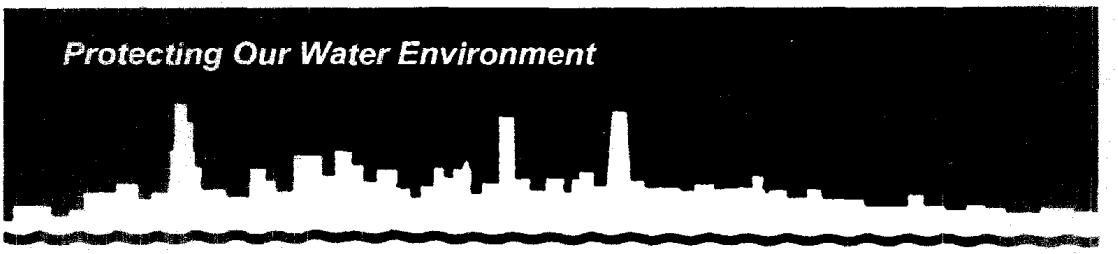

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

REPORT NO. 01-1

PEER REVIEW OF

METROPOLITAN WATER RECLAMATION DISTRICT

OF GREATER CHICAG0'S APPLICATION FOR DESIGNATION

OF PROCESSES TO FURTHER REDUCE PATHOGENS

January 2001

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PEER REVIEW OF METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S APPLICATION FOR DESIGNATION OF PROCESSES TO FURTHER REDUCE PATHOGENS

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INTRODUCTION

Background to Project

Treatment of sewage sludges generated from domestic wastewater treatment is required to minimize the risk of adverse effects when the material is subsequently used beneficially (e.g., applied to land). In 1993, the U.S. Environmental Protection Agency (EPA) published regulations establishing the appropriate processes and conditions necessary to minimize these risks. Among other things, the regulations require that bulk sewage sludge and sewage sludge that is sold or given away in a bag or other container for application to the land meet certain pathogen and vector reduction requirements. Different use restrictions apply to different categories of sewage sludge based upon EPA's determination of their risk to public health and the environment. After years of research and public comment, EPA established two categories of sewage sludge based on the treated sewage sludge's ability to meet certain requirements set out in EPA's regulations. These categories are Class A and Class B.

To achieve Class A status, pathogens in sewage sludge must meet the implicit goal of reducing pathogens (including enteric viruses, pathogenic bacteria, and viable helminth ova) to below detectable levels. The requirements necessary for sewage sludge to be classified as Class A with respect to pathogens are set out by an EPA regulation. 40 CFR § 503.32(a) provides that to achieve Class A status, sewage sludge must meet the requirements in one of six alternatives set out in 40 CFR § 503.32(a)(3) through (a)(8). In addition, the regulation provides that those pathogen requirements must be met prior to or at the same time that certain vector attraction reduction requirements are met in order for the sewage sludge to be classified Class A.

The Metropolitan Water Reclamation District of Greater Chicago (District) has a unique treatment sequence for its sludge processing. It has conducted extensive studies on the characteristics of its intermediate and final products of this sequence with the intent of gaining Class A certification for this sequence. Specifically, the District seeks certification under the requirements of Alternative 6, which requires that the sewage sludge must be treated in a process that is equivalent to a Process to Further Reduce Pathogens (PFRP). As part of this process, the District has established a Peer Review Committee (Committee) to critically review the adequacy and appropriateness of data it has submitted to EPA's Pathogen Equivalency Committee (PEC) in support of its petition for certification. This document constitutes the report of the Committee.

Objective of Committee Review

The objective of the Committee review was to provide a careful and independent peer review of the data submitted by the District in support of its certification in view of the regulatory requirements for PFRP equivalency. This Committee considered the requirements of the Clean Water Act and applicable regulations, and also considered communications between the District and the PEC. The Committee additionally considered EPA guidance, District data and other technical information in the published and unpublished literature. The Committee activities occurred in the period of August 1999 through July 2000. A complete list of documents and papers reviewed by one or more members of the Committee is given in References.

The Committee was charged by the District with making a critical independent evaluation of the relevant issues. Although District personnel were available to provide supporting information to the Committee, the evaluation and this report are products of the Committee.

Committee Composition and Methodology

There were six members of the Committee. The members and their areas of expertise are summarized below.

Dr. Charles N. Haas (Chair) L.D. Betz Professor of Environmental Engineering School of Environmental Science, Engineering & Policy Drexel University Philadelphia PA 19104	Microbial risk assessment, treatment process analysis
Dr. Raymond C. Loehr Hussein M. Alharthy Centennial Chair and Professor Department of Civil Engineering University of Texas Austin TX 78712	Waste treatment, sludge management, technical application of regulations and guidance
Dr. Nambury S. Raju Distinguished Professor Institute of Psychology Illinois Institute of Technology Chicago IL 60616	Statistical methods
Dr. Robert Reimers Professor Department of Environmental Health Sciences Tulane University New Orleans, LA 70112	Biosolids processing; parasites in biosolids
Dr. Mark Sobsey Professor Department of Environmental Sciences and Engineering University of North Carolina Chapel Hill NC 27599	Environmental virology; microbial risk assessment
LaJuana S. Wilcher, Esq. Partner LeBoeuf, Lamb, Greene & MacRae, L.L.P. 1875 Connecticut Avenue, N.W. Washington, D.C. 20009-5728 (former Assistant Administrator for Water, U.S. Environmental Protection Agency, 1989-1993)	Environmental law and policy

The Committee activities consisted of carefully reviewing documents, having an initial meeting in September, 1999, and conducting its work by electronic and written correspondence and telephone.

Outline of the Report

This report summarizes the District's sludge processes, and the relevant regulatory requirements necessary for sewage sludge to be designated as Class A under the EPA sewage sludge requirements for pathogens. Specifically, the report describes the requirements of 40 CFR § 503.32(a)(8), Class A-Alternative 6 criteria for processes equivalent to a PFRP, as well as relevant EPA guidance documents. The Committee then compares the data collected by the District to these requirements. Finally, the conclusions of the Committee are summarized.

DISTRICT SLUDGE PROCESSES

Two treatment trains produce the District's sludge being considered as meeting the PFRP status. These are the high solids sludge processing train (HSSPT) and the low solids sludge processing train (LSSPT) [1]. These two trains are illustrated schematically in Figure 1.

The Stickney Water Reclamation Plant (WRP) treats wastewater of the central area of the city of Chicago and numerous west suburban communities. It is a 1200 MGD design flow secondary wastewater treatment plant and has a service area of 260 square miles. Its main unit processes are screens, grit chambers, primary and Imhoff settling tanks, plug flow activated sludge aeration tanks, and final settling tanks. This WRP is a single stage nitrification facility. In 1998, its final effluent averaged 7 mg/l CBOD5, 5mg/l SS, and 0.53 mg/l NH4-N.

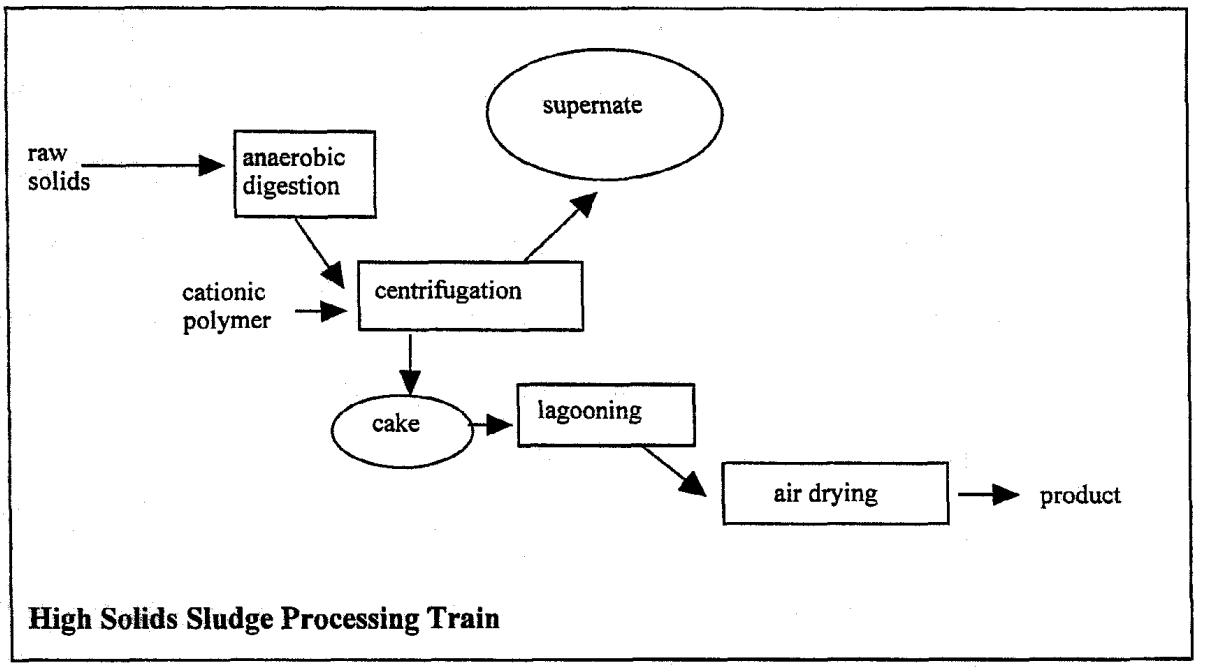
The Calumet WRP is a 354 MGD design flow secondary wastewater treatment plant treating the wastewater flow from the southern area of the city of Chicago and numerous south suburban communities. It has a service area of 299 square miles. Its main unit processes are screens, grit chambers, primary settling tanks, plug flow activated sludge aeration tanks, and final settling tanks. The WRP achieves nitrification as well as BOD removal in its aeration tanks. In 1998, its final effluent averaged 6 mg/l CBOD5, 4 mg/l SS, and 0.26 mg/l NH4-N.

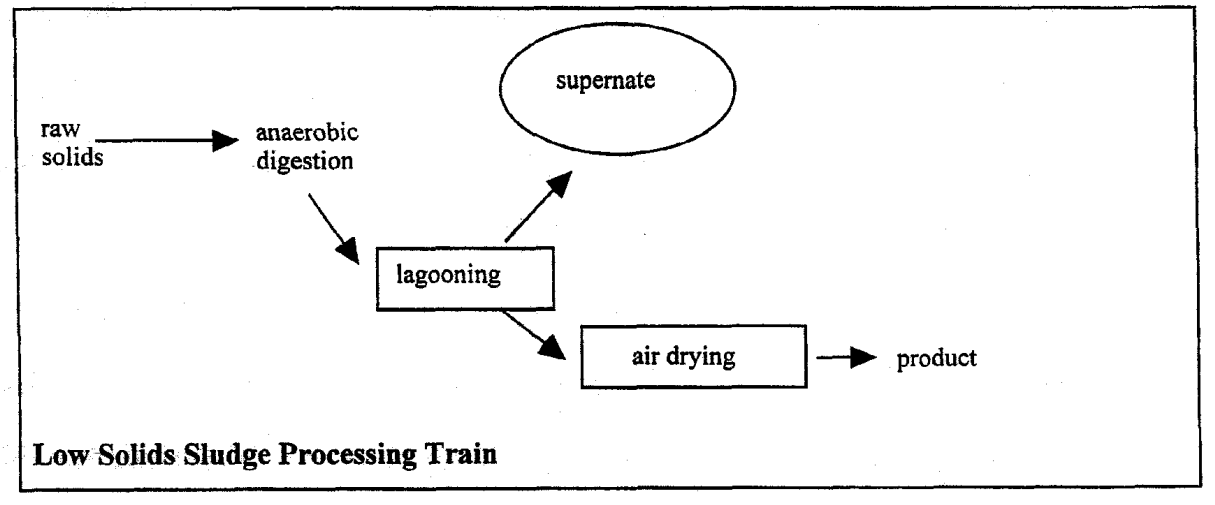
Each of the two sludge treatment trains was operated using raw solids from each of the two treatment plants - the Calumet WRP and the Stickney WRP. Hence there are a total of four systems to be considered (each of the two sludge processing trains for each of the two feed streams). These are full scale systems under continuous operation.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 1

FLOW CHART FOR SLUDGE PROCESSING TRAINS





The data taken by the District that were evaluated by the Committee were collected when the system was operated under strictly codified conditions. The control of the processes under this period of operation is described below. Details can be found in [1].

Codified Operation of HSSPT

The following are sludge treatment processes that occur in the HSSPTs at both the Calumet and Stickney WRPs:

Step 1 Anaerobic digestion. Anaerobic digestion of raw sludge (digester feed) occurs at an average detention time of 20 days at 35 +/- 2°C (95 +/- 3.6°F). This, the first step in the HSSPT is itself a Process to Significantly Reduce Pathogens (PSRP) under EPA's 40 CFR § Part 503 Regulation.

Step 2 Dewatering/Conditioning The anaerobic digester draw is treated with polymers followed by dewatering using centrifuges. This results in a concentration of the digested sludge of 25 to 30 percent solids content as a second step in the HSSPT process.

Step 3 Lagoon aging. Further sludge treatment occurs as a result of lagoon aging and stabilization of centrifuge cake in the HSSPT lagoons. This results in additional inactivation of pathogens and indicator organisms.

In this step of the HSSPT process, there is lagoon aging of centrifuge cake for a minimum of 1.5 years without any additions of new centrifuge cake. This guarantees a minimum holding time of 1.5 years for all centrifuge cake in the HSSPT lagoons, and as much as 2.75 years due to the maximum 9-

month filling and 6-month emptying times of fresh and aged centrifuge cake, respectively.

Step 4 Air-drying. The final step of the HSSPT is the air-drying of aged centrifuge cake of the HSSPT in batches on paved drying cells. No new lagoon-aged centrifuge cake is added to the drying cells after the drying process begins. Air-drying operations are conducted from April through November. The operational parameters for the HSSPT air-drying are:

1. Application of no more than 410 dry tons of lagoon-aged centrifuge cake per acre for each batch.
2. Application of the lagoon-aged centrifuge cake on the drying cell no more than 18 inches deep.
3. Complete turning, aeration and agitation of the air-drying centrifuge cake layer an average of three times per week using equipment such as a tractor with a horizontal auger or tiller.
4. HSSPT lagoon-aged centrifuge cake is held on paved drying cells without any additions of new HSSPT lagoon-aged centrifuge cake until a minimum 60 percent total solids content is achieved.

Codified Operation of LSSPT

The following are sludge treatment processes that occur in the LSSPTs at both the Calumet and Stickney WRPs:

Step 1 Anaerobic digestion. Anaerobic digestion of raw sludge (digester feed) occurs at an average detention time of 20 days at 35°C +/- 2°C (95 +/-

3.6°F). This first step in the LSSPT is itself a PFRP under the 40 § CFR 503 Regulation.

Step 2 Lagoon aging, stabilization, and dewatering. Further sludge treatment occurs as a result of lagoon aging, stabilization, and dewatering of the anaerobically digested sludge in the LSSPT lagoons (digester draw). This results in additional inactivation of pathogens and indicator organisms. In this step of the LSSPT process, there is aging of the anaerobically digested sludge in a lagoon for a minimum of 1.5 years without any additions of new digester draw. The holding time of surface layers of the digester draw added last will be a minimum of 1.5 years, while deeper layers may be held for up to 5 years because of the maximum 3-year filling cycle for LSSPT lagoons, and the maximum 6-month emptying time.

Step 3 Air-drying. The final step of the LSSPT is the batch air-drying of aged digester draw from the LSSPT lagoons on paved drying cells. No additional aged digester draw from the LSSPT lagoons is added once the drying process has begun. Air-drying operations are conducted from April through November. The modified operational parameters for the LSSPT air-drying process are:

1. Application of no more than 230 dry tons LSSPT lagoon-aged digester draw solids per acre for each batch applied on the paved drying cells.
2. LSSPT lagoon-aged digester draw to be applied on the drying cell at a depth not to exceed 15 inches.

3. Complete turning, aeration, and agitation of the drying LSSPT lagoon-aged digester draw layer three times per week using equipment such as a tractor with a horizontal auger or a tiller.
4. LSSPT lagoon-aged digester draw solids will be held on drying surfaces without any additions of new batches of LSSPT lagoon-aged digester draw until a 60 percent total solids content is achieved.

CLASS A STATUS FOR PATHOGENS – ALTERNATIVE 6

Regulatory Requirements for Class A Status

The requirements necessary for sewage sludge to be classified as Class A with respect to pathogens are set out by EPA regulation, published on February 19, 1993 pursuant to § 405 of the Federal Water Pollution Control Act (CWA). The regulation at 40 CFR § 503.32(a) provides that to achieve Class A status, sewage sludge must meet the requirements of one of six alternatives set out in 40 CFR § 503.32(a)(3) through (a)(8). In addition, the regulation provides that those pathogen requirements must be met prior to or at the same time that certain vector attraction reduction requirements are met in order for the sewage sludge to be classified as Class A. When promulgating the rule, EPA determined that the best way to meet the objective of protecting public health and the environment from the reasonably anticipated adverse effects of pathogens in sewage sludge was to require the sludge to meet certain pathogen density requirements at the time of use or disposal.

The requirements of Alternative 6, the focus of this Committee's evaluation, are detailed in 40 CFR § 503.32(a)(8). That section provides:

> "(8) *Class A -- Alternative 6.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella*, sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or given away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10(b), (c), (e), or (f).
>
> (ii) Sewage sludge that is used or disposed shall be treated in a process that is equivalent to a Process to Further Reduce Pathogens, as determined by the permitting authority."

At issue for the District is the requirement prescribed in subsection (ii), which applies to the requirements for enteric viruses and viable helminth ova. That subsection simply states that the

sewage sludge must be treated in a process that is equivalent to a PFRP, as determined by the permitting authority. Because EPA has not approved Illinois' sludge management program, EPA Region V is the permitting authority. See 40 CFR § 503.9(p).

Neither the CWA nor EPA regulations define specifically when a sludge treatment process is equivalent to a PFRP. The preamble published with the regulations, however, provides the most contemporaneous and persuasive interpretation of the regulations available and, therefore, provides the framework within which the decision must be made. The preamble provides unequivocally that the pathogen requirements in Subpart D are based on the density of pathogens in sewage sludge rather than the reduction of pathogens. The preamble states[1]:

> "Pathogen reduction was defined in the proposed regulation as the elimination or reduction of pathogenic bacteria (Salmonella sp.), protozoa, viruses, and helminth ova in sewage sludge. This definition was deleted from the final regulation because the pathogen requirements in the final regulation are not expressed in terms of quantity of pathogen reduction. They are expressed in terms of values that cannot be exceeded in the sewage sludge."

The preamble further explains that EPA originally proposed certain pathogen reduction requirements for Class A, but subsequently changed direction in the final rule to require a certain density (e.g., nondetection for viable helminth ova) at the time of use or disposal. Such a distinct reversal in direction from proposal to final rule is incontrovertible and is clear and convincing evidence of how EPA intended to interpret the pathogen requirements for Class A sewage sludge. Log reductions were not required for enteric virus and viable helminth ova. Specifically, EPA included criteria as shown in Table 1.

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[1] At Federal Register 58(32):9385, February 19, 1993.

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1

SUMMARY OF MICROBIAL CRITERIA TO BE ACHIEVED

Parameter	Value
Bacteria	Fecal coliform <1000 MPN/gram dry solids *or* *Salmonella* <3 MPN/4 gram dry solids
Viruses	<1 plaque forming unit/4 grams dry solids
Helminths	<1 viable ovum/4 grams dry solids

In the regulation, equivalency is clearly to be determined by achieving a value (absolute concentration[2]) of pathogens (virus and helminth) in the finished sludge, and not any removal requirement. This is further supported by a close reading of the Alternative 3 option: under this option, even if the raw sludge met the absolute standards for virus and helminth, it would be capable of achieving Class A status (providing also that the other requirements, e.g., as to indicator levels and vector reduction were met).

In making a decision on equivalency, EPA is granted considerable flexibility and latitude. That flexibility and latitude, however, does not extend to allow arbitrary requirements to be imposed on an entity seeking an equivalency determination, especially if these requirements are inconsistent with the EPA's clear intent when promulgating the regulations. If EPA seeks to change the requirements, it must provide the public notice and comment and then, if appropriate, complete the rulemaking changes by publication in the *Federal Register*, which it has already done with regard to several portions of the 1993 final rule.

EPA Review Process

Additional information concerning the process and criteria by which the EPA Region V, the permitting authority for the District, must review and determine whether the District's sludge treatment process is equivalent to a PFRP is described in the regulations' preamble, as well as in EPA guidance and technical documents and internal memos. As stated at 58 *Federal Register* 9350, February 19, 1993:

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[2] The regulatory language uses "density" as the parameter of microbial level. In this report, we use the term "concentration" with the intent of synonymous meaning.

"To be considered Class A under Alternative 6, the sewage sludge must, among other things, be treated in a process that is equivalent to a PFRP, as determined by the permitting authority. Although the permitting authority makes the final decision, whether a process is equivalent to PFRP, a separate group of EPA employees called the Pathogen Equivalency Committee reviews the candidate STP and makes recommendations to the permitting authority."

EPA's guidance applicable at the time the District submitted its data to the PEC (and consistent with the regulations) describes the basis upon which the PEC is to make its recommendations. That guidance states[3]:

"To be equivalent to PFRP, a treatment process must be able to consistently reduce sewage sludge pathogens to below detectable limits. For purposes of equivalency, the PEC is concerned only with the ability of a process to reduce enteric viruses and viable helminth ova to below detectable limits, because Part 503 requires ongoing monitoring of sludge produced by PFRP-equivalent processes for fecal coliform or *Salmonella* sp. (see Section 4.3) to ensure that *Salmonella* sp. are reduced to below detectable limits (i.e., to less than 3 MPN per 4 grams total solids sewage sludge [dry weight basis]). Thus, to demonstrate PFRP equivalency, the treatment process must be able to consistently reduce enteric viruses and viable helminth ova to below detectable limits, which are:

enteric viruses	less than 1 plaque-forming unit per 4 grams total solids sewage sludge (dry weight basis)
viable helminth ova	less than 1 per 4 grams total solids sewage sludge (dry weight basis)

There are two ways these reductions can be demonstrated:

- Direct monitoring of treated and untreated sewage sludge for enteric viruses and viable helminth ova.
- Comparison of the operating conditions of the process with the operating conditions of one of the listed PFRPs."

It appears that log reductions of pathogens have not been consistently, if ever, required previously by PEC in its review process. For example, in considering the equivalency of previously stockpiled composted sludges at the Blue Plains facility, an extensive sampling program of the finished

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[3] "Environmental Regulations and Technology – Control of Pathogens and Vector Attraction in Sewage Sludge," P. 92 & 97, EPA/625-R-92/013, Revised October, 1999.

material was conducted; since this was stockpiled material, no "raw" samples could have been taken, and yet an affirmative equivalency decision was reached by PEC.

The PEC's recommendation of the District's request should be consistent with existing regulatory requirements and guidance in effect at the time of the application. The PEC cannot unilaterally impose new requirements on an applicant. Hence, the key questions focused upon by this panel are the degree to which District data (Lue-Hing *et al.*, 1998) that have been collected suffice to demonstrate reliable achievement of the microbial levels specified above.

Conclusion Concerning Class A Requirements

To require helminth ova spiking and subsequent reduction prior to approving a sludge treatment process as equivalent to a PFRP is capriciously inconsistent with the express language of Subpart D of the regulations, as amplified by the extensive treatment of this topic in the preamble and by past EPA practice. This Committee finds that requiring spiking of helminth ova and subsequent logarithmic reductions is inconsistent with the regulations, contravenes EPA guidance and practice, and would not withstand judicial scrutiny.

This Committee is firmly committed to protecting human health and the environment from all reasonably anticipated adverse effects of pathogens. In spite of the issues of regulatory legitimacy described above, this Committee would make no recommendations that put human health or the environment at risk. Therefore, the remainder of this report is dedicated to addressing the degree to which District data [1] that have been collected from the District's processes, as described in District Sludge Process, are sufficient to demonstrate reliable achievement of the microbial levels specified above.

A detailed technical explanation of the reasons that spiking and subsequent logarithmic reduction procedures for helminth ova and enteric viruses, as requested by the PEC, are scientifically inappropriate, unnecessary and potentially create even greater risk to human health is given in Review of Issues Raised by PEC.

OVERVIEW OF DISTRICT DATA

In support of its petition to EPA, the District conducted a number of studies. The most directly relevant are those designated as Phase I in [1]. In this work, the operation of individual components of the low solids and high solids treatment trains were operated as discussed in District Sludge Process. During this period of codified operation, a set of 96 samples for each of 4 organisms (fecal coliforms, salmonella, virus, and helminths) were to be taken. Sampling was to be performed on raw (digester feed) sludge, digester product, lagoon product, and finished dried sludge (Table 7 in [1]). In reality more than three times the number of samples proposed was collected (Table 23 in [1]).

Over the period 1994-1997, samples were taken at each of the sampling points for each of the sludge treatment trains (HSSPT and LSSPT) and for each sludge feed at the Calumet and Stickney WRPs. These samples were processed for bacteriological, virological and parasitological analyses. The results of these analyses form the primary data set from which the Committee has drawn its conclusions.

Sampling Methods

As part of our review, the Committee also considered the sampling and analytical methodologies employed, and the QA/QC results. The sampling methods used were documented to us by the District and are described below. Our discussion of methodology appears in "Adequacy of Experimental Methodologies," "Further Evaluation of Data," and "Adequacy of Statistical Design and Analysis."

SAMPLING OF DIGESTER FEED AND DRAW

Digester feed and draw samples were collected once a month from the digester complexes of the Stickney and Calumet WRPs. These samples were collected from sampling ports established on

the feed and draw lines on each of the digesters at these WRPs. Digester feed was fed to the digesters from holding basins, where all the raw sludge (primary plus waste activated sludge) was blended. Digester draw was collected from the sampling port on a common line into which all the digesters emptied their draws. The samples were collected into a bucket and subsequently transferred into 1-gallon bottles after opening the sampling port valves and letting the sludge standing in the pipes run for a few minutes into a drain. These samples were distributed into 500-mL plastic containers with lids and analyzed at the Stickney WRP laboratory for fecal coliform, *Salmonella* sp., enteric virus, and helminth ova.

SAMPLING OF LAGOON DRAW

LSSPT and HSSPT lagoon draw samples (aged, dewatered, and stabilized digester draw in the case of the low solids lagoon and aged and stabilized centrifuge cake in the case of the high solids lagoon) were collected from the drying cells immediately after the sludge was put on them. Eight samples, two samples each from the four quadrants of the drying cells, were collected and composited and transported to the District's Stickney WRP laboratory in half gallon containers. These samples were distributed into 500-mL containers and analyzed for fecal coliform, *Salmonella* sp., enteric virus, and helminth ova.

SAMPLING OF AIR-DRIED FINAL SLUDGE PRODUCT

Eight samples of the air-dried final sludge product from the drying cells where the LSSPT and HSSPT lagoon draws were air-dried, two samples each from the four quadrants of the drying cells, were collected, composited, and transported to the District's Stickney WRP laboratory in half gallon

containers. These samples were distributed into 500-mL plastic containers with lids and analyzed for fecal coliform, *Salmonella* sp., enteric virus, and helminth ova.

SAMPLE HOLDING TIMES AND PRESERVATION

Samples for fecal coliform and *Salmonella* sp., were held in a refrigerator (at 4°C) upon receipt in the laboratory and were analyzed within 24 hours using *Standard Methods*. Samples of helminths were held under refrigeration for not more than one week.

Samples for enteric virus analyses were held in the laboratory according to procedures specified in *Environmental Regulations and Technology, Control of Pathogens and Vector Attraction in Sewage Sludge,* EPA/625/R-92/013. These were held at 4°C for up to 24 hours until concentration. If concentration could not be accomplished within 24 hours, the samples were held at –65°C until concentration. All concentrates were frozen at –65°C until assay for virus.

DISTRICT DATA IN CONTEXT OF REQUIREMENTS

Summary of Key Observations

BACTERIAL LEVELS

The primary bacterial measurements made by the District and evaluated by the Committee are summarized in Table 2, for fecal coliforms and in Table 3, for *Salmonella*. These tables summarize the full scale monitoring studies submitted in the petition for equivalency. These tables are abstracted from the March 1998 final report [1] Tables 27 through 30. It should be noted that in tabulating the minimum values, the District has substituted the theoretical detection limit where organisms were not detected. For example, if no organisms were detected in 10 g of solids, then the concentration is tabulated as 0.1/g. In the case of *Salmonella*, for example, the listed maximum values in Table 3 for product concentrations for all four locations are given as 2.2/4 grams, which would correspond to the level had a single tube of the MPN sample been positive, while in fact no positives have been found. Hence, the District reporting practices represent a conservative handling of non-detects.

In Table 2 through Table 5, in addition to microbial concentrations, the mass of sludge examined is also indicated. The large mass of solids examined for microbial concentrations increases confidence in the reliability of the results obtained.

These data demonstrate that the 40 CFR 503.32(a)(8)(i) requirements have been met in all samples of product, in that the maximum *Salmonella* concentrations are always less than 3 organisms per 4 grams. With respect to fecal coliforms, the geometric mean coliform MPN in finished samples was (in all cases) below the 1000 MPN/gram level. As indicated by the maximum value data, for some individual samples this latter value was exceeded. However, inasmuch as the requirement in regulations allows compliance with respect to either fecal coliform or *Salmonella*, the data presented show consistent compliance with the respective criteria.

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TABLE 2

FECAL COLIFORM LEVELS (MPN/GRAM DRY SOLIDS)

Location	No. of Samples	Mass Of Sludge Evaluated (gms) (*)	Fecal Coliform Data		
			Geometric Mean	Minimum Value	Maximum Value
Stickney-HSSPT-raw	33	2.4	$2.1 \cdot 10^7$	$2.24 \cdot 10^5$	$3.3 \cdot 10^8$
Stickney-HSSPT-product	33	210	18.3	0.31	23,900
Calumet-HSSPT-raw	22	1.5	$9.3 \cdot 10^6$	$1.73 \cdot 10^6$	$1.27 \cdot 10^8$
Calumet-HSSPT-product	41	300	5.58	0.27	23,000
Stickney LSSPT-raw	33	2.4	$2.12 \cdot 10^7$	$2.24 \cdot 10^5$	$3.34 \cdot 10^8$
Stickney LSSPT-product	68	480	25.6	0.27	3000
Calumet LSSPT-raw	22	1.5	$9.3 \cdot 10^6$	$1.73 \cdot 10^6$	$1.27 \cdot 10^8$
Calumet LSSPT-product	14	200	17.1	0.27	3000

(*)Rounded

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TABLE 3

SALMONELLA LEVELS (MPN/4 GRAMS DRY SOLIDS)

Location	No. of Samples	Mass of Sludge Evaluated (gms) (*)	*Salmonella* Data		
			Arithmetic Mean	Minimum Value	Maximum Value
Stickney-HSSPT-raw	31	140	70.7	1.45	480
Stickney-HSSPT-product	30	1700	0.51	0.10	2.20
Calumet-HSSPT-raw	20	70	221	2	1440
Calumet-HSSPT-product	28	2200	0.42	0.09	2.20
Stickney LSSPT-raw	31	140	70.7	1.45	480
Stickney LSSPT-product	51	3100	0.53	0.09	2.20
Calumet LSSPT-raw	20	70	221	2	1440
Calumet LSSPT-product	15	670	0.67	0.08	2.20

(*) Rounded

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TABLE 4

VIRUS LEVELS (PFU/4 GRAMS DRY SOLIDS)

Location	No. of samples	Mass Of Sludge Examined (gms) (*)	Arithmetic mean	Maximum value (+)
Stickney-HSSPT-raw	24	310	3.78	15.0
Stickney-HSSPT-product (++)	32	6800	0.2	1
Calumet-HSSPT-raw	22	270	3.9	19.4
Calumet-HSSPT-product	28	2900	0.31	1
Stickney LSSPT-raw	24	310	3.78	15.0
Stickney LSSPT-product	46	7200	0.42	1
Calumet LSSPT-raw	22	270	3.9	19.4
Calumet LSSPT-product	13	5900	0.025	0.13

(*) Rounded

(+) The maximum values are based on the theoretical detection limits. However, no viruses in the finished product were isolated.

(++) Dried product from the representative sludge processing trains.

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TABLE 5

VIABLE HEMINTH LEVELS (NUMBER/4 GRAMS DRY SOLIDS)

Location	No. of Samples	Sludge Processed (gms) (*)	Arithmetic Mean	Maximum Value
Stickney-HSSPT-raw	34	600	0.97	2.96
Stickney-HSSPT-product	34	4000	0.05	0.12
Calumet-HSSPT-raw	23	440	1.03	11
Calumet-HSSPT-product	40	6100	0.044	0.17
Stickney LSSPT-raw	34	600	0.97	2.96
Stickney LSSPT-product	66	9700	0.09	0.61
Calumet LSSPT-raw	23	440	1.03	11
Calumet LSSPT-product	15	2700	0.047	0.22

NOTE: The maximum values are based on the theoretical detection limits.

(*) Rounded

VIRAL LEVELS

The viral levels obtained during the full scale monitoring program are shown in Table 4. In no case did the viral concentration exceed 1 PFU/4 grams. While these data, taken from Tables 27 through 30 in [1], indicate some maximum virus levels in the finished product at 1 PFU/4 grams, there were in fact no detected viruses in the finished product (from examination of the data sheets) in any of the 119 final product samples. As indicated earlier in Bacterial Levels, the arithmetic mean virus levels are based on a substitution of the detection limit for non-detects. However to maintain consistency with the original District data reporting practices, we maintain this conservative depiction of the results.

Based on these results, the Committee concludes that a criterion for product virus levels equivalent to the Alternative 3 criterion (i.e., <1 PFU/4 grams) has been demonstrated. Since a total of 12,100 grams of dry solids were examined (with no viral counts shown), the overall average for the final product is estimated in reality as less than $3.3 \cdot 10^{-4}$ PFU/4 grams – or nearly four orders of magnitude below the levels of viruses suggested for equivalency.

HELMINTH LEVELS

The measured values of viable helminth ova obtained during the full scale monitoring program are shown in Table 5. As with viruses, the maximum values and arithmetic means were computed by inserting the detection limit in cases where no helminths were observed. Examination of the raw data (pooling all four sets of product samples) indicated that only 11 percent of the 155 samples were positive, and in the 22,500 grams of dry solids examined, only 26 viable helminths were observed – yielding an estimate for mean concentration (as the ratio) of 0.0046/4 grams. The highest actual observed concentration in these samples was 0.61/4 grams.

Based on these results, the Committee concludes that a criterion for product helminth levels equivalent to the alternative 3 criterion (i.e., <1 /4 grams) has been demonstrated. The maximum concentration in the 155 examined samples was 39 percent below the criterion.

Adequacy of Experimental Methodologies

Interpretation of the data taken by the District relies upon the adequacy of the experimental methods employed. The sampling and analytical techniques for fecal coliform and *Salmonella* are those generally accepted in the field. A brief discussion of the virus and helminth methodology follows.

VIRUSES

The District laboratory at the Stickney WRP measured the concentration of viruses in the sludge samples. This laboratory has a long history of analyzing viruses in biosolids, wastewater and water, with several decades of experience in this area. Throughout this study the Stickney WRP laboratory has endeavored to use the best and most sensitive modifications of established and accepted methods to detect and quantify viruses in biosolids. The currently approved method for detecting enteric viruses in biosolids, ASTM Method D4994-89 [2] specifies that biosolids or sludge sample sizes be the equivalent of 4 grams dry weight at minimum. The method actually specifies that a sample size of 12 grams dry weight be collected, in order to have a 4-gram sample available as a "backup" in case of analysis failure and to have a 4-gram sample available as a positive control. It is noteworthy that the District laboratory analyzed sample sizes much larger than the minimum of 4 grams dry weight. In most cases, sample sizes were 40 or more grams dry weight and sometimes several hundred grams dry weight of sludge solids. These larger sample sizes made it possible to lower

detection limits of viruses in final product biosolids samples from an average of 0.69 PFU/4 grams to an average of 0.0013 PFU/4 grams, an average increase in detection sensitivity of 530-fold.

To further document the reliability of their virus detection methods, the District split sludge samples with a well-established commercial laboratory and conducted an interlaboratory comparison of virus (as well as helminth) analytical data. Split sample viral analyses were applied to 7 samples of digester feed, 8 samples of digester draw, 9 samples of lagoon draw and 19 samples of air-dried final product, or 43 total samples. As shown in Table 46 of Lue-Hing *et al.* [1], virus concentrations in sludge samples were comparable with no statistically significant difference. These results provide further evidence of the performance reliability of the District laboratory in detecting viruses in their sludge samples. This substantiates the conclusion of the Committee that the air dried HSSPT and LSSPT studies do meet the <1 PFU/4 gram dry solids virus requirement for Class A biosolids defined by EPA regulations.

HELMINTHS

The District analyzed the helminth egg content of the sludge samples. The procedure used to detect helminth eggs in biosolids is the one recommended by the EPA. The performance of this method was checked by spiking studies; these studies indicate that, for the >40 gram sample size employed by the District for final product samples, recovery exceeded 80 percent [3]. They compare favorably with the recovery rates obtained by other workers using the "Yanko" procedure or other procedures. The District also prepared split samples for analysis at the laboratory of Dr. Dale Little at Tulane University and demonstrated that the method detection limit for helminths at the District laboratory was comparable to that achieved at Tulane [3].

FULL SCALE VS. PILOT PLANT APPROACH

It is noted that EPA has specifically indicated the superiority of full scale data as opposed to pilot data[3] in that great care is needed in a pilot study to assure consideration of the diversity of operating conditions (e.g., temperature, performance of sludge generating processes, etc.) that may exist in a full scale facility. The current data submitted by the District are full-scale data. We also note that for some portions of the current process, the use of pilot plants would be extremely problematic (such as for lagoons, with residence times beyond a year, for example).

Further Evaluation of Data

In this section are additional analyses of the District data. These are presented to focus on the issues of total sample mass examined for microorganisms and also on the range of microbial levels in incoming biosolids.

EXPLICIT STATEMENT OF PATHOGENS SUBJECT TO REMOVAL

In Table 6, a summary of the amount of solids examined for helminths and viruses and the number of organisms found is depicted. This is abstracted from Table 39 [1].

The overall biosolids treatment systems of the District produce a final product that are free of enteric viruses. No viruses have ever been found in a sample of the final product over a period of 20 months of monitoring (Table 6, abstracted from Table AV8, Appendix V [1]). In fact, not only have viruses never been detected in the final biosolids product but they also have never been detected in the

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[3] US EPA (1992), *op cit*, at page 66.

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TABLE 6

SUMMARY OF SAMPLING PROGRAM FOR FULL SCALE STUDIES BASED ON COMBINED RESULTS FROM LSSPT AND HSSPT FOR BOTH WRPs.

Sampling point	Mass Examined (grams) (*)		Viable Organisms Found	
	Helminths	Viruses	Helminths	Viruses
Digester feed	1032	580	177	199
Digester Draw	804	590	53	15
Lagoon Draw	2296	4160	35	0
Finished, dried product	22520	22800	26	0

(*) Rounded

draw from the biosolids lagoons in over 27 months of virus monitoring (Table 6, abstracted from Table AV6 Appendix V, [1]). Not a single virus has been detected in a total analyzed final product quantity of 22,800 grams or 22.8 kilograms. Furthermore, not a single virus has been detected in a total lagoon draw quantity of 4,160 grams or 4.16 kilograms analyzed (Table 6, abstracted from Table AV2, Appendix V [1]).

The overall virus occurrence in the digester feed material versus the final product material is: 1.39×10^6 viruses per 22.8 kilograms of digester feed versus 0 viruses per 22.8 kilograms of final product. Overall, this shows that enteric viruses are reduced more than 1,000,000-fold from the digester feed to the final product. The fact that the lagoon draw biosolids contain zero enteric viruses in a total quantity of 4.05 kilograms while the digester feed contains an average of 1.3×10^3 enteric viruses per 4.05 kilograms suggests that the overall enteric virus reduction is >1,000-fold even prior to the final stage of the sludge treatment sequence.

In the case of helminths, 26 viable organisms were found in a total of 22.5 kilograms of final product, compared to a measured 3,860 organisms per 22.5 kilograms of digester feed. This directly computes to be over a 100-fold reduction in viable helminths in the overall treatment sequence.

DIGESTER FEED VARIABILITY

Over the course of the monitoring period, there was variability in the pathogen levels in the sludge sent to the anaerobic digesters. Figure 2 summarizes the helminth and virus levels in anaerobic digester influent. This figure shows the pooled distribution for both the Calumet and Stickney sludge treatment processes. To portray the distribution in the presence of the nondetects, the Kaplan-Meir

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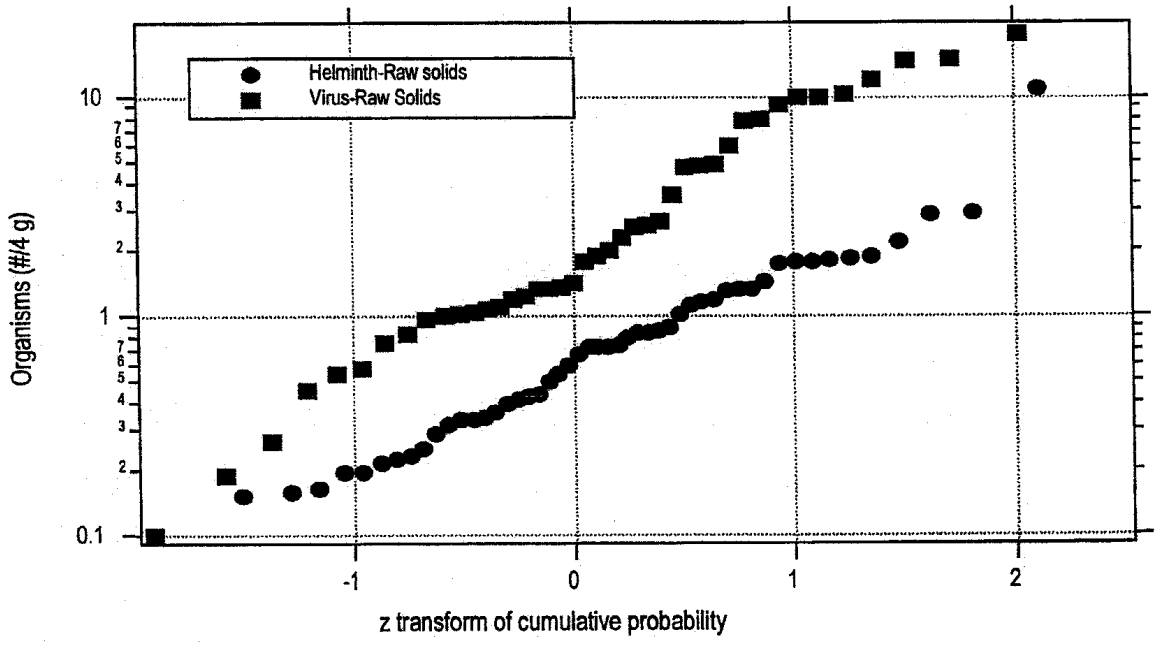
FIGURE 2

PROBABILITY DISTRIBUTIONS FOR VIRUS AND HELMINTH CONCENTRATIONS (DATA FROM CALUMET AND STICKNEY SLUDGE TREATMENT PROCESS COMBINED)



procedure was used[4]. The x-axis in this figure is the normal probability scale (i.e. zero corresponds to the median, and +/-1 correspond to one standard deviation away from the median value). From the figure, it is clear that the sampling period captured a two order of magnitude range in variability in influent concentrations of both helminths and viruses in the raw sludge.

The levels of culturable enteric viruses in the raw sludges of the District are typical of what could be expected and has been reported in the raw sludges of other municipal wastewater systems in the United States. As shown by the results in Table AV-2 of [1], enteric viruses were detected in the vast majority (43 of 47) samples analyzed at an average concentration of 3.7 PFU/4 grams dried sludge solids or about 0.93 PFU/gram dried sludge solids. At an average raw sludge solids concentration of about 5 percent, this is equivalent to about 46.5 PFU/L raw liquid sludge. This level of viruses in raw sludge is consistent with levels reported in the scientific literature [4-9].

Adequacy of Statistical Design and Analysis

A major focus of the statistical methodology employed by the District was modeling pathogen (helminth ova, *Ascaris* ova, and enteric virus) reductions across the four sludge treatment processing stages as a function of total solids. As noted in Table 2 through Table 5 of this Committee's report, a large number of samples were used for assessing levels of fecal coliform, salmonella, virus, and viable helminth at the beginning and final stages of sludge processing. The number of samples varied from a minimum of 92 to a maximum of 156. Actually observed pathogen levels (counts and concentrations) for helminth ova, *Ascaris* ova, and enteric virus are displayed in Tables 39 and AV-9 of[1]. Table 6 of this report shows some of the information contained in Tables 39 and AV-9 of [1]. As previously noted,

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[4] Haas, C.N., *et al.*, Quantitative Microbial Risk Assessment, John Wiley, New York (1999). See page 217.

these data clearly show that the pathogen reductions achieved in the finished, dried product meet or exceed the Class A requirements.

The District proposed and evaluated several models of analysis of variance (ANOVA) and analysis of covariance (ANCOVA) for fitting the observed pathogen count and concentration data. Since the pathogen counts/concentrations appeared to vary as a function of total solids, the District investigated the viability of the ANCOVA model with the total solids concentration as a covariate. Several transformations of the pathogen count/concentration data were also examined as part of the assessment of the ANOVA and ANCOVA models. All models were cross-validated, using the well-known leave-one-out technique. It was shown [1] that the simpler ANOVA model offered a good fit for helminth ova and *Ascaris* ova, whereas the ANCOVA model was shown to be better for enteric virus. The model-based (estimated), expected pathogen concentrations are shown in Table AV-13 of [1] separately for helminth ova, *Ascaris* ova, and enteric virus. These model-based results also show that the pathogen reductions achieved in the final stage meet or exceed the Class A requirements. In addition to confirming the observed pathogen reductions, this modeling exercise offered a very useful and validated mechanism for forecasting pathogen reductions in future investigations. The cross-validation component is a strength of this investigation.

District Removals in the Context of Prior Studies

The reduction of viruses and helminths during the District sludge treatment processes is entirely supported by known mechanisms of action. The following sections highlight some prior relevant work in this regard.

VIRUSES

The inactivation of viruses during the District sludge treatment processes is entirely in accord with prior observations on virus survival. For example, Ward [10] documented virus die-off rates of 1 $\log_{10}$/week at 28°C in anaerobic digestion. This work was supported by studies on a diversity of viruses in anaerobic digestion [11].

The process of drying is also known to result in inactivation of viruses [12]. The use of drying following anaerobic digestion may be a particularly strong method of inactivating viruses since it has been established that high ammonia levels (produced during anaerobic digestion) may inactivate a number of viruses at pH values above neutrality [13].

HELMINTHS

The HSSPT and LSSPT scheme for the helminth egg inactivation follows the protocol of anaerobic digestion, lagoon storage and standard drying bed operation in the summer months. In the data shown in [1], there is some reduction in the anaerobic phase, but the major inactivation of *Ascaris* eggs occurs in the lagoon storage phase. The interesting phenomenon noted is the dramatic drop in viable helminth egg concentrations in the lagoons containing 20 to 30 percent total solids (dewatered cake) over the thickened anaerobic digested lagoon stored biosolids (4 to 6 percent total solids). The concentrations of helminth eggs were 2 to 3 viable eggs per 4 grams of dry solids in the thickened anaerobically digested solids that are lagooned while the dewatered cake in the lagoons had 0.04 viable eggs per 4 grams of dry solids or 5 to 7 times lower concentrations.

In anaerobic digestion processing, the content of organic acids, aldehydes, alcohols and ammonia can greatly enhance the disinfection of microbes. In studies at Tulane [14], the anaerobic condition appears to reduce time for inactivation of helminth eggs by around 40 percent.

There are some data on the effects of organic acids and alcohols on the inactivation of *Ascaris* eggs. The first work looking at acids, alcohols, phenols, and petroleum organics was conducted during the period of 1915 to 1920 in Japan, where it was noted that inactivation was related to concentration of organics, time of exposure, climatic conditions and the ambient environment [15]. With the lower molecular weight acids, *Ascaris* egg inactivation was observed to be less effective than with the higher molecular weight organic acids (7 to 10 carbons long). The same phenomenon was denoted for organic alcohols [16].

From this data, it appears that organic acids and alcohols of 7 to 10 carbons are effective in inactivating *Ascaris* eggs at a concentration range of 600 - 100 mg/L. Composting systems have been effective in inactivating parasite eggs at 52°C under acidic environments. Epstein observed organic acid concentrations in compost up to 2.0 percent and remaining above 1.0 percent for almost 40 days [17]. Therefore, anaerobic digestion processes can result in some inactivation of parasite eggs due to high levels of organic acids and alcohols in the mesophilic temperature range [16].

Lagoon storage of biosolids following stabilization by aerobic or anaerobic digestion was found to result in the inactivation of bacteria, viruses and helminth eggs. This was first noted by O'Donnell *et al.* [18] in the 1980s and confirmed by Tulane researchers [19].

In the Tulane lagoon storage study, anaerobically stabilized biosolids were spiked with *Ascaris* eggs, *Salmonella livingston* and poliovirus and monitored over a two-year period. The studies shown in Table 7 note the time in months for total die off or log reductions [19].

From this lagoon work, the pathogen die-off was much greater than in soils. This is probably due to the higher content of organic acids, aldehydes, alcohols and ammonia available for microbial inactivation.

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TABLE 7

PATHOGEN INACTIVATION WITH TIME FOR LAGOON STORED ANAEROBICALLY STABILIZED BIOSOLIDS [19]

Pathogen	Time	Log-Reduction
Ascaris eggs	15 months	> 3 log
Total coliforms	9 months	2 log
Fecal coliforms	6 months	> 4 log
Fecal streptococcal organisms	3 months	1 to 3 log
Salmonella livingston	2 months	> 7 log
Poliovirus	6 months	> 5 log

Investigations of the high solids content of alkaline treated biosolids or anaerobically digested biosolids has noted higher die-off rates which is probably due to the higher concentration of produced biocidal constituents (organic acids, aldehydes, alcohols and ammonia). This phenomenon has been noted in ongoing studies at Tulane [20] and the University of Manitoba [21].

Indicator Studies with Clostridium

Although it is not possible to comprehensively compare the virus and other microbial reductions of the District sludge treatment processes to that of processes employed at other publicly owned treatment works achieving class A biosolids by PFRP processes, the data provided by the District indicate clearly that they produce a Class A quality final product and achieve extensive microbial reductions. In an effort to further document microbial reductions by the sludge treatment processes, samples of lagoon sludge, digester feed and draw, and dried low and high solids final products were analyzed at the University of North Carolina in the laboratory of Professor Mark Sobsey for somatic and male-specific coliphages and for spores of *Clostridium perfringens*, which are considered useful indicators of enteric viruses and parasites, respectively. Somatic and male-specific coliphages were reduced overall to non-detectable levels, corresponding to reductions of >99.2 and >99.5 percent, respectively. Coliphage are considered more resistant to inactivation than human viruses. Spores of *Clostridium perfringens* were reduced by 99.6 percent. These results lend further support to the other evidence demonstrating extensive reductions of microbes, including virus and parasite indicators of virus and parasite pathogens by the District sludge treatment processes.

REVIEW OF ISSUES RAISED BY PEC

Spiking Studies

The Committee considered the suggestions raised in prior correspondence between the PEC and the District with respect to the need/utility of conducting spiking studies to verify performance of the treatment trains under a variety of conditions. As noted in Conclusion Concerning Class A Requirements, the Committee considers this to be capriciously inconsistent with the express language of Subpart D of the regulations. Additionally, we consider these proposals to be infeasible for several reasons.

First, we believe that pilot studies would not provide a realistic predictor of several aspects of the District's process sequence - particularly the lagooning and air drying operations. Both of these operations rely on very long residence times for operation, and the intrinsic heterogeneity of the process environment is not replicable in a pilot scale test.

Second, the long residence times and large volumes of the full-scale system make it impossible to spike with sufficient organisms to document a 2-log reduction and still to have detectable organisms present in the finished product[5]. In addition, for obvious public health reasons this full scale spiking study would not be desirable. The practical barriers to conducting this type of study with particular respect to helminths are elaborated upon below.

The spiking studies are designed to insure a 2-log reduction of viable helminth eggs. This reduction is generally obtained by conducting a spiking study through the process train utilized by the

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[5] Although we reiterate that we do not find any basis for requiring a fixed level of reduction of pathogens or indicators in a sludge treatment process under Alternative 6 of the requirements.

specific municipality. There are two major impediments to conducting such spiking studies at the District WRPs:

1. Given the scale of the District operation, it would be very difficult, if not impossible to obtain the large number of *Ascaris* eggs required to spike the full-scale operating system.
2. The residence times of the individual processes in the aggregate are long, as noted in the following table:

Anaerobic Digestion	30 days
Lagoon Storage	2 to 4 years
Air Drying	2 to 3 months
Total Time	2 1/3 to 4 1/3 years

Hence a spiking study would require 4 to 8 years at a minimum to complete. In other words, the impact of a spike would not be expected to be detected in the final product in less than 4 to 8 years. This would also be true in a pilot study. Conducting such a spiking study with a very long delay time is unprecedented and, we believe, would be impractical and provide little information relative to the cost involved.

Intrinsic Resilience of System to Spikes and Surges

THEORETICAL IMPACT OF SURGES

Another issue raised in the review of the submittal by the EPA PEC is the possible sensitivity of the HSSPTs and LSSPTs to potential surges in incoming pathogen levels. As documented in Figure 2,

over the course of the sampling period, there was a 100-fold range in virus and helminth concentrations, and the finished sludge virus and helminth levels remained in the range that would be acceptable under the Alternative 3 criteria.

It is the opinion of the Committee that the intrinsic nature of the District HSSPT and LSSPT, as specified in its codified operational protocol, renders it intrinsically resilient to spikes and surges, as compared with other systems. The following is the basis for this opinion:

- The treatment train (for both the LSSPT and the HSSPT) consists of multiple units in series, each capable of achieving some degree of pathogen removal (e.g., anaerobic digestion, lagooning, drying). This "multiple barrier" approach produces a greater degree of redundancy in performance than if all microbial removal were to be accomplished in a single step. In fact, this approach is widely accepted for microbial control in drinking water treatment [22].

- Both the lagooning and the drying steps of the treatment sequence have extraordinarily long mean residence times. This means that the system has a great deal of inertia and possesses a significant capacity to equalize variations in incoming waste quality. Hence, unless the "surge" is maintained for a period of time approaching the residence time of the system (years), it is not likely to exert a great perturbation on system performance. This latter type of surge would likely be detected in routine monitoring and operational control, and hence the Committee believes that surges will not have any significant effect on the quality of the dried product from the HSSPT and the LSSPT.

CONCLUSIONS

Based on a critical detailed analysis of the available data and of the regulations, the Committee has reached the following conclusions:

- The District has complied fully with all statutory and regulatory requirements for establishing PFRP equivalency.
- The District has collected sufficient data to demonstrate that its sludge processing trains (HSSPT and LSSPT) achieve final pathogen concentrations as low as or lower than would be required under the Alternative 3 option. Specifically, the finished sludge levels of *Salmonella*, viruses, and helminths are below the maximum levels for sludge receiving Class A designation under this option.
- Therefore, the available data document that the sludge from the District Stickney and Calumet WRP HSSPT and LSSPT meet the PFRP Class A designation and should so be identified under Alternative 6 of the Part 503 regulation.

AFTERWORD

The Committee notes that as the final version of this report was being prepared, the journal papers summarizing the work performed by the District cited above appeared in Water Environment Research [23, 24]. These papers are attached in Appendix B. The peer review of these papers prior to publication in Water Environment Research reinforces the credibility in the methods and results obtained by the District, and in the reliance of this committee on such results.

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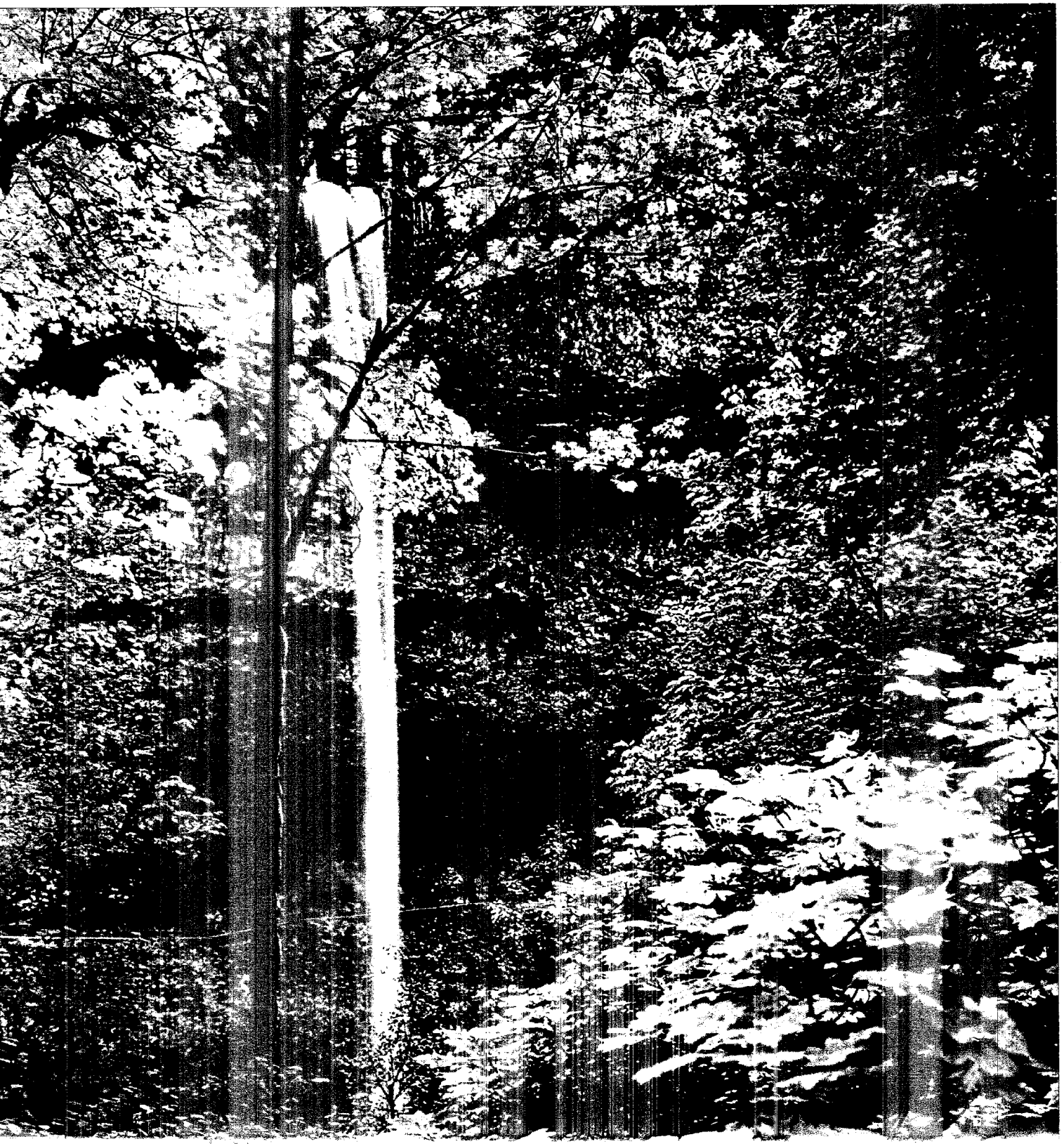
APPENDIX A

LIST OF DOCUMENTS REVIEWED

Water Environment Research

July/August 2000



Class A Biosolids Production by a Low-Cost Conventional Technology

Prakasam Tata, Cecil Lue-Hing, James J. Bertucci, Salvador J. Sedita, George J. Knafl

ABSTRACT: Encouraged by a finding that the pathogen analyses of numerous samples of the final product of the Metropolitan Water Reclamation District of Greater Chicago, Illinois (District), met the U.S. Environmental Protection Agency (U.S. EPA) Class A criteria, the District optimized and codified the operation of its sludge processing trains (SPTs), submitted a petition to the U.S. EPA Pathogen Equivalency Committee for obtaining certification of its SPTs as equivalent to a process to further reduce pathogens, and conducted a 3-year full-scale study. The objective of the study was to determine whether or not the District's SPTs consistently produced a Class A biosolids final product. The primary conclusion drawn from this optimized and codified operation study was that all batches of the final air-dried product complied with the Class A criteria as specified by U.S. EPA in the Part 503 regulations. *Water Environ. Res.*, **72,** 413 (2000).

KEYWORDS: Class A solids, biosolids, helminths, viruses, *Salmonella* sp., indicator bacteria, process to further reduce pathogens.

Introduction

The Metropolitan Water Reclamation District of Greater Chicago, Illinois (District), owns and operates seven water reclamation plants (WRPs). All seven WRPs use the activated-sludge process. All raw sludge produced at the WRPs is anaerobically digested. Most of the anaerobically digested sludge produced is further processed at the Stickney, Illinois, and Calumet, Illinois, WRPs to yield a final product containing approximately 60% solids, which is beneficially used for growing crops, establishing grass on new golf courses, and rehabilitating existing ones and for daily and final vegetative cover at landfills. Anaerobically digested sludge produced at these two WRPs is processed through two sludge processing trains (SPTs), namely, the low-solids SPT (LSSPT) and the high-solids SPT (HSSPT), which are described in the Materials and Methods section below.

The unit processes composing the SPTs and their operational protocols used to produce the final dried product from anaerobically digested sludge are described in the Materials and Methods section. These operational protocols historically have yielded satisfactory results but have not been conducted under codified conditions at the Stickney and Calumet WRPs solids processing sites. Systematic records on operational protocols, materials movement through the SPTs, holding times of solids in lagoons, and operational details of the drying cells were not maintained because they were not required. However, approximately 50 final air-dried product samples that were randomly collected from 1991 through 1994 showed that 90% of the samples met the U.S. Environmental Protection Agency (U.S. EPA) Class A sludge criteria for fecal coliforms and that a subset of 12 of these samples met the Class A criteria specified for helminth ova, *Salmonella* sp., and viruses (Tata et al., 1997). [Class A sludge criteria as specified in U.S. EPA Part 503 regulations are as follows: less than 1000 fecal coliform organisms per 1 g, less than three *Salmonella* per 4 g, less than one virus per 4 g, and less than one viable helminth ovum per 4 g dry weight of solids (U.S. EPA, 1993).]

Encouraged by this finding, the District optimized and codified its operations and submitted a petition to the Pathogen Equivalency Committee (PEC) of the U.S. EPA to obtain process to further reduce pathogens (PFRP) certification for its SPTs. Full-scale studies were initiated in the last quarter of 1994 to demonstrate that its SPTs are capable of producing a final biosolids product that meets Class A sludge criteria at all times, if they were optimized and operated under codified and controlled operating conditions.

The objectives of these studies are as follows: (1) Presentation of pathogen analysis results for the samples collected from the SPTs operated under uncodified protocols; (2) description of the full-scale studies conducted under optimized, controlled, and codified operating conditions to produce Class A biosolids product; (3) presentation and discussion of the pathogen analysis results for the SPTs operated under controlled and codified conditions; (4) demonstration of the capability of the District's conventional solids processing technology for the production of Class A biosolids product; (5) presentation of the data collected in this demonstration study to the PEC to obtain a PFRP certification for the SPTs; and (6) presentation of expected log reductions caused by hypothetical surges and uniform expansions (occurrence of different high initial densities of helminths and ascaris ova in the feed to the SPTs in isolated bursts or sustained increases). The results of the full-scale studies are presented and discussed in this paper.

Materials and Methods

Description of Existing District Sludge Processing Trains. The District uses (simultaneously) two similar but distinct SPTs that include, as the first step, the anaerobic digestion of raw sludge conducted at 35 °C at a detention time of approximately 20 days (Figure 1) at the Stickney and Calumet WRPs. These SPTs are the HSSPT and LSSPT. Approximately equal portions of the sludge withdrawn daily from the anaerobic digesters are processed through the HSSPT and the LSSPT systems. In the case of the HSSPT system, anaerobic digester draw is conditioned by a cationic polymer and dewatered (using centrifuges) to a cake containing approximately 25% solids. This cake is transported by railroad cars and placed in HSSPT lagoons at various times, except when the ambient temperature is −3.9 °C (25 °F) or less. At these low temperatures, centrifuge cake freezes in the railroad cars that transport it to the lagoon area. During such low temperature days, the centrifuges are not operated, and the digester draw is pumped into the LSSPT lagoon. The centrifuge cake is stored and aged in

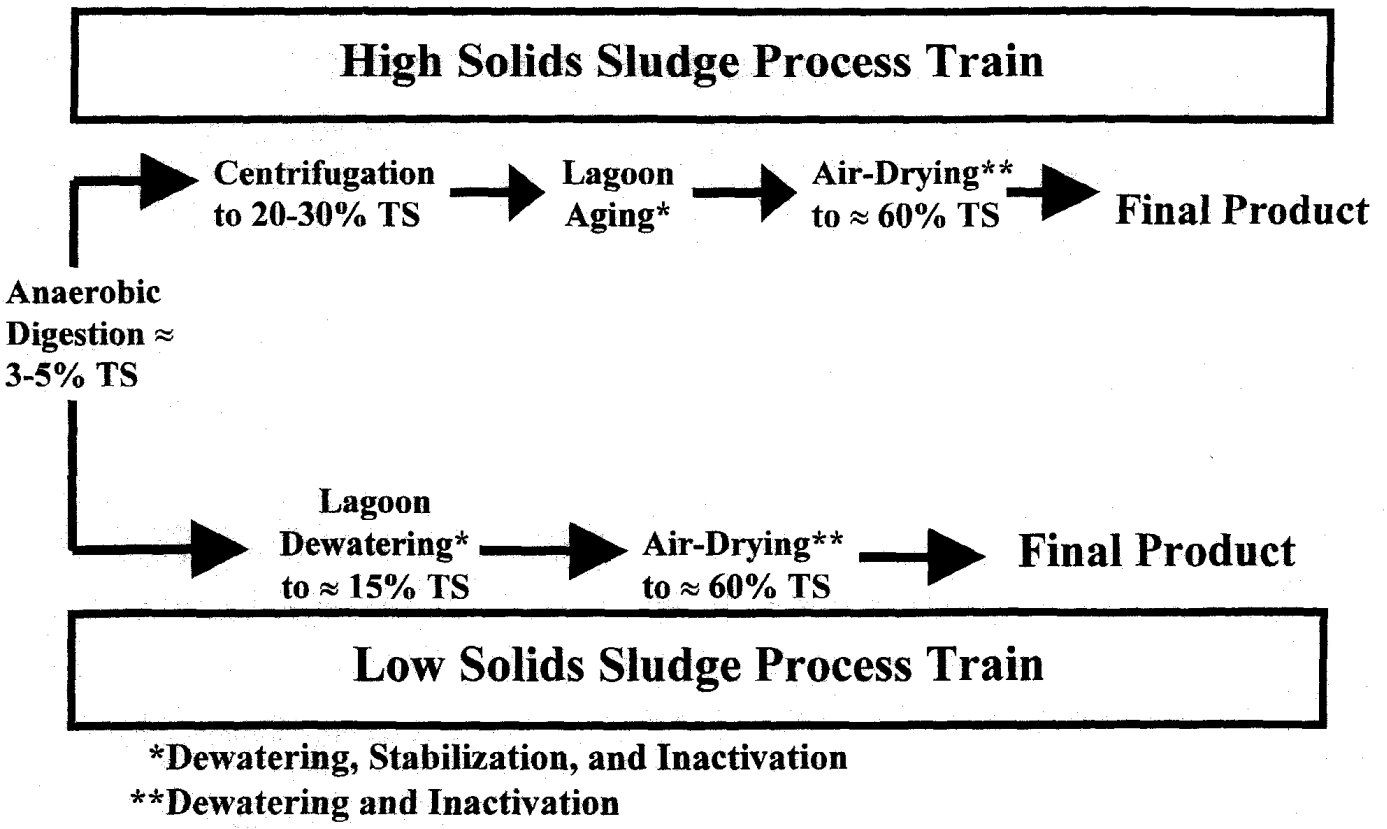


Figure 1—Sludge processing trains in the District.

lagoons to further inactivate pathogenic microorganisms and stabilize the cake solids. After storage and stabilization in the lagoons, the cake is taken out and air-dried in batches to approximately 60% total solids content on paved drying cells.

In the case of the LSSPT system, the portion of the anaerobically digested sludge not processed through the HSSPT system is pumped in batches to the LSSPT lagoons. These lagoons are filled in cycles over a period of 1 to 3 years. The sludge layer formed is then allowed to thicken further by evaporation and settling before the application of the next layer of sludge. Supernatant that separates is recycled to the WRP. This layering process continues until the lagoon is filled. Using what is known as a slackline process (U.S. EPA, 1979), the sludge is dewatered in the lagoon to produce a cake containing approximately 15% solids. The District characterizes this process as stress dewatering. This material is aged to varying time periods, anywhere from a few months to several years in the lagoons to achieve additional stabilization. Further inactivation of any pathogens and indicator organisms takes place during the lagoon aging phase. The lagoon dewatered and aged cake is then air-dried in batches to approximately 60% total solids content on paved drying cells. The District uses these two SPTs at both its Stickney and Calumet WRPs with minimal odor complaints.

The two SPTs described above fulfill the District's objective of producing an air-dried product for beneficial use. Historically, these SPTs have been operating under uncodified conditions; the overriding emphasis was to produce a 60% solids content product rather than a pathogen-free product. In the present full-scale study, the District has optimized and modified the protocol of its SPTs and imposed additional controls on their operation to ensure that the modified SPTs produce a final biosolids product that would meet Class A criteria. It should be noted that the District has been using the lagoons for further aging and stabilizing of sludge for decades. Such aging and stabilization in lagoons for a long period of time may not be possible at some treatment plants because of space limitations.

Codified and Controlled Operational Protocols—Full-scale High-Solids and Low-Solids Sludge Processing Train Study. The following protocols were optimized, codified, and strictly implemented to control the full-scale operation of the HSSPT and LSSPT systems.

The operational conditions of the anaerobic digestion process, which is a process to significantly reduce pathogens (PSRP) and an integral part of both the SPTs, remain the same. An average detention time of 20 days at a temperature of 35 ± 2 °C is maintained in the anaerobic digesters.

In the case of the HSSPT system, the operational conditions regarding centrifugal dewatering of the anaerobically digested sludge remain the same. Anaerobically digested sludge (at approximately 3 to 5% solids), which is withdrawn daily from the digesters, is first conditioned with a high-molecular-weight cationic polymer and then dewatered using Sharples Model 76000 (Alfa Laval Separation, Inc., Warminister, Pennsylvania) centrifuges to approximately 20 to 30% solids. The centrifuge cake is transported by railroad cars and placed into HSSPT lagoons, which are located approximately 8 km (5 miles) from the Stickney WRP.

In the case of the LSSPT system, digested sludge (at approximately 3 to 5% solids), withdrawn daily from the digesters, is not subjected to centrifugal dewatering and is pumped to LSSPT lagoons to achieve further stabilization, stress dewatering, and inactivation of pathogens.

The minimum solids holding time for the HSSPT and LSSPT lagoons is at least 1.5 years after last placement to ensure the aging and stabilization of sludge solids and inactivation of pathogens. The operation of the HSSPT is modified such that even the last batch of centrifuge cake discharged from railroad cars (at the Stickney WRP) or trucks (at the Calumet WRP) to the study lagoons is held for at least 1.5 years. Six to nine months are required to fill a typical HSSPT lagoon. During the minimum 1.5-year holding period that follows the addition of the last batch of centrifuge cake to the lagoon, no additional centrifuge cake is added. Rain and water, which separate, are drained from the surface of the lagoon and recycled to the head end of the respective WRPs. At the end of the 1.5-year holding period, the aged centrifuge cake is removed and trucked to the drying cells. Two to 6 months are required to empty the HSSPT lagoon and transport the sludge solids to the drying cells for drying. Thus, all solids in the HSSPT lagoon are held for a minimum of 18 months and as long as 33 months because of the maximum 9-month filling and 6-month emptying time.

At the end of the filling period in the LSSPT, the final batch of anaerobically digested sludge added is held for a minimum of 1.5 years. Following this holding period, all of the solids from this lagoon are withdrawn over a period of 2 to 6 months and dried on paved drying cells. Thus, the solids holding time is a minimum of 18 months and as long as 5 years (3 years for filling, plus the minimum 1.5-year storage, plus 6 months for emptying) in the LSSPT lagoons.

Air-drying the sludge solids taken from the HSSPT and LSSPT lagoons is carried out from April through November. Any batch of sludge from the HSSPT and LSSPT lagoons applied to the drying areas is held until a minimum of 60% total solids content is obtained without any further additions of sludge to the drying bed.

Air-drying the sludge solids taken from the HSSPT and LSSPT lagoons is done at no more than 92 and 52 kg/m^2 (410 and 230 dry ton/ac) of the paved drying cells, respectively. These application rates were determined based on many years of practical experience of the District's Maintenance and Operations Department staff. Solids taken from the HSSPT and LSSPT lagoons are applied on the drying cells to a depth of no more than 460 and 380 mm (18 and 15 in.), respectively, to be consistent with the loadings of 92 and 52 kg/m^2. These refinements are part of the optimization program.

Complete turning, aeration, and agitation of solids withdrawn from the HSSPT and LSSPT are performed on the drying beds at an average of three times per week using equipment such as a tractor with a horizontal auger or a tiller. To be conservative, when fewer than two agitations occur in a week, for example, during rainy periods, all such agitations were not used in the computation. It should be noted that, in the air-drying process, the sludge is formed into windrows when it reaches a solids concentration of 30 to 35%. During periods of rainfall, this allows rainwater to drain freely from the paved air-drying beds and increases pathogen destruction as a result of the higher temperatures achieved in the windrows.

Short-circuiting through the SPTs is eliminated by ensuring that (a) no additional batches of sludge are added to the filled lagoons, in which aging, dewatering, and inactivation are occurring, and (b) solids undergoing air-drying on the paved drying beds are not mixed with any other solids during the drying process.

Analyses of Indicator Organisms and Pathogens. Because of the large number of samples collected in the study, the analyses of fecal coliforms, *Salmonella* sp., viruses, and helminth ova were performed by the District's Analytical Microbiology Laboratory and by two outside consulting laboratories. Approximately 20 and 35% of the total samples collected in the study were analyzed for *Salmonella* sp. and viruses, respectively, by the BioVir Laboratories, Benicia, California. The remaining samples were analyzed in the District's laboratories. Approximately 30% of the total number of samples were analyzed for helminth ova by the Dr. Dale Little laboratory, Tulane University Medical Center, New Orleans, Louisiana, and the remainder were analyzed in the District's laboratory. All samples were analyzed for fecal coliforms at the District's Analytical Microbiology Laboratory. All the laboratories in this study used the same analytical methods.

The fecal coliform analyses were performed using A1 medium (Method 9221 E) according to *Standard Methods* (APHA et al., 1992). Enumeration of *Salmonella* bacteria was performed according to the method described by Kenner and Clark (1974). Enteric viruses were enumerated according to the method described in the *Annual Book of ASTM Standards* (ASTM, 1989). Viable helminth ova were enumerated according to the method described by Yanko (1987) as modified by District staff to increase the sensitivity of the method.

To increase the sensitivity of the detection limits of the helminth ova analyses, in the modified method, larger sample sizes of 500 g of liquid sludge and 300 g of centrifuge cake were used during the controlled full-scale HSSPT and LSSPT study. Typically, the conventional sample sizes of approximately 100 g of liquid sludge and 30 g of centrifuge cake samples are used during the uncodifed operations when no controlled procedures are used.

Statistical Analysis of Pathogen Data. The statistical methodology of analysis of covariance, originally recommended in the planning of the full-scale study and used for the analysis of preliminary data, was developed by the District's biostatistician. The applicability of these statistical techniques and results of the analyses were confirmed following consultations with personnel from Cornell University (Ithaca, New York) and DePaul University (Chicago, Illinois) (Federer, 1997, and Knafl, 1997).

Data collected in the recently completed study were further subjected to a series of statistical analyses. Analysis of covariance and one-way analysis of variance models were considered. To choose between these alternative procedures, cross-validation (Stone, 1974) was used for selecting the modeling procedure with minimal standard prediction error. The chosen model adjusts for the varying mass of solids used for microbiological analyses and yields estimates of the expected pathogen density at each stage of the SPTs. To assess the helminth ova and virus reduction capability of the SPTs from digester feed (stage 1) to the air-dried product (stage 4) stages of the SPTs, data collected about the helminth ova and virus densities were used to compute empirical estimates of probability density functions and cumulative density functions resulting from the organism densities for the raw sludge and final air-dried product.

In lieu of seeding the District's full-scale SPTs with viable helminth ova in large numbers to determine the pathogen inactivation capabilities of the SPTs or log reductions of pathogens, a

Table 1—Density of fecal coliforms, *Salmonella* sp., viruses, and viable helminth ova in Stickney, Illinois, water reclamation plant high-solids and low-solids sludge processing trains: full-scale codified operation.

Type of organism and related statistical values[a]	Sample source			
	Digester feed	Digester draw	Lagoon draw (codified)	Air-dried final product (codified)
Fecal coliforms, MPN/g total solids dry weight				
HSSPT geometric mean	2.12×10^{7}	2.02×10^{5}	1.88×10^{2}	1.83×10^{1}
LSSPT geometric mean	2.12×10^{7}	2.02×10^{5}	1.51×10^{2}	2.56×10^{1}
Salmonella, MPN/4 g total solids dry weight				
HSSPT arithmetic mean	7.07×10^{1}	2.57×10^{1}	2.76×10^{-1}	5.06×10^{-1}
LSSPT arithmetic mean	7.07×10^{1}	2.57×10^{1}	5.33×10^{-1}	5.32×10^{-1}
Virus, PFUs/4 g total solids dry weight				
HSSPT arithmetic mean	3.60	1.21×10^{-1}	0.00	0.00
LSSPT arithmetic mean	3.60	1.21×10^{-1}	0.00	0.00
Viable helminth ova, number/4 g total solids dry weight				
HSSPT arithmetic mean	9.61×10^{-1}	3.79×10^{-1}	7.84×10^{-1}	1.91×10^{-2}
LSSPT arithmetic mean	9.61×10^{-1}	3.79×10^{-1}	3.94×10^{-2}	1.32×10^{-2}

[a] MPN: most probable number, and PFUs: plaque-forming units.

statistical methodology was used to determine the effect of hypothetical surges of initial densities of helminth ova and uniform expansions in the distribution of these densities on the final air-dried product. The details of this statistical methodology are presented in a companion paper (Tata et al., 2000).

Results

Optimized Operation and Pathogen Content of Samples Obtained from Sludge Processing Trains Operated Under Controlled, Codified Conditions. From the end of October 1994 through the end of September 1997, the District's SPTs were operated using the codified operating protocols described above. The codified conditions for detention time and operating temperature of the digesters were met. The actual holding times for aging the digested sludge in the LSSPT lagoons at the Calumet and Stickney WRPs in this study were more than the minimum specified holding time of 1.5 years, and the average detention times in the Calumet and Stickney LSSPT lagoons were 2.5 and 2.0 years, respectively. The average detention times for aging centrifuge cake in the HSSPT lagoons at the Calumet and Stickney WRPs were 1.6 years in comparison to the codified minimum detention time of 1.5 years.

The average lagoon draw loading rates of the Stickney and Calumet WRP LSSPT air-drying cells were 41.9 and 59.9 kg/m^2 (187 and 267 dry ton/ac), respectively. These loading rates were lower by 9.7 kg/m^2 (43 dry ton/ac) and higher by 8.3 kg/m^2 (37 dry ton/ac), respectively, of the 51.6 kg/m^2 application rate in the codified operating protocol. The lagoon draw loading rates of the Stickney and Calumet HSSPT air-drying cells were 96.2 and 59.9 kg/m^2 (429 and 267 dry ton/ac). The specified application rate according to the codified operating protocol was 91.9 kg/m^2 (410 dry ton/ac). Although the actual rate of 96.2 kg/m^2 of HSSPT lagoon draw at the Stickney WRP drying cells was very close to the codified rate of 91.9 kg/m^2, the 59.9 kg/m^2 application rate at the Calumet HSSPT drying cells was lower than the codified application rate.

Samples of digester feed, digester draw, lagoon draws (stabilized aged anaerobic sludge and centrifuge cake), and air-dried final product were collected at various times from various process stages of the Stickney and Calumet LSSPT and HSSPT systems, which were operated under controlled and codified conditions. These samples were analyzed for fecal coliforms, *Salmonella* sp., enteric viruses, and viable helminth ova. Results of these analyses are presented in Tables 1 and 2. It can be seen that all of the air-dried final product samples from the LSSPT and HSSPT systems met the Class A criteria, indicating that the District's SPTs produced a Class A biosolids product at all times under the controlled operating conditions specified in the Materials and Methods section.

It should be noted that many of the digester feed and draw samples did not meet Class A criteria. To ensure the compliance of the final air-dried samples with the Class A criteria (by increasing the sample mass used for extracting the organisms), the method detection limits were lowered significantly for all types of samples (digester feed, digester draw, lagoon draws, and air-dried product) to as low as 0.001 3 to 0.694 4 and 0.002 0 to 0.280 1 per 4 g of dry weight of solids for viruses and helminth ova, respectively. The lowest detection limit values of the ranges indicated were achieved for the air-dried final product. Detection limits are the reciprocal of the dry mass of the sample used. For the enumeration of helminths and viruses, a large mass of the final air-dried product was used for each analysis. The samples analyzed yielded helminth ova and virus densities that were below these lower detection limits, indicating that all of the final air-dried product samples satisfied the Class A criteria.

Log Reductions of Pathogens Obtained in the Sludge Processing Trains. In this study, the fecal coliform and *Salmonella* log reductions were computed from the actual data pooled for the LSSPTs and HSSPTs of the Calumet and Stickney WRPs. The cumulative log reductions that occurred through the different stages of the LSSPTs and HSSPTs of the Calumet and Stickney WRPs are presented in Table 3. Approximately 6 and 2.4 log reductions were achieved for the fecal coliform and *Salmonella* sp. for the combined LSSPT and HSSPT systems.

Using a statistical approach as described in the companion paper

Table 2—Density of fecal coliforms, *Salmonella* sp., viruses, and viable helminth ova in Calumet, Illinois, water reclamation plant high-solids and low-solids sludge processing trains: full-scale codified operation.

Type of organism and related statistical values[a]	Sample source			
	Digester feed	Digester draw	Lagoon draw (codified)	Air-dried final product (codified)
Fecal coliforms, MPN/g total solid dry weight				
HSSPT geometric mean	9.31×10^{6}	6.78×10^{4}	1.05×10^{2}	5.58
LSSPT geometric mean	9.31×10^{6}	6.78×10^{4}	6.85×10^{1}	1.71×10^{1}
Salmonella, MPN/4 g total solids dry weight				
HSSPT arithmetic mean	2.21×10^{2}	7.46×10^{1}	8.28×10^{-1}	4.19×10^{-1}
LSSPT arithmetic mean	2.21×10^{2}	7.46×10^{1}	2.90	6.73×10^{-1}
Virus, PFUs/4 g total solids dry weight				
HSSPT arithmetic mean	3.83	4.28×10^{-1}	0.00	0.00
LSSPT arithmetic mean	3.83	4.28×10^{-1}	0.00	0.00
Viable helminth ova, number/4 g total solids dry weight				
HSSPT arithmetic mean	9.56×10^{-1}	2.86×10^{-1}	7.44×10^{-3}	1.54×10^{-3}
LSSPT arithmetic mean	9.56×10^{-1}	2.86×10^{-1}	6.25×10^{-2}	3.75×10^{-3}

[a] MPN: most probable number, and PFUs: plaque-forming units.

(Tata et al., 2000), the expected cumulative log reductions of the viruses and viable helminth and ascaris ova for the combined LSSPT and HSSPT systems were computed and are presented in Table 4. Complete inactivation of viruses and log reductions of 2.05 and 2.19 in total helminth and ascaris ova, respectively, occurred through the District's SPTs.

The sequential inactivation rates of the various organisms between stages are computed from the data presented in Tables 1 through 4 and are presented in Table 5. It can be seen from a comparison of the sequential inactivation rates in the various stages of the SPTs that the anaerobic digestion stage has the greatest values and accounts for most of the inactivation because the number of organisms were initially high in this stage (which has a relatively short detention time of 20 days compared with the long detention times of the other stages).

Log reductions within the range of 1.53 to 3.5 and 1.15 to 2 were recently reported for fecal coliforms and *Salmonella* sp. during anaerobic digestion, respectively, by Ponugoti et al. (1997), and these are comparable to the log reductions that occurred in this study. Pedersen (1981) also reported similar reductions. A high reduction of fecal coliforms occurred (2.59 logs) during lagoon aging–stabilization of the District's anaerobic digester draw, as evidenced by the difference between the cumulative 4.65 log reductions that occurred through the anaerobic digestion and lagoon aging–stabilization processes and the 2.06 log reduction of fecal coliforms that occurred in the anaerobic digester stage (Table 3). A smaller log reduction of fecal coliforms (1.31 logs, the difference between the cumulative log reduction of 5.96 from stage 1 through stage 4 and that from stage 1 through stage 3 of 4.65) occurred during the air-drying process of the Calumet and Stickney LSSPT and HSSPT systems.

Table 3—Cumulative logarithmic reductions of fecal coliforms and *Salmonella* sp. in the District's full-scale sludge processing trains.

SPT processing stage	Range of sludge processing train stages	Detention time, d	Cumulative detention time, d	Pathogen densities		Cumulative logarithmic reduction	
				Fecal coliforms	*Salmonella*	Fecal coliforms	*Salmonella*
1: Digester feed	1 → 1	0	0	1.41×10^{7}	1.30×10^{2}	0.00	0.00
2: Digester draw	1 → 2	20	20	1.23×10^{5}	4.76×10^{1}	−2.06	−0.44
3: Lagoon draw							
LSSPT (3.1)	1 → 3.1	821	841	1.42×10^{2}	8.81×10^{-1}	−5.00	−2.17
HSSPT (3.2)	1 → 3.2	584	604	8.07×10^{2}	2.10	−4.24	−1.79
LSSPT + HSSPT	1 → Combined lagooning	703[a]	723	3.17×10^{2}	1.47	−4.65	−1.95
4: Air-dried product							
LSSPT (4.1)	1 → 4.1	63	904	2.39×10^{1}	5.64×10^{-1}	−5.77	−2.36
HSSPT (4.2)	1 → 4.2	67	671	9.48	4.64×10^{-1}	−6.17	−2.45
LSSPT + HSSPT	1 → Combined drying	64[a]	787	1.54×10^{1}	5.18×10^{-1}	−5.96	−2.40

[a] Detention time for the combined data was calculated by taking average of LSSPT and HSSPT detention times.

Table 4—Cumulative logarithmic reductions of viruses and viable helminth and ascaris ova in the District's full-scale sludge processing trains.

SPT processing stage	Range of sludge processing train stages	Detention time, d	Cumulative detention time, d	Estimated expected densities			Estimated cumulative logarithmic reduction		
				Virus[a]	Helminth ova[a]	Ascaris ova[a]	Virus[b]	Helminth ova[b]	Ascaris ova[b]
1: Digester feed	1 → 1	0	0	3.64	1.01	3.52×10^{-1}	0.00	0.00	0.00
2: Digester draw	1 → 2	20	20	1.17×10^{-1}	3.70×10^{-1}	1.52×10^{-1}	−1.44	−0.82	−1.18
3: Lagoon draw LSSPT + HSSPT	1 → Combined lagooning	703[c]	723	4.08×10^{-22}	1.69×10^{-1}	5.38×10^{-2}	∞	−1.26	−1.46
4: Air-dried product LSSPT + HSSPT	1 → Combined drying	64[c]	787	7.10×10^{-22}	1.04×10^{-2}	3.99×10^{-3}	∞	−2.05	−2.19

[a] Estimated expected densities for virus, helminth ova, and ascaris ova were taken from Table 3 of Tata et al. (2000).
[b] Estimated cumulative logarithmic reductions for virus, helminth ova, and ascaris ova were taken from Table 5 of Tata et al. (2000).
[c] Detention time for the combined data was calculated by taking the average of LSSPT and HSSPT detention times.

As in the case of the fecal coliforms, most of the log reductions in *Salmonella* sp. were attributable to lagoon aging–stabilization (Table 5). *Salmonella* sp. log reductions similar to those observed in this study (approximately 1.5 logs) were also recently reported (Jepsen et al., 1997) as caused by storage of centrifuge cake. The relatively small magnitude of the log reductions observed is not indicative of the ability of the Stickney WRP SPTs to inactivate *Salmonella* sp.; the lower value is attributable to the considerably lower density of *Salmonella* sp. in the digester feed. High reductions of approximately 4 logs for *Salmonella typhimurium* were reported by Ahmed and Sorensen (1995) in seeded sludges processed under aerobic conditions, attributed to the large initial numbers. Because of the low numbers of enteric viruses and viable helminth ova occurring in raw sludge and their subsequent inactivation in the digestion process, lagoon aging–stabilization, and air-drying stages of the District's SPTs, their detection is difficult in the final air-dried product.

Expected Log Reductions of Surges and Uniform Expansion of Helminth Ova in the District's Sludge Processing Trains. The District is interested in determining whether its SPTs are capable of achieving a final air-dried product of Class A quality if they were to experience surges and uniform expansions of hel-

Table 5—Sequential logarithmic reductions and inactivation rates of pathogenic organisms between successive stages of the District's full-scale sludge processing trains.

SPT processing stage	Range of sludge processing train stages	Detention time, d	Sequential logarithmic reduction					Sequential inactivation rate[a]				
			Fecal coliforms	*Salmonella*	Virus	Helminth ova	Ascaris ova	Fecal coliforms[b]	*Salmonella*[b]	Virus[c]	Helminth ova[c]	Ascaris ova[c]
1: Digester feed	1–1	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2: Digester draw	1–2	20	−2.06	−0.44	−1.44	−0.82	−1.18	-6.99×10^{5}	−4.12	-1.76×10^{-1}	-3.20×10^{-2}	-1.00×10^{-2}
3: Lagoon draw LSSPT (3.1)	2–3.1	821	−2.94	−1.73	—	—	—	-1.50×10^{2}	-5.69×10^{-2}	—	—	—
HSSPT (3.2)	2–3.2	584	−2.18	−1.36	—	—	—	-2.09×10^{2}	-7.79×10^{-2}	—	—	—
LSSPT + HSSPT	2 - Combined lagooning	703[d]	−2.59[d]	−1.51[d]	∞	−0.44	−0.28	-1.75×10^{2}	-6.56×10^{-2}	-1.66×10^{-4}	-2.86×10^{-4}	-1.40×10^{-4}
4: Air-dried product LSSPT (4.1)	3.1–4.1	63	−0.77	−0.19	—	—	—	−1.87	-5.03×10^{-3}	—	—	—
HSSPT (4.2)	3.2–4.2	67	−1.93	−0.66	—	—	—	-1.19×10^{1}	-2.44×10^{-2}	—	—	—
LSSPT + HSSPT	Combined (lagooning–drying)	64[d]	−1.31[d]	−0.45[d]	∞	−0.79	−0.73	−4.71	-1.49×10^{-2}	0	-2.48×10^{-3}	-7.78×10^{-4}

[a] Inactivation rate is in organism density reduction per day. Unit for inactivation rate for fecal coliforms is the number of organisms inactivated per gram (dry weight) of sludge per day. For other types of organisms, the inactivation rate is expressed in the number of organisms inactivated per 4 g (dry weight) per day. For example, the inactivation rate for fecal coliforms between feed and draw = (No. of organisms in draw/g − No. of organisms in feed/g)/(average detention time, days).
[b] Computed using pathogen densities of Table 3.
[c] Computed using estimated expected densities of Table 4.
[d] Detention time for the combined SPTs was calculated by taking the average of LSSPT and HSSPT detention times (see Table 4).

Table 6—Estimated probability of meeting Class A requirements under hypothetical surges and expansions in initial pathogen densities.[a]

Effect of hypothetical surges				Effect of hypothetical uniform expansions		
Probability of surge	Size of surge	Helminth ova[b]	Ascaris ova[b]	Expansion factor[c]	Helminth ova[d]	Ascaris ova[d]
0	—	0.997 52	0.999 96	1	0.997 52	0.999 96
				5	0.983 15	0.997 71
0.001	50	0.997 44	0.999 90	10	0.970 87	0.993 33
	100	0.997 43	0.999 90	20	0.955 67	0.986 25
	500	0.997 43	0.999 89	30	0.946 60	0.981 08
	1 000	0.997 43	0.999 89	40	0.940 62	0.977 14
	5 000	0.997 43	0.999 89	50	0.936 57	0.974 25
	10 000	0.997 43	0.999 89	60	0.933 18	0.971 84
				70	0.930 72	0.970 14
0.005	50	0.997 10	0.999 67	80	0.928 3	0.968 63
	100	0.997 07	0.999 63	90	0.927 22	0.967 41
	500	0.997 05	0.999 62	100	0.925 78	0.966 23
	1 000	0.997 05	0.999 62			
	5 000	0.997 05	0.999 62			
	10 000	0.997 05	0.999 62			
0.01	50	0.996 68	0.999 38			
	100	0.996 62	0.999 31			
	500	0.996 58	0.999 29			
	1 000	0.996 58	0.999 29			
	5 000	0.996 58	0.999 29			
	10 000	0.996 58	0.999 29			
0.05	50	0.993 33	0.997 05			
	100	0.993 03	0.996 70			
	500	0.992 83	0.996 60			
	1 000	0.992 81	0.996 60			
	5 000	0.992 81	0.996 60			
	10 000	0.992 81	0.996 60			

[a] All estimated probabilities for meeting Class A criteria for viruses are 1.000 00; all lagoon aged and final air-dried sludge product samples had an extremely low viral density ($\sim 10^{-20}$ PFU/4 g).
[b] Estimated probability for meeting Class A criteria at the indicated size of surge.
[c] Indicated factor is the number of times by which the initial density of ova increases in the digester feed and remains at that level.
[d] Estimated probability for meeting Class A sludge criteria at the indicated expansion factor.

minth ova at the first stage (digester feed). The District applied statistical methodology to study these effects. The basis and details of this methodology are given in a companion paper (Tata et al., 2000). Briefly, the underlying principle of this methodology is that the percent inactivation of surges of helminth ova follows the same pattern as that currently occurring in the District's SPTs, that is, the probable distribution for the proportions of surviving helminth ova at various stages of the SPTs will be similar to the distribution of those in the SPTs examined in this study.

Table 6 presents the probabilistic levels at which the final air-dried product would meet the criteria for helminth and ascaris ova for surges of up to 10 000 times the average initial pathogen densities and at different probabilities of surge occurrences. For example, if a surge of 10 000 times the normal density of organisms occurs 5% of the time (0.05 probability), the final air-dried product would meet the Class A criteria at a probability level of 0.992 81 and 0.996 60 for total viable helminth ova and ascaris ova, respectively.

If the initial total helminth and ascaris ova densities increase by a 100-fold (expansion factor of 100) and are sustained, the probabilities that the final air-dried product would meet Class A criteria of these pathogens are 0.925 78 and 0.966 23, respectively (Table 6). With respect to the enteric viruses, the probability of achieving a Class A biosolids product is 1.0 at the indicated surge levels and expansion factors. Because the indicated probabilities are extremely close to 1.0 in the case of helminth ova and exactly 1.0 for viruses, the District's SPTs are indeed capable of producing Class A biosolids product even when they are hit with surges of these pathogens.

In Table 6, results of statistical computations were also shown for hypothetical increases of helminth ova densities in the range of 1 to 100 times in the sludge fed to the digesters. The indicated expansion factors in this table represent the multiple by which the initial densities of total helminth and ascaris ova increased as a result of an increase in their densities, for various reasons, in the digester feed and remained at that level on a sustained basis. These results indicate that at a 100-fold increase in the initial densities of helminth ova, a Class A biosolids product can be produced with a probability of 0.925 78 and 0.966 23, and these probabilities are even greater with lower expansion factors.

Discussion

The District originally intended to conduct a 1-year study to investigate the feasibility of consistently producing a Class A biosolids product using its existing SPTs and accordingly submitted a proposal to U.S. EPA's PEC. Instead, it expanded the study to a period of 3 years and collected 331 samples from the four stages of the Calumet and Stickney WRP SPTs (in contrast to the 96 samples originally proposed to PEC). Of these samples, 318 were analyzed for fecal coliforms, 293 were analyzed for *Salmonella* sp., 250 were analyzed for enteric viruses, and 320 were analyzed for helminth ova. The total number of samples collected and number of analyses performed for each of the organisms indicated above were approximately 250% more than what was originally proposed to PEC. The magnitude of the study was increased to ensure that the results of this study were reproducible and sustainable.

The results of this 3-year study clearly indicate that the concentrations of fecal coliforms, *Salmonella* sp., enteric viruses, and helminth ova in the air-dried final product of the District's SPTs are below the numerical limits specified for a Class A biosolids product in the recently promulgated Part 503 regulations (U.S. EPA, 1993). This study is the first to demonstrate that a Class A biosolids product can be produced by optimizing and operating simple, well-known unit processes in a proper sequence, such as anaerobic digestion followed by lagoon aging–stabilization and air-drying on paved drying cells under codified conditions.

U.S. EPA's PEC expects municipal agencies to demonstrate at least a 2-log reduction of helminth ova and a 3-log reduction of viruses in their solids processing operations, should they request a PFRP certification for their SPTs. It is possible that this expectation had a precedent. U.S. EPA previously proposed, in the *Federal Register*, certain requirements for municipal agencies that petition U.S. EPA to obtain certification for their processes as equivalent to processes to significantly reduce pathogens (PSRP) (U.S. EPA, 1989). These requirements were 2-log reductions of fecal coliforms and fecal streptococci or fecal coliforms and enterococci and correspond to a 1-log reduction in pathogenic virus and helminth ova (U.S. EPA, 1989). However, these requirements were rejected as a result of public comments, and currently no specific log reduction requirements exist for indicator and pathogenic bacteria, viruses, or helminths for either PSRP or PFRP processes in the recently promulgated Part 503 regulations. Instead, these final regulations contain specific numerical limits for fecal coliforms (<1000 per 1 g of dry solids), *Salmonella* sp. (<3 per 4 g of dry solids), enteric viruses (<1 per 4 g of dry solids), and helminth ova (<1 per 4 g of dry solids) for a Class A biosolids product.

Although it is not required by the Part 503 regulations to achieve a specified log reduction for the indicator and pathogenic organisms, the PEC requested that the District demonstrate specific log reductions to establish that the District's SPTs are equivalent to PFRPs. The desired reductions were 3 logs for viruses and 2 logs for helminth ova.

This approach by U.S. EPA's PEC puts the onus on the District to demonstrate that the process can achieve at least a 2-log reduction in viable helminth ova and a 3-log reduction in enteric viruses. This PEC request, however, is not a regulatory requirement. It is impractical for the District to demonstrate such log reductions unless the digester feeds entering the full-scale process trains are seeded with large numbers of helminth ova and viruses that were previously subjected to the conditions that exist in the collection system. It is also not safe from a public health point of view to seed full-scale SPTs with large numbers of viruses and helminth ova. The validity of seeding laboratory-scale units with helminths from pig intestines (as suggested by some because of the difficulty in obtaining large numbers of helminth ova of human origin) is questionable. Such experiments cannot provide the dynamic similitude of full-scale system performance with respect to the inactivation of helminth ova adapted to the environmental conditions of the human intestine and their subsequent exposure to the conditions in municipal sewers and treatment unit processes after they are discharged from infected humans.

Such deficiencies associated with seeding are particularly troubling for the District's full-scale systems, which produce nearly 500 000 kg (~1 000 000 lb dry weight) of wastewater solids daily. Hence, the District did not conduct any seeding studies. However, such seeding studies were not necessary to demonstrate that the final air-dried product met Class A criteria for the numerous air-dried samples analyzed; all met the Class A criteria.

The high degree of inactivation that obviously takes place in the SPTs can be attributed to several factors. These can be characterized into three groups, namely, system-related, physicochemical, and biological factors. With regard to the system-related factors, an individual unit process, such as digestion or lagooning in an SPT, has a certain inherent ability to inactivate pathogens. When operated separately, that is, in parallel, these unit processes may not produce the same inactivation rates observed as when they are operated in sequence. It is the combined effect of all unit processes operating in a consistent sequential mode (digestion followed by aging–stabilization in lagoons followed by air-drying on paved drying cells) that reliably produces a Class A biosolids product from the District's SPTs. In this study, reductions (expressed in logs) that occurred in fecal coliforms, *Salmonella* sp., viruses, and helminth ova cumulatively increased through the stages of the SPTs. At each stage in the SPT, the pathogenic organisms and helminth ova are subjected to a high degree of physiological stress. When they enter a succeeding stage under a highly stressed or debilitated condition, they are unlikely to survive the altogether different environmental conditions present there.

Long detention times in the unit processes of the SPTs, varying temperatures, and changing ionic concentrations and osmotic pressures in the various stages of the SPTs are some of the key physicochemical factors that cause the inactivation of pathogenic organisms and helminth ova. Prolonged detention times for the aging–stabilization (a minimum of 1.5 years) of anaerobically digested sludge in lagoons is undoubtedly responsible for the inactivation of viruses and helminth ova as evidenced by the data presented in this paper. Studies conducted by Reimers et al. (1990) also indicated that ascaris eggs, *Salmonella livingstone*, and *Poliovirus Type 1* were inactivated when sludge was stored in a lagoon for 15 months. In a study conducted by the District in 1978, *Salmonella* sp. were never recovered from lagoons in which anaerobically digested sludge was stored for a minimum of 60 days (Lue-Hing et al., 1990). In another study conducted by the District under a U.S. EPA contract, no viruses were detected in either the supernatant or sediment samples collected from freshly lagooned anaerobically digested sludge during a 2-month period (MSDGC and IIT, 1979).

Physiological stress is caused to various organisms during the various stages of the SPTs operating under different environmental

conditions. For example, anaerobic digestion of the digester feed was conducted at 35 ± 2 °C. Digested sludge is further stabilized in lagoons, where there are a wide range of temperatures from below freezing to approximately 30 °C. The transfer of lagoon-dried material to the arid and dehydrating conditions that exist in the air-drying stage cause another stress and will aid in the inactivation of the debilitated organisms transferred.

Other physical factors, such as the climate in Chicago, permit at least one freeze–thaw cycle during the 15 months of lagoon aging–stabilization process; freezing followed by thawing causes the lysis of organisms, thereby causing their inactivation (Sanin et al., 1994). Similarly, solar and UV radiation effects during the air-drying of lagoon aged–stabilized solids on paved surfaces also enhances the inactivation of organisms. Elevated drying surface temperatures caused by the absorption and retention of heat from the sun by the dark surfaces of the paved drying cells assist in inactivating pathogenic organisms. The desiccation of particulate material, increased concentration of salts, and resulting osmotic effects that occur during the air-drying process also have a detrimental effect on the survival of any organisms including pathogens. The above factors exist in the SPTs and enhance the inactivation of pathogens in raw sludge.

Among the chemical factors, ammonia-nitrogen contained in the anaerobically digested sludge is known to inactivate pathogens (Fenters et al., 1979). Biological factors such as interspecies competition for nutrients, antagonism, predation, and complex interactions between organisms and the abiotic factors of their environment also contribute to the inactivation of pathogens and other microbial communities. Thus, there are many factors inherent in the HSSPT and LSSPT systems that account for the pathogen reductions that have been documented.

Results of the study have shown that the optimized and codified operational protocols used in this study in conjunction with a conventional solids processing technology, such as anaerobic digestion followed by lagoon storage of dewatered cake and subsequent air-drying on paved drying beds, do produce a Class A biosolids product. This study provides important input to the identification of processes to produce a Class A product, thereby promoting the beneficial use of biosolids.

Conclusions

The conclusions that may be drawn from the results of pathogen analyses of the numerous digester feed, digester draw, lagoon-aged–stabilized digester draw and centrifuge cake, and air-dried product samples collected from the SPTs operated under the codified and controlled conditions during the 3-year study are as follows.

All of the air-dried product samples collected during the controlled study period met the U.S. EPA Class A criteria with respect to fecal coliform, *Salmonella*, viruses, and helminth ova. Statistical analysis of the data indicated that at least a 2.0-log reduction of viable helminth ova occurred in the District's SPTs. Viruses were decreased by a 1.44-log reduction in the anaerobic digestion stage. No viruses were detected after lagoon storage and air-drying stages. All samples of the aged centrifuge cake and anaerobically digested sludge taken from the lagoons, before the air-drying step, also met the U.S. EPA Class A criteria.

Lagoon aging–storage of anaerobically digested sludge and centrifuge cake for 18 months produces a Class A final biosolids product. The incorporation of optimized and codified operating protocols in the existing conventional SPTs at the District (i.e., anaerobic digestion followed by dewatering–lagoon stabilization and air-drying on paved cells) consistently produced a Class A biosolids product. Statistical evaluation of the pathogen data collected also indicated that the District's SPTs would continue to produce a Class A biosolids product with a high probability, even if surges or expansions in initial densities of helminth ova occur in raw sludge.

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