2nd Generation Autothermal Thermophilic Aerobic Digestion: Conceptual Issues and Process Advancements

by

Kevin L. Staton* and **James E. Alleman***
Richard L. Pressley** and **Jim Eloff****

***School of Civil Engineering**, **Purdue University**, West Lafayette, Indiana 47907-1284
Phone: *765-494-7705*; FAX: *765-494-0395*
Email: *staton@purdue.edu*, *alleman@ecn.purdue.edu*
Web: *http://ce.ecn.purdue.edu/~alleman*

****Thermal Process Systems**, 779 Courtney Drive, Crown Point, Indiana 46307-4365
Phone: *219-663-1034*; FAX: *219-663-7248*
Email: *rpressley2@compuserve.com*
Web: *www.thermalprocess.com*

BACKGROUND

Kambhu and Andrews (1969) conducted the first research effort focusing on 'autothermal thermophilic aerobic digestion' (ATAD) technology in the late 1960's. Using a computer simulation, these researchers theoretically demonstrated that autothermal operation was possible with systems supplied both with high-efficiency aerators and influent TSS levels ranging between 4 and 6% solids.

In the following decade, this 'autothermal' concept was then pragmatically validated at a number of full-scale plants using both high-purity oxygen aeration and self-aspirating aeration (Jewell and Kabrick, 1980 and U.S. EPA, 1990). Today, a considerable number of these ATADs have been constructed in Europe, particularly in Germany due to their enforced restrictions on pathogen destruction. Furthermore, given the rising level of interest in these ATAD systems, the U.S. Environmental Protection Agency developed a detailed report on the involved technology (1990).

However, in spite of their apparent technical benefits, relatively few of these systems have been built to-date in the United States. As of 1990, there were no such units whatsoever, and over the past decade only ~30 ATAD units have been placed in operation. Furthermore, several of these latter plants have exhibited rather erratic performance levels. Solids destruction levels have fluctuated significantly, and in many instances the 'aerobic' nature of these systems has frankly been dubious. In fact, a number of these units have exhibited not only troublesome, anaerobic off-gas odor problems (e.g., elevated mercaptan levels, hydrogen sulfide, etc.) but also poor, sub-design loading capacities.

This paper, therefore, will provide a technical assessment of the upcoming, 2nd generation improvements being developed for, and implemented with, these ATAD systems such that the latter shortcomings can be obviated. In addition, the key conceptual issues with ATAD operations will be addressed, covering both design and operational details.

KEY CONCEPTUAL DETAILS

1st *versus* 2nd Generation ATAD Process Overview

Although there appears to be no consistent design approach used by the majority of ATAD system designers (i.e., including Fuchs, Krüger, UTB, Lotepro, CBI-Walker, etc.), the majority of what could aptly be described as '1st generation' systems bear a number of fairly common attributes, as follows:

1) Most 1st generation ATAD units are built with multiple tanks (i.e., 2 or more units) designed to operate in a serial flow pattern,
2) Most 1st generation ATAD units are designed to provide a fairly low cumulative HRT, commonly below 10 days and often less than one week *(NOTE: due to the typical semi-batch-type operating scheme used in ATAD reactors, HRT is equal to SRT).*
3) Most 1st generation ATAD units are equipped with mechanical aerators, and in many instances these aeration systems are top-mounted; in turn, these aerators often have to be shut down during loading and wastage events due to the drop in liquid levels, and
4) Most 1st generation ATAD units have constant speed aeration systems, such that their oxygen transfer capacity has no inherent variability.

As compared to these traits, however, there are a number of new design features associated with the upcoming '2nd generation' ATAD design, including:

1) 2nd generation ATAD units tend to provide less complex reactor schemes, including single-tank designs,
2) 2nd generation ATAD units tend to provide higher HRT levels, commonly higher than that of the 1st generation designs (i.e., greater than 10 to 12 days).
3) 2nd generation ATAD units tend to provide improved high-efficiency aeration and mixing systems, including jet-type or other type units, and
4) 2nd generation ATAD units tend to provide control schemes for regulating aeration rates (i.e., variable pump and/or blower speeds, etc.) based either on timers, or on-line 'oxidation-reduction potential' (ORP) monitoring.

THERMOPHILIC DIGESTION TEMPERATURES

The thermophilic digestion realm, as visually depicted by Figure 1, covers a temperature span from the mid-40^o to low-60^{o}C range. In some instances, even hotter temperatures have been observed within ATAD systems, extending as high as 70+^{o}C, particularly for reactors receiving high biodegradable COD loadings.

However, these types of hyper-thermophilic conditions do not appear to be suitable to the intended goal of solids digestion. As a result solids loading and aeration practices are maintained in a fashion that limits these undesired excursions.

Conversely, most 'mesophilic' aerobic digestion systems operate at a far lower temperature, few of which ever realize upper temperature extremes much beyond 30°C. As a result, the microbial character (see following discussion) of an ATAD reactor system is distinctly different from that of a traditional mesophilic digestion system.

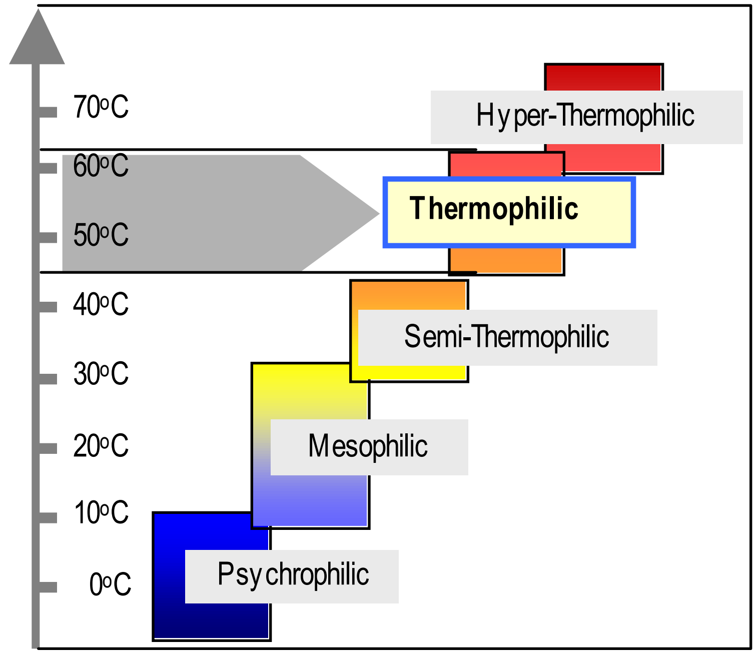

Figure 1
Thermophilic Digestion Temperatures

MICROBIAL CHARACTER

Given the elevated temperatures maintained within an ATAD system, the viable microbial biomass is composed of so-called 'thermophiles' whose physiological nature and lifestyles have, as yet, not been fully established. In all likelihood, this bacterial consortia is comparable to that which would be found within composting biomass, although it is unlikely that there would be any fungal presence. Yet another unique, and clearly beneficial, feature of ATAD systems is that their extended HRTs at elevated temperatures will effectively yield a pathogen-free product.

The 'aerobic' *versus* 'anaerobic' circumstance of this biomass, though, is still not well understood. On the one hand, the 'aerobic' premise of an ATAD operation stems from the fact that air or oxygen is routinely supplied using highly efficient gas transfer systems. Molecular analysis of these cultures, however, has revealed the viable (i.e., live) presence of both aerobic and anaerobic thermophiles, including *Clostridium* forms whose expected growth conditions would more normally be qualified as that of a strict anaerobe. On the one hand, it is not readily evident whether these types of 'anaerobic' cells are actually able to thrive within an aerated ATAD reactor, or whether they were simply present within the incoming solids and somehow maintained their viable state given this reactor environment.

Simply put, additional research will have to be conducted in the future to characterize and comprehend the microbial makeup of these systems. At the same time, this research effort must commensurately address several seemingly interrelated factors, particularly focusing on the reactor discharge streams, both liquid and gas phase.

PROCESS HRT

The new 2nd generation ATAD systems appear to be shifting towards higher HRT levels extending beyond 10 to 12 days. This in itself presents an inherent question. Is the HRT measured from the influent or effluent? Evaporation in this heated environment is often in the order of 20-30%. The longer retention times often based on influent lead to even longer HRTs as actually measured in the system regardless of flow scheme. As such, two benefits are accordingly realized with this increase. First, the commensurate reduction in volume replaced each day (e.g., $1/12^{th}$ tank volume *versus* $1/6^{th}$) leads to a beneficial reduction in the temperature swing experienced with incoming solids whose temperatures are considerably below that of the reactor (e.g., at 25-30^{o}C *versus* 55-65^{o}C). Secondly, these higher HRT levels usually result in improved levels of oxidative conversion with the protein, lipids, etc. released from digested, hydrolyzed cells. In turn, this improvement not only reduces the resultant level of effluent soluble COD, but also appears to help with reducing excessive foaming tendencies. In addition, there is limited evidence to suggest that solids dewatering performance with the ATAD product may be improved at higher HRT levels, but additional study will also be necessary to fully validate this condition.

APPLIED SOLIDS LEVELS

As is the case with all ATAD operations, the incoming solids levels must typically be kept above 6-8% TS and ~4% VS. In turn, these concentrated VS inputs provide the necessary energy-rich substrate to support the 'autothermal' mode of an ATAD operation. Given these incoming TS levels and the inherent viscosity of these solids at ambient-level temperatures (i.e., at 25-30^{o}C). Special provisions (e.g., air diaphragm, positive displacement, etc.) will typically be required to pump these cool, incoming solids streams, but the resultant ATAD discharge (i.e., with its elevated temperature and considerably lower TS level) will be far easier to pump…even using standard centrifugal units.

OPERATING D.O. AND OUR LEVELS

Most ATAD vendors and operators believe that ambient dissolved oxygen levels of approximately 0.5 mg/L are acceptable within these systems. This type of operating environment is often classified as microaerobic, i.e., oxygen demand of the biomass is greater than the oxygen supply of the aeration equipment. However, the truth of the matter is that very little data has actually been collected on this parameter. Few, if indeed any, available D.O. probes work at these elevated temperatures, and even if such a unit were to be found or developed the likely D.O. levels will be so low that accurate measurements will be rather questionable.

Yet another important factor is that within the expected thermophilic range, the maximal solubility of oxygen drops to a value of approximately 4 mg/L. These highly loaded, and highly active, thermophiles will maintain a far higher oxygen uptake rate (i.e., OUR) than is normally observed in traditional mesophilic digestion units, such that the operating D.O. level must be quite low in order to maintain the necessary transfer gradient. As a result, the actual operating D.O. of an ATAD could well be so low that its measurement becomes a moot point.

AERATION AND MIXING STRATEGIES AND RATES

Oxygen transfer and mixing within an ATAD system is affected by a variety of factors, as follows:

1) the reactor's elevated solids levels will tend to complicate both oxygen transfer and mixing,

2) as mentioned previously, the drop in maximal oxygen solubility at thermophilic temperatures will also work against O_2 transfer,
3) the ATAD system's thermophilic biomass typically expresses a considerably higher oxygen uptake rate than other aerobic systems, although these microbes are seemingly tolerant of low D.O. conditions,
4) fluid viscosity will decrease with temperature, though, which should help to improve gas transfer,
5) surface tension will also decrease with temperature, leading to a similarly helpful impact on gas transfer, and
6) diffusivity would similarly be expected to increase, thereby complementing desired oxygen transfer.

Rather unexpectedly, the net result of these factors is that gas transfer constants (i.e., k_La values) observed under mesophilic conditions do not appear to change all that much when shifting to ATAD-level systems. Furthermore, there is also a trend amongst newer 2nd generation ATAD systems to employ bottom mounted jet-type mixing and aeration systems (see Figure 2), whereby benefits are derived with higher oxygen transfer efficiencies, available control over shear intensity, and the ability to mix and aerate irrespective of tank depth. Rather obviously, though, the applied horsepower per unit volume with these jets must be increased beyond that of standard mesophilic units, primarily to insure adequate gas transfer given the elevated OUR levels. Typical design parameters correspondingly include 0.5 to 0.6 mixing HP per 1000 gallon tank volume plus 3 to 4 scfm air supply for the same (1000 gal) tank volume.

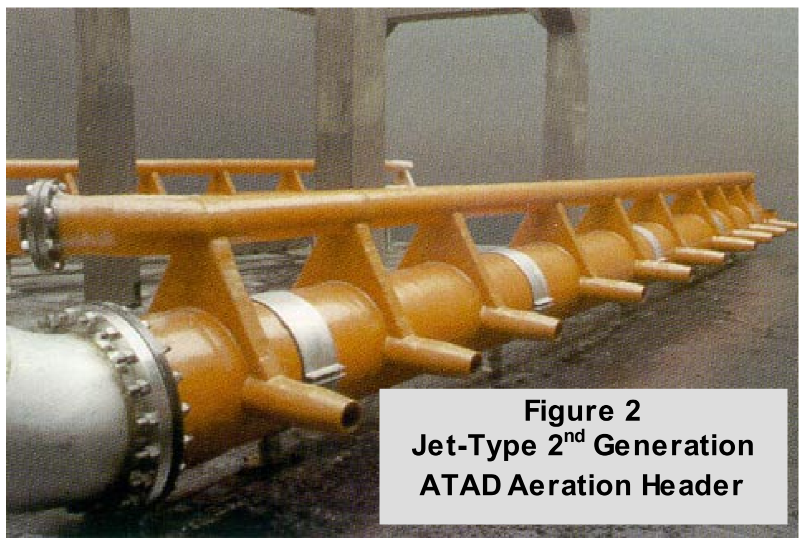

Figure 2
Jet-Type 2nd Generation
ATAD Aeration Header

Lastly, as is schematically described in the following figure (i.e., see Figure 3), these latter types of jet aerators can provide an attractive degree of flexibly to manipulate aeration and mixing intensity by way of variable frequency drive (VFD) motor control hardware. In turn, the applied level of horsepower can be trimmed back and forth (e.g., as dictated by ORP monitoring; see following discussion) in a fashion that ultimately saves energy while at the same time helping to insure the desired 'aerobic' nature of the operation.

Indeed, Figure 3 schematically depicts the problem often encountered with 1st generation ATAD systems (with their constant oxygen supply rate) where there are extended periods of deficient aeration….at which point the O_2 deficit negates the desired aerobic environment. In turn, the resultant onset of anaerobic conditions leads to undesired fermentative reactions and problems (e.g., with off-gas odors, etc.).

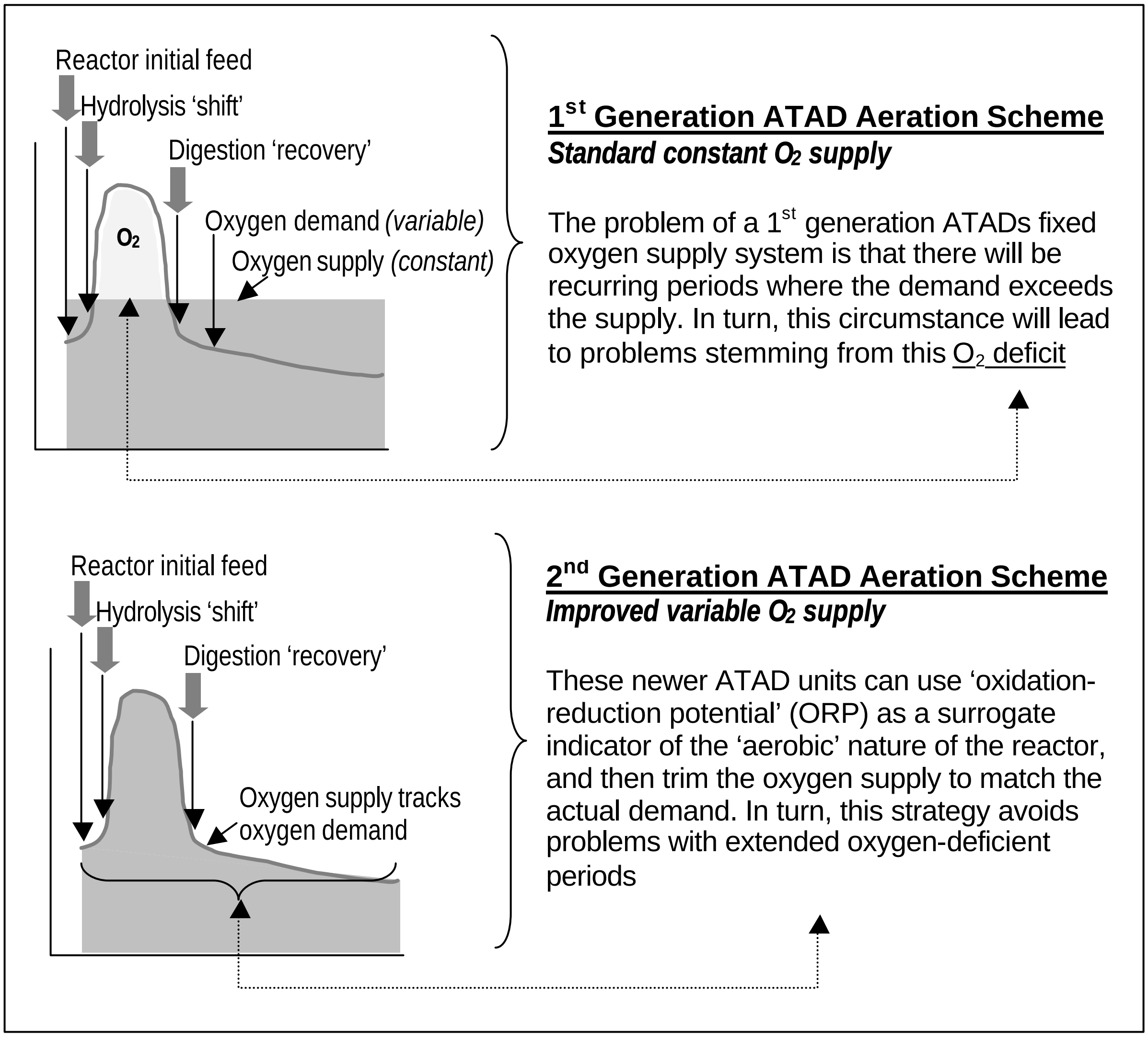

Figure 3
Thermophilic Digestion Temperatures

Conversely, as shown with the 2nd generation schematic (with a variable oxygen supply rate) given in this same figure, the ability to taper aeration in relation to respirometric demand provides for a considerably improved approach to aeration.

PROCESS ORP MONITORING

Whereas on-line monitoring of dissolved oxygen in ATAD systems has proven to be quite difficult, if not altogether impossible, there is a move underway to shift towards oxidation-reduction potential (ORP) as a surrogate indicator of the aerobic *versus* anaerobic character of these operations. As compared to the upward shift in oxygen demand schematically depicted in Figure 3, pragmatic observations of the ORP signal measured with these reactors typically exhibits an inverse, mirror-image profile.

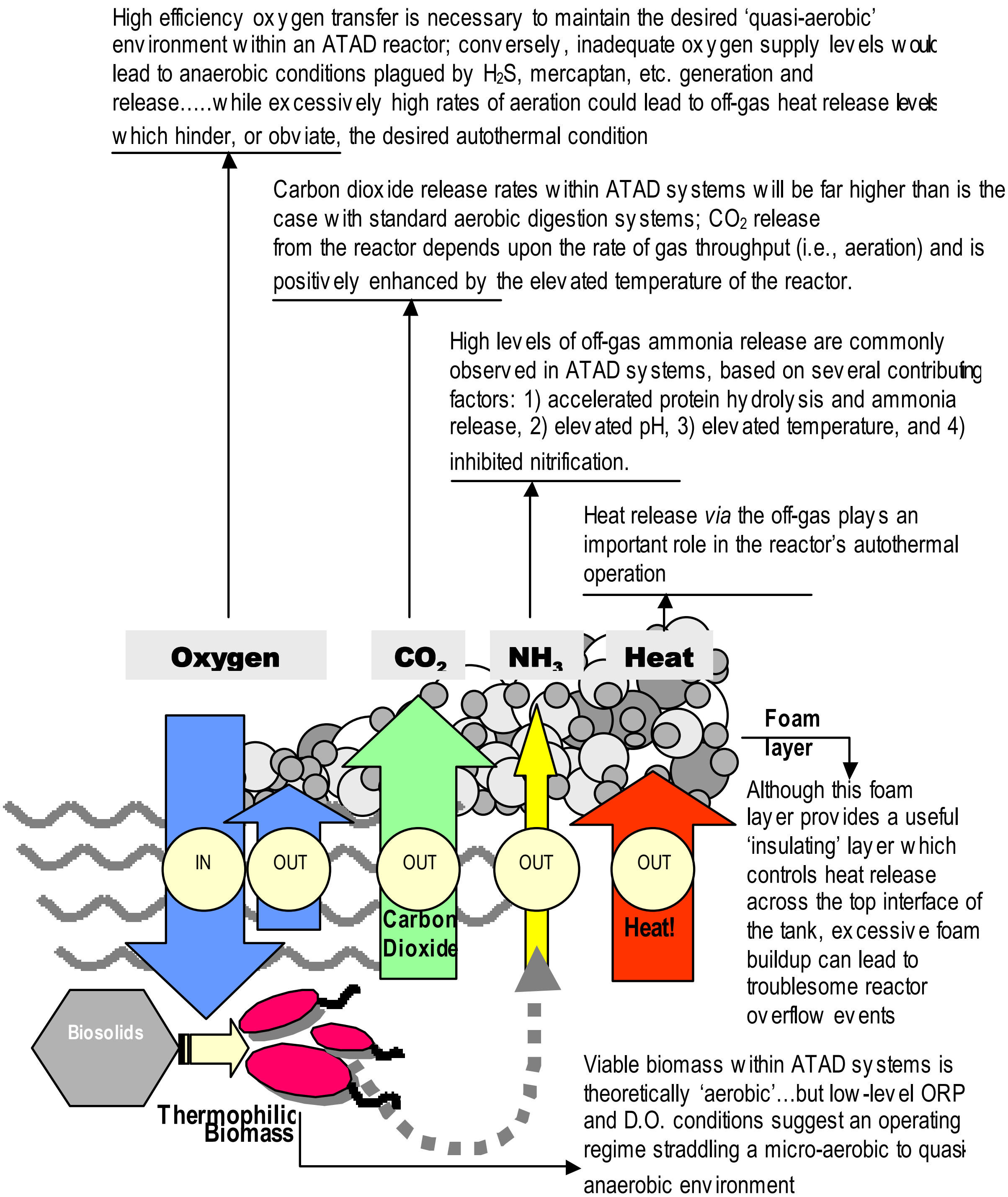

Figure 4
Biochemical and Thermodynamic Aspects of ATAD Systems

The upper end of these ORP values typically range between +50 and +150 mV during most of the cycle. There is, however, an intermediate transient 'bump' downwards to considerably lower values (e.g., -200 to –500 mV) during a period that appears to correspond to accelerated solids lyses and degradation.

PROCESS pH

The pH levels typically observed in ATAD systems tend to be slightly basic (above 8) [U.S. EPA, 1990]. In fact, in some instances pH levels between 8.5 and 9.5 have been measured in some of the newer, jet-aerated reactors. A variety of reasons have been proposed for this phenomenon, and there are circumstantial beliefs that these elevated levels are in some fashion tied to the hydrolytic release and subsequent acid-base transformation of reduced nitrogen. However, at this point, there is no clearly defined rationale for this behavior.

FREE AMMONIA (NH_3) RELEASE

With reactor pH levels commonly maintained in the basic range, free ammonia stripping from ATAD systems (i.e., such as that depicted in Figure 4) is a commonplace occurrence. The equilibrium chemistry of the NH_4^+-NH_3 couple changes with increased temperatures, at which point partitioning of reduced ammonia to the gaseous, NH_3 phase is favored. And since biological nitrification at temperatures much above 40-45°C effectively stops, this ammonia stripping phenomenon correspondingly represent the sole opportunity for its removal.

In terms of ATAD operation, high off-gas discharge ammonia concentrations combined with low reduced sulfur presence empirically identify a 'healthy' reactor condition. Conversely low discharge ammonia concentrations and high reduced sulfur levels correspondingly appear to characterize an 'unhealthy' reactor condition. Here again, ongoing research is focusing on the development of a definite correlation between these off-gas parameters.

OFF-GAS AND ODOR ISSUES

ATAD systems are commonly equipped with a reactor cover and associated off-gas processing scheme, not only to reduce heat loss across the top of the tank but also to scrub ammonia and malodorous, reduced organics and/or inorganics (e.g., mercaptans, hydrogen sulfide, etc.). In some instances, off-gas recycling back to the aeration header for an upstream activated sludge complex has been practiced as a means of simplistically cleansing this gas stream.

As mentioned previously, an ATAD process is only effective if the reactor is operating in an aerobic state with extremely low reduced sulfur compounds. If, indeed, these reduced compounds (e.g., sulfur, mercaptans, etc.) develop with the reactor, the responsible reducing condition will inherently be contrary to the desired oxidation of these same contaminants. Fortunately, even if some nominal level of these reduced contaminants are created and released via the off-gas, a downstream fixed-film aerobic biofilter process has proven to be very efficient in breaking down odors that include the complete matrix of aerobic, microaerobic and oxygen-starved systems. Indeed, these biofilters offer a controlled environment to provide sufficient time and conditions to breakdown and reduce these odorous compounds.

REACTOR FOAMING ASPECTS

Foam production within an ATAD reactor is a mixed blessing. On the one hand, excessive foaming, as had been observed at a number of 1st generation ATAD locations, creates aesthetic and operational difficulties. However, as described in Figure 4, the presence of this foam can play a beneficial role in terms of insulating the reactor's top surface.

Active measures are commonly required to control the degree of foam buildup, typically using mechanical foam cutters mounted in the reactor roof with blades set at a pre-set height on the reactor's top cover. Yet another new, 2nd generation strategy for controlling foam presence and height makes use of a so-called 'foam-cone' scheme tied into the jet aerator system. The vertical riser and top-mounted foam-cone unit subsequently allows foam to be physically aspirated in a downward fashion into the aeration header, at which the foam is destabilized during its ejection through the jet nozzles.

REPRESENTATIVE '2nd GENERATION ATAD' CASE STUDY

One of the first full-scale 2nd generation ATAD facilities was launched in Feb 1996 at a Midwest wet corn milling operation, with the intent of destroying VS and COD in order to reduce biosolid mass and volume. During the ensuing 4 years of operation, this facility has successfully averaged ~60-65% VS destruction and ~50% TS destruction. Several other advantages that were not originally understood have also been identified.

The cake solids levels generated at this facility increased by ~25% using the same belt press with a different polymer program. Before the ATAD was installed this operation's 2 meter belt press was used 24 hours per day and generated a ~12% cake. Based upon 15,000 pounds per day DS, they were loading 3 semi-trailers per day and hauling to a storage facility for land application. After starting their new ATAD operation, though, only 6 hrs per day of belt press was required per day, generating ~16% cake solids. The resultant combination of mass reduction and increased cake solids subsequently reduced the requisite number of trucks to just one per day.

The plant also has received the first permit in the state to haul their ATAD material to a compost facility. In fact, the involved compostor proved to be very willing to accept this material given both its ability to provide a thermophilic seed as well as valuable ammonia, sulfur, and moisture. Yet another important factor was that this ATAD product had no objectionable odor.

The involved composting operation blended the dewatered ATAD solids with spent horse bedding and other organic material. The beneficial, catalytic impact of these ATAD solids was readily demonstrated by a ~40% reduction in the overall composting time. The finished material may now be distributed to any location without limitations, including that of golf courses which have been repeat customers for several years. Here again, as with the original ATAD product, the compostor has not experienced any problems with their customers complaining about odors.

The plant influent has a low concentration of pathogens and was not installed as a pathogen control system. However, they are required to do pathogen testing on a periodic basis to satisfy the permit requirements. The facility has repeatedly produced very low pathogen numbers. The combination of long HRT and consistent operating temperatures assures successful pathogen kill.

The process has a considerable amount of flexibility, both in terms of operation and physical layout. The operational factors have proven the system to be very easy to operate. Today the system has the ability to accept large swings of feed material, and does so while generating a consistent product.

The retrofit potential saves capitol investment. This plant was originally an abandoned storage tank. The old equipment was removed and the new equipment installed without major modifications to the tank. A second reactor was retrofitted into an adjacent chemical spill tank in 1998 and started up in May of 1999.

The quality of the 2nd generation ATAD effluent is significantly improved as compared to 1st generation material. The O_2 uptake requirement of the finished material appears to follow a direct correlation to the VS reduction. The highly putrescible odor generating VS is destroyed in the reactor. As a result the reactor effluent after dewatering takes on an odor very similar to peat. The material has a high percentage of free nitrogen that acts as an immediate nutrient source and organic nitrogen for a slow release nutrient source.

SYNOPSIS

The following table summarizes the range of digestion results which have been observed to-date with 2nd generation ATAD systems:

Observed Real-World 2nd Generation ATAD Performance Levels	
Waste Material Source	Typical VS or COD Reduction
Municipal Extended Air	35-45%
Municipal Activated Sludge	40-50%
Municipal High VS	45-60%
Industrial Extended Air	40-50%
Industrial Activated Sludge	50-65%
Industrial High COD	55-70%

Simply put, the attractiveness of these results validates the relative improvement in performance that has been gained by the shift from 1st to 2nd generation ATAD technologies. Continued research is, however, still being conducted with this technology to secure further advancements with both the stability of these operations and their overall efficiency.

REFERENCES:

1. United States Environmental Protection Agency, *Environmental Regulations and Technology: Autothermal Thermophilic Aerobic Digestion of Municipal Wastewater Sludge*, EPA/625/10-90/007, 1990.

2. Kambhu, K., and J. F. Andrews, "Aerobic Thermophilic Process for the Biological Treatment of Wastes - Simulation Studies," *J. Water Pollut. Control Fed.*, 41: R127, 1969.

3. Matsch, L. C., and R. F. Drnevich, "Autothermal Aerobic Digestion," *J. Water Pollut. Control Fed.*, 49: 296, 1977.

4. Jewell, W. J., and R. M. Kabrick, "Autoheated Aerobic Thermophilic Digestion with Aeration," *J. Water Pollut. Control Fed.*, 52: 512, 1980.