VERTAD™ – AUTO-THERMOPHILIC AEROBIC DIGESTION: DEMONSTRATION-SCALE TEST RESULTS

by

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ABSTRACT

VERTAD™ is an auto-thermophilic aerobic digestion process, employing a subsurface vertical reactor to aerobically digest mixed primary and secondary wastewater treatment solids. High metabolic activity results in heat generation, which enables the production of Class A Biosolids at short solids retention times (SRT). Currently the Technology Assessment Program of the King County Wastewater Treatment Division, Seattle, WA, is evaluating the VERTAD™ process. A demonstration facility was constructed in 1998 and operated through 1999 at the County's South Treatment Plant in Renton, WA. The process consists of a deep vertical reactor (107 m deep, 50 cm diameter) with a capacity of 225 to 900 dry kg solids per day (5000 population equivalent). Successful results in demonstration-scale tests have prompted the County to consider VERTAD™ as a retrofit for existing facilities, and for future projects.

The process was tested at detentions times from 2 to 6 days and temperatures of 56 to 67°C. The requirements for Class A Biosolids (40 CFR 503.32 Alternative 1) were met at an average detention time of 4 days and 60°C. With a 4 day solids detention time, the VERTAD™ reactor achieved greater than 40% volatile solids destruction; 45-50% organic nitrogen destruction; and fats, oil and grease (FOG) destruction greater than 80%. Pathogen destruction was excellent, with fecal coliform and salmonella generally below detection limits. An oxygen transfer efficiency (OTE) of 50% was attained easily in the system. In addition, the VERTAD™ product was simply float thickened with dissolved CO_2 to 8-12% solids. The thickened product dewatered to over 30% solids with a relatively low polymer demand. Bench-scale anaerobic digestion of the VERTAD™ product resulted in 67% total volatile destruction with a 4 day SRT in VERTAD™ and an 11 day mesophilic anaerobic SRT.

The results of this demonstration project provided the basis for development of full-scale design parameters and cost estimates. The present worth of capital and operating costs for a system using VERTAD™ as a pretreatment to anaerobic digestion was similar to that of traditional mesophilic digestion, primarily due to the significant operating cost savings with low energy and polymer requirements. Improved dewaterability lowered the associated haul and disposal costs of King County biosolids. The minimal footprint requirement for VERTAD™, and production of Class A Biosolids, make the technology an ideal retrofit for current Class B Biosolids facilities.

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1. INTRODUCTION

VERTAD™ is an auto-thermophilic aerobic digestion process developed by NORAM Engineering and Constructors Ltd. (Vancouver, BC). Unlike conventional ATAD processes, this technology employs a subsurface vertical reactor to aerobically digest mixed primary and secondary wastewater treatment solids. Enhanced oxygen transfer in the process facilitates high metabolic activity resulting in heat generation. This enables the production of Class A biosolids at short solids retention times (SRT).

1.1 Process Advantages

The VERTAD™ sludge digestion system is a state-of-the-art aerobic thermophilic process that converts municipal primary and secondary sludges to Class A Biosolids, as defined by EPA CFR-503. It uses an in-ground hyperbaric aeration reactor – a device that has been proven effective through more than 20 years of commercial operation in biological processes. The VERTAD™ reactor's patented design features give it the following advantages over conventional ATAD and anaerobic systems:

- Excellent Volatile Solids destruction (> 40% in a 4 day HRT);
- Produces a Class 'A' Biosolid product (40 CFR 503.32, Alternative 1);
- Flotation thickening using dissolved gases in the product;
- Thickened product dewaters to high solids content with low polymer demand;
- Efficient space utilization means minimal plant footprint required;
- Highly efficient (low energy demand) oxygen transfer;
- Low volumes of process air to treat in subsequent off-gas biofilters;
- Power costs are substantially lower than conventional aeration processes;
- Enhanced microbial degradation due to efficient, high energy mixing;
- Autothermal operation produces heat that is available for recovery;
- Constructed using conventional well drilling or mining techniques;
- Simple open-pipe aeration device requires no maintenance;
- Odor, VOC, and ammonia emissions are minimal compared to conventional processes;

- Off-gas from head tank is contained and easily routed for biofilter treatment;
- Lower capital cost than conventional Class A technologies;
- The system can be economically enclosed in a building in locations where climatic conditions are unfavorable or if it is desirable for the plant to architecturally blend in with the surrounding environment;
- The system is uncomplicated, easy to operate and maintain, and well suited to fully-automated unattended operation;
- The in-ground reactor is much less likely to sustain damage in an earthquake than above-ground reactors.

1.2 Process Applications

The VERTAD™ process is ideal for treating sludge from VERTREAT™ systems, or from conventional biological treatment plants treating municipal sewage or industrial wastes. It is suitable for greenfield sites or can be used to expand existing facilities by incorporation as an aerobic pretreatment before conventional digestion systems. It has particular advantages in applications with the following conditions:

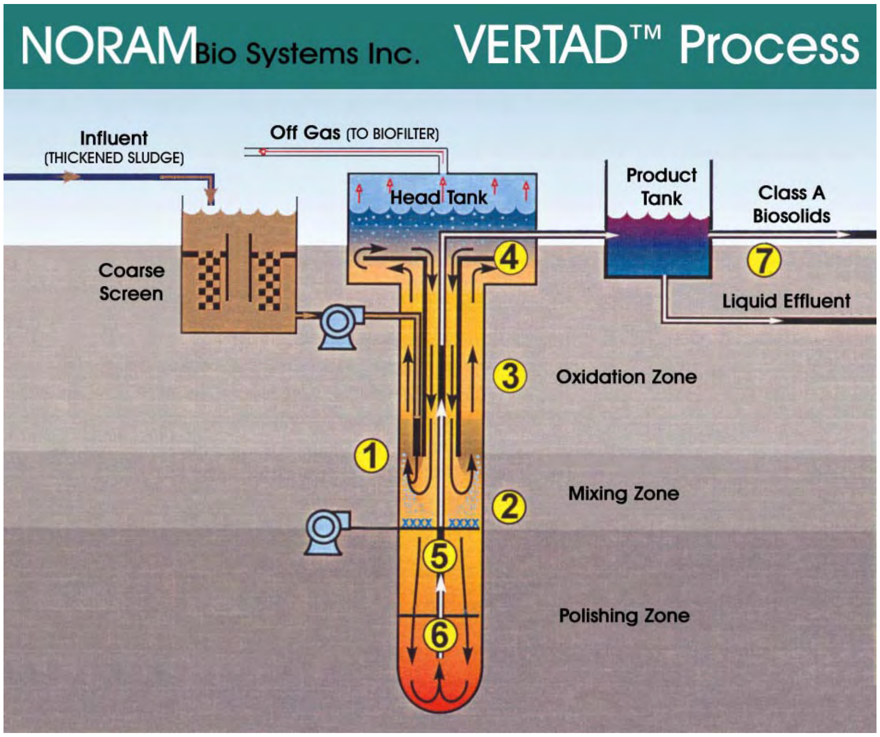
- Sites with high sludge disposal and/or trucking costs;
- Applications in which Class A Biosolids are required;
- Sites with space constraints;
- Retrofits and plant expansions;
- Sites with high precipitation or extreme temperatures;
- Sites close to residential areas;
- Locations where large unsightly plants are undesirable (i.e. recreation areas);
- Sites in areas with high seismic activity.

1.3 Reactor Features

The principal difference between VERTAD™ and conventional ATAD systems is its in-ground hyperbaric aeration reactor. Installed by conventional drilling techniques, the VERTAD™ reactor is typically 110 m (350 ft) deep, occupying only a fraction of the area used by conventional surface digestion systems. The diameter of the reactor, which can range from 0.75 m to 3 m, (2.5 ft to 10 ft) is determined by the quantity of sludge requiring treatment.

While traditional surface tankage ATAD processes employ two or three tanks in series to achieve sufficient temperatures and prevent short-circuiting, VERTAD™ combines the stages within a single reactor. As shown in Figure 1, the VERTAD™ reactor has three separate treatment zones: the oxidation zone, the mixing zone, and the lower plug-flow or soak zone. The oxidation zone is the upper portion of the reactor, and includes a central concentric draft tube for circulation. The mixing zone is immediately below the oxidation zone. Air required for bio-oxidation within the upper zone is injected into the mixing zone. The injected air also provides airlift circulation. The lower plug-flow zone is designed to prevent short circuiting, and provides the high-temperature residence time required to kill pathogens such as salmonella and fecal coliform, ensuring that the product meets the Class A Biosolids requirements set forth by the EPA in CFR-503.

Figure 1 – VERTAD™ Process Flow Diagram



1.4 Process Description

1) Screened sludge feed is delivered into the mixing zone where it is mixed with partially digested recirculating sludge.
2) Compressed air is continuously added below the mixing zone to provide the oxygen required by the microorganisms to digest the sludge. The high hydrostatic pressure ensures a high oxygen transfer rate.
3) Air bubbles rising up the outer annulus create circulation up the annulus, into the head tank, and down a central draft tube.
4) Off-gas containing excess air and carbon dioxide formed by microbial respiration disengages in the head tank and vents to an off-gas biofilter that effectively breaks any foam and removes odors.
5) A small fraction of the recirculating sludge moves from the mixing zone into the lower plug flow zone, which is designed to prevent short-circuiting. In this zone, residual organic materials are digested and the high temperature ensures that pathogens are destroyed.
6) Class A Biosolids are withdrawn from the bottom of the reactor through a central discharge pipe and transferred rapidly to a product tank at the surface.
7) The rapid depressurization of the digested Class A Biosolids causes the solids to separate in the product tank by flotation, and yields Class A Biosolids pre-thickened to around 10% solids. The subnatant liquid is recycled back to the sewage treatment plant for processing prior to discharge.

A demonstration project was supported by the Technology Assessment Program of the King County (WA) Wastewater Treatment Division. This program was developed in 1991 to evaluate and test technologies to reduce the environmental impacts of treatment plant operations including the space required for solids handling, biosolids truck traffic and odor emissions. The VERTAD™ technology was selected for evaluation based on the potential for a very small footprint, low odor emissions, and production of Class A biosolids. A demonstration facility was constructed in 1998 and operated through 1999 at the South Treatment Plant (STP) in Renton, WA. Successful results in these tests have prompted the County to consider VERTAD™ as a retrofit for existing facilities, and for future projects.

The VERTAD™ demonstration project consisted of design, construction, and operation of a demonstration-scale, deep vertical reactor for thermophilic aerobic digestion located at the South Treatment Plant (Renton, WA). The project team led by E&A Environmental Consultants, Inc. (E&A) was responsible for the planning, design, construction and testing of the facility. The technology owner, NORAM Engineering and Constructors Ltd., was actively involved in all aspects of the test program. King County provided engineering, operations and maintenance support throughout the project. The facility was completed in January, 1998 and testing was completed in December, 1999.

The test program was based on the following objectives:

1. Evaluate the SRT and temperature required for compliance with the Vector Attraction Reduction and Class A pathogen requirements of EPA 40 CFR 503.32 Alternative 1;
2. Evaluate reactor hydraulics, oxygen transfer efficiency (OTE), and energy balance;
3. Determine the dewaterability of the VERTAD™ product (cake solids, polymer demand);
4. Evaluate "dual-digestion" – VERTAD™ as pretreatment for mesophilic anaerobic digestion;
5. Perform an economic analysis of the technology.

This paper presents the performance results of the VERTAD™ demonstration project and discusses the implications of full-scale application of the technology at King County treatment plants.

2. METHODOLOGY

2.1 Facility Design and Construction

The demonstration facility is located at the South Treatment Plant (STP) operated by King County in Renton, WA. STP is a 115 MGD facility with primary clarification, activated sludge secondary treatment, co-thickening of primary and secondary solids by dissolved air flotation, anaerobic digestion and belt press dewatering. A summary of the design parameters for the demonstration facility is provided in Table 1.

Table 1 – Design Parameters for VERTAD™ Demonstration Facility

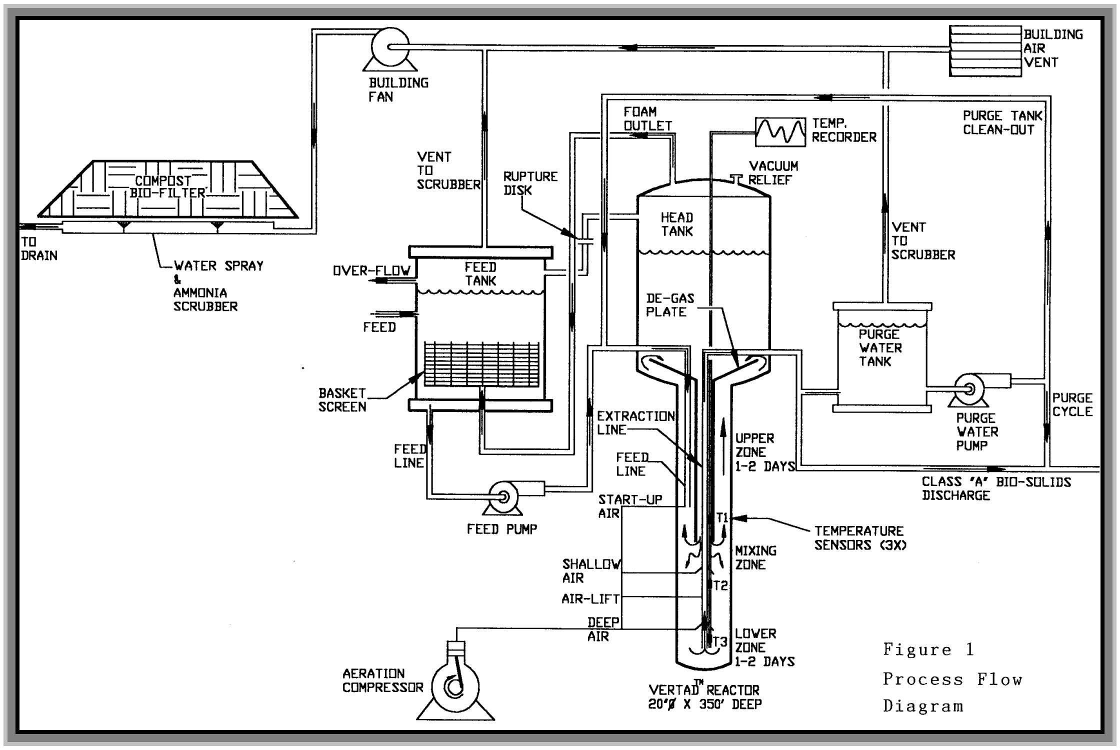
VERTAD™ Demonstration Project Facility Design Summary

Influent Characteristics	Value
Influent	Thickened Municipal Biosolids (THS)
Loading	500 to 1,500 lbs solids/day (2,500-7,500 pop. equivalent)
Solids Concentration	6.5%
VSS	78 – 80%
Primary Sludge	60%
WAS	40%
Temperature	20 – 21°C
Biofilter treatment – building exhaust	800 cfm
Biofilter loading rate	5 cfm/sf
Feed Rate @ 3 day HRT	1,770 gallons/day
@ 6 day HRT	889 gallons/day
Equipment Inventory	
VERTAD™ BIOREACTOR	
Casing	1 @ 20 inch diameter by 350 feet deep
Draft tube	1 @ 10 inch diameter by 143 feet deep
Extraction	1 @ 3 inch diameter by 347.5 feet deep
Reactor Volume Total	740 cubic feet (cf)
Liquid	710 cf
VESSELS	
Feed Tank	1 @ 60 inch diameter by 72 inch high
Digester Head Tank	1 @ 60 inch diameter by 72 inch high
Purge Water Tank	1 @ 38 inch diameter by 48 inch high
MECHANICAL	
Aeration Compressor	87 scfm, 150 psi, 25 HP
Feed Pump	1-10 gpm, 50 psi, 3 HP
Purge Water Pump	20 gpm, 26 foot TDH, 5 HP

The main component of the VERTAD facility is a 50 cm diameter, 107 m deep (20 inch x 350 ft) subsurface, vertical reactor. The reactor tube was placed by conventional drilling technology using the dual air rotary drilling method. Subsurface geology consisted of 50 m of coarse sand and gravel alluvium above a bedrock of siltstone and shale. There were indications of flowing groundwater above the bedrock. Prior to project initiation, the County conducted an assessment of the potential for earthquake damage to a deep reactor. The study concluded that damage to the reactor likely would be less than that to surface tankage (Dames and Moore, 1994). This finding is consistent with similar studies that have been carried out for Pacific Rim installations including Japan, Alaska, British Columbia, and California.

The vertical reactor has three separate treatment zones. A diagram of the process illustrating these three treatment zones is shown in Figure 1. A diagram of the demonstration facility is shown in Figure 2. The upper zone of the shaft (surface to 44 m depth) contains a central concentric draft tube for circulation. The shallow aeration header introduces compressed air below the draft tube to induce flow up the annular space and down the draft tube. Thickened solids are introduced into this completely mixed zone. The lower zone extends below the draft tube down to the deep aeration header (44 m to 96 m depth). High oxygen transfer rates are attained in this zone under pressures of 5 to 10 atmospheres. Mixing between the upper and lower zones occurs gradually over several hours. An unaerated plug-flow zone extends below the deep aeration header to the bottom of the reactor (96 m to 107 m depth). This zone is hydraulically separate from the aerated upper zones (as confirmed by tracer tests). Stabilized product is withdrawn using airlift through a 7.6 cm pipe that extends to within 0.5 m of the bottom of the reactor. Product is batch discharged at intervals sufficient to ensure strict adherence to the time/temperature requirements for pathogen destruction of Class A Biosolids.

Figure 2 – VERTAD™ Demonstration Facility Process Flow Diagram



The support equipment for the reactor includes a thickened solids (THS) supply loop, a feed storage tank, a feed pump with variable frequency control, a purge water system, a 25 Hp air compressor, a heat exchange system, a programmable logic controller (PLC), and a biofilter for off-gas treatment. The batch product withdrawal and feeding cycles (continuous or batch) are fully controlled by via PLC. Levels are continuously monitored by differential pressure sensors in the feed tank and reactor head tank. Temperatures are continuously monitored by sensors hanging at five elevations in a wet well in the center of the reactor. The THS supply loop provides a continuous supply of fresh undigested solids from the STP solids system storage tank. The feed tank provides 2.2 m^3 of feed storage. Process air to the reactor is provided by a continuous duty, rotary screw compressor that requires 18.6 kW to produce 2.5 sm^3/min at 1035 kPa (87 scfm at 150 psi). Compressed air is injected at 48 m and 96 m deep. The process air supplies oxygen for biological metabolism and induces mixing in the reactor. Air that is not dissolved produces voidage (volume of bubbles per unit volume of liquid) and is released from the reactor liquor in the head tank. A weighted check valve on the off-gas pipe provides up to 35 kPa (5 psi) back pressure to the head tank which reduces voidage. The off-gas is directed to the bottom of the feed tank to provide additional back pressure and capture foam and latent heat in the influent solids. The test facility is housed in a temporary building that is provided with utilities and air collection. Building exhaust and reactor process off-gas passes through a water scrubber for ammonia removal and is then processed through a biofilter. A picture of the building the houses the VERTAD™ demonstration plant is provided in Figure 3.

Figure 3 – VERTAD™ Demonstration Facility at Renton, WA

A system to add supplemental heat to the reactor was installed after it became evident that heat loss from the pilot reactor exceeded the heat generated biologically and thermophilic temperatures could not be maintained. The reactor was not insulated and has a high surface area to volume ratio, which facilitates heat transfer to the environment. Also, flowing water was identified in three zones during drilling. Water moving past the reactor can remove substantial heat. To compensate for heat loss to the environment, reactor feed was initially preheated via steam injection using an 80,000 Btu/hr. propane-fired steam boiler. This was replaced later in the test period with a boiler (500,000 Btu/hr) that supplied hot water to heat exchanger loops hanging in the reactor. This system provided direct control of the temperature in the reactor. The supplemental heating system was added rather than using a sludge-sludge heat exchanger to capture heat from the product.

While the VERTAD™ plant referenced is often cited as a pilot or demonstration scale facility, it should be noted that this plant can process the solids from a 7,500 population equivalent. A 7,500 population equivalent would be serviced by a 0.75 MGD VERTREAT™ facility that would feed solids to a VERTAD™ plant of roughly this size. So while this plant is considered small by King County standards, it would be a full-scale facility for smaller municipalities.

2.2 Test Plan

The testing program was designed to meet the goals of the King County research program to evaluate the viability of the technology with respect to reactor hydraulics, energy requirements, product quality and the ability to meet the vector attraction reduction and pathogen destruction requirements of Class A Biosolids. An additional goal was to develop the design criteria necessary for full-scale design and cost evaluation.

A range of operating conditions were tested in the facility. Prior to biological startup, cold water testing was conducted to evaluate reactor hydraulics and to test equipment. Next, pre-heating of the reactor using a hot water boiler provided data on heat loss to the environment in the absence of biological heat generation. Biological testing with varied HRT, temperature, aeration rates, and feed solids spanned the periods of January 15 to May 7, 1998, November 10 to December 17, 1998, and August 4 to December 23, 1999. Suspensions in operation between the various testing periods allowed ongoing modifications of the facility for improved data acquisition and control. During the third testing period, stable operation was achieved over a range of detention times and temperatures. In order to test a full range of conditions and determine the capabilities of the VERTAD™ process, some operating conditions were applied that did not provide a Class A Biosolids product. However, these imperative tests provided insights into the critical effects of such variables as sludge viscosity, oxygen transfer efficiency, and heat loss. The range of operating conditions that were tested for the process are summarized in Table 2.

Table 2 – Summary of Operating Ranges

Range of Operating Conditions	
Operating Variable	*Operating Range*
Hydraulic Residence Time (Days)	2 to 6
Temperature (°C)	55 to 70
Aeration (scfm)	20 to 80
Feed Solids Content (%)	3.5 to 7

The controlled parameters of the test program were the solids retention time (SRT), temperature, and aeration rate. The approach was to establish stable operations at specified operating conditions for a minimum of three detention times. During the fourth detention time, data was averaged to yield the reported values for the reactor performance under those stable conditions.

Samples were collected for laboratory analysis of the thickened solids feed (THS), feed and head tank (upper zone) solids, and final product solids (from the deep extraction line). These samples were tested for total solids (TS), volatile solids (VS), pH, total Kjeldahl nitrogen (TKN), ammonia (NH_4), chemical oxygen demand (COD), and alkalinity (ALK) by the STP laboratory according to Standard Methods. Fecal coliform and salmonella analyses were conducted by the King County Environmental Laboratory. Additional laboratory and field testing included measurement of fat, oil and grease (FOG), total carbon (TC), total organic carbon (TOC), off-gas analysis, density testing, oxidation reduction potential (ORP), dewaterability, and dissolved oxygen (DO). Daily grab sample analyses of TS and VS were conducted while the remaining parameters were measured weekly. More frequent sampling and composite analyses were conducted during the fourth detention time. Temperatures, levels and flows were logged and trended continuously via PLC using a Siemens WinCC trending program. Oxygen concentration in the off-gas was measured using a portable oxygen analyzer (first with a Quintox gas analyzer, and later a Teledyne Portable Flue Gas Oxygen Analyzer).

The dewatering characteristics (polymer demand, cake solids content, and filtrate quality) of the digested product were tested by several dewatering equipment vendors (CIBA, U.S. Filter, Andritz). Five gallon samples were delivered to vendor laboratories were testing was performed on bench scale centrifuges, belt presses, and capillary suction time (CST) test equipment. Onsite testing was conducted to compare VERTAD™ product to the mesophilically digested STP biosolids using jar testing to determine polymer demand, and press tests to assess the maximum achievable dry cake solids content.

Tracer tests using both lithium chloride (LiCl) and salt (NaCl) were conducted to assess the reactor hydraulic characteristics and to confirm that no short-circuiting was occurring in the reactor. LiCl or NaCl was batch loaded into the reactor and samples were collected from the reactor head tank and the product during batch product withdrawals. In the case of tracer tests involving LiCl, the samples collected were analyzed for Lithium content, and profiles were developed. For the salt traces (only performed in water), conductivity changes were measured in the samples taken from several depths in the reactor. Samples from lines at 213 and 268 ft depths were drawn continuously by a peristaltic pump at a rate of 1.3 lpm through 3/8" ID tubing weighted to keep it in place. Enough salt was added to increase the conductivity to approximately 10 times the background concentration, ensuring good resolution. Conductivity was measured using the STP conductivity analyzer after proper temperature equilibration. This has automatic temperature compensation so readings need no further correction.

Bench-scale testing was conducted at the University of Washington to assess the effect of VERTAD™ pretreatment on subsequent mesophilic anaerobic digestion (dual digestion). VERTAD™ product (4 day SRT) was fed to 3L anaerobic digesters maintained at 11 and 15 day detention times. A control digester was fed STP thickened solids at an 11 day SRT. The digesters were maintained at 35°C. The main parameters used to evaluate digester performance included volatile solids destruction efficiency, gas production and percent methane, and product dewaterability using CST testing.

Odor panel testing was performed on samples collected from the VERTAD™ process. The odor panel analyses was conducted by Odor Science & Engineering, Inc (OS&E). These tests were aimed at measuring the odors generated by the VERTAD™ process and the effectiveness of the biofilter for odor treatment. Odor was quantified by dilution-to-threshold (D/T) ratio and panelists described the odor character.

3. RESULTS AND DISCUSSION

3.1 Volatile Solids Destruction

A summary of the digestion performance results is presented in Table 3. The values reported are averages over a detention time after the process was stable for three detention times. A complete mass balance was achieved for each of these tests from which the reported efficiency values were calculated.

Table 3 – Volatile Solids Reduction at Varied Temperature and Residence Times

Test	HRT (days)	Temperature (ºC)	Aeration Rate (scfm)	VS Reduction (%)
Dec'98	4	56	56	40.9
Sept'99	4	65	80	42.2
Nov'99	3.4	56	36	42.3
Dec'99	5.5	61	30	43.5*

The effect of solids residence time on VS reduction was demonstrated by the testing. Greater than 40% VS reduction was demonstrated at a 4 day SRT. This efficiency appears to decrease approximately linearly as the residence time is reduced. In testing at a 2 day SRT and 67°C, a 21% VS reduction was demonstrated. As shown in Table 3, a 5.5 day SRT resulted in a 43.5% VS reduction. This value is considered conservative because concurrent testing of reactor response to oil and sugar addition complicated results due to the additional load on the system. Results from the three detention time conditioning period for the 5.5 day SRT test were averaging at 50.7% VS reduction prior to the supplemental additions. From these results it is believed that VS reduction will approach 50% at a detention time of approximately 6 days at 60°C (360°C-days).

In general, it was found that an increase in temperature for a given solids retention time resulted in greater VS reduction. Testing indicated that although temperature certainly affects biological activity, it is believed that the effects on water loss and oxygen transfer efficiency on reactor performance are much more significant and important.

Important findings about the effect of reactor sludge viscosity on oxygen transfer resulted in testing centered on controlling the reactor solids. With solids controlled at below 4.5% TS, oxygen transfer efficiency nearly doubled, allowing a subsequent decrease in aeration rates. Decreased aeration rates minimized the amount of water loss (as latent heat) from the reactor for a given temperature. The difference between the Dec'98 and Nov'99 results can be explained by this finding. The two test periods were both operated at a temperature of 56°C, however the Nov'99 trial was operated at a reduced SRT (3.4 days compared to 4 days), and at a reduced aeration rate (36 scfm compared to 56 scfm). The major difference between the two trials was that in the case of the Nov'99 trial, the reactor solids concentration was being controlled at 3.5% TS, and in the Dec'98 trial, the reactor solids concentration was 4.7%. Ultimately, the increased ability to transfer oxygen in to the mixture allowed a decreased SRT while simultaneously provided increased VS reduction.

The requirements for Class A biosolids were met at an average detention time of 4-days at 60°C. As shown in Table 3, the system readily achieved greater than 40% volatile solids destruction at varied detention times and temperatures. In order to satisfy the volatile solids destruction criteria of 38% (U.S. EPA, 1990) in conventional ATADs, Kelly et al. (1993) suggested a 400°C-day product was necessary. The VERTAD™ results indicate that a 240°C-day product exceed the EPA requirements, with greater than 40% volatile solids destruction.

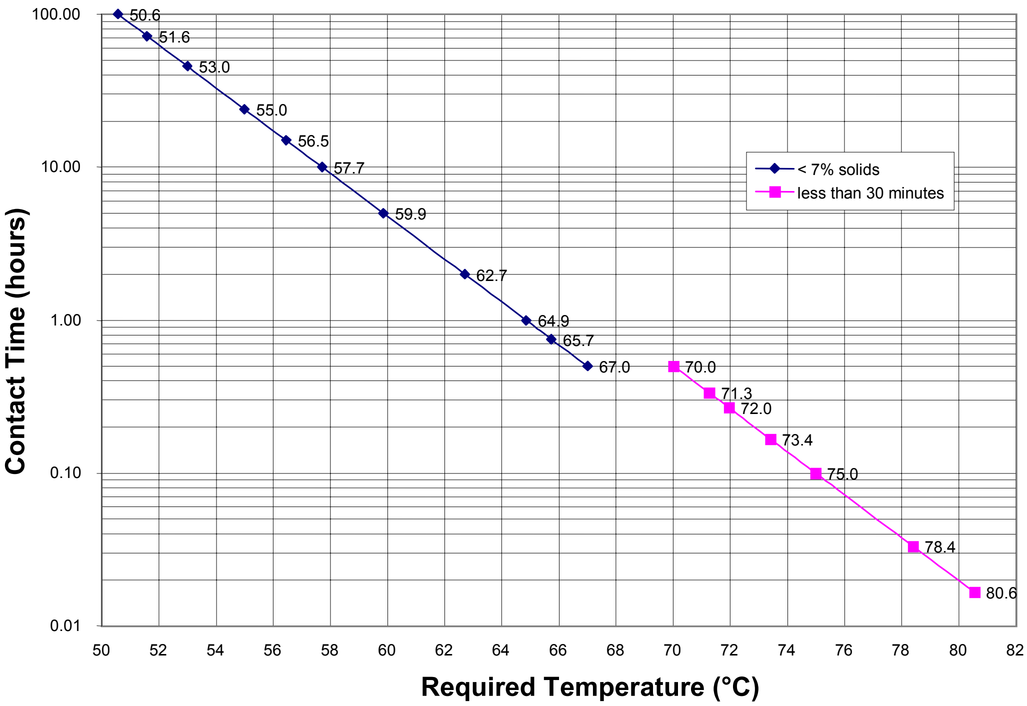
3.2 Pathogen Destruction

Pathogen destruction was excellent with a 7 log reduction in fecal coliform and both fecal coliform and salmonella below detection limits in the Class A Biosolids product. Fecal coliform and salmonella were measured in the feed solids and digested VERTAD™ product weekly during the first operating period and intermittently during the third operating period. Fecal coliform in the feed solids averaged 5.39E+07 MPN/g dry solids and salmonella averaged 5.87 MPN/4 g dry solids. Densities in the VERTAD™ product were consistently below the detection limit (fecal coliform: 5 MPN/g, salmonella: 1.6 MPN/4g).

3.3 Reactor Mixing

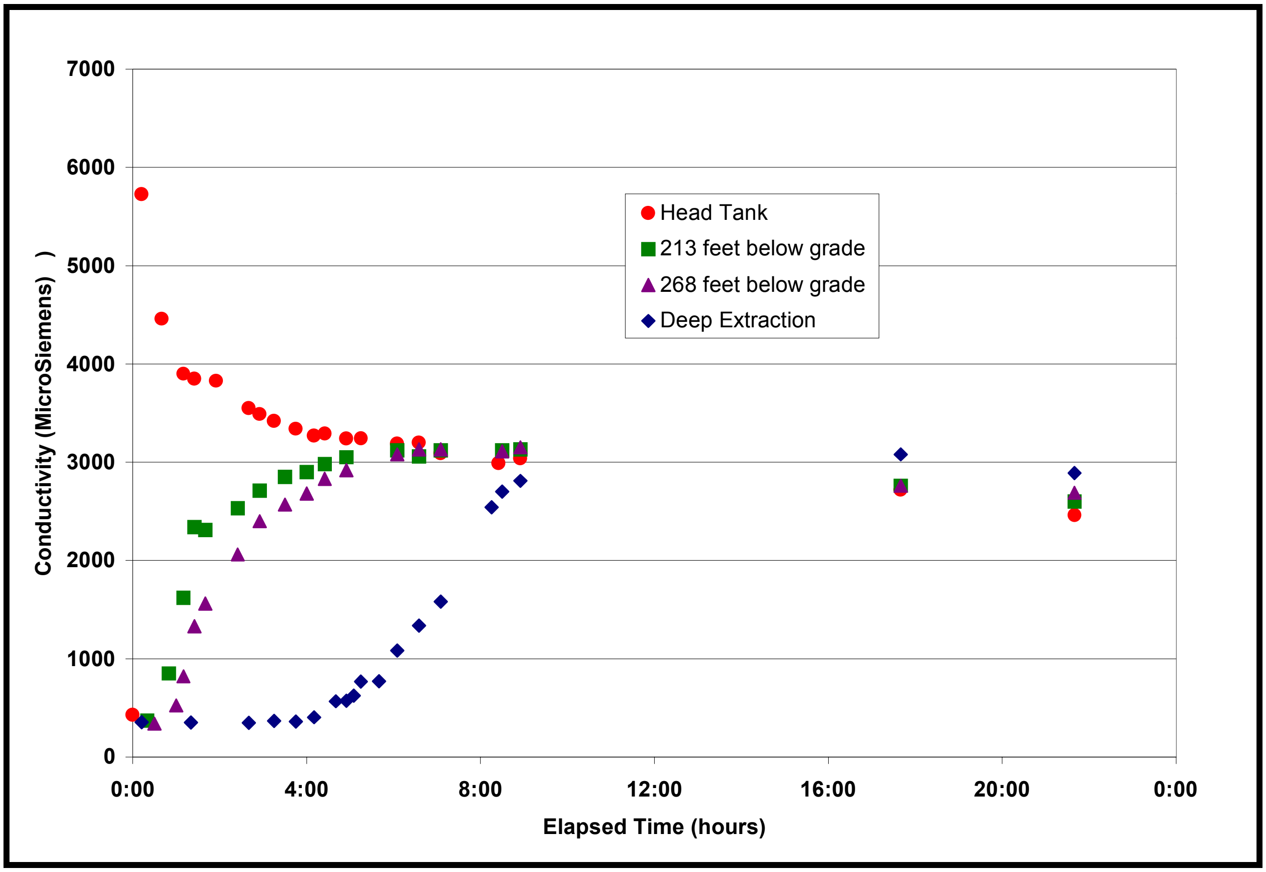
The selected alternative for attaining Class A pathogen control in the VERTAD™ process is by maintaining temperatures for the required contact time. Time and temperature requirements from the biosolids regulations (40 CFR 503) are shown in Figure 4.

Figure 4 – 40 CFR 503 Class A Time and Temperature Requirements for Solids < 7%



In order to test the reactor's compliance with time-temperature requirements, salt tracer studies were performed in the system. Samples were taken at regular intervals from four points in the system: the head tank (surface), 213 feet below grade surface (bgs), 268.5 feet bgs, and the deep extraction line. Critical distances in the system are: Upper Aeration Head - 158 ft bgs, Lower Aeration Head - 315 ft bgs, and Deep Extraction Line - 347 ft bgs. Head tank and intermediate sample points allowed observation of the saline dispersion as it moved through the reactor, providing an indication of the mixing time between the aeration headers. The deep extraction point allowed observation of the saline pulse, showing the time for a single particle to breakthrough the soak zone. A pulse of saline was pumped into the reactor quickly with enough salt for a 10 fold increase in reactor conductivity. After the pulse of saline, the system was fed and discharged continuously at a rate of approximately 2 gpm (HRT of approximately 2 days). The conductivity profile versus time for the reactor tracer study is shown in Figure 5.

Figure 5 – VERTAD™ Salt Tracer Study Confirming NO Short Circuiting



Tracer results are consistent with a model in which:

- The upper zone (head tank to upper aeration head) is well mixed, with a time constant of the order of minutes.
- The lower zone (upper aeration head to lower aeration head) is mixed gently by fluid rising in the wake of bubbles with a net turnover time which depends strongly upon air flow. In this study the lower aeration was 8 scfm, resulting in gentle mixing over approximately 90 minutes. Here, simple theory based on the assumption that a bubble draws up its own volume of fluid are in reasonable agreement.
- The soak zone is effectively plug flow.

The mixing test clearly indicates that the salt tracer did not reach the deep extraction point until approximately 4 hours had elapsed. This eliminates any concerns about short-circuiting in the reactor soak zone. The theoretical time for breakthrough (based on the 2 gpm extraction rate and the soak zone volume for plug flow) is 4 hours 20 minutes. To our knowledge, this is the first continuous feed, single reactor design that complies with the EPA time-temperature regulations.

Salt tracer studies confirmed that the VERTAD™ patented reactor design complies with time-temperature requirements (40 CFR 503 Class A Time and Temperature Requirements for Solids Less Than 7%). These studies verify the true plug flow nature of the soak zone, and eliminate any concerns about short-circuiting in the system. While it is believed that the demonstration facility's vertically stacked zone configuration complies with the time and temperature requirements, two variations are available to further assure compliance:

- Installation of a flow restricting physical barrier between the slowly mixed and soak zones,
- Maintaining a surface batch contact tank in which the VERTAD™ product is held for the required time at the appropriate temperature (using heat generated from the VERTAD™).

3.4 Flotation Thickening

During dewatering testing, concurrent work indicated that the VERTAD™ product could be easily thickened after being discharged from the reactor. VERTAD™ effluent has the characteristic of high dissolved carbon dioxide concentrations due to the biological metabolism and the high pressure in the reactor. Acidifying the effluent (with sulfuric acid or alum) to approximately pH 5, releases the CO_2 as small bubbles which attach to biosolids particles and float them to a compact blanket. Further testing resulted in float thickening of the VERTAD™ biosolids from 3.5% TS to 8 - 12% total solids, with a capture efficiency of approximately 95%. Results were similar with both sulfuric acid and alum. Ferric chloride was not used, but it is expected to provide a similar result.

Analysis of the float thickened solids and the subnatant showed that nutrients partitioned into the digested biosolids. Thickened biosolids contained a phosphorus concentration 20 to 40 times the concentration in the subnatant. In the testing using sulfuric acid, ammonia slightly partitioned into the biosolids due to the formation of ammonium sulfate. This result means that the phosphorus load that is typically recycled to the secondary treatment plant is being retained in the biosolids for beneficial reuse.

The downstream implications of this flotation thickening step are as follows:

- Significantly reduces the size of the dewatering system,
- Charge neutralization aids in dewatering,
- Reduced recycle nutrient loading on the treatment facility,
- Increased nutrient value of the Biosolids.

3.5 Product Dewaterability

Test methods for dewatering included onsite press tests as well as outside laboratory testing at Andritz, CIBA, and other vendors using bench scale belt presses and centrifuges. Samples tested included mesophilic anaerobic sludge from the STP, biosolids directly from the VERTAD™ reactor, VERTAD™ float thickened biosolids, and product from the combined VERTAD™ to anaerobic bench-scale test work.

Onsite press testing was performed using a set polymer dose of 17 lbs/ton for the mesophilic anaerobic sludge from the STP, biosolids directly from the VERTAD™ reactor, and the VERTAD™ float thickened biosolids. Cake solids were measured and the filtrate quality was reported qualitatively. The results are presented in Table 4.

Table 4 – Onsite Press Testing of VERTAD™ Product Dewaterability

Characteristics	Anaerobic	VERTAD™	Acid Float Thickened VERTAD™
Cake Solids (%)	20	32	31
Polymer Dose (lbs/ton)	17	17	17
Filtrate Quality	Clear	Very Turbid	Very Clear

Testing demonstrated that greater than 30% cake solids could be attained with both the biosolids directly from the VERTAD™ reactor and the VERTAD™ float thickened biosolids whereas the anaerobically digested solids dewatered to 20% cake solids. In the case of the VERTAD™ reactor biosolids, the filtrate quality was poor, with losses of solids making the filtrate look very turbid. This indicated that a higher polymer dose would be required with the straight VERTAD™ product to obtain an acceptable filtrate quality. The VERTAD™ float thickened product outperformed both the anaerobic and VERTAD™ products. Not only did the VERTAD™ float thickened product have a very clear filtrate (clearer than that from the anaerobic dewatering tests); it obtained the best result from a cake solids perspective. This testing illustrated that the float thickening process greatly enhances the dewaterability of VERTAD™ biosolids.

Outside laboratory testing at Andritz, CIBA, and other vendors, was performed on samples of mesophilic anaerobic sludge from the STP, biosolids directly from the VERTAD™ reactor, and the VERTAD™ float thickened biosolids. Polymer dosing was optimized using 95% solids capture efficiency for the filtrate quality. Cake solids and solids capture efficiency were measured and reported. The results are presented in Table 5.

Table 5 – Andritz Lab Centrifuge Testing of VERTAD™ Product Dewaterability

Characteristics	Anaerobic	VERTAD™	Acid Float Thickened VERTAD™
Cake Solids (%)	12-14	31-34	31-34
Polymer Dose (lbs/ton)	20.4	38	13.8
Capture Efficiency (%)	95	96	99.5

The Andritz test results showed that greater than 30% cake solids could be attained with both the VERTAD™ reactor product and the acid float thickened product. Similar to onsite press testing, higher polymer doses were required for the VERTAD™ product withdrawn directly from the reactor (approximately double the polymer required for the anaerobic sludge). The anaerobic biosolids dewatered very poorly with the lab centrifuge, only attaining a maximum cake solids concentration of 14%. Like onsite press testing, the VERTAD™ acid float thickened product showed remarkable dewatering characteristics. It dewatered to high cake solids concentration (31-34%) with a lower polymer dose than that required for anaerobic sludge (13.8 and 20.4 lbs/ton, respectively). The conclusion is that the float thickening enhances the dewaterability of the VERTAD™ product. This is likely due to a charge neutralization that seems to act like a coagulant, aiding in dewatering.

It is generally accepted that thermophilically digested aerobic biosolids can be dewatered to higher cake solids than anaerobically digested biosolids, however this has historically come with the expense of greater polymer demand (Murthy et al., 2000). Murthy et al. performed an examination of an autothermal process to isolate the cause of high polymer demand and high recycle chemical oxygen demand (COD). They found that the presence of monovalent ions in solution such as sodium, potassium, and ammonium ions can interfere with charge-bridging mechanisms occurring in the floc. This is a problem in conventional ATAD systems because the release of ammonium ions is the result of the absence of nitrification in the thermophilic process (Burnett, C.H., 1994). This free ammonia release appears to be less pronounced in the VERTAD™ process, possibly due to the pressure in the reactor which results in the combination of free ammonia with dissolved CO_2, forming ammonium bicarbonate.

Murthy et al (2000) also found that the amount of biopolymer (proteins and polysaccharides) in solution was heavily correlated to increased polymer demand. They concluded that the concentration of biopolymers in solution was minimized by limiting the solids retention time (SRT) of thermophilic digestion, and by minimizing the concentration of monovalent ions (specifically ammonia) in solution. These factors favour the VERTAD™ process because a relatively short SRT of 240°C-day is enabled by the high oxygen transfer achieved in the system, and ammonium bicarbonate is formed in the reactor, minimizing free ammonia.

3.6 Organic Nitrogen & FOG Destruction

A summary of the digestion performance results for VS, FOG, and organic nitrogen is presented in Table 6. The values reported are averages over one detention time after the process was stable for three detention times. A complete mass balance was achieved for each of these tests from which the reported efficiency values were calculated.

Table 6 – Volatile Solids, FOG, and Organic Nitrogen Reduction

Test	HRT (days)	Temperature (°C)	VS Reduction (%)	Org-N Reduction (%)	FOG Reduction (%)
Dec’98	4	56	40.9	57.9	91.7
Sept’99	4	65	42.2	49.8	80.8
Nov’99	3.4	56	42.3	44.1	--
Dec’99	5.5	61	43.5*	49.9	80.4

The reduction of organic nitrogen and fats, oils and grease were relatively high considering the short solids retention times that the VERTAD™ process was tested at. The results were similar to the reduction efficiencies attained in the STP anaerobic digesters at a 28 day SRT.

The organic nitrogen reduction was calculated based on the difference between TKN and ammonia in the feed and product. Organic nitrogen reduction generally exceeded the total VS reduction. Analysis of the Dec’98 samples showed that protein degradation (assuming 6.25 kg protein/kg org-N) and FOG reduction accounted for 64% and 9%, respectively, of the VS reduction. The remaining VS reduction was attributed to carbohydrate reduction which is primarily comprised of cellulose and lignin. The preferential degradation of Org-N and FOG was further confirmed by visual inspection of the product which is very fibrous.

These results are significant since undigested Org-N and FOG are generally responsible for the objectionable character of biosolids. These results also have significance when considering a dual digestion flowsheet with VERTAD™ pretreatment ahead of anaerobic digestion. The technologies appear to be complementary in that the VERTAD™ technology readily degrades fats and proteins, compounds known to cause scum buildup and mixing problems in anaerobic digesters, and the anaerobic digestion process is capable of destroying the cellulose material still present in the VERTAD™ product.

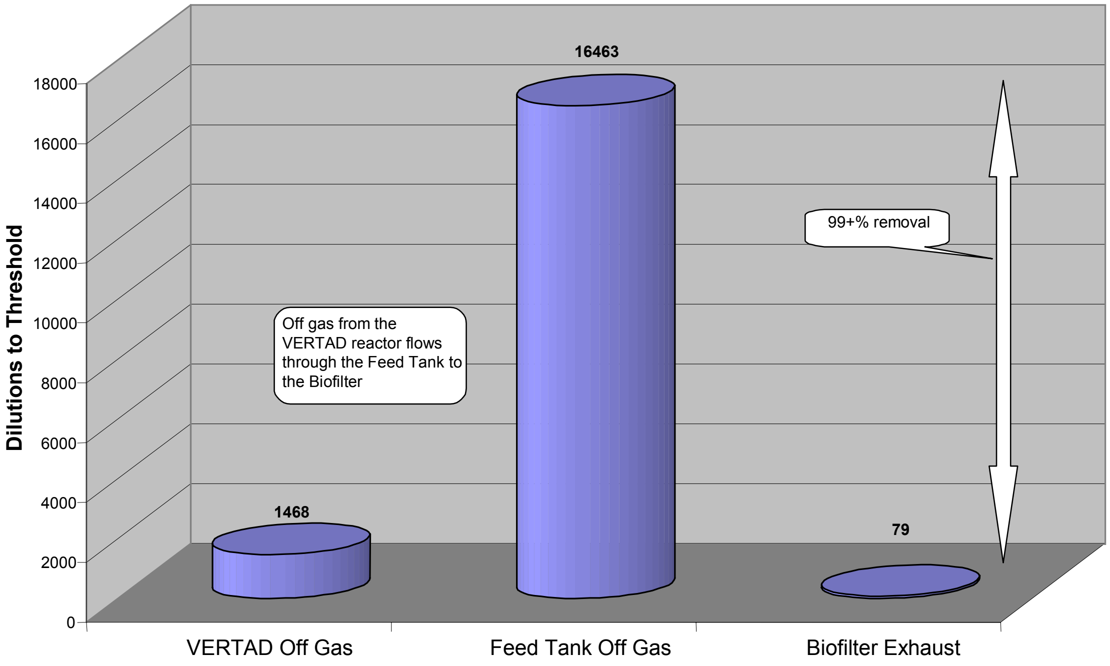
3.7 Odor & Off-Gas Control

In the VERTAD™ system, the self-contained nature of the head works allows easy control over off-gas emissions. Off-gas can be easily routed to biofilters to remove the trace ammonia and dimethyl sulfide (DMS) compounds common with aerobic digestion technologies. Because of the high oxygen transfer efficiency in the bioreactor, the VERTAD™ process needs only a fraction of the air volume used in a conventional ATAD. As a result, significantly less off-gas is produced in the VERTAD™ process, reducing the size of biofilter required for off-gas treatment.

Gaseous emissions from the VERTAD™ system are considerably smaller than those produced in conventional aeration processes. As mentioned previously, ammonia is converted to ammonium bicarbonate in the reactor, helping to eliminate ammonia emissions. In order to minimize the ammonia release from the system, reactors are operated at a maximum temperature of 60°C, preventing the dissociation of the ammonium bicarbonate.

Odor panel testing was performed on samples collected from the VERTAD™ process. The odor panel analyses was conducted by Odor Science & Engineering, Inc (OS&E). These tests measured the odors generated by the VERTAD™ process and the effectiveness of the biofilter for odor treatment. Odor was quantified by dilution-to-threshold (D/T) ratio and panelists described the odor character. The results of the odor panel work are provided in Figure 6.

Figure 6 – Odor Panel Results



These results show that most of the VERTAD™ demonstration facility derived odor comes from the feed tank (16,463 D/T in 675 scfm) rather than the VERTAD™ reactor (1,468 D/T in 36 scfm). The biofilter removed 99.5% of the odor loading (16,463 D/T in, and 79 D/T {avg} out).

Odor panel testing has indicated that the off-gas from the VERTAD™ process is generally odor-free. Character descriptors for the VERTAD™ off-gas prior to the feed tank included more terms such as compost, earthy and vegetation. The off-gas from the untreated feed sludge tank changed the odor panel characterizations to focus on terms such as sludge and manure type odors.

These results have highlighted the need to treat the off-gas directly from the reactor in a biofilter. The reduced odor of the VERTAD™ off-gas is primarily attributed to the fact that the compounds primarily responsible for the objectionable character of unstabilized wastewater solids (FOG, Org-N) are the highest degraded fractions in VERTAD™.

3.8 Oxygen Transfer Efficiency

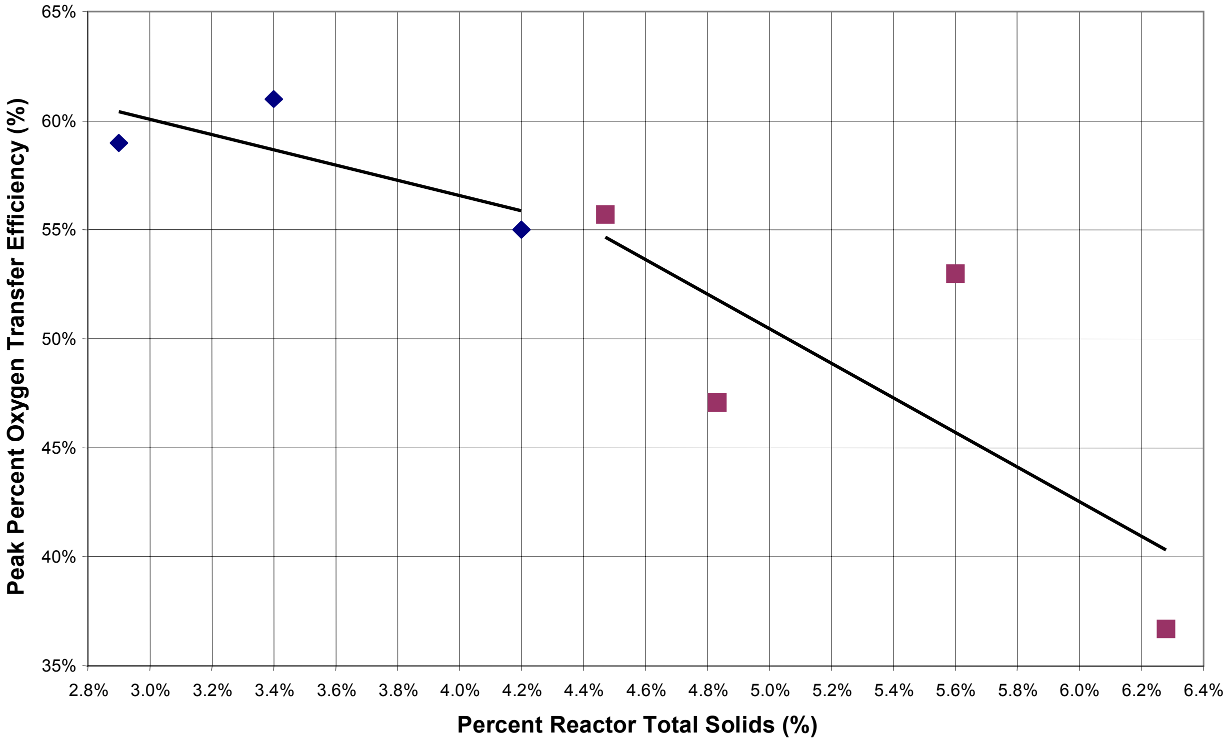
Oxygen transfer studies were performed to test the oxygen transfer rate (OTR) first into water and determine the theoretical maximum efficiency of the system, and second into sludge to determine the oxygen transfer efficiency attainable in the digestion process.

The test method used to determine the oxygen transfer rate into water came from the ASCE (American Society of Civil Engineers). This test involved the initial scavenging of dissolved oxygen with sodium sulfite and a cobalt chloride catalyst (Na_2SO_3 & $CoCl_2$), followed by reoxygenation to near the saturation level for the operating temperature. Throughout these tests DO was measured at multiple points, allowing the development of a mass transfer model.

The OTR was measured for water, allowing calculation of the OTE in the system. The oxygen transfer efficiency was approximately 66% into water at 54°C (129°F). This OTE represents a significant advancement in aeration technology over conventional aeration systems using air, which typically attain 10-20% OTE into water at 20°C, a lower temperature which facilitates oxygen transfer through increased solubility.

Sludge viscosity was found to have a pronounced effect on the oxygen transfer efficiency (OTE). As shown in Figure 7, an OTE of 50% was attained easily at a reactor concentration less than 4.5% TS. At greater than 4.5% TS, the transfer efficiency was diminished, as low as 35%.

Figure 7 – Viscosity Effects on Peak Oxygen Transfer



Although sludge is highly non-Newtonian, and the concept of a Newtonian viscosity which is independent of shear rate is not strictly valid, some valuable order of magnitude generalizations can be made about transfer performance at higher VS destruction. In general, the oxygen transfer efficiency is improved at higher VS destruction because the viscosity of the bulk liquid is decreased with increased destruction, and decreased viscosity facilitates increased oxygen transfer.

Transferring oxygen into thick sludge is not easy – even at pressure, due to mass transfer limitations on the liquid side. Metcalf and Eddy (1991) suggest that viscosity may decrease by a factor of 2 or more over the range of 3 to 6% for undigested sludge, with viscosity declining rapidly as sludge is digested. Doubling fluid viscosity changes oxygen diffusivity in the sludge in inverse proportion (i.e. it is halved); the mass transfer coefficient, and mass transfer rate will likely change by a similar order of magnitude. This is supported by the VERTAD™ OTE data which suggests that the OTE is nearly halved with a doubling in reactor solids, and that 4.5% is the practical operating cutoff before the sludge viscosity seriously affects the OTE.

The effect of oxygen transfer upon heat release was corroborated during the oxygen transfer testing. During testing each test involving a lower aeration rate saw a systematic decrease in the reactor temperature. Each time the aeration rate was reduced, biological heat generation was reduced and a step change in temperature occurred.

The VERTAD™ system achieves very high oxygen transfer efficiency, greater than 50% OTE can be expected when the viscosity of the reactor contents is controlled with a solids concentration less than 4.5% TS. These high oxygen transfer rates are associated with the pressure and depth at which compressed air is introduced to the bioreactor. The high OTE results in enhanced digestion of the sludge and a decreased detention time to meet the Class A Biosolids requirements.

The OTE for other ATAD systems is generally not reported in literature presumably due to the proprietary nature of the systems, however, some independent data collected from an ATAD facility suggests that the VERTAD™ process compares favorably in terms of oxygen transfer efficiency. While the VERTAD™ system achieves an average oxygen transfer efficiency of 50%, a conventional ATAD system that was tested only achieved an average of approximately 24% across a three stage system, presumably due to the high viscosity and low temperatures in early stages.

The increased oxygen transfer in the VERTAD™ system is thought to be the primary factor in decreasing the solids retention time to meet EPA vector attraction requirements. As mentioned previously, Kelly et al. (1993) have suggested that a 400°C-day product is necessary in ATADs to attain a volatile solids destruction of 38%. The VERTAD™ results indicate that a 240°C-day product exceed the EPA requirements, with greater than 40% volatile solids destruction. The difference in oxygen transfer and subsequent heat release in the two systems could explain this.

3.9 Heat Balance

The small diameter of the demonstration reactor results in a large surface area to volume ratio, necessitating supplemental heat addition at the facility to maintain temperature. A heat balance was performed using measured reactor heat loss data, influent and effluent temperatures, estimated biological heat production, aeration energy and the measured supplemental heat necessary to maintain a set temperature. The heat balance showed that auto-thermophilic conditions would be maintained if the reactor diameter were increased to 0.8 m. (2.6 ft), thus decreasing the relative surface area. Reactors of larger diameter will require a heat removal system to prevent overheating, and recovered hot water will be available to the treatment plant for space heating and for digester heating in linked anaerobic systems.

3.10 VERTAD™ Process Simplicity and Stability

The biological process was found throughout the testing program to be relatively simple to operate, resistant to upset, and to rapidly recover from disruptions caused by electrical and mechanical system failures. The straightforward process controls consist of providing a supply of food on a relatively uniform basis and providing air. In a full-scale system the operational controls are expected to require less operator attention than an anaerobic digestion process. The VERTAD™ process operates well over a range of pH conditions and temperatures. Although the process does not generate gas, it does produce hot water and does not require the extensive gas handling, cleaning, and safety equipment.

The ability of the process to recover quickly from upset conditions was demonstrated on numerous occasions as the result of power outages and failure at the feed system, boiler, or control system. During these occasions, the process was stressed by lack of food, cooling, and aeration. In all situations the process recovered rapidly.

3.11 VERTAD™ Followed by Anaerobic Digestion (Dual Digestion)

The process of dual digestion involves the use of an autothermal aerobic digestion process as a pretreatment step before mesophilic anaerobic digestion. In conventional dual digestion systems the aerobic step usually has a contact time of about 24 hours and pure oxygen is typically used to support biological metabolism. Dual digestion is a well established Class A process.

The VERTAD™ process was evaluated as a pretreatment step to mesophilic anaerobic digestion. The impetus to test the combined digestion is the fact that King County treatment facilities, and many solids generators, need to maximize solids destruction in order to minimize solids handling costs. The effect of VERTAD™ pretreatment on subsequent mesophilic anaerobic digestion was tested using bench scale reactors in studies performed at the University of Washington by Jenny Yoo (supervised by Dr. David Stensel). The results of the dual digestion study are presented in Table 7.

Table 7 – Dual Digestion using VERTAD™ and Mesophilic Anaerobic Digestion

Comparison of Anaerobic Control with Combined System Performance

	11 day SRT Anaerobic Control	15 day Anaerobic with VERTAD™	11 day Anaerobic with VERTAD™
Solids Retention Time (days)			
VERTAD™	0	4	4
Anaerobic	11	15	11
Total	11	19	15
Volatile Solids Reduction (%)			
VERTAD™	0	40	40
Anaerobic	52	49	45
Total	52	70	67
Anaerobic Gas Production			
Liters Methane / day	2.8	2.0	2.5
Liters Methane / gram COD removed	0.51	0.39	0.36

The results indicate that following VERTAD™ with mesophilic anaerobic digestion provides additional reduction of volatile solids with the production of significant gas volume. Anaerobic digestion of the VERTAD™ product resulted in 67% total volatile destruction with a 4-day SRT in VERTAD™ and an 11-day mesophilic anaerobic SRT, and 70% total volatile destruction with a 4-day SRT in VERTAD™ and a 15-day mesophilic anaerobic SRT. Comparatively, a control anaerobic digester obtained 52% VS destruction with an 11-day SRT. While the control digester showed greater VS reduction in the anaerobic stage than the VERTAD™ fed anaerobic digesters (presumably due to the lower VS content in the feed from VERTAD™), the total reduction efficiencies of the dual digestion systems were much higher than that of the anaerobic control.

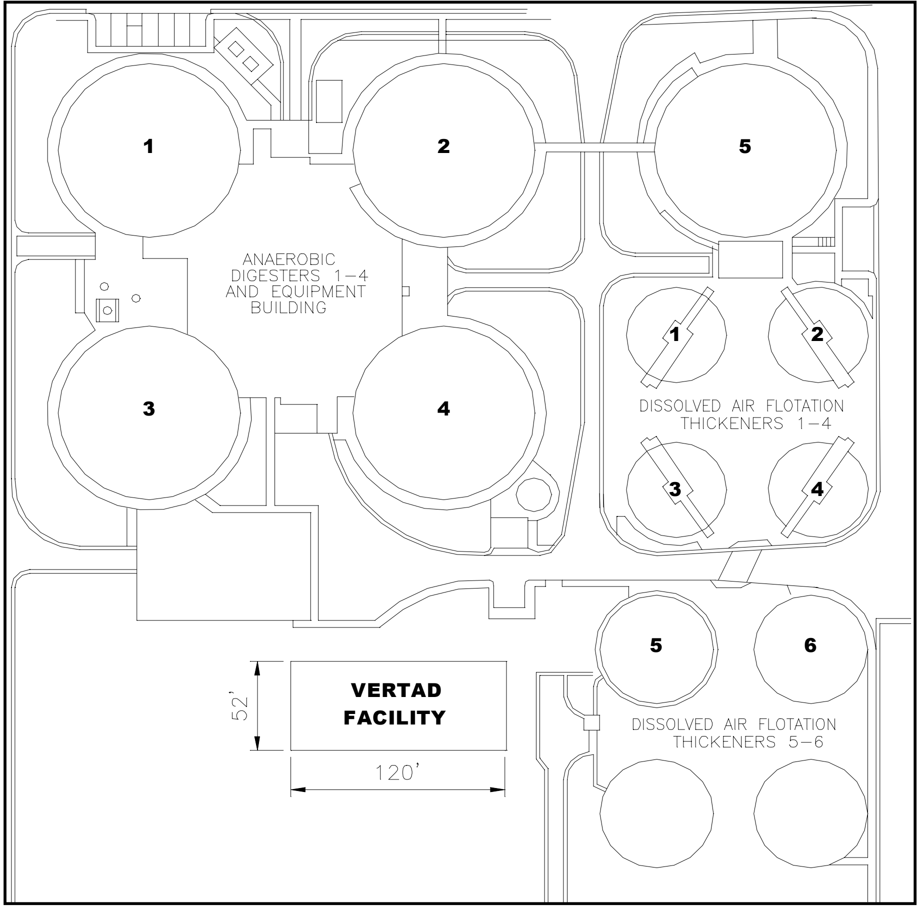
The technologies appear to have a synergy from a performance and operability perspective. For example, the VERTAD™ technology readily degrades fats and proteins, whereas anaerobic digestion is capable of cellulose destruction. Observations during the bench scale testing were that the control digester experienced considerable foaming and had mixing problems. The dual digestion systems had no foaming problems and were readily mixed, indicating lower viscosity. This may be attributed to the efficient Org-N and FOG destruction in the VERTAD™ process.

The ability to float thicken the VERTAD™ product presents itself as another benefit for the combined system. Thickened product could be fed to anaerobic digestion, allowing operation at higher solids concentrations. The lower volumetric flow associated with the thicker feed would allow for either reduced digester volume requirement or increased solids retention time. Biosolids with higher total solids concentration would decrease the volumetric flow to dewatering equipment and would likely improve dewatering performance. Several high solids concentration processes are currently being advocated including the Anoxic Gas Flotation Process (Burke *et al*., 1998). Qualitative indications from the limited dewatering testing of the combined product were that it dewatered to high cake solids (estimated at 24% cake solids) at very low polymer doses (5-6 lbs/ton).

Incorporation of a post-VERTAD™ mesophilic anaerobic digestion step shows considerable promise. The technologies appear to be complementary in many respects from a solids destruction and operability standpoint. This synergy of technologies results in enhanced VS destruction, capable of up to 70%, making VERTAD™ an attractive retrofit option for existing anaerobic systems. The minimal footprint requirement for the VERTAD™ process make it an ideal retrofit for facilities that require additional capacity, or current Class B biosolids generators that wish to produce Class A Biosolids. Figure 8 is a schematic showing the South Treatment

Plant with a VERTAD™ retrofit that could either pre-treat the entire sludge stream to Class A time-temperature criteria (similar to Concept 2 from Figure 9) or treat 25 dry tons/day to Class A Biosolids in a stand alone VERTAD™ facility (similar to Concept 3 from Figure 9).

Figure 8 – Example of VERTAD™ Retrofit at the King County South Treatment Plant



Anaerobic Digesters are each 7853 ft^2 and include:

- Capacity = 25 dry ton/day
- 1 Anaerobic Digester
- Thickening, Dewatering, Off-gas Handling & Sludge Storage are **NOT** included
- Class B Biosolids Product

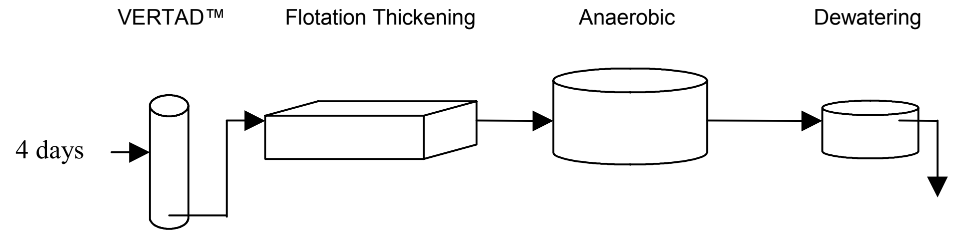
Proposed VERTAD™ Facility is 6240 ft^2 and includes:

- Capacity = 25 dry ton/day (@ 4-day HRT)
- 2 VERTAD™ Digesters
- 2 Head Tanks
- 2 Off-gas Biofilters
- 6 Heat Exchangers
- 2 Flotation Tanks
- 1 Sludge Storage Tank
- 2 Centrifuges
- Class A Biosolids Product

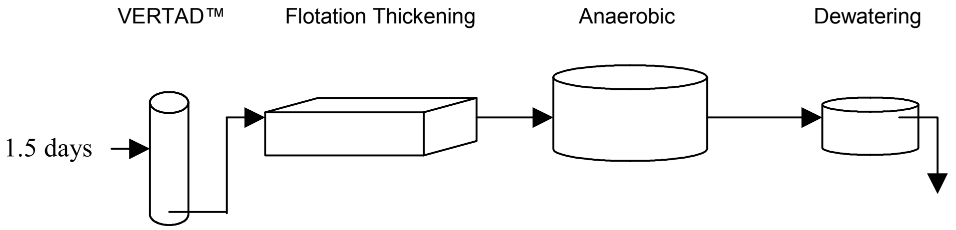
3.12 Full-Scale Design and Economics

The results of the demonstration project provided the basis for full-scale design parameters and cost estimates for the VERTAD™ process. Planning level designs were developed for three alternatives for solids treatment facilities at a planned future 36 MGD treatment plant in King County. The alternative flowsheets presented in Figure 9 were developed in detail for the County.

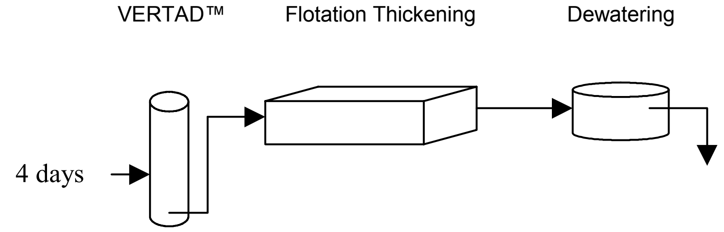
Figure 9 – VERTAD™ Process Flow Diagrams



Concept 1: Class A VERTAD™ Digestion Followed by Anaerobic Digestion



Concept 2: Time-Temperature VERTAD™ Followed by Anaerobic Digestion



Concept 3: Class A VERTAD™ Stand Alone Digestion Process

The present worth of capital costs for a system with VERTAD™ pre-treatment prior to anaerobic digestion was similar to that of mesophilic anaerobic digestion alone. The present worth of operating costs was significantly less than conventional anaerobic, primarily due to savings in dewatering and haul cost in the VERTAD™ system.

Additional benefits not accounted for in the capital and operating cost analysis are expected to further improve the comparison, making VERTAD™ a favourable choice for King County. These additional benefits include, but are not limited to:

- The value of Class A Biosolids (the potentially increased market for beneficial reuse);
- Low grade heat recovered from the process can be utilized for space heating;
- Decreased land requirements for the VERTAD™ process;
- VERTAD™ product synergy with a subsequent anaerobic digestion step (improved mixing, less scum, higher solids concentration, decreased size of dewatering facility, improved dewatering);
- Reduction in the NIMBY effect due to minimal odor release, and an aesthetically pleasing (out-of-sight) facility design.

3.13 Capital Costs

Except for very small flow facilities, the capital cost of a VERTAD™ system is lower than that in conventional plants of similar size. Decreased land requirements, considerably less surface tankage (less concrete), less dewatering equipment and fewer pumps are some of the key elements decreasing the capital cost.

Several factors support the reduced capital costs and land requirements of VERTAD™ systems. These factors amount to VERTAD™ requiring 10-20% of the total land required for conventional anaerobic plants of equivalent capacity – reducing visual and environmental impact. Some of these factors include:

- 80% of the bioreactor volume is below grade – eliminating surface tankage.
- Due to the high oxygen transfer efficiency in a VERTAD™ system, the residence time required in the bioreactor is decreased relative to conventional technologies – making the required reactor volume smaller.
- The solids are easily float-thickened to 8-12% TS out of the VERTAD™ bioreactor. Float thickening in this manner significantly reduces the size of the downstream dewatering facility.

3.14 Operating Costs

The most significant savings realized in the VERTAD™ process relate to the aeration system. The basis of the VERTAD™ process is that the oxygen transfer efficiency is significantly higher than that in a conventional aerobic digestion system due to the pressure at the depth where air is introduced to the bioreactor. In a recent comparison study of the energy requirements between VERTAD™ and ATAD processes, it was found that VERTAD™ out-performed a conventional ATAD process, operating with 31 to 45% less energy per pound of VS destroyed in the system. It was also found that the VERTAD™ process obtained a doubling in oxygen transfer over the conventional ATAD system with 50% OTE compared to 24% OTE, respectively. These results are summarized in Table 8.

Table 8 – Comparison of VERTAD™ and Conventional ATAD Processes

Parameter	ATAD (Design)[1]	ATAD (Case Study)[2]	VERTAD™ (Design)[3]
Power Usage (kW·hr/ton TS fed)	442	520 – 641	315
Power Usage (kW·hr/kg VS destroyed)	1.52	1.85 – 2.32	1.27
Aeration (m^3/hr/m^3 active reactor volume)	4	Not Measured	1.7
Time for VS Destruction of 40-42% (days)	5 - 8	12 - 15	3.5 - 5
Average System OTE (%)	Not Reported	24%	50%

1 EPA Technology Transfer #EPA/625/10-90/007 – “Autothermal Thermophilic Aerobic Digestion of Municipal Wastewater Sludge”

2 Measurements at a full-scale, 4 ton TS/day ATAD facility.

3 VERTAD™ design numbers based on the King County findings.

A VERTAD™ reactor operating at 4% solids can attain an oxygen transfer efficiency of approximately 50%. The resulting aeration power requirement is less than 1.3 kW·h/kg (1,200 kW·h/ton) of volatile solids destroyed or 0.35 kW·h/kg (315 kW·h/ton) of total solids treated. No additional mixing energy is needed; therefore, the power requirement is much lower than the combined aeration and mixing power consumed by conventional aerobic processes.

This air that is economically, and efficiently introduced to the bioreactor aids in several other process functions at no incremental cost. Not only does the air satisfy the primary requirement of providing the microbes with dissolved oxygen, it serves as an air lift pump – eliminating the need for mixers in the bioreactor. The air indirectly provides the dissolved gasses necessary for solids flotation in the flotation cell that follows the bioreactor – decreasing the size of the downstream dewatering equipment.

Savings on operating costs have also been realized in the VERTAD™ system due to decreased chemical requirements. The VERTAD™ biosolids dewater to high cake solids with a very low polymer demand. VERTAD™ product can be dewatered to 30% to 35% solids using a conventional centrifuge, with less than 20 lb/ton polymer addition. The exceptionally low polymer consumption reduces operating costs considerably.

The ability to effectively dewater biosolids is extremely important due to the high costs associated with haul and application or landfilling. The high solids content of the dewatered product reduces trucking and disposal costs reducing operating costs considerably. The nutrient value of the Class A Biosolids product makes it favourable in any beneficial reuse program.

4. CONCLUSIONS

The following conclusions were made based on the results of this demonstration project:

1. The VERTAD™ reactor readily circulates thickened solids (4-6% TS); The upper zones are well mixed while the lower zone is hydraulically separate, providing strict adherence to the Class A pathogen requirements of EPA 40 CFR 503.

2. The vector attraction reduction and pathogen destruction requirements for Class A Biosolids were achieved with a 4 day solids retention time (EPA 40 CFR 503, Alternative 1).

3. Oxygen transfer efficiency was greater than 50% when the reactor total solids concentration was at or below 4.5%.

4. VERTAD™ product easily float thickened to 8-12% TS by pH-shift CO_2 release; thickened product dewaters to greater than 30% cake solids with low polymer demand (14 lbs/ton).

5. Organic nitrogen and fats, oils and greases were preferentially degraded over organic solids comprised primarily of cellulose.

6. Mesophilic anaerobic digestion of VERTAD™ product provided overall volatile solids destruction of 67% and gas production of 0.36 L CH_4/g COD removed with a combined solids retention time of 15 days (4 day SRT in VERTAD™ followed by an 11 day SRT in anaerobic digestion).

7. VERTAD™ has low operating cost due to low energy requirements (1.27 kW•hr/kg VS destroyed), low polymer requirements (14 lbs/ton), and low trucking/disposal costs (> 30% TS cake).

8. A cost evaluation of full-scale implementation at King County treatment facilities indicated that a combined system of VERTAD™ and mesophilic anaerobic digestion has a similar present worth of capital and operating costs compared to traditional anaerobic digestion.

9. The VERTAD™ process has a minimal footprint requirement making it an ideal retrofit for facilities that require additional capacity, or current Class B biosolids generators that wish to produce Class A Biosolids.

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