., 1968). Limited work was reported in the 1969 and 1970 literature about mixing CaO with a moist (dewatered) sludge. When this occurred it was noted that slaking took place with the production of enough heat to readily raise the temperature to 100°C (Liljegren, 1969; Bastgren, 1970). The investigators noted that the temperature was sufficient to destroy bacteria, viruses and other pathogens if the lime was thoroughly mixed with the sludge.

The City of Milwaukee in the 1920s introduced the concept of drying at its Jones Island Plant, applying it to its dewatered activated sludge and selling the product as a fertilizer, because of its high nitrogen, phosphorus, and potash content. While not a major consideration, Milwaukee did two things that led to the control of disease. First they conditioned the sludge to a pH of about 3.0 with the addition of ferric chloride and secondly dried it to near ten percent moisture at a temperature of 82°C. Any organisms present were subjected to the effects of very low pH, high temperature and desiccation (Archer, 2006). Today numerous cities dry their sludges.

Composting according to the University of Illinois Extension Service is an ancient technology. There are Roman and biblical references to composting as well as numerous accounts of farmers' composting practices in subsequent millennia. George Washington, the nation's first president, was also the nation's first recognized composter. He was acutely aware of the negative effects of farming on the soil resource, and he built a "dung repository" to make compost from animal manure so he could replenish the soil's organic matter. The work performed with sludge between about 1950 and the 1970s was mainly concerned with producing an aesthetically pleasing product, one that could be beneficially used in agriculture, and one that reduced the sludge mass. At the same time it was realized that by controlling the moisture content of the material being composted with addition of bulking material, odors could be controlled and temperatures could rise very high. In later years the process was optimized with addition of air and control of temperature to achieve kill of pathogenic microorganisms by U.S. Department of Agriculture researchers (USDA) (Horvath, 1978; Burge et al. 1978).

Research in the 1960s and 1970s showed that gamma rays and high-energy electrons can achive sludge disinfection. They destroy organisms by altering the colloidal nature of the cell contents (protoplasm). Gamma rays are high-energy photons produced by certain radioactive elements. High-energy electrons are electrons accelerated in velocity by electrical potentials in the vicinity of 1 million volts." Work at the Metropolitan Sanitary District of Chicago found irradiation with Cobalt-60 very effective in reducing bacterial numbers (Etzel et al. 1969).

In the 1800s, Louis Pasteur discovered that heating wine prevented spoilage and invented a process we now call "pasteurization." This typically involves heating the fluid milk to 63°C for 30 minutes. The process of pasteurization was first applied to milk in the early 1900s, after it was discovered that milk can transmit tuberculosis, brucellosis, diphtheria, scarlet fever, and Q-fever to human. Sewage sludge pasteurization began in Europe during the 1960s with the practice of heating the fluid sludge to 70°C for 30 minutes (Roediger, 1967). It began in plants in the USA in the 1970s (Cornell University, 2007).

EMERGENCE OF US REGULATIONS FOR PATHOGEN AND VECTOR ATTRACTION CONTROL

In the early 1900s the need for wastewater treatment was linked with importance of dissolved oxygen to aquatic life, aesthetic properties of surface waters (odor, color, solids), and measurement of organic matter in sewage as biological oxygen demand (BOD). In 1948, however, the Federal Water Pollution Control Act went into effect providing federal funds for water quality surveys and construction of collection systems and treatment plants. This funding was increased in 1952 and then again in 1966 with the Clean Water Restoration Act. Following creation of the Environmental Protection Agency in 1970 came the Federal Water Pollution Control Act of 1972, PL 92-500 and the Clean Water Act of 1977, PL 95-217. These laws authorized Federal funding of 75% (85% for innovative and alternative technology projects) of the eligible costs involved in the construction of municipal wastewater treatment plants and sludge treatment and disposition facilities; authorized EPA to issue comprehensive sewage sludge management guidelines and regulations; authorized the NPDES

(National Pollution Discharge Elimination System) for point source discharges and development of area wide waste treatment or water quality management plans for non-point source pollution; required the implementation of pretreatment standards for industrial discharges that enter POTW's; and established a major research and demonstration program to develop improved wastewater treatment and sludge management practices. Under authority of the Resource Conservation and Recovery Act of 1976, "Criteria for Classification of Solid Waste Disposal Facilities and Practices," 40CFR257 was promulgated on September 13, 1979, and addressed the land application of industrial and municipal wastewater sludges for food-chain crop production. The regulation incorporated inputs from EPA, the Food and Drug Administration, and the U.S. Department of Agriculture. Its purpose was to protect public health by requiring sludge management practices that eliminate or minimize human contact with sludge contaminants. The regulation applied to all municipal and industrial sludges destined for land application, including sludge products that are distributed and marketed (USEPA, 1989). It defined two types of treatment/disinfection processes; Process to Further Reduce Pathogens (PFRP) and Process to Significantly Reduce Pathogens (PSRP). These processes are defined in Tables 2 and 3. The intent of PFRP processes is to reduce pathogenic organisms to below their analytical detection limits, while that

Table 2. Processes to Further Reduce Pathogens (PFRPs)

1. Composting a) Using the within-vessel composting method or the static aerated pile composting method, the temperature of sewage sludge is maintained at 55°C (131°F) or higher for 3 consecutive days. o**r b)** Using the windrow composting method, the temperature of the sewage sludge is maintained at 55°C (131°F) or higher for 15 consecutive days or longer. During the period when the compost is maintained at 55°C (131°F) or higher, there shall be a minimum of five turnings of the windrow.
2. Heat Drying Sewage sludge is dried by direct or indirect contact with hot gases to reduce the moisture content of the sewage sludge to 10% or lower. Either the temperature of the sewage sludge particles exceeds 80°C (176°F) or the wet bulb temperature of the gas in contact with the sewage sludge as the sewage sludge leaves the dryer exceeds 80°C (176°F).
3. Heat Treatment Liquid sewage sludge is heated to a temperature of 180°C (356°F) or higher for 30 minutes.
4. Thermophilic Aerobic Digestion Liquid sewage sludge is agitated with air or oxygen to maintain aerobic conditions and the mean cell residence time (i.e., the solids retention time) of the sewage sludge is 10 days at 55°C (131°F) to 60°C (140°F), with a volatile solids reduction of at least 38%.
5. Other Methods Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods. Any of the processes listed below, if added to a PSRP, further reduce pathogens.
6. Beta Ray Irradiation Sewage sludge is irradiated with beta rays from an electron accelerator at dosages of at least 1.0 megarad at room temperature (ca. 20°C [68°F]).
7. Gamma Ray Irradiation Sewage sludge is irradiated with gamma rays from certain isotopes, such as Cobalt 60 and Cesium 137, at dosages of at least 1.0 megarad at room temperature (ca. 20°C [68°F]).
8. Pasteurization The temperature of the sewage sludge is maintained at 70°C (158°F) or higher for 30 minutes or longer.
9. Other Methods Other methods or operating conditions may be acceptable if pathogens are reduced to an extent equivalent to the reduction achieved by any of the above add-on methods.

of the PSRP processes is only to partially (by one log) reduce the number of pathogens. Both PSRP and PFRP processes contained stabilization requirements to minimize the biosolids attractiveness to vectors like flies, birds, etc. by stopping permanently or temporarily putrefaction. For biological processes the requirement was to reduce the volatile solids by > 38%. For lime treatment the requirement was to add sufficient lime to keep the pH above 12 for two hours, and for heat drying the requirement was to raise the solids concentration to $\geq$ 90 %.

What was the origin of the criteria for several of the PFRP technologies? Research work at the USDA's Beltsville, MD laboratories led to development of a composting manual and the criteria (time and temperature) for operation of within vessel and deep pile processes to achieve a stable product and one that contains no detectable pathogens (Willson et al. 1977; Burge et al. 1978). Criteria for operation of windrow systems including time, temperature, and number of turnings was largely developed from experience at Chicago and Los Angeles (Horvath, 1978). The heat drying criteria were based on information obtained from the U.S. Food and Drug Administration (FDA) and the experience gained by the City of Milwaukee in producing Milorganite for many decades. Testing conducted by the USEPA of several samples of material found it to essentially be sterile. Pasteurization, while not able to accomplish stabilization, was able to reduce pathogens below the detection limit as defined in the criteria which was based on studies by the FDA, EPA's Health Effects Laboratory, and work in Germany (Ward et al. 1978, Roediger, 1967). Criteria for thermophilic aerobic digestion was based on EPA pilot scale research and operation of plant scale systems (Jewell et al. 1978, Matsch et al. 1977, and Kabrick et al. 1979).

Table 3. Processes to Significantly Reduce Pathogens (PSRPs)

1. Aerobic Digestion Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Values for the mean cell residence time and temperature shall be between 40 days at 20°C (68°F) and 60 days at 15°C (59°F), with a volatile solids reduction of at least 38%.
2. Air Drying Sewage sludge is dried on sand beds or on paved or unpaved basins. The sewage sludge dries for a minimum of 3 months. During 2 of the 3 months, the ambient average daily temperature is above 0°C (32°F).
3. Anaerobic Digestion Sewage sludge is treated in the absence of air for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Values for the mean cell residence time and temperature shall be between 15 days at 35°C to 55°C (131°F) and 60 days at 20°C (68°F), with a volatile solids reduction of at least 38%.
4. Composting Using either the within-vessel, static aerated pile, or windrow composting methods, the temperature of the sewage sludge is raised to 40°C (104°F) or higher and remains at 40°C (104°F) or higher for 5 days. For 4 hours during the 5-day period, the temperature in the compost pile exceeds 55°C (131°F).
5. Lime Stabilization Sufficient lime is added to the sewage sludge to raise the pH of the sewage sludge to 12 for $\square$ 2 hours of contact.
6. Other Methods: Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

Now considering the criteria for several of the PSRP technologies: anaerobic digestion standards were developed from the experience of numerous utilities and reported in several professional papers and

documents (WPCF 1977, Fair et al. 1954, Stern et al. 1977). Similar sources of information were employed for operation of aerobic digestion processes (WPCF 1977, Jaworski et al. 1963). The work for developing the lime stabilization process was primarily done by the USEPA research laboratory in Cincinnati and by EPA sponsored plant scale research and was peformed with the addition of hydrated lime to liquid sludge (Farrell et al. 1972, Noland et al. 1978, Berg et al. 1968.)

Since PSRPs reduce but do not eliminate pathogens, PSRP-treated sludge still has a potential to transmit disease. Thus it was and is essential that time be allowed for the sludge once land applied to undergo further pathogen reduction by natural attenuation. To protect public health, the regulations minimized the potential for direct and indirect exposure to sludge by controlling public access, the growing of human food crops, and grazing by dairy or meat-producing livestock at sites where PSRP-treated sludges were applied. Specifically, public access to the site was restricted for at least 12 months following application of the PSRP treated sludge, and grazing by animals whose products are consumed by humans was prevented for at least 1 month following application. The one month waiting period was based on the typical survival rate of viruses and bacteria on vegetation. Crops for direct human consumption (i.e. crops such as fruits and vegetables that would not be processed to minimize the presence of pathogens prior to distribution to the consumer) could be grown on the land only if the edible portion of the crop would not come in contact with the sludge, or if the growing of these crops was delayed by at least 18 months from the time of sludge application. The 18-month waiting period was based on the anticipated survival of the hardiest pathogens, helminth eggs and following discussions with the FDA.

Thus, the infectious disease prevention strategies used for sewage sludge spread on land incorporated a multiple barrier approach. They involved a disinfection process, a stabilization process and where necessary human and animal access along with crop harvesting restrictions.

1979 to 1993

The 1979 Rule established a limited number of methods of treatment to reduce pathogens and vector attraction was very prescriptive. To provide room for new developments, the 1979 regulation allowed for processes demonstrated to be equivalent to PSRPs and PFRPs. Subsequently, EPA instituted a Pathogen Equivalency Committee (PEC) to evaluate processes brought to its attention and recommend to regulatory staff whether the processes were "equivalent" to the named processes. The PEC, based on recommendations of the World Health Organization (1981) and the EPA Health Effects Laboratory (Kowal 1985) expected a PSRP equivalent process to show more than a one log reduction of *Salmonella s*p. or enteroviruses. They expected a PFRP equivalent process to show a three log reduction of *Salmonella* sp. and enteroviruses, and 2 log reduction of viable helminth eggs. Research during this 14 year period continued with studies of pathogen die-off in soil and disinfection/stabilization process performance. Some effort was made to use a risk based approach to determine acceptable levels of pathogens in sludge. Not enough data, however, was available.

1993 Regulation Improvement

In 1993, EPA promulgated the 40CFR503 sewage sludge regulations, which replaced the Part 257 rule relative to minimum federal requirements on sewage sludge use and disposal requirements. Like Part 257, the Part 503 regulations contain the PSRP and PFRP disinfection processes. However the vector attraction components were separated-out and more options added. The public access and harvesting restrictions under 40CFR257 were modified. This 1993 Rule added alternatives for achieving disinfection and divided all the alternatives into Class A or Class B. Acceptable levels of pathogenic

and/or indicator organisms for treated sludge intended for beneficial use (biosolids) following its disinfection and vector attraction reduction control (VAR) were established (USEPA, 1993). The requirements for a sludge to be Class A with respect to pathogens can be met with any one of six alternatives. Common to every alternative is the necessity that the density of *Salmonella* species be reduced to less than three MPN per four grams of dry sludge solids or the fecal coliforms be less than 1000 MPN per gram of dry sludge solids. Since levels of fecal coliforms per gram of untreated sludge often approach 10^8, it is expected that there will be at least a five log reduction. The alternatives, briefly stated, are described below and comments based on experience gained from their employment are provided.

Alternative 1. Time (D-days) & temperature (t-°C) are related by the equation: $D = 31,700,000/10^{0.14t}$ or $50,070,000/10^{0.14t}$. The first equation applies when the total solids are $\geq$ 7%; $t \geq$ 50°C and time is $\geq$ 20 minutes. If the sludge particles are small and are heated by warmed gases or an immiscible liquid, the minimum time is 15 seconds. This equation also applies when the solids <7%, t >50°C and time is $\geq$ 15 sec to<30 min. The second equation applies for total solids < 7 %; $t \geq$ 50°C and $D \geq$ 30 minutes. These requirements were established from FDA requirements for eggnog, data from German sources, and other data collected during composting experiments in the U.S.A. (U.S. EPA 1992). Many facilities approach Alternative 1 without realizing that it was derived from experience with fluids. In fluids, as opposed to dewatered sludges, it is not difficult to insure that all particles meet the requirements for time and temperature. In general these processes are intended to apply to batch or plug flow reactors rather than continuous flow reactors. It is critical that these sludge treatment processes are completed without short circuiting occurring.

Alternative 2. This alternative is based on disinfection research done by the N-Viro Energy Systems, Inc. in the late 1980s (U.S.EPA, 2003). The pH is raised to above 12 for greater than 72 hours, the temperature is above 52°C, and, after the 72 hours, the treated sludge is air-dried to 50 % solids or greater.

Alternative 3. The sludge is first analyzed for viable helminth eggs and enteric viruses. If these organisms are not present (less than one ovum and less than one plaque-forming unit [PFU] per four grams of solids), the process is Class A only until the next monitoring period. If the organisms are present in the feed but not in the product, the product produced in the future is Class A for pathogens provided that the process operating conditions are consistent with those utilized during the test.

Alternative 4. The sludge is analyzed for viable helminth eggs and enteric viruses. If they are below one viable ovum and one virus PFU per four grams of solids, the material is Class A with respect to pathogens.

NOTE: Alternatives 3 and 4 are only useful when substantial numbers of enteric viruses and helminth ova are present in the raw sludge, an unlikely event, and monitoring is done to measure the effectiveness of the treatment process. Several states do not allow these alternatives.

Alternative 5. The sludge is treated by a PFRP. The three processes most frequently used are composting, pasteurization, and heat drying. With composting it is critical that all parts of the sludge pass through a zone where they can be held for no less than 3 days at 55°C and then be removed without contamination. Pasteurization for sludge means holding its temperature at 70°C or above for at least 30 minutes. Achieving these results by mixing a powder, quicklime (or similar reagent), with semisolid material, sludge, is not by any means easy. Some minimal level of moisture is necessary.

Alternative 6. The sludge is treated by a process equivalent to a PFRP. Some technologies found to be equivalent are: two-stage (a thermophilic aerobic digester followed by a mesophilic anaerobic digester) sludge stabilization; autothermal thermophilic aerobic digestion; two-phase thermo-meso anaerobic digestion; and OxyOzonation (USEPA, 2003)

Requirements for a sludge to be Class B with respect to pathogens are met by employing one of the following three alternatives:

Alternative 1. The geometric mean fecal coliform density (either MPN or CFU per gram of dry sludge solids) of seven samples shall be less than 2,000,000. Here, since levels of fecal coliforms in the untreated sludge were thought to approach 10^8 at the time the regulations were written, at least a two log reduction was expected. However, since levels of fecal coliforms now (2013) found in raw sludge are falling, many sludges can meet the Alternative 1 requirements with no treatment. As such it is recommended that this alternative only be used with a sludge that was treated.

Alternative 2. The sludge is treated by a PSRP. The commonly employed processes are: aerobic digestion, air drying, anaerobic digestion, composting (less stringent thermal requirements than the PFRP), and lime stabilization (USEPA, 2003).

Alternative 3. Sludge is treated by a process equivalent to a PSRP.

The eight site restrictions that must be followed for application of Class B sludge are shown below.

1. Aboveground food crops that touch the soil are not harvested for 14 months after sludge application.
2. Below-ground food crops are not harvested for 20 months after application if sludge has remained on the soil surface for four months or more prior to incorporation.
3. Below-ground food crops shall not be harvested for 38 months after sludge application if the sludge has been on the surface of the soil for less than four months before incorporation.
4. No crops shall be harvested for 30 days after application of sludge.
5. Animals shall not be allowed to graze for 30 days after application of sludge.
6. Turf grown on land where sludge is applied shall not be harvested for one year after application when it is to be placed on a lawn or other site with high potential for public exposure unless otherwise specified by the permitting authority.
7. Public access is restricted for one year if there is high potential for public exposure.
8. Public access is restricted for 30 days if there is low potential for public exposure.

Demonstration Requirements for a Process to be Classified PSRP or PFRP Equivalent

The effectiveness of disinfection technologies used to treat sewage sludge is evaluated by the presence/absence of the most treatment-resistant organisms (presuming they are present in the raw, untreated material). Enteric viruses and helminth ova were selected as indicators of treatment effectiveness because they are regarded by microbiologists working with sewage sludges as the most treatment-resistant organisms, and they can be quantified. By destroying the most resistant microbial forms, it follows that all other less resistant pathogenic microbes will be eliminated by that same treatment process. No treatment process is designed to produce a sterile product because the complete absence of microbes in a nutrient rich material invites a population explosion of the first microbes to recolonize, which might be the pathogenic species. The presence of competing nonpathogenic microbes provides a biological buffer that prevents an overwhelming restructuring of the microbe abundances (or populations) present in the material.

Table 4 below broadly shows EPA's requirements for demonstrating equivalency of an innovative or alternative technology to a PSRP or PFRP. EPA must in addition be able to understand how the proposed technology acts to disinfect and know what the key process control parameters are. To demonstrate adequate pathogen destruction, the untreated sludge must contain adequate numbers of organisms. For example, to demonstrate PFRP equivalency the untreated sludge needs to contain at

least 1,000 PFU of enteric viruses /4 g TS (dry weight basis); and 100 viable Ascaris spp. ova/4 g TS. If the untreated sludge does not naturally contain these density levels, the applicant must spike it to achieve these levels. Detailed information on demonstrating equivalency can be found at: http://www.epa.gov/nrmrl/pec/ .

Table 4. Requirements for Demonstrating Equivalency

PSRP Equivalency	PFRP Equivalency
> 1 log reduction of Salmonella sp. or > 2 log reduction of fecal coliforms	$\geq$ 3 log reduction of enteroviruses
> 1 log reduction of enteroviruses	$\geq$ 2 log reduction of viable Ascaris sp. ova
Final product contains < 2,000,000 fecal coliforms/g	Final product contains < 1000 fecal coliforms or < 3 Salmonella sp./4 g; < 1 pfu/4g of entericviruses and < 1 helminth ova/ 4g

Stability Considerations

As the definition of the word "stabilize" implies, the goal of stabilizing sludge is to prevent any further change. Sludge odors and putrescibility should be minimized and as such attractiveness to vectors and possible spread of disease. Obviously reducing vector attractiveness is only an approach to stability but does not guarantee that a material is *completely* stabile. Unfortunately sludge stability cannot be determined by a universally accepted standard test. The situation is complicated because the best measure varies with the type of stabilization process employed. It could be said that VAR (or odor, as one is a consequence of the other) is the most relevant and reasonable criterion. However, quantification is difficult, subjective and expensive. The options for controlling vector attraction given in the 1993 Rule are shown in Table 5. Options 1 to 8 and 12 are designed to prevent the attractiveness of biosolids to vectors by a treatment that modifies the characteristic of the sludge organic matter, which is responsible for this attraction. Options 9 to 11 put barriers to prevent vectors for coming into contact with biosolids.

These methods have been widely described by Bruce and Fisher (1984), US EPA (2003) and Switzenbaum et al. (2002). The reduction of VS by 38 % is the most widely used measurement with processes like anaerobic digestion and aerobic stabilization to show adequate VAR. It is followed in employment by the specific oxygen uptake rate (SOUR) test, alkaline addition, dry solids concentration, and injection or incorporation. The intent of the biological treatment processes is to reduce the biodegradable organic material to a level where odors are no longer produced and vectors are no longer attracted. Not surprisingly these test values are not optimal. Adjustments are needed. For example we know that biological digestion processes can as a function of the sludge being digested achieve volatile solids reductions from 20 to 70 % or higher. Most designers today would expect to obtain at least 50 % VSR and often much higher. Thus what is ideally needed in place of the 38 % value is a formula into which the parameters for a specific sludge are inserted. The SOUR number now can only be used within a narrow temperature range and with a relatively low solids concentration. These conditions need to be expanded and further we need to address the extent of VSR during thermophilic digestion of sludges. Better tests are already available for composted materials such as measuring the evolution of CO_2 and the use of such techniques for evaluation of product stability need to be considered.

Table 5. **U.S. Vector attraction reduction options (US EPA, 1993; 2003)**

Option	Requirement
1	Minimun of 38% mass reduction of volatile solids
2	For anaerobically digested biosolids not meeting option 1, demonstrate vector attraction reduction by bench-scale anaerobic digestion (less than 17% reduction of volatile solids over 40 days at 30–37ºC)
3	For aerobically digested biosolids not meeting option 1, demonstrate vector attraction reduction by bench-scale aerobic digestion (less than 15% reduction of volatile solids over 30 days at 20ºC)
4	For aerobically treated biosolids, the specific oxygen uptake rate should be equal or less than 1.5 mg/h/g DS at 20ºC
5	Aerobic treatment of biosolids at temperatures greater than 40ºC (average of 45ºC) for 14 days or longer
6	Increase of the pH to above 12, followed by maintaining the pH at 12 or higher for 2 hours and at 11.5 or higher for an additional 22 hours
7	Reduce moisture content of biosolids that do not contain unstabilized solids to at least 75% solids
8	Reduce moisture content of biosolids that do contain unstabilized solids to at least 90% solids.
9	Injection of biosolids beneath the land surface
10	Incorporation of biosolids into the soil
11	Cover sludge placed on surface with soil or other material
12	Raise pH of domestic septage to > 12 by alkali addition

Future Concerns with Pathogens in the Environment

Concerns about the potential health risks from pathogens associated with the land application of wastes will continue into the foreseeable future. Some relatively recent pathogens of interest are shown in Table 6. Over the last decade, at least one new pathogen per year has been recognized as a public health threat (WHO, 2003). Many of these are zoonotic organisms meaning they originate with animals. This is due to a number of factors including 1) changes in the way we produce our food supply, 2) the international transportation of food and people on a global scale, 3) advances in molecular biology, which allow us to identify new pathogens and trace their source, 4) the evolution of pathogens, 5) changing demographics of the population (older and more immune-compromised individuals who have a greater risk of serious illness are increasing in numbers), and 6) application of microbial risk assessment to quantify risks from environmentally transmitted pathogens.

Table 9 - Emerging Pathogens in Raw Sludge

Bacteria	Viruses	Parasites
E. coli-0157-H7	Picobinravirus	*Toxacara*
E. coli-enterohemorragic	Picotrirnaviruses	*Baylisascaris*
Listeria monocytogenes	Coronaviruses	*Echinococcus*
Leptospira spp.	Toroviruses	*Toxoplasma*
	Hepatitis E Virus	Microsporidia
	Caliciviruses	
	Myxoviruses	

FINAL CONSIDERATIONS: WHERE DO WE GO FROM HERE?

To be able to consider future requirements for controlling pathogenic microorganisms and how sludge is stabilized, beyond public health issues, it is important to reflect on the signals that are being given by the regulators, users of biosolids and the communities including both the treatment plant and its neighbors. This can partially be done by looking at the findings of a 2007 NEBRA report, the findings of a 2010 Expert Meeting of the Water Environment Federation's National Biosolids Partnership (NBP), UK's Safe Sludge Matrix, the draft EC product quality and treatment recommendations, and recent action of Canada's Quebec Province. This approach was used in a recent paper titled, "Controlling Pathogens and Stabilizing Sludge/Biosolids: A Global Perspective of where we are today and where we need to go" (Sobrados-Bernardos et al. 2012).

Figure 3 highlights the pressures that a 2007 survey of US practices identified for biosolids programs (NEBRA, 2007). The numbers across the top show the number of individuals/groups surveyed and which, out of 250, identified the subject area as a priority. Highest priority was attributed to public involvement. Another very high priority was nuisance issues which included items like odors, truck traffic, and dust. These concerns were reinforced by the findings of a December, 2010 meeting of experts that the NBP held (WEF, 2011). Participants focused substantially on the persistence of public perception (of health) issues. These in turn have driven local and state regulatory and policy actions limiting biosolids management options including land application bans and the introduction of more restrictive management practices such as fence line setbacks and incorporation requirements.

Top pressures on biosolids recycling programs
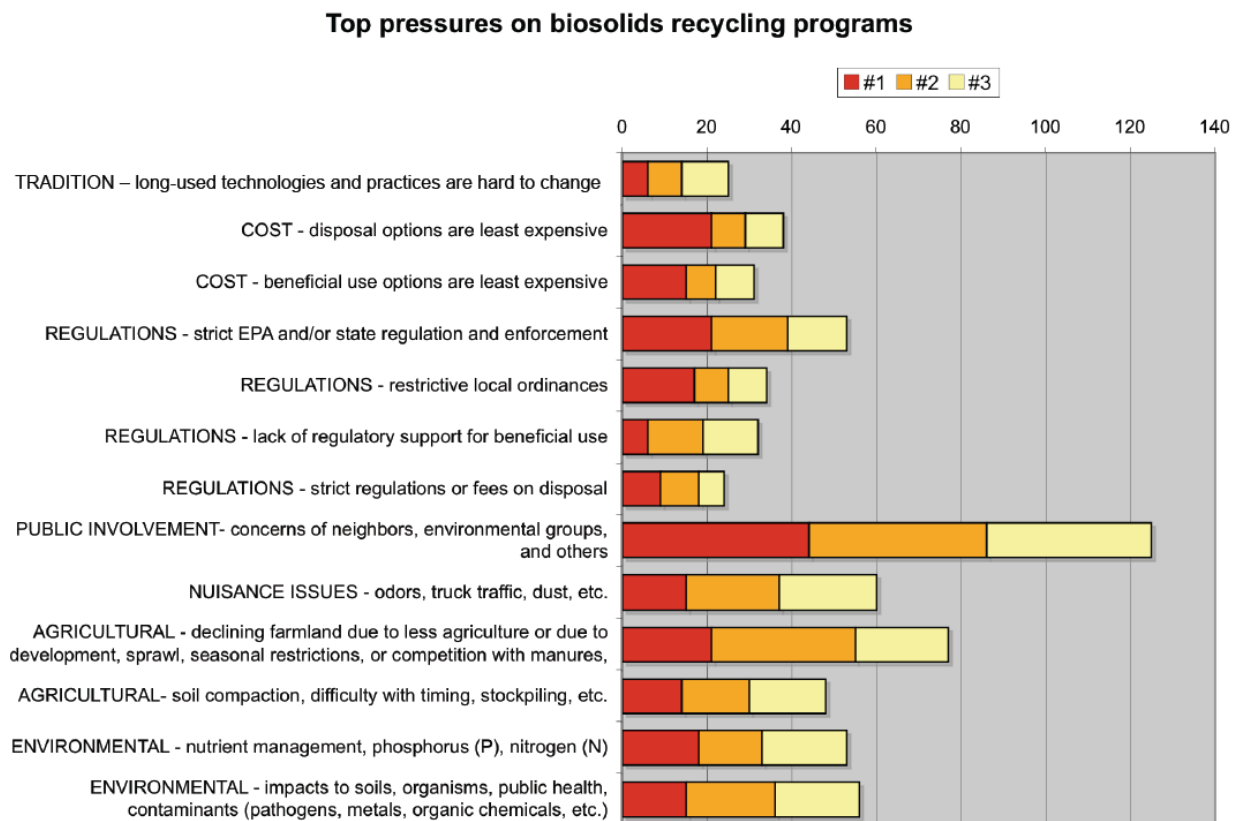
Figure 3. Pressures on Biosolids Programs (After NEBRA, 2007)

The perception that Class A treated sludge is healthier than Class B treated sludge by the public has led to more Class A product production. Closely tied by participants to persistent public perception problems were odors associated with biosolids processing, handling, and end use/disposal. Some localities are taking a "zero tolerance" approach to odor (WEF, 2011). Since some evidence exists that malodors may trigger health effects, the Ministry of Sustainable development, Environment and Parks in Quebec, Canada (MDDEP) developed an odor classification system for biosolids and other fertilizing residuals (FRs) that are applied on farm land (NEBRA/Beecher, 2010). It uses the system in its regulations of biosolids and other FRS. Specifically, 38 different types of typical biosolids and FRs are given a default odor designation. As the odor level increases, increasingly stringent management requirements, such as increased setbacks, are required. "Out of category" biosolids / FRs cannot be land applied without further treatment for odors. The regulatory system has proven effective in reducing odor complaints. However, it has led to elimination of land application in the province of some biosolids that were deemed too odorous (NEBRA/Beecher, 2010).

The Future of Disinfection and Stabilization Requirements: Author's View

Wastewater treatment plants will continue to produce sludges and a significant amount of that sludge will after appropriate processing be beneficially used in agriculture.

Public health officials in Europe, the US and essentially internationally agree that **<u>untreated sludge is not to be used in agriculture for either food or non-food crops.</u>** This practice is to protect humans as well as animals from infectious disease causing microorganisms.

Rather where sludge is to be beneficially used in agriculture an approach that employs multiple protective barriers in the sludge treatment scheme is recommended and includes:

- A disinfection process
- A stabilization (Vector Attraction) process – In some approaches disinfection and stabilization occur in the same process.
- Product quality monitoring
- Application of access and crop harvesting restrictions

These barriers need to put in place when any biosolids are used in agriculture. The degree of treatment required for a sludge and the access and crop harvesting restrictions to be applied depend on the intended beneficial use of the sludge. An admittedly conservative approach is currently recommended by the UK and EC and is shown in Figure 4 (British Retail Association et al. 2001). As already noted no untreated sludge is to be used in agriculture. In some cases conventionally treated sludge can be used with the implementation of the indicated application, harvesting and grazing restrictions. Sludges receiving enhanced treatment can be used with all kinds of crops with only the need to observe minor grazing and harvesting interval restrictions to guaranty that all pathogens have been reduced to very low and undetectable levels.

Disinfection
Conventionally treated sludge or biosolids has been subjected to a defined treatment process and standards that ensure $\geq$ a 2 log reduction of indicator organisms and $\geq$ a log reduction of pathogens. Class B – PSRP are an example of conventional treatment processes. Enhanced treated sludge or biosolids will contain no detectable levels of pathogenic organisms. Class A – PFRP, Class A,

Alternative 1 (time and temperature relationships) and Class A, Alternative 2 – Alkaline Treatment are examples of enhanced treatment processes.

Product Quality
Recommendations employed in the UK and recommended by EC for enhanced treated sludge/biosolids follow:

- *E. coli* – < 100 MPN/ g dry solids
- *Salmonella sp* – Non detect in 50 g dry solids

Add where significant levels of helminths and/or enteroviruses are known to be present and where further there are questions concerning the disinfection process.

- Helminth ova – Total ova of < 1/ 4g dry solids and non detectable levels of viable ova
- Viruses - Entero viruses of < 1 pfu / 4 g dry solids

Some utilities may have difficulty meeting the above limits and need to upgrade their disinfection process by improving its heating, mixing or other component to insure that the temperature, pH, etc. is uniform throughout and the detention time is what it needs to be.

CROP GROUP	UNTREATED SLUDGES	CONVENTIONALLY TREATED SLUDGES	ENHANCED TREATED SLUDGES
FRUIT	✗	✗	✓
SALADS	✗	✗ (30 month harvest interval applies)	✓
VEGETABLES	✗	✗ (12 month harvest interval applies)	✓
HORTICULTURE	✗	✗	✓
COMBINABLE & ANIMAL FEED CROPS	✗	✓	✓
GRASS & FORAGE - GRAZED	✗	✗ (Deep injected or ploughed down only)	✓
GRASS & FORAGE - HARVESTED	✗	✓ (No grazing in season of application)	✓

(SALADS–VEGETABLES–HORTICULTURE, Enhanced: 10 month harvest interval applies)

(GRASS & FORAGE, Conventionally treated: 3 week no grazing and harvest interval applies)

(GRASS & FORAGE, Enhanced treated: 3 week no grazing and harvest interval applies)

✓ All applications must comply with the Sludge (Use in Agriculture) Regulations and DETR Code of Practice for Agricultural Use of Sewage Sludge (to be revised during 2001).

✗ Applications not allowed (except where stated conditions apply)

Figure 4. Sewage Sludge Matrix

Stabilization Barrier
All sludges need to be stabilized by a treatment process to the point where a) any odors still present in the biosolids are non offensive and b) biodegradable material remaining is minimal enough that vectors are not attracted. It is recognized that stabilization may occur at the same time as disinfection with some processes. Recommended methods follow:

- Reducing the moisture content of the biosolids to $\leq$ 25 % (Note: This is only acceptable when some assurance can be given that the dried material will not be rewetted. (This is particularly important if little pretreatment of the sludge occurs before drying.)
- Reducing the biodegradable organic content of biosolids by biological treatment as follows:
  - Aerobic digestion with effectiveness measured by:
    - Specific oxygen uptake rate should be equal or less than 1.5 mg/h/g DS at 20ºC
    - A leveling off of volatile solids destruction with time
  - Anaerobic digestion with effectiveness measured by:
    - A leveling off of volatile solids destruction with time
    - A leveling off of gas production with time
  - Composting with effectiveness measured by:
    - A leveling off of oxygen uptake rate
    - A leveling off of carbon dioxide evolution
    - Allowance for adequate curing of product – this can be from 40 to 90 days.
- Incorporation or injection of biosolids into the soil.

Notes: It is recognized that several of the measures included above will require testing to determine the best values for a particular biosolids**.** For example very high levels of volatile solids destruction ($\geq$ 55 %) can occur during the digestion of some sludges in the allotted time of 15 days.

Recommendation

- Measure odor in a field setting of the applied biosolids using an olfactometer. See Beecher (2010).

Access and Crop Harvesting Restrictions

Typically regulatory requirements for the residence time of sludge in design of disinfection and stablilization processes are not large. As such it is understandable that the allowance of additional time for further attenuation of any remaining (even if undetectable by current analytical procedures) pathogens in sludge and putrescible matter is both beneficial and a further disease barrier. The US's regulations for Class B treatment allow for this circumstance. On the other hand, the US's regulations do not require it for Class A treated sludges. The UK and the European Community, however, do feel this is a necessary precaution to take. And , in fact, some of the US' states also do. Certainly most public health officials agree.

REFERENCES

Archer, M. (2006), Personal Communication, Milorganite Market Development, Milwaukee, Wisconsin, May 10.

Babbitt, H. E. and Banmann, E. R. (1958). *Sewerage and sewage treatment*. 9th Ed. John Wiley and Sons. Inc. New York.

Baker, M.N. and Taras, Michael J. (1981). *The quest for pure water: The history of the twentieth century, volume 1 and 2.* Denver: AWWA.

Bastgren, W. (1970), Sterilization of sewage sludge. Ger. Offen. 1,806,372 (Chem. Abs. 73, No. 28,633, p. 1970).

Beecher, N (2010) *Odor classification of biosolids to mitigate nuisances : a Québec approac*h, Proceedings of the WEF 2010 Residuals & Biosolids Conference, Savannah, GA, pp 720-726.

Berg, G., Dean, R.B. and Dahling, D.R. (1968). Removal of poliovirus 1 from secondary effluents by lime flocculation and rapid sand filtration. *J. Am. Water Works Assoc*. 60:193-198.

British Retail Consortium, Water UK and ADAS (2001), The Safe Sludge Matrix: Guidelines for the Application of Sewage Sludge to Agricultural Land, April 2001, 3rd Edition.

Bruce, A.M. and Fisher, W.J.. (1984). Sludge stabilization. Chapter 1 in Sewage sludge stabilization and disinfection. Water Research Center/Ellis Horwood Limited. Great Britain.

Burge, W., Colacicco, D., Cramer, W., and Epstein, E. (1978), "Criteria for Control of Pathogens During Sewage Sludge Composing," pp 124-129, in *Procs. Nat. Conf. on Design of Municipal Sludge Compost Facilities*, Chicago, Aug , Information Transfer, Inc., Rockville, Md.

Christman, K.(1998). The history of chlorine. *Waterworld,* 14 (8), 66-67.

Cornell University (2007), *Heat Treatments and Pasteurization*, http://www.milkfacts.info/Milk%20Processing/Heat%20Treatments%20and%20Pasteurization.htm, February 26.

Etzel, J. E., Born, G.S., Stein, J., Helbing, T.J. and Baney, G.(1969), Sewage sludge conditioning and disinfection by gamma irradiation, *Am J Public Health Nations Health*, November; 59(11): 2067–2076.

Fair and Moore (1954), cited by Fair, G. M., and Geyer, J. C., *Water Supply and Waste-water Disposal*, John Wiley and Sons, N.Y.

Farrell, J. B., Smith, J. E., Jr., Hathaway, **S. W.,** and Dean, R. B.(1974), "Lime Stabilization of Primary Sludges." J. ***Water Pollut. Contr. Fed.,*** 46, 1 13.

Grabow, W.O.K.(1969). The bactericidal effect of lime flocculation flotation as a primary unit process in a multiple system for the advanced purification of sewage works effluent. *Water Resource*s. Vol. 3, p. 943.

Horvath, R.W. (1978), "Operation and Design Criteria for Windrow Composting of Sludge," pp 88-95, in *Proc. Nat. Conf. on Design of Municipal Sludge Compost Facilities*, Chicago, August, Information Transfer, Inc., Rockville, MD.

Jaworski, N., Lawton, G. W., and Rohlich, G.A.(1963) "Aerobic Sludge Digestion" in *Advances in Biological Waste Treatment*, Macmillan Company, N.Y.

Jewell, W.J. and Kabrick, R.M. (1978) "Autoheated Aerobic Thermophilic Digestion with Air Aeration," 51st Ann. WPCF Conf., Anaheim, CA (Oct. 1978).

Kabrick, R.M., Jewell, W.J., Salotto, V.V. and Berman, D. (1979) "Inactivation of Viruses, Pathogenic Bacteria and Parasites in Autoheated Aerobic Thermophilic Digestion of Sewage Solids," 34th Ann. Purdue Industr. Waste Conf. (May 1979).

Kowal, N.E. 1985. Health Effects of Land Application of Municipal Sludge. EPA Rept. No. EPA/600/1-85/015.

Liljegren, J.R. (1969). *Methods of separating inorganic impurities from sewage and making a soil improving composition from the impurities separated*. U.S. Pat. 3,476,683.

Matsch, L.C. and Dvnevich, R.F. (1977) "Autothermal Aerobic Digestion," JWPCF, 49, 2.

NCR (National Research Council). (1996). *Use of reclaimed water and sludge in food   crop production.* National Academy Press, Washington DC.

NEBRA (North East Biosolids and Residuals Association) (2007), *A National Biosolids Regulation, Quality, End Use, and Disposal Survey - Final Report*, July 20, NEBRA, P.O. Box 422, Tamworth, NH

Noland, R.F., Edwards, J.D. and Kip M. (1978) "Full Scale Demonstration of Lime Stabilization," USEPA Report EPA-600/2-78-171.

Riehl, M.L.(1952). Effect of lime-treated water on survival of bacteria. *Journal American Water Works Association*. Vol. 44, p. 466.

Roediger, H.(1967) *The Technique of Sewage Sludge Pasteurization: Actual Results Obtained in Existing PLants; Economy*, International Research Group on RFefuse Disposal (IRGRD), Information B ulletin No. 21-31, Auguest, 1964 – December, 1967, pp. 325-330.

Schlenz, H. E.,(1937), discussion of "Standard Practice in Separate Sludge Digestion," *Proceedings, ASCE*, 63, p. 1114, June 1937.

Sobrados-Bernardos, L and Smith, J.E., "Controlling Pathogens and Stabilizing Sludge/Biosolids: A Global Perspective of Where We Are Today and Where We Need To Go?" Proceedings of

the Water Environment Federation's 26th Annual Residuals and Biosolids 2012; Advancing Residuals Management: Technologies and Applications Conference; March 25-28, 2012, Raleigh, NC.

Stern, G. and Farrell, J.B. (1977). Sludge Disinfection Techniques. *Proc. of Nat. Conf. on Composting Municipal Residues and Sludges*, Washington, D.C., Information Transfer, Inc., Rockville, MD. Pages 1117-1122.

Switzenbaum, M.S., Pincince, A.B., Donovan, J., Epstein, E., and Farrell, J.B. (2002), Developing Protocols for Measuring Biosolids Stability, Water Environment Research Foundation Report 99-PUM-3, 2002.

U.S. EPA, (1975). *Lime Stabilized Sludge: Its Stability and Effect on Agricultural Land*. National Environmental Research Center. Washington, D.C. 20460. EPA-670/2-75-012. April.

U.S. EPA (1979). *Process Design Manual for Sludge Treatment and Disposal*, EPA/625/1-79/011, Cincinnati, Ohio, September.

U.S. EPA (1989) *Environmental Regulations and Technology: Control of Pathogens in Municipal Wastewater Sludge*, EPA/625/10-89/006, Center for Environmental Research Information, Cincinnati, OH.

U.S. EPA.(1992) *Technical Support Document for Reduction of Pathogens and Vector Attraction in Sewage Sludge.* EPA/822/R-93-004. Washington, DC.

U.S. EPA.(1993) 40 CFR Parts 257, 403, and 503 (FRO-4203-3): Standards for the use and disposal of sewage, final rule. *Fed. Register*, 58, 9248. US Government Printing Office, Washington, DC. February 19, 1993

U.S. EPA.(2003). *Environmental Regulations and Technology: Control of Pathogens and Vector Attraction in Sewage Sludge*, EPA/625/R-92/013, revised July, 2003, Cincinnati, OH.

Ward, R.L. and Brandon, J.R. (1978) "Effect of Heat on Pathogenic Organisms Foundin Wastewater Sludge," pp. 122-127 in 1977 Conf. on "Composting of Municipal Residues and Sludges," Aug. 1977, pub. Information Transfer, Inc., Rockville, Md.

WEF (2011) Charting the Future of Biosolids Management, Water Environment Federation – National Biosolids Partnership Report, May 19, 2011, Alexandria, VA.

World Health Organization. 1981. The Risk to Health of Microbes in Sewage Sludge Applied to Land. Report of a WHO Working Group, Stevenage 6-9 January 1981, EURO Reports and Studies 54, WHO Regional Office, Copenhagen

WHO.(2003) *Emerging Issues in Water and Infectious Diseases.* World Health Organization, Geneva, Switzerland.

Willson, G.B., Epstein, E., and Parr, J.R. (1977) "Recent Advances in Compost Technology," pp. 167-172, in Proc. 3rd Nat. Conf., "Sludge Management, Disposal, and Utilization," Miami Beach, Dec. 1976, pub. Information Transfer, Inc., Rockville, Md.

WPCF (1977) "Wastewater Treatment Plant Design," WPCF Manual of Practice No. 8, Water Pollution Control Federation, Washington, DC.