Continuous Multi-Stage Autothermal Aerobic Digestion Process

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ABSTRACT**:** The ATAD process has been used within the wastewater treatment community for a number of years. Over this period of time a significant amount of data and operating experience has been collected and a variety of ATAD process and system configurations have evolved. This paper presents a review of the ATAD evolution and presents the next generation of ATAD technology in the context of this historical record, along with the more recent availability of new design and implementation tools. This combination of experience and technology can provide a new efficient system to meet the current Class A Biosolids requirements.

KEYWORDS: ATAD, Class A Biosolids, Pasteurization, Counter Current Gas and Liquid Flow

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INTRODUCTION

This paper presents a novel approach for designing auto-thermal aerobic digestion systems (ATAD) to meet the current requirements for Class A biosolids. The ATAD process has been in commercial practice for many years and over that period of time it has been incorporated into a number of different configurations. This paper provides a brief historical perspective on the evolution of the ATAD process and outlines how the specific development of a number of process characteristics encouraged the development of the current continuous, multi-stage process. As part of this evolution the emergence of several key design parameters is highlighted. The benefits of over thirty years of collective industry ATAD experience are incorporated into the current process

The core of the paper presents a novel approach for designing a new generation of ATAD systems. This approach is based on an integrated model which incorporates the key ATAD design issues:

- ☐ Biological System Parameters
- ☐ Heat & Mass Balances
- ☐ Aeration & Mixing Requirements

The integration of these items enables the design of multi-stage systems, using a variety of liquid and gas flow patterns. This approach optimizes the ATAD process performance, while minimizes energy consumption. A number of design examples are developed using the integrated, mutli-stage approach.

The conclusions from this work indicate that the current generation of the ATAD process can be a very effective sludge stabilization process. The development of the current approach has benefited greatly from the experience of a number of ATAD systems over the course of many years, along with the use of a variety of new modeling tools.

HISTORICAL PERSPECTIVE

The general aerobic digestion process has long been known as an effective sludge stabilization system. The fundamental nature of bio-oxidation of sewage sludges was established some time ago(1). followed by the development of specific digestion processes(2,3) .However, the ATAD (autothermal, thermophilic, aerobic digestion) version of the process is an approach which has developed only over the last thirty years. Further, after initial interest and the installation of a number of commercial systems in the 1970's and 1980's, the process was not broadly commercially acknowledged again until fairly recently. This renewed interest has been driven largely by the desire to produce Class A biosolids, for which the ATAD process offers several unique characteristics. Most notable of these attributes is the thermophilic temperature.

In one form or another a variety of organizations have been instrumental in the development and commercialization of ATAD technology over the past thirty years. Although this list is not intended to be exhaustive, some of some of the key players include the following:

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- Union Carbide
- Fuchs
- Kruger-Fuchs
- US Filter
- Air Products
- Dayton Knight
- CBI Walker
- Thermal Process Systems

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Figure 1 UNOX system at Speedway, Indiana

Some of the earliest work on autothermal systems was done by the Environmental Systems Group at Union Carbide during the 1970's. At the time this organization was actively marketing the *Unox* high purity oxygen activated sludge process for wastewater treatment. This process used oxygen as the aeration gas within covered, multi-stage reactors. Based on the success of the Unox process, a high purity oxygen aerobic digestion process was developed using a similar covered, staged configuration. To support this new process, a variety of development projects were undertaken, including a full scale demonstration project at Speedway, Indiana.

During the initial phase of the Speedway (Figure 1) Unox operation a spare reactor was available during a portion of 1972 and a full scale demonstration was conducted in this reactor. This reactor consisted of 4 stages each 22' X 22' X 16' SWD (57,932 gallons). High purity oxygen was fed to the digester reactor and the stages were aerated and mixed with PBT surface aerators. There were two demonstration phases in the first flow averaged 14,250 gallons per day with a content of 2.14% TSS and 1.64 % VSS. During the second phase the flow averaged 20,700 gallons per day with a content of 3.06 % TSS and 2.02 % VSS. The digester retention time during these trials averaged about 11.6 days, with a digester temperature of about 34 ^{O}C. Over these conditions the volatile solids destruction arranged from 41 to 53%. (4).

The Speedway demonstration was quite useful in that it demonstrated that auto-thermal operation was achievable. This program also identified the important process design correlations. As one example, it became apparent that the generally accepted heat of destruction of 9,000 BTU / pound VSS_R, proposed by Kambu and Andrews was somewhat optimistic.

Through the early Speedway work a number of key ATAD variables were characterized, including the following:

- Oxygen Consumption 1.29-1.87 pounds oxygen/pound VSS_R
- Heat Evolved (calculated) ~ 6000 BTU / pound VSS_R
- $K_d = 0.12/d\ (1.023)^{(T-20)}$
- K_d is the reaction rate coefficient, day^{-1}, at temperature T, ^{O}C

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- $BVSS_{@\,t=t} / BVSS_{@\,t=0} = [\,1 / 1 + K_d\,(\,RT_Q)]^N$

BVSS is Biodegradable Volatile Suspended Solids
K_d is the reaction rate coefficient
RT_Q is the retention time based on Q
N is the number of stages in series

Following the development work at Speedway and other locations, fifteen high purity ATAD systems were designed and installed in conjunction with Unox wastewater treatment systems. These installation could be categorized as 1st generation ATAD systems. In all of these applications, oxygen was available on-site for the Unox process. Also, the covered, staged ATAD digesters could be conveniently integrated with the Unox reactors. Typically, in these applications the primary sludge and waste activated biosolids were thickened to at around 3% solids and then fed into a staged, (usually 2 or 3 stages), covered reactor. The sludge retention time varied from three to ten days. In this mode ATAD temperatures of 55-60 °C were usually attained and selective testing indicated that a high level of pathogen destruction was generally achieved. In these original ATAD systems the gas and liquid flowed counter-currently. Also, the vent gas from the ATAD process was subsequently fed to the Unox reactor, so any potential odor issues were largely mitigated.

An approach that can be categorized as 2nd Generation ATAD Technology was promoted by Fuchs in Europe and then later Kruger-Fuchs in North America . With this ATAD system, air would be used as the aeration gas. This method required a different approach for achieving auto-thermal operation within the ATAD reactors. Emphasis was placed on aeration efficiency, insulation, and heat recovery (10), (11), (12), (13), (14), and (15).
During this period of time, the EPA published a *Technology Transfer* document in 1990(16), which indicated that a significant number of ATAD units were operating in Europe and producing a pasteurized biosolids product. In these systems the biosolids feed ranged from 2113 to 31,704 gallons per day. Fuchs subsequently teamed with I. Kruger to market this ATAD technology in North America.
The ATAD system used by Kruger-Fuchs was a two stage unit. Heat was retained within the ATAD reactor by using an aerator which minimized air flow through the system and thereby reduced heating losses associated with vent gas. An improved insulation approach was also implemented, including the use of a "foam layer". Approximately fifteen Kruger-Fuchs systems of this general type were installed. However, one of the critical issues identified with this type of ATAD installation was the need for appropriate vent gas handling and additional equipment was ultimately required to address this issue (17).

A contemporaneous ATAD system to the Kruger-Fuchs process was marketed by US Filter as the Jet Tech ATAD. This process also used a two stage ATAD reactor. Jet aerators were used, presumably to minimize airflow and retain the heat of biological decomposition. A small number of these systems were installed. These installations were subsequently adapted with vent gas odor control. (18).

A more recent version of the ATAD process has been commercialized by Thermal Process Systems, which has incorporated a number of "learnings" from the historical ATAD record. These systems generally appear to operate well (20), (21). They incorporate biofilters for odor control. This process also uses the insulation principles originally developed by Fuchs, which involve the use of a controlled foam layer and good wall insulation. The Thermal Process Systems' approach also addresses the issue of variable oxygen demand

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and dissolved oxygen level from batch feeding This approach was originally cited in early Union Carbide ATAD work including where dissolved oxygen and oxygen demand are specifically addressed and a specific patent for Dual Digestion where a method for controlling oxygen transfer based on temperature was defined (19). The TPS process is a single stage system which may not result in an optimum design, particularly for larger installations. However, there are a number of current installations which certainly confirms the expanding overall interest in ATAD technology.

Several key "learnings" can be derived from the evolution of the ATAD process over the last thirty years. These "learnings' form the basis for improvements in the ATAD process that have increased its efficiency and will continue to broaden its attractiveness as a truly state-of-the-art biosolids production process. Some of these specific "learnings' include the following items:

- ☐ Confirmation of decay rates, oxygen consumption and related heat production
- ☐ Sustainable thermophillic temperature levels
- ☐ Ability to destroy a variety of pathogenic organisms
- ☐ Beneficial affect of staging
- ☐ Criticality of feed sludge concentration
- ☐ Vent Gas Handling

BIOLOGICAL SYSTEM PARAMETERS

A number of important biological system parameters were identified and developed over the thirty year evolution of the ATAD process. These parameters have been continuously refined as additional laboratory information and full scale operating data becomes available. The key biological system parameters form the underlying basis for the ATAD process and reflect its ability to address the current sludge stabilization standards. The nature of the relationships for each of the key parameters, along with their absolute values in a specific case, are critical to the design and subsequent operation of an ATAD system. The values of these biological system parameters also have a very significant affect on subsequent equipment selection. Four of the more important biological system parameters are described below:

Volatile Solids Destruction (Decay Coefficient K_d)

From the historical record a variety of data were available to provide a meaningful value for the decay coefficient within the thermophilic range. Data originally obtained during the Speedway demonstration indicated a relationship of $K_d = 0.12\ (1.23^{(T\text{-}20)}\ )$ Subsequent laboratory scale data from a variety of sources, indicated that this relationship was reasonable, although there is some variability in the literature data.

Heat Generation

Internal heat generation is obviously critical in the design and operation of an autothermal system, because it is the only source of heat available to produce the required thermophilic temperatures. The value of the heat produced by the volatile solids destruction has been evaluated from a variety of demonstration scale and bench scale studies. It has been found

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that the value of this parameter is inversely proportional to the overall amount of VSS which is destroyed. Based on these findings it has been postulated that the thermophilic bacteria oxidize the energy- rich compounds first and that the amount of heat available is dependent on the compounds making up the food substrate. The average unit heat production can vary from approximately 20,000 BTU/lb. VSS removed at 10% overall VSS reduction, to about 6,000 BTU/lb. VSS removed, at 40% overall VSS reduction. However, there is a fairly wide band associated with this correlation.

Oxygen Consumption

Historical data were obtained from a variety laboratory studies and large scale operations to validate the unit oxygen consumption per pound of volatile solids destroyed. In all cases there is a fairly broad range of values reported, with a typical range being 1.3 to 1.9 lbs. oxygen per pound of volatile solids destroyed. Because this parameter is critical to the sizing of the aeration system equipment (including dissolution and air supply), a conservative value should generally be used for design purposes.

Pathogen Destruction

Although there were no regulatory requirements associated with ATAD's back in the 70's, a variety of collaborative work was undertaken between Union Carbide and the U.S. EPA to evaluate the "pasteurization effect". As part of this work, bacterial analyses were done on digested sludge from bench scale ATAD reactors by personnel from both Union Carbide and the EPA Advanced Wastewater Treatment laboratory in Cincinnati, OH (5). This original work was some of the first evidence to indicate the time temperature relationship for the destruction of pathogens, such as Salmonella and Aeruginosa.

Temperature ^{O}C	Time to Less Than Detectable Conc., hours
45	<24
50	< 5
55	< 2

This initial pasteurization information was subsequently greatly expanded and now is reflected in the current Federal Regulations for Class A Biosolids production.

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CONTINUOUS SYSTEM ATAD CONCEPT

The continuous multi-stage ATAD process can be categorized as a 4th Generation ATAD process. This process incorporates a number of key learnings from the variety of previous ATAD systems and applies a novel component of internal heat transfer within the process. This approach “recycles” the sensible heat of the gas and the latent heat of evaporation from the water vapor, by the use of counter current gas and biosolids flow, through a muti-stage ATAD reactor. (22).

The temperature profile is a key attribute of the multi-stage process. Within the overall system profile, each stage has a unique temperature that is uniform throughout the stage in both phases and is also relatively constant over time (given a constant feed stream). Within the multi-stage approach the specific temperature profile can be adapted to the individual process requirements. Typically, the temperatures will increase stage-wise through the reactor. Alternatively, the last one or two stages may be designed to operate in the mesophilic range to mitigate potential odor affects.
Using an integrated ATAD systems model, a number of cases have been developed to show the affects of the multi-stage process on the operating conditions in the digester, and its associated Class A biosolids capability.

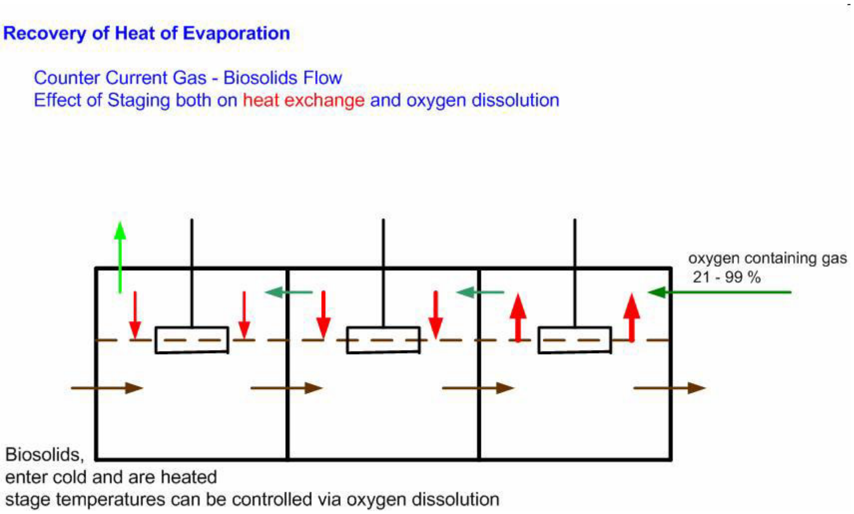

Figure 2 InNova-ATAD Heat Recovery from Counter Current Gas Biosolids Flow

It appears that the system can be configured such that it will be the first continuous flow system to meet the PFRP 503 Class A Biosolids requirements. This can be done either by a configuration with enough thermophilic stages with enough residence time to meet plug flow time temperature criteria or through a modified configuration wherein in a continuous flow multi stage train feeds a set of parallel batch reactors that hold the sludge at thermophilic temperatures long enough to meet the time temperature requirement.

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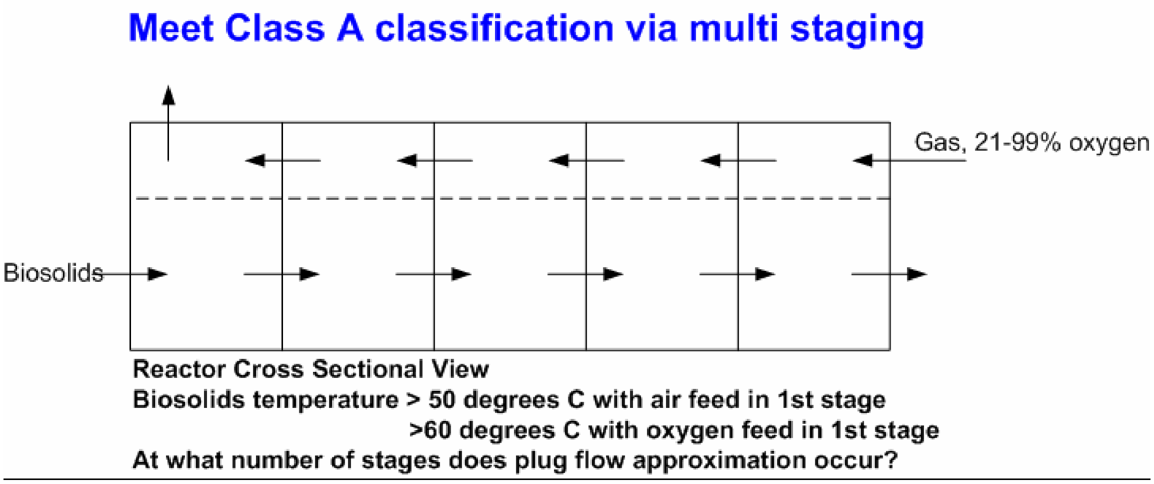
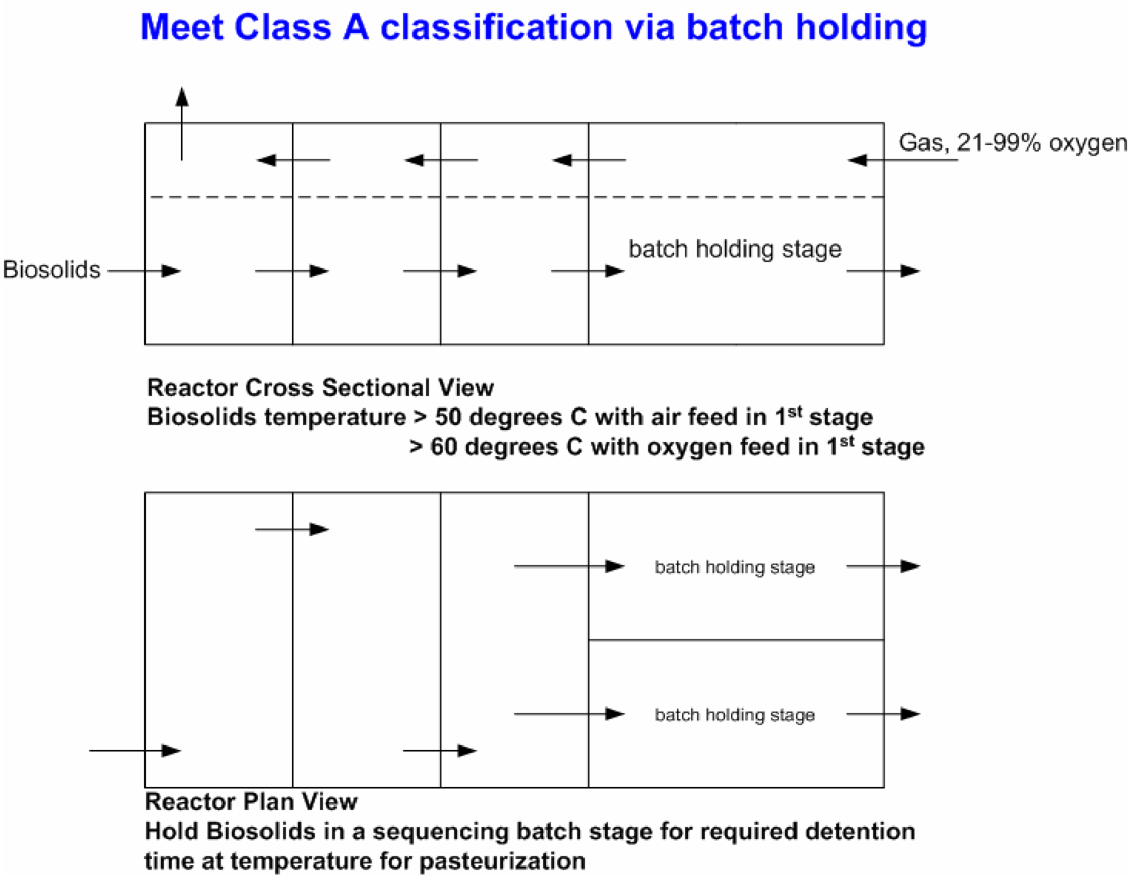


Meet Class A classification via multi staging

Reactor Cross Sectional View
Biosolids temperature > 50 degrees C with air feed in 1st stage
>60 degrees C with oxygen feed in 1st stage
At what number of stages does plug flow approximation occur?

Figure 3 InNova-ATAD configuration to meet PFRP Class A
With Multistage Counter Current Gas-Biosolids Flow



Meet Class A classification via batch holding

Reactor Cross Sectional View
Biosolids temperature > 50 degrees C with air feed in 1st stage
> 60 degrees C with oxygen feed in 1st stage

Reactor Plan View
Hold Biosolids in a sequencing batch stage for required detention time at temperature for pasteurization

Figure 4 InNova-ATAD configuration to meet PFRP Class A
withMultistage Counter Current Gas-Biosolids Flow
Sequencing Batch Pasteurizing Stages

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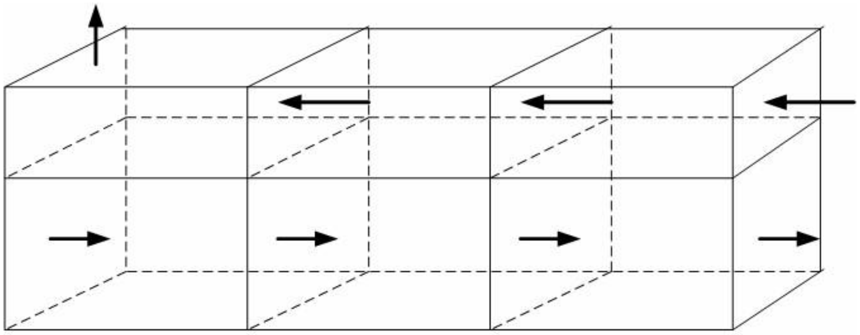


Influent

	flow, gal/day	TSS, %	VSS/TSS	BVSS/VSS	Temperature C
Primary	7600	4.4	0.73	0.70	12 and 24
Secondary	7600	5.0	0.73	0.55	12 and 24

Heat Release 7500 BTU/ pound VSS consumed @ 10 days

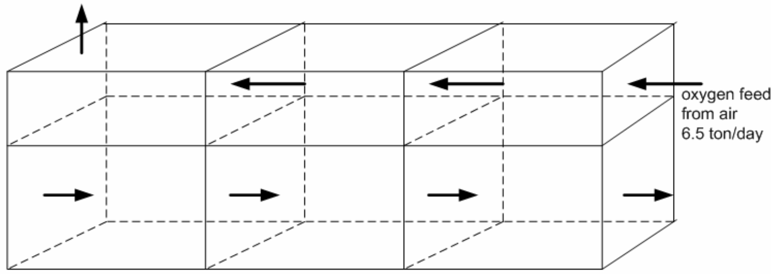
Stage size
24' x 24' x 15' @ 12' swd

Aerator-Oxygenator

SAE	3.5 lbs oxygen/ishp-hr
alpha	0.7
beta	0.92

Figure 5 The Base Cases and Data Base

Air Feed Simulation



@12C feed			
Stage Temperature C	50.8	56.2	45.5
Stage BVSS, mg/L	15,214	9848	6988
Aerator, ishp	25	20	10

@24 C feed			
Stage Temperature C	56.8	58.2	46.3
Stage BVSS, mg/L	15,219	9849	6976
Aerator, ishp	25	20	10

Figure 6- The Simulation Using Air as the Feed Gas

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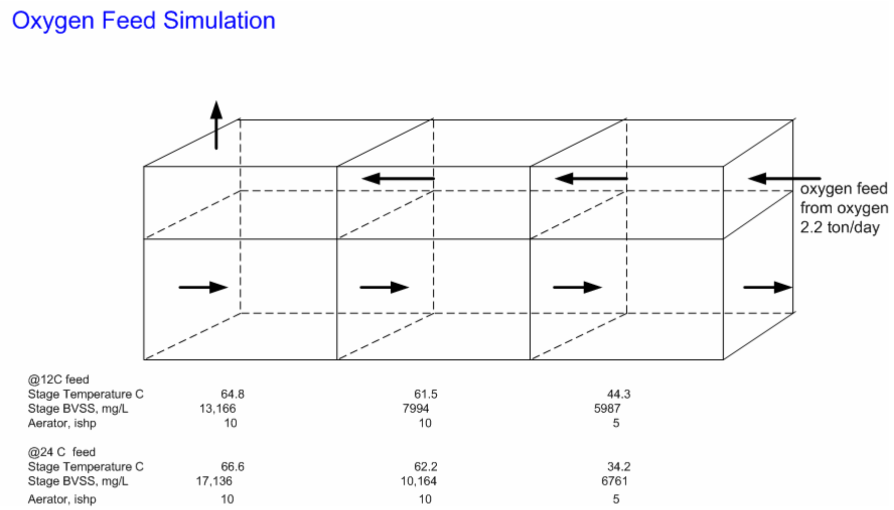

@12C feed			
Stage Temperature C	64.8	61.5	44.3
Stage BVSS, mg/L	13,166	7994	5987
Aerator, ishp	10	10	5
@24 C feed			
Stage Temperature C	66.6	62.2	34.2
Stage BVSS, mg/L	17,136	10,164	6761
Aerator, ishp	10	10	5

Figure 7 - The Simulation Using Oxygen as the Feed Gas

From these examples it can be seen that counter current gas and biosolids flows can produce auto-thermal thermophilic temperatures, even with relatively low feed solids temperatures. As expected, the use of oxygen as the feed gas provides significantly higher temperatures than with air as the feed gas. However, neither design has been completely optimized. Although, oxygen is not routinely provided at wastewater treatment plant sites, there are an increasing number of nominally sized supply systems commercially available. This situation makes the use of oxygen in the ATAD process a viable option.

The previous design cases illustrate the internal heating effects of counter- current gas and biosolids flows within multi-staged reactors. An integrated system simulation model which incorporates biochemical reactions, gas mass balances, and thermodynamics balances was used to develop these ATAD designs.

DESIGN CONSIDERATIONS

Because aerobic digestion is an inherently energy intensive process (i.e. compared to anaerobic digestion), it is absolutely imperative that mixing and aeration components reflect the highest efficiency attainable. Further, it has become apparent that effective mixing and oxygen dissolution are also critical for achieving successful process performance. The conditions reflected in the process design model (e.g. temperature & VSS destruction) will only be achieved if the entire aeration volume is aerobic and fully utilized (i.e. completely mixed). Complete mixing is also important to prevent solids deposition in the corners and bottom of the ATAD reactor. The overall issue of ATAD mixing is further complicated by the elevated viscosities associated with higher solids concentrations required to achieve thermophilic temperatures. Within an ATAD system, the oxygen dissolution issue is also complicated by the high temperatures and concomitantly low oxygen saturation values. The current requirements for ATAD technology demand new forms of analysis and new types of equipment to meet the new performance needs associated with Class A biosolids.

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To address these more demanding mixing and aeration issues, a variety of new fluid analysis tools are now available. These include the *Fluent* computational fluid dynamics (CFD) software, which has been specifically adapted to wastewater and digestion applications and has become a very powerful tool for addressing the physical requirements of current ATAD systems. The continuous multi-stage ATAD process described in the previous section employs a novel type of surface aerator as the primary mixing and oxygen dissolution device. A variety of evaluations and commercial applications have demonstrated the effectiveness and energy efficiency of this new aerator. The evaluation approach included a large number of CFD simulations using the referenced model. Using the case shown below several typical simulation results are shown in this section.

Example CFD Simulation Case

(Reactor Stage Dimensions 32.5' x 32.5' x 8.25' SWD, TSS @ 5%)

	Hi-Flo II	PBT with BM
Shaft Horse Power	10	11.7
Shaft Speed, rpm	52	70
Aerator Diameter, inches	60	54
Bottom Mixer, inches	none	50
Stage Volume, gallons	65,355	65,355
HP/1000 gallons	0.15	0.18

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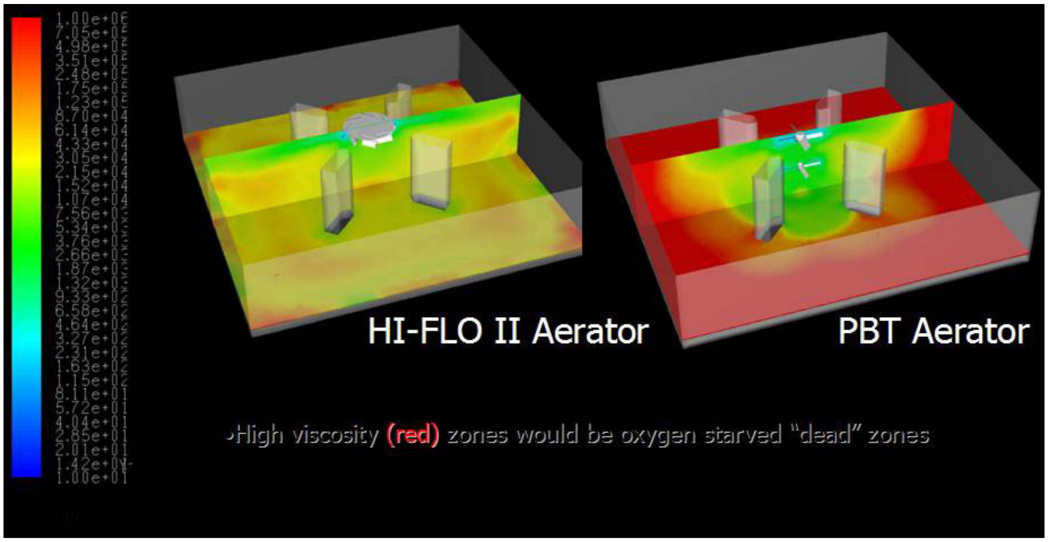
Figure 8 - Viscosity Profile using the Hi-Flo II and the PBT with bottom mixer

Viscosity is a function of shear rate in biosolids fluids. As shown in this simulation the high shear rate of the Hi-Flo II device is lowering the viscosity through out the reactor while the PBT is doing so only in a small pocket of biosolids.



•High viscosity (red) zones would be oxygen starved "dead" zones

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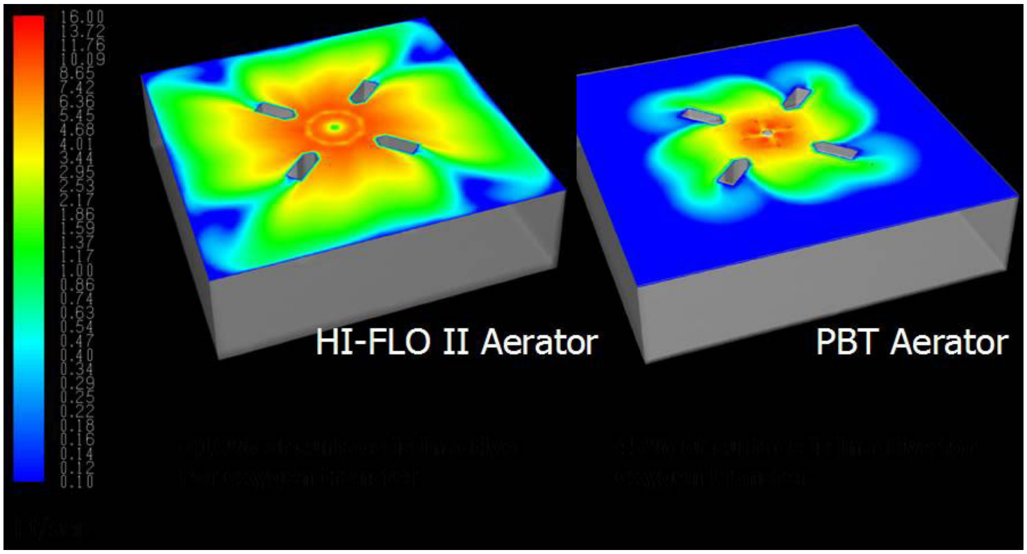

Figure 9 - Surface Velocity Using the Hi-Flo II and the PBT with BM

Surface velocity is indicative of surface turbulence and oxygen transfer. The Hi-Flo II has twice the surface area active for aeration and re-aeration as compared to a conventional system.

COMPARISON OF VELOCITY IN THE STAGE VOLUME:

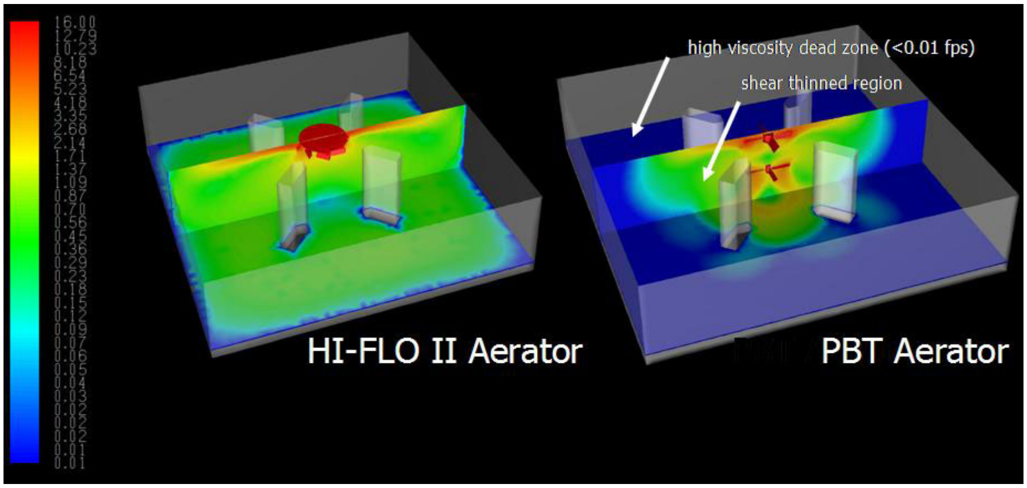

Figure 10 - Volumetric Velocities Using the Hi-Flo II and the PBT with BM

In this simulation it can be seen the basin velocities are substantially higher with the Hi-Flo II device, which is moving the contents of the whole basin, while the conventional mixer is “digging out” only a pocket. This phenomenon clearly has significant implications for both mixing and bulk oxygen transfer.

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CONCLUSIONS

1. Staging in ATAD systems improves treatment effectiveness and energy efficiency.

2. The high viscosity and high temperature conditions associated with the ATAD process require a rigorous analysis of the oxygen transfer and mixing requirements

3. The principle cause of operational failure of the ATAD process, in most instances, is not the ability to attain thermophilic temperatures but the disregard for odors generated by the process. Odors emanating from the ATAD process can be controlled to a level that is not objectionable to the public. This has been accomplished at several locations where odors were a problem.

4. The important design criteria: the time temperature relationship for pasteurization, the value of K_d over the temperature range, the heat production per mass of BVSS converted, and the oxygen consumption per mass of BVSS converted have been established and can be effectively used within an integrated design approach

5. The important biosolids characteristics, especially viscosity, that influence oxygen transfer are known and can be applied in a oxygen dissolution design to obtain auto thermal heating, significant BVSS conversion, and significant pathogen pasteurization in ATAD operation.

6. A new multi-stage ATAD process has been developed that can provide ATAD operation at significant cost savings when compared to previous ATAD processes. This process can be configured to produce PFRP 503 class A biosolids in either continuous or semi-continuous flow operation

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