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SPECIAL ISSUE

100th Anniversary of the Activated Sludge Process: 1914 - 2014

AMERICAN ACADEMY OF ENVIRONMENTAL ENGINEERS AND SCIENTISTS

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His contributions to industrial waste management included the development and application of activated sludge technology. In his honor, AAEES created the new category of Industrial Waste Management as part of the Excellence in Environmental Engineering and Science Competition.

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147 Old Solomons Island Road, Suite 303
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410.266.3311, FAX: 410.266.7653
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Cover Photo: Hazen and Sawyer, 2014 Excellence in Environmental Engineering and Science Competition Honor Award Winner in Design for the project, Newtown Creek Wastewater Treatment Plant Secondary Treatment Upgrade.

PRESIDENT'S PAGE

Christian Davies-Venn, PH.D., P.E., BCEE

NEW BEGINNINGS

I am honored and humbled by this privilege to serve as the president of the American Academy of Environmental Engineers and Scientists. First, I want to thank the recent past presidents of the Academy, Michael Selna and Pasquale Canzano, for their great service to and leadership of the Academy. The Academy just went through two recent transitions: last fall the Academy moved into a new office suite in Annapolis, Maryland; and in December we were pleased to welcome our new Executive Director, Burk Kalweit. I thank all those who worked tirelessly to ensure that these transitions went smoothly.

In my remarks following my inauguration as President at our fall Board of Trustees (BOT) meeting in Wilmington, Delaware, I noted that one of my main areas of focus will be to energize our membership which has remained flat or slightly retracted recently. To address this concern, the Membership Development and Outreach Committee, under the leadership of Bob Williams, has launched an aggressive membership recruitment campaign. This includes referrals of new applicants by AAEES members; letters to colleagues, professors and state representatives; calls to principals of consulting firms and ranking agency officials encouraging referrals; brochure of testimonials and member savvy advertisement promoting the value and benefits of AAEES certification; and PowerPoint presentation for use by professors to promote benefits of licensure and certification. Thanks to the efforts of Hunter Nolen and Dick Pope and inputs from the BOT, a value proposition was developed that serves as a practical tool for effectively communicating the Academy's values to our sponsors, agency leaders, members, and potential members.

We realize that the success of this membership campaign depends on the collective efforts and active involvement and participation of all AAEES members. Each of us can participate through: promoting the value of certification to eligible friends and colleagues; personal contacts and encouragement of young professionals; sponsoring, coordinating, or participating in a technical conference, webinar, workshop, or symposium; and participating in the various programs and activities offered by the Academy. Please visit the Academy's website at www.aaees.org for more details.

As part of our strategic planning efforts, we are exploring expanding our membership program and activities internationally to take advantage of the potential opportunities in this area. We have initiated a pilot program with India which we hope would be expanded to attract well-qualified environmental professionals in other countries who value certification in environmental engineering and science. This will bring greater prestige to the Academy and serve the expanding need for certified engineers and scientists in a global economy.

I plan to devote my efforts, in concert with the Board of Trustees, towards communicating the advantages of specialty certification and Academy affiliation with consulting firms, public agencies, industries and universities as we respond to the changing environmental marketplace while keeping our vision and priorities in focus.

Another area of focus that is of priority to me is enhancing diversity within the Academy. Through our Diversity Work Group, we are reaching out to various engineering and science organizations and societies to promote the benefits of AAEES board certification with the goal of broadening the diversity of our membership to include a wide range of nationalities, ethnicities, and minorities, as well as gender and age diverse groups.

The Academy continues to strengthen and expand its Student Chapters by providing assistance, mentoring, and recognizing student achievements. Thanks to the efforts of Dan Oerther and others, we have strengthened our partnership with the Association of Environmental Engineering and Science Professors (AEESP) which puts us in an excellent position to more effectively serve our student body through student development initiatives and by encouraging them to become life-long learners and guiding them through licensure and certification. The Academy continues its important role of improving environmental engineering and science education through its participation with the Accreditation Board for Engineering and Technology (ABET). The Education Committee is being re-named and re-structured to better reflect the Academy's responsibilities to ABET.

I am grateful to our dedicated staff, our volunteers who serve on various committees, and to our State Representatives who act as liaisons to our membership. I have had the opportunity to discuss these challenges and opportunities with many of you as well as other stake holders and based on these discussions, I am encouraged and optimistic about the future of our profession. I look forward, with your help and support, to a productive year as we strive to advance the mission and vision of the Academy and elevate the profile of the environmental profession. I wish to encourage and challenge those members who have not been actively involved in the Academy to consider doing so. Please feel free to let me or the staff know if you have any ideas, concerns, or wish to volunteer or contribute in any way to the success of the Academy. A

> "Through our Diversity Work Group, we are reaching out to various engineering and science organizations and societies to promote the benefits of AAEES board certification with the goal of broadening the diversity of our membership to include a wide range of nationalities, ethnicities, and minorities, as well as gender and age diverse groups."

Burk Kalweit

DO YOU KNOW WHO THESE PEOPLE ARE?

One of the things that is most interesting about organizations like the American Academy for Environmental Engineers and Scientists is that you never know what surprises are just around the corner. A couple of weeks ago, someone left me a voicemail that was very faint and somewhat scratchy and hard to hear. Given the press of other things to worry about, I figured I would just let it go. After all, if it was really important whoever it was would call back and, hopefully, I would be around to take their call. As luck would have it, the person did call back. Unfortunately, the quality of the second call was a little worse than the first one.

However, I did manage to catch a phone number at the very end and I made a return call. This, of course, ended up being just a voice mailbox to which I left a message with my name and number asking for a call back and apologizing for the length of time that had passed before I had gotten back to them. I also suggested that they send me an email with some background so I could do a double check on what the intent of the call was.

The next morning, I found a note in my inbox asking if we could arrange a phone call with the person who had called and some friends of hers. That's when it began to come together. The part of the message that I could not clearly make out before referred to the desire of the caller to set up a student chapter for the Academy at a local university. She was wondering what kind of program we had to offer and how she and her group of friends could begin to participate with us to exchanging information that would satisfy their interest in environmental engineering and science. Rather than send her the standard list of the topical areas in which the Academy offers certification, I thought I would turn the tables. I asked that the group send me a list of the things that they were interested in so that I might be able to compare it to what we cover as recognized areas of specialty within the field.

Here is the list that I got back from the student group:

- Environmental Chemistry
- Environmental Policy (EPA)
- Water Management
- Renewable/Sustainable Energy (economic policy) & Utility companies
- Public health
- Remediation
- Consulting
- Disaster Management

I was pleasantly surprised by the interesting mix of topics and areas of specialization that appeared on the list. What struck me was the range of the listed items. It goes across the spectrum from social science and policy determination all the way over to hard science and technology development.

Which got me to thinking; is this group representative of how college students in general think these days? If so, we may be beginning to see a significant change in how we practice environmental engineering and science appearing on the horizon. This was something that I wanted to probe into a bit so I was eager to arrange the phone call with the group.

And that was my next pleasant surprise. When I got on the phone with the young lady who initially called, Carrie, she spoke of her club and how she had assembled, at the suggestion of one of her faculty members, a group of fellow students who were interested in environmental engineering and sciences as a career choice. Or put another way, they were interested in pursuing a career that enables them to do something that would have a positive impact on the environment. I had assumed that this meant that Carrie and perhaps three or four of her friends had gotten together and decided to initiate the club. I was wrong. The club as she defined it actually consisted of 15 to 20 students with active discussions with another 10 to 15 who are interested in finding out more about what the chapter did and how it might relate to their specific interests. There clearly was something going on there.

In the phone call, I asked about why people were interested in the environmental engineering and sciences area. I got a variety of answers. Some were predictable -- students who are interested in the technology, people who had what we might characterize as hard-core environmentalist type concerns, and people who just wanted to get more familiar with environmental issues and what might be done to address them.

But there was a second thread of responses to that question and the answers there were far more intriguing. Several of the people on the call mentioned their concern about climate change and global warming and the fact that they would like to be part of a solution to that problem. Others mentioned a desire to find out more about sustainability concerns and how the earth could support another 2 billion or more people who were projected to be added to the world's population in the next 25 years. There were also mentions of the fact that environmental engineering and science is closely related

> "I suddenly realized that listening to the students was not unlike listening to the impassioned speeches of rock stars or country music stars when they are doing a charity event. None of them claims to have all the answers. Instead, the musicians make it clear that they are doing this event because it is the best way they are able to have an impact."

to developmental issues in the Third World. Others mentioned the need for all of us to get more concerned about our stewardship of increasingly scarce resources of all kinds.

This group more or less summarized their collective intent by stating that they were attracted to the field because it offered them a chance to make a difference in how we treat the world and its people. They also mentioned their desire to help people -- not just in the United States, but around the world -- to live better, safer, healthier lives. They stated that they were interested in this field because it offers the potential to deal with the biggest challenge that mankind has ever faced. And that was said in all due seriousness. It was not platitude and it was not something that was said lightly. And if you haven't figured it out yet, I will confirm your suspicions that the people in the picture on the previous page are the group that I talked to.

What made this such a remarkable experience was the level of excitement, enthusiasm, and energy concerning the issues that we discussed. The intensity level went beyond keen interest. These people are very serious about their career choice. These people were even more serious about their personal intent to become part of the solution. And finally, these people wanted to go beyond the standard educational experience offered by the University. They wanted to be a step up and a step ahead when they graduate. They want to be able to hit the ground running the first day on the job and they want to be involved in things that make a difference.

That's when it struck me. I suddenly realized that listening to the students was not unlike listening to the impassioned speeches of rock stars or country music stars when they are doing a charity event. None of them claims to have all the answers. Instead, the musicians make it clear that they are doing this event because it is the best way they are able to have an impact. And the intrinsic truth of those impassioned pleas comes through as genuine. The performers and the organizers really do care. They see themselves as being almost morally obligated to contributing to a cause in a way that leverages their celebrity. No, they don't get involved at the nuts and bolts level. Instead, their focus is on collecting the resources that enable building solutions by people who are the subject matter experts. And there is no disputing the results that these kinds of events have achieved over the years.

What came through to me loud and clear in the phone call was the fact that this student group was completely sincere in their interest in the field of environmental engineering and science. They know that this is not an easy field to be successful in. However, they firmly believe that they have what it takes to make the grade. That belief is rooted in a desire to be a change agent for the environment and the need to better manage our impact on the environment as the world's population continues to grow.

Which led to another epiphany. Listening to these students talk about what they wanted to do and why they wanted to do it made me realize; these are the rock stars of environmental engineering and science. They want to have an impact. No, let me restate that. They intend to have an impact and they are going the extra mile in preparing to make a meaningful contribution to the effort. They realize that their future does not include rock star money. Instead they are looking forward to a career in a field that is doing critical work. It's all about passion, commitment and determination.

They don't expect to be the next Zuckerberg, Gates, or Jobs. Instead, they will be looking to stand on the shoulders of the current generation of environmental engineers and scientists as they go forward in their careers. They want to be able to combine education and passion with a solid foundation on which to build.

And that is the challenge to the Academy and its members. We are the ones with the obligation to create an environment that enables the next generation to succeed. That is a considerable endeavor and a considerable responsibility because the issues the next generation will address are arguably more difficult than those of the past 50 years. We at the Academy look forward to working with you to ensure that we live up to that responsibility.

100th Anniversary of the Activated Sludge Process: 1914 - 2014

INTRODUCTION

The next to the last oughts were a difficult time for environmental engineering and science. The multiplicative effects of burgeoning population growth and industrial production were wreaking havoc on river systems and the wastewater treatment plants designed to protect them. Worse, technologists had hit a wall in terms of removing oxygen demanding materials. Strangely enough, they could completely nitrify wastewaters, but they couldn't get much beyond 50% removal of carbonaceous oxygen demand. What to do?

Welcome to a series of articles celebrating the 100th Anniversary of the Activated Sludge Process. To start, Daniel Schneider takes us through a brief history of wastewater treatment, the invention of the activated sludge process, and the subsequent controversy surrounding its genesis and adoption.

Ardern and Lockett's groundbreaking paper, delivered to a large gathering of wastewater treatment professionals on April 3, 1914, at the Grand Hotel in Manchester England, explained the genesis and technical foundation of their breakthrough invention of activated sludge. This article is reproduced in its entirety in this issue. Ardern and Lockett demonstrated the almost complete removal of carbonaceous oxygen demand by reusing (activating) sludge to treat wastewater. In doing so, they solved the carbonaceous oxygen demand removal roadblock.

From a reaction kinetic standpoint, engineers quickly hit upon the metric of food to microorganism ratio as a fundamental control metric. It had only one problem: it took five days to measure. Along came Alonzo Lawrence and Perry McCarty to provide the mathematical modeling insight to the activated sludge process that produced the sludge age control concept: something that you could measure and use the same day.

Ross McKinney proposed the vastly counterintuitive idea that it was better to have the lower reaction rate characteristic of the back end of a plug flow reactor spread evenly throughout an aeration basin than the higher rates characteristic of the front end. Stability trumped speed; the tortoise beat the hare.

Richard Dick tells the story of the integration of sludge thickening concepts into the design of final clarifiers, and the subsequent improvements in this field.

Glen Daigger takes us on a guided tour of nitrogen removal mechanisms and processes, showing the huge amount of progress in this area. His article can be seen as paired with James Barnard's pioneering article on phosphorous removal, showing us the past and current state of nutrient removal that is critical to the maintenance of sound ecosystems.

Finally, George Tchobanoglous and H. David Stensel give us a tour of where they think biological treatment processes are headed in the future: reuse, dispersal, modification etc.

The Academy's 100th Anniversary celebration of the Invention of Activated Sludge was developed by a small ad-hoc workgroup consisting of Academy members (Herb Ward, Jeff Greenfield, Paul Koch, David Vaccari, David Marabello and myself), and staff (Yolanda Moulden and Sammi Olmo). My deepest appreciation to all of them.

Someone remarked to me that it must have been difficult to pull together and edit such an array of technical/historical articles. Not really! Arguably, our 100th Anniversary Workgroup had assembled the most experienced team of writers in the history of *Environmental Engineering and Science*. No one missed a deadline or the mark. It is just built into their DNA. Many thanks to Daniel Schneider, Alonzo Lawrence, Andy Middleton, Ross McKinney, Glen Daigger, James Barnard, Richard Dick, H.David Stensel and George Tchobanoglous. And of course, Edward Ardern and William T. Lockett.

But there is more! Besides this special issue of *Environmental Engineer and Scientist*, the Academy has added a one time only Ardern and Lockett prize to the annual Excellence in Environmental Engineering and Science Competition for the best Activated Sludge/Biological Process project. In conjunction with all of this activity, we are running a special anniversary session at the New Jersey Water Environment Association in May, featuring approximately a dozen speakers on various aspects of activated sludge -- both historical and present. We'll probably wrap the whole thing up in an E-book for our members and the technical community at large.

Ardern and Lockett were all about sustainability. They reused bacteria from primary treatment and concentrated it to make an engineered model of nature -- riverine system or the human gut -- to clean our wastewater. This was and is a shining example of how humankind collectively adapts to our increasing numbers and activities, and in doing so, expands the carrying capacity of our sole planetary home. We expect much more to come in the next hundred years… and beyond.

Brian P. Flynn, P.E., BCEE
Past President, AAEES

WHO INVENTED ACTIVATED SLUDGE?

Daniel W. Schneider[1]

In this, activated sludge's 100th anniversary, we can ask a question that vexed the sanitary engineering community for decades following the meeting of the Society of Chemical Industry in Manchester, England, in which the activated sludge process was first publicly described. *Who invented activated sludge?* Many individuals could lay claim: Gilbert Fowler, Edward Ardern, William Lockett, Ernest Moore Mumford, Harry Clark. From our perspective, the answer may seem obvious. Activated Sludge was invented by the scientists who conducted the ground-breaking research and first reported it in the literature, Ardern and Lockett. However, activated sludge quickly became embroiled in a decades-long fight over who invented the process and was, thus, entitled to patent rights.

Gilbert Fowler was the chemist in charge of the Manchester Rivers Committee's sewage research. As the head of research at Manchester, he directed Ardern and Lockett in their experiments. Fowler is most commonly credited with the invention of the activated sludge process along with Ardern and Lockett. Other researchers, however, also made claims to its invention. Harry Clark, chemist at the State of Massachusetts' experiment station at Lawrence, had conducted key experiments that inspired Fowler in his studies and challenged Fowler over his claims. Other scientists and engineers were involved in early studies that could potentially be credited with the process's invention, including Ernest Moore Mumford who worked with Fowler on early bacteriological treatment schemes.

What everyone at the time could probably agree on, however, is that Walter Jones, owner of the hydraulic engineering firm Jones and Attwood, did not invent the activated sludge process. Yet he was the one legally credited as the single, true inventor, and held the patents on the process in his name. Finally, and perhaps most importantly, many engineers of the period argued that activated sludge was not invented at all; rather, it was a natural process that was "discovered" rather than "invented." As such, it belonged to the public at large.

Debate about who invented activated sludge was propelled chiefly by early efforts to commercialize and profit from the invention (Schneider, 2011). Many sanitary engineers, primarily employed by municipalities and state boards of health, saw this push as inimical to the goal of improving the health of cities and ameliorating the severe pollution of rivers, lakes, and oceans. These public engineers developed a wide-ranging critique of sewage treatment patents. As with any advance in science, activated sludge grew out of previous research and ascribing credit was complex. Complicating attribution of the process was the widespread effort, funded by local governments around the world, to develop effective sewage treatment technologies. There was a great degree of sharing the results of work, and scientists and engineers crossed the Atlantic to visit various cities where new technologies were being tried.

The activated sludge process developed from this trans-Atlantic exchange of scientists and information, in which several research threads in England and the United States on the industrial use of microorganisms came together. Gilbert Fowler (Figure 1), a chemist and bacteriologist at Manchester University, was working with a young bacteriologist Ernest Moore Mumford, who was investigating the clogging of a biological sewage filter by an "iron organism." Mumford collected these bacteria and began to establish the conditions in which they grew and deposited iron. Naming it M.7, he found that in the presence of iron, air and a source of organic nitrogen like peptone, the bacteria would precipitate iron compounds (Mumford, 1913).

In the meantime, in 1911, Harry Clark, chief chemist at the Lawrence experiment station, run by the State of Massachusetts, was investigating the impact of domestic sewage and trade wastes on the life of rivers. He and his co-workers placed fish in aquaria and began adding sewage to determine "how much sewage the fish would stand and live." They found that, in order to keep the fish alive in more and more polluted waters, they had to bubble increasing amounts of air into the bottom of the aquaria. As they kept adding sewage, they noted that growths began developing on the sides of the aquaria. When they stopped blowing air, they discovered that all of the suspended and colloidal material from the sewage dropped out, turning the turbid water clear. They quickly abandoned the studies on fish and concentrated on understanding the clarification of the sewage. They began bubbling air into containers of sewage (Figure 2). After blowing air for several weeks, they were able to purify newly added sewage in a matter of just 24 hours (Clark, n.d.).

Fowler's research on the M.7 bacteria and Clark's research on aeration came together when Fowler visited the Massachusetts experiment station in 1912. Fowler was consulting to the New York Sewerage Commission and, like many sanitary scientists, made it a point to travel to Lawrence and tour the experiment station. There, Clark showed Fowler the bottle experiments and explained their success in purifying sewage. Fowler had previously written that "the subject of sewage disposal is mainly a question of the separation of solids from liquids," and began thinking about how to "clot" out sewage particles from the water. When he returned to Manchester he and Mumford began experimenting with cultures of M.7, bubbling air and using sewage instead of peptone as the nitrogen source. They found that sewage could be clarified with this organism, producing a "limpid sparkling and non-putrefactive effluent." (Fowler and Mumford, 1913) Fowler's M.7 research proved to be impracticable, however, and it was never adopted, but the mechanical apparatus used to conduct the work laid the basis for the activated sludge apparatus.

At the same time Fowler and Mumford were working on the M.7 process, Fowler had instructed his assistants at the Manchester Rivers Committee, chemists Edward Ardern and William Lockett, to repeat the experiments of Clark that he had seen in Massachusetts. Ardern and Lockett placed sewage in a small quart bottle, and started to bubble air until all of the nitrogen had been converted to nitrate. Complete nitrification took six weeks-too long to be useful in treating sewage directly. But their next step was crucial and set their experiments apart from those of Clark. Instead of discarding the sludge that accumulated in the bottle, they saved it and decanted the liquid. They then added fresh sewage and began to aerate anew. This time, nitrification took only three weeks. They kept decanting the liquid, reserving the accumulated sludge and adding fresh sewage, and with each repetition, the time to nitrification was steadily reduced, until they could completely oxidize sewage in just 24 hours. They began to refer to this sludge as "active" to distinguish it from "ordinary" sewage sludge such as might be collected in a sedimentation tank (Lockett n.d.).

With this active sludge process, now renamed "activated" sludge, Ardern and Lockett felt they were on the verge of a revolution in sew-

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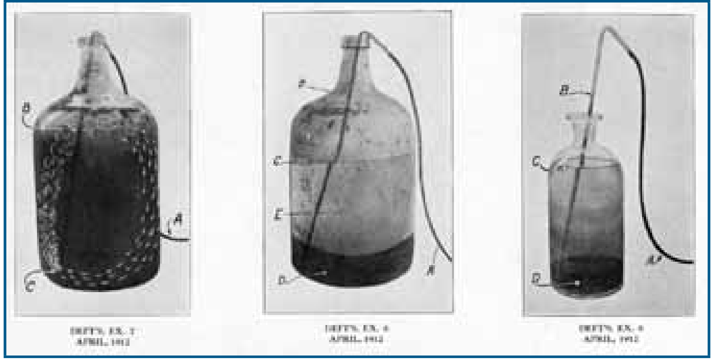
1. Department of Urban and Regional Planning, University of Illinois at Urbana-Champaign, 611 Taft Drive, Champaign, IL 61820; ddws@illinois.edu

FIGURE 1
Gilbert Fowler. Fowler is widely credited as the inventor of the activated sludge process. *Some studies in biochemistry by some students of Dr. Gilbert J. Fowler (Bangalore: Phoenix Printing House, 1924).*

age treatment. "Results so far obtained indicate that it may radically affect the whole problem of the purification of sewage," wrote Lockett in a draft of their paper (Lockett n.d.). The activated sludge process of biological sewage treatment was introduced to the world at the Society for Chemical Industry meetings held in Manchester England on April 3rd, 1914, in a paper entitled "Experiments on the Oxidation of Sewage Without the Aid of Filters." Ardern had invited sewage workers from around the country, and attendees were expecting to hear of a major breakthrough in sewage treatment. It was the best-attended meeting of the section ever, with perhaps 200 scientists and engineers in attendance (Ardern n.d.). Later that year, the society's journal published the first of several papers reporting Ardern and Lockett's work and made the process widely known internationally. Within just the next year, 15 cities around the world began testing the process and building sewage works to utilize it.

The report on activated sludge, however, also initiated a decades-long fight over the invention of activated sludge. The response of the engineering community to the activated sludge process was conditioned to a great extent by concerns over its patent status. Engineers, particularly in the United States, had been challenging the patent on the septic tank process in the courts for over a decade, and the septic tank patent had roiled the sanitary engineering community (Schneider, 2011). On a visit to European sewage treatment plants late in 1914, Edward Bartow, Professor of Sanitary Engineering at the University of Illinois, went to Manchester to meet with Fowler, where he saw the experiments with activated sludge. Bartow was tremendously excited by the results, but he expressed great concern to Fowler over the patent status of the process. "Have you made any arrangements to have the process handled by any firm in the United States?" Bartow asked. "I hope that no firm will get hold of patents on the process and cause trouble," he continued, "such as was caused by the Cameron Septic Tank Company" (Bartow, 1915a).

FIGURE 2
Aeration experiments of Harry Clark at the Lawrence Experiment Station. These bottle experiments were the basis for Ardern and Lockett's experiments on activated sludge. *Activated Sludge Inc. v. The City of Milwaukee,* Defendant's Book of Charts. Milwaukee Metropolitan Sewerage District, Records Office, Box 8303.



Fowler replied that he was "anxious to avoid anything like the experience of the Septic Tank Syndicate" (Fowler, 1915). However, despite these assurances from Fowler, Bartow's wish that "no firm will...cause trouble" was not realized. For, from a very early stage in the research on activated sludge, Fowler was secretly involved in negotiations with Walter Jones of Jones & Attwood, Ltd., a sewage and hydraulic engineering firm, to establish a syndicate to develop and market the activated sludge process. At first, Fowler was not interested in patenting activated sludge. As the commercial potential of the process became clear, however, he began to abandon his prior convictions and applied himself wholeheartedly to the business aspects of the scheme. Fowler's business associates had advised him not to take out the patent himself, as this might be a blemish on his reputation and affect the appearance of scientific objectivity. Rather, he should allow the syndicate to take out the patents. Fowler allowed Walter Jones to patent activated sludge, receiving £1000 in return. In legal proceedings from that point, Jones claimed to have invented activated sludge (Figure 3): "Be it known that I, WALTER JONES, a subject of the King of England, residing at Amblecote, Stourbridge, in the county of Worcester, England, have invented new and useful Improvements in or Connected with the Purification of Sewage and Analogous Liquids" (Jones, 1917). Activated sludge promised to be an extremely lucrative business, and sewage patents were a key component of Jones & Attwood's business strategy. "The Sewage Work of the World is a big thing," wrote J.A. Coombs, Jones & Attwood's chief sewage engineer, "and the firm are by no means selfish in trying to corner it"(Haworth, n.d.).

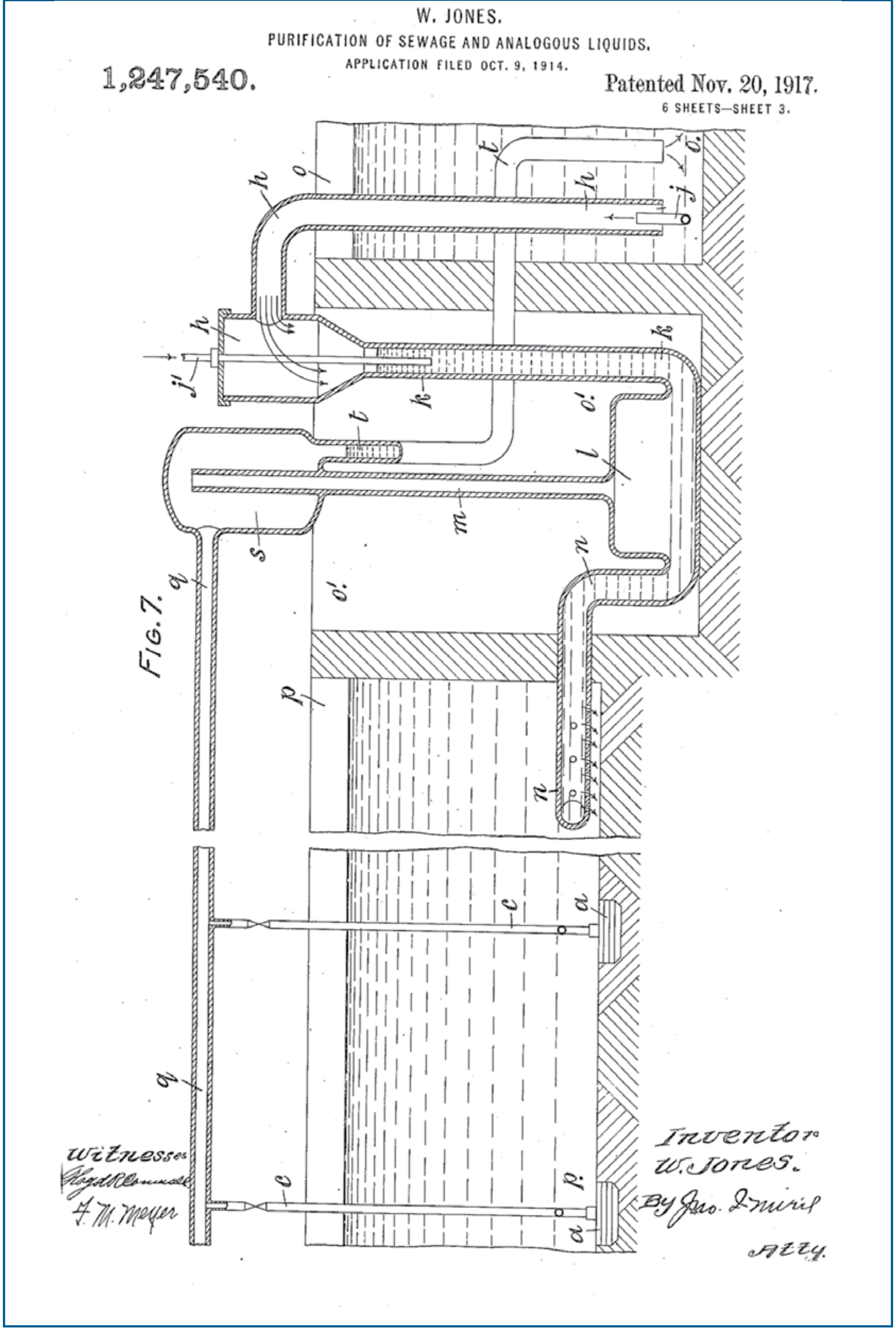
Soon after Ardern and Lockett's pathbreaking paper, activated sludge was taken up by many cities in both England and the U.S., where engineers established experimental plants to test and develop the process, the most prominent being Milwaukee, Wisconsin (Figure 4). When engineers in the U.S. first heard of activated sludge, they assumed that its use would be "free to all" since there had been "no public mention of patents on either the tank or the process." (British and American Patents on Activated Sludge, 1916) Rather, engineers looked to the published papers of the Manchester researchers for guidance. "The papers of Ardern and Lockett describe the process so well that each engineer or chemist feels that he is capable of following along the lines described in their paper without additional assistance," Bartow reported to Fowler, concerning Fowler's desire to consult for American cities that might build activated sludge plants. Regarding the use of Jones & Attwood's appliances for diffused air, Bartow noted that "American practice has dealt so largely with mechanical water filtration that the supplying of air does not seem to them to be a difficult problem and they are going ahead with various devices of their own." (Bartow, 1915b).

As news reached America that the original process had indeed been patented in England and that applications were pending for U.S. patents, engineers immediately thought of the septic tank and began to organize against the activated sludge patents in a similar way. At the 1916 meeting of the American Society of Civil Engineers, engineers called for the establishment of a special committee to "to prevent, if possible, the patenting of this process by English engineers to whom Fowler has signed over his interests and rights." (Clark, n.d.)

The acting secretary of the committee was T. Chalkley Hatton, recently hired as Chief Engineer for the Milwaukee Sewerage Commission. Hatton was particularly incensed over the activated sludge patents, as Milwaukee had hired Fowler to consult on their activated sludge experiments, and only after months of correspondence did Fowler intimate that the process was patented. Because Hatton assumed these patents would be on the specific apparatus that Jones and Attwood had designed, he appeared little concerned since he was moving forward with plans and equipment of his own, rather than Jones and Attwood's appara-

FIGURE 3

The first activated sludge patent in the U.S., granted to Walter Jones as the inventor of the process. U.S. Patent 1,247,540. This patent covered both apparatus and the process.



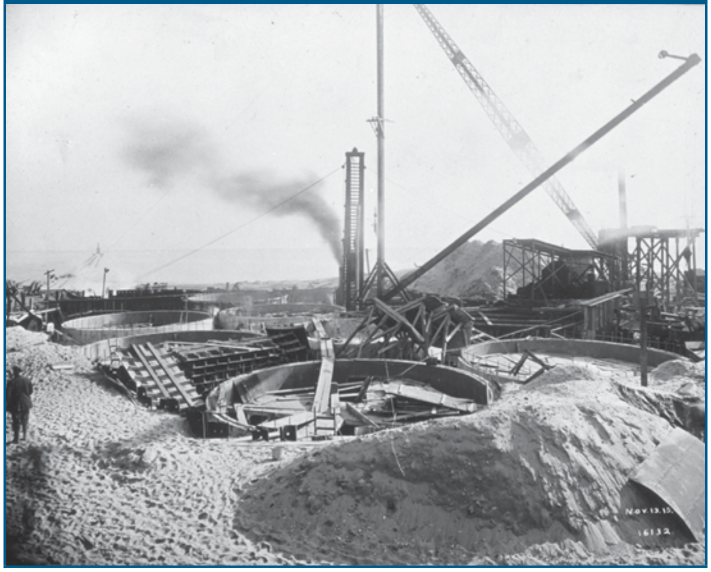
tus. After further correspondence, however, Hatton began to worry. "In your last letter just received you suggest to my mind inquiring about patents," wrote Hatton. "I should like to know from you, what if any patent rights have been obtained which might govern the use of the process with which we are experimenting." (Hatton to Fowler, 1913) So began years of tense correspondence and decades of litigation. Milwaukee had designed their Jones Island treatment plant from scratch, using data from their own experimental plant, yet Jones & Attwood claimed infringement. Jones & Attwood formed a separate company, Activated Sludge Inc., and sued the Sanitary District of Chicago in 1925 and Milwaukee in 1929. In 1933, the Milwaukee case was decided first, in favor of Activated Sludge. (Sewage Plant System Stolen, Geiger Rules, 1933) Armed with this initial victory in the Milwaukee case, Activated Sludge Inc. filed suit against over 100 cities in 1933, ranging from tiny West Concord, Minnesota, population 613, to Los Angeles and Houston (Patent 1,247,540).

Sanitary engineers disputed the patents on a number of grounds. In part, this challenge centered on a contest over credit for the invention, with Harry Clark challenging Fowler's priority. Opponents also argued that Ardern and Lockett, or even the City of Manchester, were the true inventors, not Fowler, and certainly not Jones. But perhaps most fundamentally, they challenged the idea that activated sludge was invented at all. Sanitary engineers recognized a fundamental difference between the ethics of patenting apparatus and patenting processes in sewage treatment. Much of the apparatus used in a sewage plant-pumps, distributers, diffusers-was patented, and engineers organized no protests over these patents. Rather it was patents on processes themselves that created the most controversy. Hatton, on learning of the activated sludge patents responded to Fowler, "I imagine such patent rights, if any, must have been issued on appliance rather than process" (Hatton, 1915). While apparatus might be patented, natural processes could not.

The most fundamental critique of the sewage patents centered on the contested position of the bacterial processes involved in treating sewage. Proponents of bacterial processes in general considered biological sewage treatment to rest on natural processes. Cameron emphasized how his septic tank was based on "natural agencies." Fowler, for instance, wrote "the changes which go on in an activated sludge

FIGURE 4

Testing station, Milwaukee, Wisconsin. Milwaukee built this station to test the activated sludge process and provide data for the design of their Jones Island plant. Activated Sludge, Inc., sued for patent infringement.



tank are essentially the same as those taking place in arable soil.” (Fowler, 1925) But as a natural process, biological treatment had another fundamental property. It could not be patented, privatized or monopolized - it belonged to the public at large. As a trial judge in the septic tank patent controversy expressed it, “this development of bacteria is a fundamental truth in nature... It is a process of nature... and not patentable.” As “nature’s means and methods,” he continued, these bacterial processes are “common property, and cannot be appropriated and monopolized by any one” (*Cameron Septic Tank Co. v. Village of Saratoga Springs,* 1907).

Opponents of the activated sludge patents made the same arguments. Earle Phelps, sanitary scientist at the U.S. Public Health Service, made this most explicit. He decried the “important fact too often overlooked by engineers, namely, the distinction between a process of sewage disposal and an apparatus or device for carrying out that process.” For Phelps, there were “but two essential or basic processes, namely anaerobic decomposition and aerobic oxidation...Upon these two real processes of organic decomposition all modern bio-chemical methods of sewage treatment are based.” (Hammond, 1916). Phelps charged that Activated Sludge, Inc. was attempting to patent the process of organic decomposition itself.

The courts, however, ruled that the activated sludge process patents were not on “the discovery of the bacteria, nor their characteristic activities” but rather on the means for providing conditions for the bacteria “to function to the best advantage.” The appeals court went into great detail describing “the processes of nature” involved in sewage purification. Starting with nitrification and the nitrogen cycle, the opinion described aerobic and anaerobic decomposition in soils and “running streams,” and how in sewage irrigation and trickling filters “nature’s process was followed or approximated,” because the bacteria were attached to soil particles or stones. “In nature’s processes and in all artificial filters...the aerobic bacteria were fixed, and the polluted water or sewage was brought to the bacteria,” they asserted. In contrast, with activated sludge, “the situation is reversed, so that the bacteria instead of being fixed are put into circulation and brought to the sewage.” According to the court, activated sludge thus differed from “nature’s processes” of purification and could be patented (*Milwaukee v. Activated Sludge,* 1934). While Fowler and others, in order to naturalize the novel process, had emphasized the continuity between the natural process of land treatment and activated sludge, the appeals court placed a clear demarcation along that same continuum between natural and artificial. Sewage irrigation and filtration were “natural,” the court implied, because the bacteria grew on fixed surfaces. Activated sludge was artificial, and thus patentable, because the bacteria were freed from surfaces.

Declaring activated sludge to be patentable, the court then proceeded to determine the true inventor. Even though Ardern, Lockett and Fowler worked for Manchester, the court chose to accept the fiction that they all, in fact, were working under Walter Jones’ direction, and that Jones was thus the true inventor of activated sludge. After over 20 years in the courts and numerous appeals, the patents were finally held to be valid and infringed. Milwaukee was assessed damages of almost $5 million and almost had to shut down its treatment plant altogether. They were later able to settle for $818,000, while Chicago was assessed $950,000. The other 100-plus cities and towns in the U.S. were forced to pay an additional $600,000.

The activated sludge process is now in the public domain. But the patent controversy has had many implications. The decisions in the activated sludge and other sewage patent cases provided the underpinnings for intellectual property in biotechnology generally (Schneider, 2011). But these controversies also helped cement the commitment to the public interest on the part of many engineers and scientists involved in sewage treatment and environmental protection more broadly.

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EXPERIMENTS ON THE OXIDATION OF SEWAGE WITHOUT THE AID OF FILTERS

The following article is reproduced from the Journal of the Society of Chemical Industry, Volume XXXIII, No. 10,pgs. 523-539, Edward Ardern, M.Sc., and William T. Lockett, M.Sc.

MANCHESTER SECTION

MEETING HELD AT THE GRAND HOTEL ON FRIDAY, APRIL 3RD, 1914: MR. J. H. HOSEASON IN THE CHAIR

It has long been known that if sewage be exposed to the air for a sufficient period of time, the organic contents are gradually oxidised, with the formation of a deposit of so-called "humus" and the final production of nitrate from the ammonium salts and the nitrogenous organic matter.

This purification change of which the course of the reaction has been so carefully studied and thoroughly worked out by Adeney in his researches on behalf of the Royal Commission of Sewage Disposal, takes place, however, comparatively slowly, and even if aided by direct aeration, by no means becomes a practical method of sewage purification.

Numerous investigators have from time to time endeavoured to utilise aeration methods in the practical solution of the sewage problem, but until quite recently without any reasonable amount of success.

Among the earlier investigations may be mentioned those of Dupré and Dibdin[1] on the aeration of London Sewage, and those of the Massachusetts State Board of Health relating to the use of aeration in the filtration of sewage through gravel and sand filters. Dr. Drown[2], chemist to this Board, concluded from the results of a series of experiments, that the oxidation of organic matter in water was not hastened by vigorous agitation with air.

Waring[3] of the United States was one of the first to apply aeration methods in the purification of sewage on a working scale.

In 1880 Hartland patented an aeration chamber for the purification of sewage or tank effluent, which Kaye Parry[4] employed in experiments undertaken in 1887, while in 1892 Lowcock conducted experiments on the aeration of filter beds by a forced air supply.

In the latter year Mason and Hine[5] published the results of a research on the aeration of mixture of sewage and water in which they concluded that aeration had but little oxidation effect on the sewage.

In 1897 Fowler[6] investigated the effect of aeration on the effluent resulting from the chemical precipitation of Manchester sewage, without any very tangible results being obtained, at any rate so far as the total of oxidation was concerned.

It would thus appear that the results of the earlier investigations on the subject of aeration of sewage, indicated that aeration per se could not be considered as a practicable adjunct in the process of sewage purification.

Recently, however, the subject has been reopened by the work of Black and Phelps, Clark, Gage and Adams, and Fowler and Mumford.

In dealing with the question of the pollution of the New York Harbour, Black and Phelps[7] studied the possibilities of the application of aeration to the treatment of sewage.

Their experiments dealt with the aeration of both fresh and partially septicised sewage, in various types of tanks and it was shown that under certain conditions it was possible by means of a reasonable amount of aeration to remove the more readily putrescible matters from the sewage and thereby to a certain extent increase its stability.

Black and Phelps were so far convinced of the practicability of such methods of treatment of sewage, as to recommend that the sewage from a certain section of the New York area should be dealt with on these lines, prior to discharge into the waters of the harbour.

In the Annual Report of the Massachusetts State Board of Health for the year 1912, published at the end of 1913, is described an investigation by Clark and Do. M. Gage on the possibilities of the use of aeration for preliminary treatment of sewage prior to filtration. They found that simple aeration of sewage for 24 hours reduced the free and albuminoid ammonia to some extent and that with sewage which was both aerated and seeded with green growths - *Protococcus* and *Scenelesmus* - the albuminoid ammonia was even more noticeably reduced. Later it was found that appreciable nitrification was obtained within 24 hours in the aerated sewage containing the green growths.

Subsequently Clark and Gage found that aeration for a much shorter period, in a tank containing slabs of slate about one inch apart, covered with a compact brown growth of sewage matters, was sufficient to coagulate the sewage colloids, and thus to produce a well clarified non-nitrified effluent capable of satisfactory filtration at several times the normal rate.

Later Fowler and Mumford[8] carried experiments on the action in the presence of air, of an organism designated "M7" (isolated by Mumford from ponds receiving water discharged from a colliery) on sewage containing a certain proportion of iron salts.

This organism has the property of precipitating the iron as ferric hydroxide from solutions of iron salts.

In the paper referred to, it is stated that sewage (in presence of a certain quantity of iron salts) inoculated with this organism, can be thoroughly clarified by six hours aeration. The resultant effluent after settlement of the separated organic colloids, was quite clear and practically free from colloids. It is further stated that although the ordinary methods of analysis failed to reveal the extent of the change effected by the above treatment, the effluent after aeration was always non-putrefactive on incubation, and could be readily oxidised and nitrified by filtration at a high rate.

In quite a recent publication Clark and Adams[9] give the results obtained during 12 months operation of the specially constructed tank used in their earlier experiments previously referred to.

It is shown that a rather better coagulation of the organic colloids and purification of the sewage generally, can be obtained by means of aeration for a period of five hours, under the conditions of experiment, than is obtained by efficient chemical precipitation, and at a considerably reduced cost.

The effluent resulting from the aeration treatment was applied to trickling filters 10 feet deep, at rates varying from 8 to 10 million gallons per acre per day, with the production of a well-nitrified and thoroughly stable filtrate.

In connection with the experiments carried out by Clark and his col-

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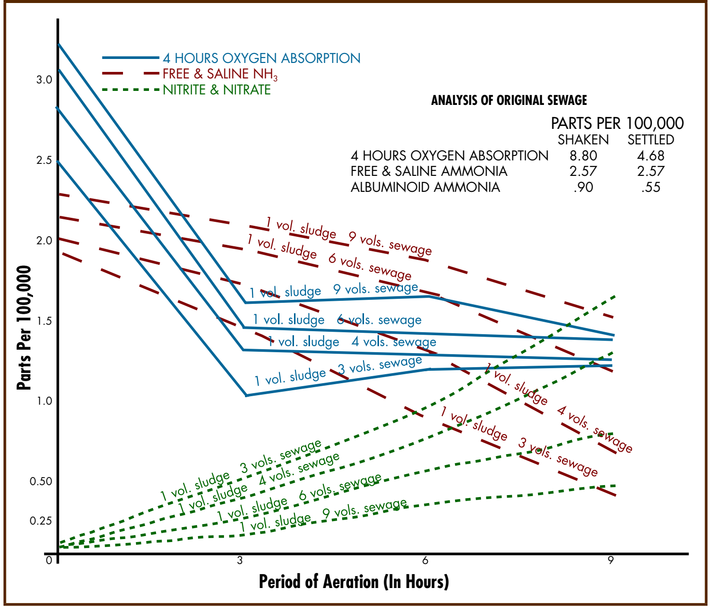
1. Report to Royal Commission on the Metropolitan Sewage Disposal, 1884, Vol. 2.
2. Clark and Adams, Engineering Record, February 7th, 1914, p. 158.
3. Halter and Baker, 1984, Sewage Disposal in the United States, P. 535.
4. Trans. Inst. C.E. Ireland, Vol. XX., 1888.
5. Journ. Amer. Chem. Soci., Vol. 14, p. 7.
6. Annual Report, 1897, Rivers Dept., Manchester Corporation
7. Mass Inst. of Technology, Contributions from the Sanitary Research Laboratory, Vol. VII., Boston, Massachusetts, 1911.
8. Journal of Roy. San. Inst., November, 1913.
9. Engineering Record, February 7th, 1914, p. 158.

FIGURE 1
Effect of Varying Proportions of Activated Sludge



leagues, it should be mentioned that the sewage treated was considerably more dilute than the majority of English sewages, as will be seen from the following average analytical returns taken from the paper quoted.

	Parts per 100,000
Oxygen consumed	3.52
Free and saline ammonia	3.62
Albuminold ammonia	0.57

The researches of Clark, Gage, and Adams, and of Fowler and Mumford show a marked advance on previous work, but it will be seen that in the case of the former investigators the idea of surface contact is retained, as evidenced by the construction of the aeration tank, and that in order to produce a nitrified and stable effluent, further treatment in filters is still required.

With regard to the method of treatment suggested by Fowler and Mumford, while the clarification is effected in the absence of surface contacts, the questions of inoculation and the addition of iron salts are introduced and the provision of filters for the rapid treatment of the clarified effluent remains.

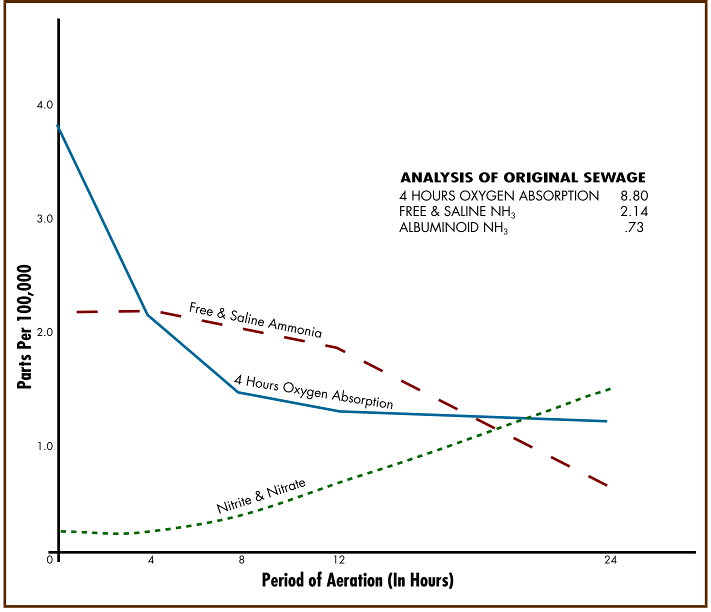
In a previous communication to this section of the Society[10] in regard to the effect of the waste liquor from sulphate of ammonia plants on the oxidation of sewage, the present authors, in conjunction with Dr. Fowler, gave some results of the direct aeration of sewage.

It was noted that while some coagulation of the colloid matter took place in the course of twenty-four hours aeration, a period of several weeks elapsed before nitrification was complete.

In November, 1912, Dr. Fowler visited the States in connection with the question of the pollution of the New York Harbour. Shortly after his return he described to the authors a laboratory experiment which he had seen in progress at the Lawrence Experiment Station, Massachusetts, which evidently referred to the earlier work of Clark and his colleagues on the aeration of sewage in the presence of green organisms, as the bottle in which the sewage was aerated was coated inside with strands of algal growth. Dr. Fowler suggested that new work might with advantage be carried out on somewhat similar lines.

Acting on this suggestion, further investigations with regard to the subject of aeration of sewage, were undertaken by the authors.

FIGURE 2
Course of Reaction: Experiment No. 14



An account of the results which have so far accumulated is given in the following paragraphs.

PRELIMINARY EXPERIMENTS

In a series of preliminary experiments, samples of Manchester raw sewage, contained in bottles of 80 oz. capacity, were aerated until complete nitrification ensued; the aeration being effected by drawing air through the sewage by means of an ordinary filter pump.

In the case of the first experiment, about five weeks' continuous aeration was required in order to obtain complete nitrification, as had been previously observed. At the end of this period the clear oxidised liquid was removed by decantation, and a further sample of raw sewage aerated in contact with the original deposited matter, until the sewage was again completely nitrified.

This method of treatment was repeated a number of times with the retention in each case of the deposited solids.

It was found that as the amount of the deposited matter increased, the time required for each succeeding oxidation gradually diminished until eventually it was possible to completely oxidise a fresh sample of crude sewage within twenty-four hours.

For reference purposes and failing a better term, the deposited solids resulting from the complete oxidation of sewage have been designated "activated sludge." Reference to its general characteristics, chemical composition and biological contents will be made later.

As a result of these preliminary experiments the following observations may be made:

(a) In order that the final nitrification change may proceed without hindrance, it is necessary that the alkalinity or basicity of the sewage should be rather more than equal to the nitric acid resulting from nitrification of the ammonium salts. In some cases it has consequently been found necessary to add a small quantity of alkali prior to complete nitrification.

(b) It is essential that the activated sludge should be kept in intimate contact with the sewage during aeration.

This point is illustrated by an experiment, the results of which are given in Table 1 from which it will be seen that while the initial effect on the oxidisable matters as measured by the oxygen absorption test, is not materially affected, on further aeration a marked improvement is shown in the case where the activated sludge is kept in intimate contact with the sewage, than where such conditions do not obtain. Further, in regard to the amount of nitrifica-

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[10] This Journal, No. 10, Vol. XXXI., 1912.

TABLE I
Effect of "Intimate" Contact

Results in parts per 100,000	Experiment (7a)								Experiment 8(a)							
	4 Hours oxygen absorption		Free and saline ammonia		Albuminoid ammonia		Nitrite and nitrate		4 Hours oxygen absorption		Free and saline ammonia		Albuminoid ammonia		Nitrite and nitrate	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Original	3.88	4.06	2.71	2.71	.33	.33			5.20	5.31	2.43	2.36	.47	.485	.07	.07
After 4 hours aeration	2.46	1.77	2.71	2.50	.215	.145			2.90	2.90	2.36	2.28	.30	.29	.17	.15
After 24 hours aeration	1.26	.60	2.57	.15	.105	.05	nil	1.72	2.00	1.28	2.28	1.22	.215	.10	.07	.86

A = sludge in contact with sewage without intimate mixture.

B = intimate mixture of sewage and sludge.

In each case the samples were settled for 2 hours prior to analysis.

In this experiment a proportion of 1 vol. activated sludge to 25 vols. sewage was employed.

TABLE IA
Ratio of Sludge to Sewage

Results in parts of 100,000		Experiment 91a																	
		Raw sewage		1 vol. sludge to 9 vols. sewage				1 vol. sludge to 6 vols. sewage				1 vol. sludge to 4 vols. sewage				1 vol. sludge to 3 vols. sewage			
		Shaken	Settled	Original	3 Hrs.	6 Hrs.	9 Hrs.	Original	3 Hrs.	6 Hrs.	9 Hrs.	Original	3 Hrs.	6 Hrs.	9 Hrs.	Original	3 Hrs.	6 Hrs.	9 Hrs.
4 Hours oxygen absorption (total)		8.80	4.08	3.26	1.60	1.63	1.40	3.08	1.43	1.40	1.32	2.80	1.28	1.28	1.22	2.51	1.00	1.17	1.20
Crystalloids.			2.57	1.72	.91	.80	.80	1.63	.80	.76	.76	1.37	.68	.68	.68	1.31	.63	.68	.66
Colloids, etc.			2.11	1.54	.69	.83	.60	1.46	.63	.64	.54	1.43	.60	.60	.54	1.20	.37	.49	.54
Oxidisable matter removed	Total				1.66	1.63	1.86		1.65	1.68	1.76		1.52	1.52	1.58		1.51	1.34	1.31
	Crystalloids				.81	.92	.92		.83	.87	.87		.69	.69	.69		.68	.63	.65
	Colloids, etc.				.85	.71	.94		.83	.82	.92		.83	.83	.89		.83	.71	.66
Per cent. reduction on raw sewage		–	47	63	82	81	84	65	84	84	85	68	85	85	86	72	89	87	86
Per cent. reduction on settled sewage		–	–	30	66	65	70	34	69	70	72	40	73	73	74	46	79	75	74
Free and saline ammonia		2.57	2.57	2.28	2.07	1.86	1.50	2.14	1.93	1.64	1.14	2.00	1.71	1.28	.64	1.93	1.43	.86	.37
Reduction of free NH_3		–	–	–	.21	.42	.78	–	.21	.50	1.00	–	.29	.72	1.36	–	.50	1.07	1.56
Per cent. reduction on raw sewage		–	–	11	19	28	42	17	25	36	56	22	33	50	75	25	44	67	86
Albuminoid ammonia		.90	.33	.315	.16	.15	.12	.315	.15	.12	.10	.30	.13	.10	.08	.26	.10	.08	.005
Reduction in albd. NH_3					.155	.165	.195		1.65	.195	.215		.17	.20	.22		.16	.18	.195
Per cent. reduction on raw sewage		–	63	65	82	83	87	65	83	87	89	67	86	89	91	74	89	91	93
Per cent. reduction on settle sewage		–	–	5	52	55	64	5	55	64	70	9	61	70	76	21	70	76	80
Nitrite and nitrate (in terms of NH_3)				.06	.12	.32	.43	.04	.23	.54	.7	.04	.36	.74	1.28	.07	.47	.93	1.64
Amount of NH_3 oxidised				–	.06	.26	.37	–	.19	.50	.73	–	.32	.70	1.24	–	.40	.86	1.57
Per cent. of NH_3 oxidised				2	5	12	17	2	9	21	30	2	14	29	50	2	18	36	64

Except in the case of the original shaken sample, two hours settlement was allowed prior to analysis.

tion very much greater differences are to be observed. This is of considerable importance, as it will be seen from later experiments that the maintenance of the activity of the sludge is considerably influenced by the extent to which the oxidation is carried.

(c) That the relation of the volume of the activated sludge to the volume of sewage treated is of importance, more especially in regard to the rate of nitrification.

This latter point is clearly shown by the results of an experiment which was actually carried out much later on in the course of this investigation and which are given on Table 1a (p.526*) and plotted in Figure 1.

It will be seen from this table and diagram that while apart from the dilution effect, the reduction in the amount of oxidisable matter is not seriously affected by the varying proportions of activated sludge, the amount and rate of nitrification are influenced in a marked degree.

OXIDATION OF MANCHESTER SEWAGE

Once having accumulated a sufficient volume of activated sludge in the manner previously described, a series of determinations were made of the effect of aeration in contact with the sludge, of various samples of Manchester sewage received at Davyhulme.

In general a proportion of one volume of activated sludge to four volumes of sewage was taken, although in the earlier experiments a much smaller proportion of sludge was employed.

A number of typical results are recorded in Table 2. In each of the experiments quoted the samples of sewage taken are twenty-four hours average samples.

Reference to this table will show that an extraordinarily high degree of purification can be obtained within a reasonable period of time by aeration in contact with the activated sludge.

On the average, aeration under the conditions of experiment for a period of six hours, with subsequent settlement, is sufficient to obtain a percentage purification as measured by the four hours Oxygen Absorption and Albuminoid Ammonia Tests, quite equal to that yielded by efficient bacterial filters. In all cases the resultant effluent is non-putrefactive on incubation.

The amount of nitrification obtained during this period depends to a certain extent on the concentration or strength of the sewage dealt with. In several instances, when treating wet weather sewage, six hours' aeration has been found sufficient to completely oxidise the ammonia present (see Table 2, Expt. No. 30). With average strength Manchester sewage the free and saline ammonia content is entirely removed in from 10 to 18 hours' aeration.

It should be mentioned that all the experiments have been worked on the fill and draw method, and it may be reasonably anticipated that equally good results would be obtained with a less aeration period, when working on a continuous flow system.

* Note: Reference to page number in original published article. This artifact continues throughout the article.

TABLE II
Oxidation of Manchester Sewage

Results in parts per 100,000	Experiment 14						Experiment 22								Experiment 25							
	Raw sewage	R.S. + sludge	After aeration in contact with sludge for:				Raw sewage	R.S.*	Original settled.		After aeration for				Raw sewage	R.S.*	Original settled		After aeration for			
											6 hours		12 hours						6 hours		12 hours	
	Shaken	Settled	4 hrs.	8 hrs.	12 hrs.	24 hrs.	Shaken	Shaken	R.S.* alone	R.S. + sludge	R.S.* alone	R.S. + sludge	R.S.* alone	R.S. + sludge	Shaken	Shaken	R.S.* alone	R.S. + sludge	R.S.* alone	R.S. + sludge	R.S.* alone	R.S. + sludge
4 hours oxygen absorption	8.80	3.83	2.09	1.40	1.26	1.17	14.90	10.63	7.46	6.09	6.57	1.83	5.20	1.31	15.32	10.06	6.97	5.91	5.26	2.20	4.91	1.29
Per cent. reduction on raw sewage	–	56	76	84	86	87	–	29	50	59	56	88	65	91	–	34	55	61	66	86	68	92
Free and saline ammonia	2.14	2.14	2.14	1.93	1.80	.96	3.43	3.00	3.00	3.00	2.57	1.31	2.14	nil	2.43	2.29	2.29	2.29	2.29	1.14	2.14	nil
Per cent. reduction on raw sewage	–	nil	nil	10	16	55	–	13	13	13	25	62	38	100	–	6	6	6	6	53	12	100
Albumnoid ammonia	.73	.345	.265	–	.12	.105	1.10	.82	.53	.54	.415	.16	.365	.135	1.07	.67	.36	.36	.44	.165	.305	.105
Per cent. reduction on raw sewage	–	53	64	–	84	86	–	25	52	51	62	85	67	88	–	37	66	66	59	85	72	90
Nitrite and nitrate (in terms of NH_3)	–	.20	.20	.32	.60	1.46	–	–	nil	.51	nil	1.80	nil	2.58	–	–	–	–	nil	1.50	nil	2.30
Per cent. oxidised	–	9	9	15	28	68			nil	15	nil	52	nil	75	–	–	–	–	nil	62	nil	95
	1 vol. sludge to 12 vols. sewage						1 vol. sludge to 4 vols. sewage								1 vol sludge to 4 vols. sewage							

* = Original sewage with 20 per cent. water added, to obviate dilution effect of sludge

	Experiment 30					Experiment 81					Experiment 86					Experiment 89				
	Raw sewage	Original settled		After 6 hrs. aeration		Raw sewage.		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for		
	Shaken	Alone	+sludge	Alone	+sludge	Shake	Settled	3 hrs.	6 hrs.	9 hrs.	Shaken	Settled	3 hrs.	6 hrs.	9 hrs.	Shaken	Settled	3 hrs.	6 hrs.	9 hrs.
4 hours oxygen absorption (total)	11.20	7.29	4.57	6.63	2.09	13.37	9.40	2.00	1.37	1.20	14.27	9.30	2.97	1.34	1.12	14.63	10.10	2.17	1.50	1.29
Crystalloids															.78			1.14	.81	.80
Colloids, etc.															.34			1.03	.69	.49
Per cent. reduction on raw sewage	–	35	59	41	81	–	30	85	90	91	–	–	79	91	92	–	31	85	90	91
Per cent. reduction on settled sewage	–	–	–	–	–	–	–	79	85	87	–	–	68	86	88	–	–	79	85	87
Free and saline ammonia	1.57	1.57	1.29	1.57	nil	3.71	3.71	2.80	2.00	1.14	3.30	3.30	2.86	2.14	1.36	4.14	4.14	3.43	2.00	1.43
Per cent. reduction on raw sewage		nil	18	nil	100	–	–	25	46	72	–	–	13	35	59	–	–	17	52	65
Albuminoid ammonia	.50	.385	.385	.385	.15	1.36	.70	.18	.105	.08	1.19	.62	.205	.10	.08	1.43	1.04	.22	.115	.105
Per cent. reduction on raw sewage		23	23	23	70	–	49	87	92	94	–	48	83	92	93	–	27	85	92	93
Per cent. reduction on settled sewage		–	–	–	–	–	–	74	85	89	–	–	69	84	87	–	–	79	89	90
Nitrite and nitrate (in terms of NH_3)		nil	.07	nil	1.70	–	–	.10	.52	.92	–	–	.04	.34	.80	–	–	.04	.80	1.14
Per cent. oxidised		nil	4	nil	100+	–	–	3	14	25	–	–	1	10	24	–	–	1	19	28
	1 vol. sludge to 3 vols. sewage					1 vol sludge to 4 vols. sewage					1 vol. sludge to 4 vols. sewage					1 vol. sludge to 4 vols. sewage				

Outdoor experiments are being commenced in which a continuous flow of a mixture of sewage and activated sludge will be passed through an aeration chamber.

COURSE OF REACTION

In all cases it has been noted that there is a rapid initial effect on the oxidisable matters both colloidal, etc., and crystalloidal, with the production in a period of about three hours of a well-clarified effluent.

The later stages of aeration are largely confined to the nitrification of the ammonium compounds.

In order to clearly illustrate this course of the reaction the results of an early experiment (see Table 2, p. 527*, Exp. 14) are quoted, in which a small proportion only of activated sludge was employed, as in the later experiments with an increased proportion of sludge the first change occurs rapidly and consequently nitrification is established so early as to partially mask the course of the reaction.

The results of this experiment are plotted in Fig. 2 from which it will be seen that the purification change follows on the lines demonstrated by Adeney.

In view of this fact it was thought of interest to endeavour to sectionise the purification process into (a) a carbonaceous fermentation and (b) a nitrification process, with the idea of comparing the results with those obtained by the original method of working.

ATTEMPT TO SECTIONISE THE OXIDATION PROCESS

For the purpose of this experiment a partially activated sludge was taken, which while it was capable of effective the first change, i.e., the removal of the oxidisable matter did not actively promote nitrification.

TABLE III
Results of Sectionised Experiments

Results in parts per 100,000		Experiment 40					Experiment 41					Experiment 45					Experiment 47				
		Raw sewage		Effluent after aeration in contact with			Raw sewage		Effluent after aeration in contact with			Raw sewage		Effluent after aeration in contact with			Raw sewage		Effluent after aeration in contact with		
		Shaken	Settled	α sludge	β sludge	αβ sludge	Shaken	Settled	α sludge	β sludge	αβ sludge	Shaken	Settled	α sludge	β sludge	αβ sludge	Shaken	Settled	α sludge	β sludge	αβ sludge
4 Hours oxygen absorption		12.68	8.92	3.26	2.28	2.34	9.70	6.63	2.86	2.06	2.00	10.06	7.90	3.48	2.70	2.09	17.14	13.00	6.00	3.28	2.94
Per cent. reduction calculated on	Raw sewage			74	82	81			71	80	80			65	75	80			65	81	83
	Settled Sewage			63	74	73			57	69	70			56	66	74			54	75	77
Free and saline ammonia		3.86			3.86	3.86	3.00			3.28	3.28	3.70			3.28	2.86	4.28			4.14	3.43
Per cent. reduction calculated on raw sewage					nil	nil				nil	nil				11	23				3	20
Albuminoid ammonia		1.70	1.04		.36	.36	1.10	.50		.25	.245	1.10	.70		.405	.35	1.61	1.02		.405	.45
Per cent. reduction calculated on	Raw sewage				79	79				77	78				63	68				75	72
	Settled sewage				65	65				50	51				42	50				60	56
Nitrite and nitrate (in terms of NH_3)					.12	.36				.11	.17				.12	.16				.04	.06
Per cent. of ammonia oxidised					3	9				4	6				3	4				1	1
Temperature									6.2°C.			5.5°C.		7.5°C.	7.5°C.	9.0°C.					

α Sludge = Partially activated sludge - non-nitrifying
β and αβ Sludge = Thoroughly activated sludge - capable of vigorously promoting nitrification

Three large bottles were used.

(1) Containing a certain volume of this partially activated sludge (α sludge).

(2) (β sludge and (3) (αβ sludge) Containing a similar volume of thoroughly activated sludge which had been proved capable of vigorously promoting nitrification.

The experiment was carried out in the following manner. Equal volumes of the same sample of sewage were introduced into bottles Nos. 1 and 3 and aeration commenced. At the end of two hours' aeration the contents of bottle No. 1 were allowed to settle for two hours and the supernatant liquor was decanted into bottle No. 2. Another sample of sewage was then added to bottle No. 1 and aeration resumed. After a further two hours' aeration the contents of each of the bottles were allowed to settle for two hours.

In this manner an effluent was obtained from bottle No. 2 which had received two hours' aeration in contact with the partially activated (α) sludge and a further two hours' aeration in contact with actively nitrifying (β) sludge, and from bottle No. 3 an effluent which had been aerated for six hours in contact with thoroughly activated (αβ) sludge.

This method of operation was repeated as often as was reasonably practicable within the twenty-four hours, with the result that the partially activated sludge and nitrifying sludge (bottles Nos. 1 and 2) dealt with three volumes of sewage each working day, as compared with the two volumes treated by the thoroughly activated sludge.

The results obtained during the course of this experiment are given in Table 3 (p. 528*).

Reference to this table will show that there was no very material difference in the effluents yielded by the two methods of working.

At the same time it will be seen that the results with the ordinary activated sludge show a marked deterioration as compared with those previously obtained, particularly in regard to the amount of nitrification.

In the absence of any other altered factor this decreased efficiency might reasonably have been ascribed to the fact that while in the previous experiments any particular sample of sewage was always aerated in contact with the activated sludge for from 20 to 24 hours to ensure complete nitrification, in the present case, at the end of first six hours' aeration the purified liquor was replaced with a further sample of sewage.

Unfortunately, however, during the course of this series of experiments, low temperatures were experienced, not only with the sewage dealt with, but also in the laboratory, owing to trouble with the heating apparatus.

It was thus impossible to say to what extent, if any, either of these two factors influenced the results obtained, and instead of continuing sectionised experiments on these lines, attention was diverted to the study of the questions involved.

Before leaving this part of the subject it may be stated that while the above experiment failed to determine the possibilities of sectionising the oxidation process the matter has not been lost sight of, and it is the intention of the authors to return to this question at an early date.

MAINTENANCE OF SLUDGE ACTIVITY

In order to determine how far the purification effect of the activated sludge was influenced by not carrying the oxidation process to complete nitrification the following experiment was carried out.

Activated sludge of known efficiency was divided into four equal volumes and placed into separate bottles, viz., A, B, C, and D, each of four litres capacity and containing a sample of the same sewage.

The following procedure was then adopted:

Bottle A. Sewage aerated for six hours in contact with activated sludge, followed by two hours' settlement, sample of purified effluent taken, remaining contents of bottle aerated for 14 to 16 hours longer.

Bottle B. Sewage aerated in contact with activated sludge for ten hours, sample taken at end of six hours.

This operation was repeated twice during the twenty-four hours.

Bottle C. Sewage aerated in contact with activated sludge for six hours, sample taken and purified effluent removed as in A. Sludge was then aerated for the remainder of the day.

Bottle D. Sewage aerated for six hours in contact with activated sludge, followed by two hours' settlement and subsequent removal of purified effluent by decantation.

This operation was repeated three times during the twenty-four hours.

It will be seen that with similar aeration the sludge in bottle D. dealt with three volumes of sewage to two volumes in case of bottle B. and one volume in the case of bottle A., while the sludge in bottle C. also only dealt with one volume of sewage, but the amount of air required for aeration was reduced by the fact that for from 14 to 16 hours the sludge alone was aerated.

A series of results obtained during the course of this experiment are given in Table 4 (p. 528*).

The results of the first experiment of this series (Experiment 54) are given in order to show that the activity of the sludge in each case was identical. As

TABLE IV
Oxidation of Manchester Sewage Under Various Conditions

A = 1 Filling with 20 hours aeration.
B = 2 Fillings with 10 hours aeration each
C = Filling with 6 hours aeration with subsequent aeration of sludge alone
D = 3 Fillings with 6 hours aeration each

		FIRST WEEK																							
Results in parts per 100,000		Experiment 54						Experiment 55						Experiment 56						Experiment 57					
		Original		After 6 hours aeration				Original		After 6 hours aeration				Original		After 6 hours aeration.				Original		After 6 hours aeration.			
		Shaken	Settled	A	B	C	D	Shaken	Settled	A	B	C	D	Shaken	Settled	A	B	C	D	Shaken	Settled	A	B	C	D
4 Hours oxygen absorption		15.90	9.30	1.71	1.77	1.91	1.69	14.74	9.60	1.86	2.09	2.57	2.00	13.60	10.50	1.66	1.83	2.28	2.09	16.80	9.90	1.48	1.52	1.86	2.00
Per cent. reduction calculated on	Raw sewage			89	89	88	89			87	86	83	86			88	87	83	85			91	91	89	88
	Settled sewage			82	81	79	82			81	78	73	79			84	82	78	80			85	85	81	80
Free and saline ammonia		4.60	–	2.86	2.86	2.86	2.70	3.60	–	2.57	3.43	3.30	3.15	3.50	–	1.30	2.30	2.36	2.30	3.30	–	1.57	2.43	2.00	2.57
Per cent. reduction calculated on raw sewage				38	38	38	41			29	5	8	12			65	37	36	37			52	26	39	22
Albuminoid ammonia		1.19	.73	.25	.26	.265	.25	1.04	.73	.22	.22	.305	.205	.84	.50	.28	.205	.205	.35	.87	.47	.135	.135	.15	.18
Per cent. reduction calculated on	Raw sewage			78	78	78	79			79	79	71	80			67	76	76	58			84	84	83	79
	Settled sewage			66	64	64	66			70	70	58	72			44	59	59	30			71	71	68	62
Nitrite and nitrate (in terms of NH_3)		–	–	.91	.91	.86	1.00	–	–	.86	.06	.14	.06	–	–	1.02	.12*	.12	nil	–	–	.71	.17	.20	.07
Per cent. of ammonia oxidised				20	20	19	22			24	2	4	2			29	3	3	nil			22	3	6	2

		SECOND WEEK												THIRD WEEK											
		Experiment 59						Experiment 62						Experiment 65						Experiment 66					
		Shkn.	Sttld.	A	B	C	D	Shkn.	Sttld.	A	B	C	D	Shkn.	Sttld.	A	B	C	D	Shkn.	Sttld.	A	B	C	D
4 Hours oxygen absorption total		15.20	10.50	2.09	1.92	2.03	2.26	16.68	11.00	1.46	2.20	1.52	3.37	14.86	10.00	1.74	2.03	1.71	2.57	15.66	11.20	1.46	1.74	1.51	2.74
Crystalloids			6.57	1.00	1.06	.94	1.34		6.63	–	–	–	–		5.37	1.09	1.12	1.11	1.31		6.52	1.06	1.03	.97	1.71
Colloids, etc.			3.93	1.09	.86	1.09	.92		4.37	–	–	–	–		4.63	.66	.91	.60	1.26		4.68	.40	.71	.54	1.03
Per cent. reduction calculated on	Raw sewage			86	87	87	85			91	87	91	80			88	86	89	83			91	89	90	83
	Settled sewage			80	82	81	79			87	80	86	69			83	80	83	74			87	84	87	76
Free and saline ammonia		3.57	–	2.14	2.72	2.14	2.86	3.86		2.14	3.70	2.28	4.14	3.93		2.43	3.14	2.00	3.43	3.60		1.70	2.30	1.70	3.15
Per cent. reduction calculated on Raw sewage				40	24	40	20			45	4	41	–			38	20	49	13			53	36	52	13
Albuminoid ammonia		1.16	.62	.18	.18	.18	.205	1.27	.79	.205	.265	.18	.39	1.10	.53	.165	.22	.15	.28	1.58	.62	.105	.165	.105	.25
Per cent. reduction calculated on	Raw sewage			84	84	84	82			84	79	86	69			85	80	86	73			93	90	93	84
	Settled sewage			71	71	71	68			74	67	77	57			69	58	72	47			83	73	83	60
Nitrite and nitrate (in terms of NH_3)				396	.38	.60	.09			.17	.03	.22	.04			.20	nil	.19	nil			.36	.03	.33	nil
Per cent. of ammonia oxidised				27	11	17	3			4	1	6	1			5	nil	5	nil			10	1	9	nil

*12 is in the original article. Believed by the editors of this publication to be 0.12.

the experiment proceeded, while the oxidation effect as measured by the oxygen absorption test differed only slightly according to the method of working, a marked difference was observed in the amount of nitrification. In the case of the sludge contained in Bottle A., which only dealt with one sample of sewage per day, the nitrification was maintained as in the first experiment, but in each of the other methods of working the nitrification was seriously impaired, in fact almost inhibited.

It was observed, however, that the sludge in Bottle C. after the removal of the oxidised effluent, had not been well aerated during the period of working. Accordingly means were adopted to improve this aeration. The results obtained during the second and third week's working, of which typical examples are given (Experiments 59-66) show that the effect of this improved aeration was to maintain the activity of the sludge and consequently to yield similar results to those obtained when the whole of the sewage and sludge was aerated for 22 hours.

TABLE V
Effect of Temperature

Results in parts per 100,000		Temp.	Experiment 93					Experiment 94					Experiment 95					Experiment 96				
			Raw sewage.		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for		
			Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settked	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.
4 Hours oxygen absorption	Total	5° C	10.63	7.370	2.23	1.88	1.60	15.31	9.00	3.03	2.74	2.69	13.94	7.80	3.09	2.72	2.83	11.80	8.50	2.80	2.63	2.28
	Crystalloids	5° C		5.26	1.16	.91	.88		5.09	1.44	1.26	1.17		4.34	1.32	1.06	1.04		4.80	1.23	1.09	1.00
	Colloids, etc.	5° C		2.44	1.07	.97	.72		3.91	1.59	1.48	1.52		3.46	1.77	1.66	1.79		3.70	1.57	1.54	1.28
Total		15° C			1.57	1.37	1.29			2.29	1.48	1.49			1.97	1.40	1.17			1.77	1.37	1.17
Crystalloids		15° C			.88	.83	.83			1.26	.94	.96			1.16	.83	.77			1.16	.81	.71
Colloids, etc.		15° C			.69	.54	.46			1.03	.54	.53			.81	.57	.40			.61	.56	.46
Per cent. reduction calculated on	Raw sewage	5° C			79	82	85			80	82	82			78	81	80			76	78	81
	Do.	15° C			85	87	88			85	90	90			86	90	92			85	88	90
	Settled sewage	5° C			71	76	79			66	70	70			60	65	64			67	69	73
	Do.	15° C			80	82	83			75	84	84			75	82	85			79	84	86
Colloids, etc, removed		5° C			1.37	1.47	1.72			2.32	2.43	2.39			1.69	1.80	1.67			2.13	2.16	2.42
		15° C			1.75	1.90	1.98			2.88	3.37	3.38			2.65	2.89	3.06			3.09	3.14	3.24
Free and Saline ammonia		5° C	4.43	4.43	4.43	4.00	3.71	3.86	3.86	3.57	3.36	3.29	2.50	2.50	2.64	2.36	2.21	3.28	3.28	2.64	2.64	2.43
		15° C			3.80	3.07	2.43			3.07	2.28	1.36			1.93	1.12	.23			2.43	2.07	1.14
Per cent. reduction		5° C			nil	10	16			7	13	15			nil	5	12			20	20	26
		15° C			14	30	45			20	41	65			23	55	91			26	37	65
Albuminoid ammonia		5° C	.98	.54	.27	215	.165	1.16	.62	.335	.37	.42	1.30	.56	.40	.35	.35	.98	.46	.28	.305	.27
		15° C			.165	.13	.065			.23	.205	.165			.215	.15	.08			.15	.17	.115
Per cent. reduction calculated on	Raw sewage	5° C			72	78	83			71	68	64			69	73	73			71	69	72
	Do.	15° C			83	87	93			80	82	86			83	88	94			85	83	88
	Settled sewage	5° C			50	60	69			46	40	32			28	37	37			39	34	41
	Do.	15° C			69	76	88			63	67	73			62	73	86			67	63	75
Nitrite and nitrate		5° C			.07	.17	.26			.04	.06	.06			.03	.04	.14			.14	.07	.12
(in terms of NH_3)		15° C			.07	.54	.97			.04	.40	.86			.10	.60	1.14			.04	.27	.54
Per cent of ammonia		5° C			2	4	6			1	2	2			1	2	6			4	2	4
Oxidised		15° C			2	12	22			1	10	22			4	24	46			1	8	16

It will be seen that the results obtained with the sludge contained in Bottle D. gradually deteriorate with the total inhibition of nitrification. In the case of the sludge in Bottle B. the falling off in its activity was not so marked, although the nitrification was considerably reduced.

It is evident from the results of this experiment that the activity of the sludge is gradually diminished, when working on the fill and draw method, if it is called upon to treat further samples of crude sewage, prior to the complete nitrification of the previous sample dealt with.

The results also show that this difficulty may be overcome by simple aeration of the sludge alone, until the free and saline ammonia content is removed.

INFLUENCE OF TEMPERATURE

In order to determine the influence of temperature on the oxidation process a series of experiments extending over several weeks were carried out on the aeration of Manchester sewage in contact with activated sludge at temperatures varying from 5°-30°C. A number of typical results are given in Tables 5, 6, and 7 (pp. 529-531*).

It should be mentioned that in all the experiments quoted in this section of the work, the activated sludge dealt with one volume only of sewage per day. Samples were taken after three, six and nine hours' aeration respectively and then aeration was resumed until the next dose of sewage was treated.

It was found that the oxidation process could be maintained within a fairly wide range of temperature. At temperatures constantly below 10°C., a very marked deterioration in the results was observed, especially with regard to the removal of the colloidal matters. Also nitrification was practically inhibited within a period of nine hours' aeration. It is fairly evident that this effect would be accumulative over a prolonged period of working with the probable eventual production of inactive sludge.

At temperatures varying from 12 - 14°C., which is the usual air temperature of the laboratory, the activity of the sludge was well maintained with the production at all times of a satisfactory effluent.

It was further observed that with a temperature of 20°C. equally good results were obtained as regards the removal of the oxidisable matter and clarification effect, with an increase in nitrification during the later periods of aeration.

Working with temperatures as high as 30°C. it was found that the initial clarification effect was to some extent interfered with and that the effluent resulting from subsequent settlement showed a slight deterioration as compared with that obtained when working at temperatures from 12 - 20°C. This effect became less marked as the aeration continued and once nitrification was established it proceeded at a slightly increased rate as compared with that obtained at temperatures below 20°C.

OXIDATION OF VARIOUS SEWAGES

It was thought of interest to compare the results obtained with Manchester sewage, which contains an undue proportion of a variety of trade effluents, with those of more purely domestic sewage.

Samples of sewage were therefore obtained from the following sewage works:

(a) Moss Side Sewage Works	Urmston
(b) Withington Sewage Works	Chorlton
(c) Gorton Sewage Works	Gorton
(d) Macclesfield Sewage Works	Prestbury

In view of the difficulty of obtaining average representative samples of sewage from the above works, it was decided to work with samples of maximum strength, i.e., in each case the samples were taken in the after, and con-

TABLE VI
Effect of Temperature

Results in parts per 100,000		Temp.	Experiment 73					Experiment 74					Experiment 75					Experiment 76				
			Raw sewage		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for		
			Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.
4 Hours oxygen absorption		13°C	12.11	8.30		1.46		10.50	6.40	1.26	1.26	.91	10.30	7.40	1.51	1.31	1.09	12.10	8.80	1.66	1.37	1.37
		20°C				1.49				1.23	1.29	.91			1.63	1.31	1.03			1.63	1.31	1.40
		30°C				2.20				2.03	1.97	1.51			1.91	1.49	1.89			2.11	1.71	–
Per cent. reduction calculated on	Raw sewage	13°C				88				88	88	91			85	87	89			86	89	89
	Do.	20°C				88				88	88	91			84	87	90			87	89	88
	Do.	30°C				82				81	81	86			81	86	82			83	86	80
	Settled sewage	13°C				82				80	80	86			80	82	85			81	84	84
	Do.	20°C				82				81	80	86			78	82	86			82	85	84
	Do.	30°C				74				68	69	76			74	80	75			76	81	–
Free and saline ammonia		13°C	3.80			2.14		2.14		1.43	.71	nil	2.56		2.14	1.43	.54	2.56		2.14	1.64	.79
		20°C				2.43				1.29	.23	nil			2.14	1.29	.20			2.21	1.57	.36
		30°C				2.57				1.57	.57	nil			2.36	1.71	.29			2.29	1.93	.60
Per cent. reduction calculated on raw sewage		13°C				41				33	67	100			16	44	79			16	36	69
		20°C				36				40	89	100			16	50	92			14	39	86
		30°C				32				27	73	100			8	33	89			11	25	77
Albuminoid ammonia		13°C	.96	.61		.105		.84	.36	.13	.10	.08	.70	.44	.165	.13	.095	.96	.64	.16	.105	.08
		20°C				.105				.10	.10	.08			.18	.115	.095			.15	.105	.08
		30°C				.265				.22	.165	.11			.20	.165	.105			.20	.15	.12
Per cent. reduction calculated on	Raw sewage	13°C				89				85	88	90			76	81	86			83	89	92
	Do.	20°C				89				88	88	90			74	84	86			84	89	92
	Do.	30°C				72				74	80	87			71	76	85			79	84	88
	Settled sewage	13°C				83				64	72	78			63	70	78			75	84	88
	Do.	20°C				83				72	72	78			59	74	78			77	84	88
	Do.	30°C				57				39	54	69			55	63	76			69	77	81
Nitrite and nitrate (in terms of NH_3)		13°C				.63				.10	.44	1.34			.11	.81	1.19			.10	.50	1.21
		20°C				.21				.17	.76	1.31			.09	.56*	1.43			nil	.57	1.64
		30°C				.06				.09	.60	1.17			.03	.31	1.24			.03	.21	1.00
Per cent. of ammonia oxidised		13°C				17				5	21	63			4	32	46			4	19	47
		20°C				6				8	32	61			3	20	56			nil	20	64
		30°C				2				4	28	55			1	12	48			1	8	39

*The original article had 56; an obvious mistake.

sequently this fact must be borne in mind in considering the results which are given in Tables 8 and 9.

In connection with these results attention should be drawn to the following:

(A) MOSS SIDE SEWAGE

Experiments on this sewage were carried out in the earlier part of the investigation and consequently the proportion of activated sludge to the sewage treated was considerably less that in the later experiments. Further in order to more clearly demonstrate the actual oxidation effect of the activated sludge in the control experiment the sewage aerated alone was diluted with a volume of tap water equal to that of the sludge employed in the experiment. The analytical figures given for the shaken sample of sewage refer to the sample actually taken plus the diluting water.

Sample A

This was a Monday afternoon sample, and obviously contained an excessive amount of soapy matter. It will be seen from the table that this soapy matter exerted a considerable emulsification or deflocculation effect as shown by the increase in the four hours' oxygen absorption and albuminoid ammonia of the "original" settled sample after mixing with the activated sludge, and in consequence of this effect the results obtained were not so striking as the previous ones, although considerable nitrification was obtained within six hours. It would appear that in the case of sewages containing undue proportion of soapy matter, preliminary treatment with lime might be advantageously employed.

Sample B

It will be seen from the analytical returns that this was a stronger sewage than the preceding one, but contained less soap. In this case no preliminary emulsification was observed and a much greater purification was effected in the earlier stages of aeration.

(B) WITHINGTON SEWAGE

The sewage from the Withington works was considerably weaker than that received from the Moss Side works and consequently as would be anticipated, complete oxidation ensued within a greatly reduced period of aeration. It may be noted that two hours' aeration in contact with activated sludge, with subsequent settlement was sufficient to produce an effluent which was non-putrefactive on incubation.

TABLE VII
Effect of Temperature

Results in parts per 100,000		Temp.	Experiment 79					Experiment 80					Experiment 81					Experiment 82				
			Raw sewage.		After aeration for			Raw sewage		After aeration for			Raw sewage		After aeration for			Raw sewage.		After aeration for		
			Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.	Shaken	Settled	3 Hrs.	6 Hrs.	9 Hrs.
4 Hours oxygen absorption		13°C	11.66	8.30	1.80	1.09	1.03	11.77	8.40	2.20	1.43	1.20	13.37	9.40	2.00	1.37	1.20	13.60	8.80	1.77	1.31	1.29
		20°C			2.17	1.28	1.11			1.97	1.54	1.26			2.37	1.37	1.34			2.06	1.43	1.12
		30°C			3.26	2.06	1.43			2.60	1.77	1.40			3.26	2.06	1.71			2.51	1.69	1.66
Per cent. reduction calculated on	Raw sewage	13°C			85	91	91			81	88	90			85	90	91			87	90	90
	Do.	20°C			81	89	90			84	87	89			82	88	90			85	89	92
	Do.	30°C			72	82	88			78	85	88			76	85	87			82	88	88
	Settled sewage	13°C			78	87	88			74	83	86			79	85	87			80	85	85
	Do.	20°C			74	85	87			77	82	85			75	83	86			77	84	87
	Do.	30°C			61	75	83			69	79	83			65	78	82			72	81	81
Free and saline ammonia		13°C	2.86	2.86	1.93	1.14	.39	3.20	3.20	2.57	1.93	1.57	3.70	3.70	2.80	2.00	1.13	3.70	3.70	2.57	1.71	1.14
		20°C			2.00	.93	nil			2.36	1.29	nil			2.93	2.21	1.00			2.64	1.64	.64
		30°C			2.43	1.64	.53			2.57	1.93	.80			3.07	2.86	1.50			2.80	2.22	.60
Per cent. reduction calculated on raw sewage		13°C			33	60	86			20	40	51			24	46	69			31	54	69
		20°C			30	67	100			26	60	100			21	40	73			20	56	83
		30°C			15	42	82			20	40	75			17	23	59			24	40	84
Albuminoid ammonia		13°C	.84	.50	.205	.095	.065	.98	.50	.215	.12	.10	1.36	.70	.18	.105	.08	.98	.62	.165	.105	.085
		20°C			.23	.105	.07			.205	.13	.10			.22	.13	.08			.195	.105	.085
		30°C			.45	.22	.12			.23	.165	.12			.405	.25	.18			.23	.12	.085
Per cent. reduction calculated on	Raw sewage	13°C			76	80	92			78	88	90			87	92	94			73	89	91
	Do.	20°C			73	87	92			79	87	90			84	91	94			80	89	91
	Do.	30°C			46	74	86			77	73	88			70	82	87			77	88	91
	Settled sewage.	13°C			59	81	87			57	76	80			74	85	89			73	83	86
	Do.	20°C			54	79	86			59	74	80			69	81	89			69	83	86
	Do.	30°C			10	56	76			54	67	76			42	64	74			63	81	86
Nitrite and nitrate (in terms of NH_3)		13°C			.06	1.14	1.79			.06	.43	.69			.10	.51	.92			.10	.31	1.20
		20°C			.03	1.14	1.83			.04	.69	1.83			nil	.28	1.06			nil	.46	1.48
		30°C			nil	.57	1.14			.03	.31	.83			nil	.20	.52			nil	.20	1.20
Per cent. of ammonia oxidised		13°C			2	40	63			2	14	22			3	14	25			3	8	32
		20°C			1	40	64			1	22	57			nil	8	29			nil	12	40
		30°C			0	20	40			1	10	26			nil	5	14			nil	5	32

(C) GORTON SEWAGE

It is evident from the analysis given in Table 9 that the sample dealt with was an exceedingly strong sewage. With three hours' aeration a remarkable change was effected as measured by the usual tests. After six hours' aeration an extremely well clarified effluent was obtained, but unfortunately owing to an accident it is not possible to give the chemical analysis.

Despite the highly concentrated nature of this sewage 9 hours' aeration was sufficient to yield an entirely satisfactory effluent showing a rather higher percentage purification on the raw sewage than that which is yielded by efficient bacterial filters. Within a period of 9-18 hours the whole of the free and saline ammonia was removed from the sewage.

(D) MACCLESFIELD SEWAGE

The sample of Macclesfield sewage was very turbid and was said to contain waste refuse of a mucilaginous character derived from silk works. With this type of sewage the oxidation proceeds satisfactorily although the percentage purification effected is not quite so good as in the case of Gorton sewage. A well clarified effluent was obtained with six hours' aeration in contact with activated sludge and subsequent settlement. The whole of the free saline ammonia was removed within a period of sixteen hours.

QUALITY OF EFFLUENTS

It has frequently been observed that effluents obtained from the oxidation process, while having a comparatively low oxygen absorption as measured by the permanganate test and a low albuminoid ammonia content, may absorb an undue proportion of dissolved oxygen on incubation for a number of days. When once the free and saline ammonia content of an effluent is very considerably lowered even without material alteration in the four hours' oxygen absorption and albuminoid ammonia figures, the amount of dissolved oxygen absorbed by the effluent is enormously reduced. It would thus appear that the stage to which nitrification has advanced is one of the factors governing the amount of dissolved oxygen absorbed by an effluent. Experiments are in progress with a view to throwing further light on this subject, but the data so far available is insufficient to allow of any definite conclusions. It is quite certain however, that in the effluents obtained, the amount of oxygen absorbed from permanganate bears no relation whatever to the amount of dissolved oxygen absorbed.

ACTIVATED SLUDGE

Activated sludge accumulated in the manner previously described is quite inoffensive, dark brown in colour and flocculent in character, and despite its low specific gravity separates from water or sewage at a rapid rate. After prolonged settlement the activated sludge however rarely contains less than 95 per cent of water.

TABLE VIII
Oxidation of Various Sewages

Moss Side Sewage																							
Results in parts per 100,000		Sample A											Sample B										
		Original			After aeration for								Original			After aeration for							
		Shaken	After 2 hrs. settlement		3 Hours		6 Hours		12 Hours		24 Hours		Shaken	After 2 hrs. settlement		3 Hours		6 Hours		12 Hours		24 Hours	
			Alone	+ sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge		Alone	+ sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge	Sewage	Sewage + sludge
4 Hours oxygen absorption (total)		9.83	8.57	10.88	8.71	5.55	8.88	4.00	5.76	2.16	3.60	1.49	11.66	9.00	8.10	8.50	2.74	7.60	2.34	4.16	1.54	3.43	1.51
Crystalloids			4.06	3.88	3.68	1.62	3.54	1.26	2.00	.96	–	–		4.23	3.89	2.86	1.57	2.967	1.11	–	–	–	–
Colloids, etc.			4.51	7.00	5.03	3.93	5.34	2.74	3.76	1.20	–	–		4.77	4.21	5.61	1.17	4.63	1.23	–	–	–	–
Per cent. reduction calculated on	Shaken sample		13	nil	10	43	8	59	41	78	63	85		23	30	27	77	35	80	64	87	71	87
	Settled sample		–	nil	nil	35	nil	53	33	75	58	83		–	10	6	70	16	74	54	83	62	83
Free and saline ammonia		6.00	6.00	6.14	6.07	5.43	5.71	4.43	5.14	3.28	3.57	1.14	6.00	6.00	6.00	5.57	4.29	5.14	3.29	3.43	1.21	2.86	nil
Per cent. reduction			–	nil	nil	10	5	26	11	45	40	81		–	nil	7	29	14	45	43	80	52	100
Albuminoid ammonia		1.19	.96	1.36	.90	.67	.83	.33	.74	.29	.585	.15	2.20	1.27	1.26	1.09	.40	.83	.22	.79	.16	.63	.10
Per cent. reduction calculated on	Shaken sample		19	nil	24	44	30	72	38	76	51	87		42	43	50	82	62	90	64	93	71	95
	Settled sample		–	nil	6	30	13	66	23	70	39	84		–	1	11	69	35	83	38	89	50	92
Nitrite and nitrate (in terms of NH_3)			nil	.12	nil	.42	nil	.98	nil	1.43	nil	3.92		nil	.07	nil	.50	nil	1.14	nil	2.57	nil	3.50
Per cent. of ammonia oxidised			nil	2	nil	7	nil	16	nil	24	nil	65		nil	1	nil	8	nil	19	nil	43	nil	58

Withington Sewage																			
		Original		After aeration for								Original		After aeration for					
		Raw sewage		2 Hours		4 Hours		6 Hours		9 Hours		Raw sewage		3 Hours		6 Hours		7 Hours	
		Shaken	Settled	Alone	+ sludge	Alone	+ sludge	Alone	+ sludge	Alone	+ sludge	Shaken	Settled	Alone	+ sludge	Alone	+ sludge	Alone	+ sludge
4 Hours oxygen absorption	Total	5.12	3.77	2.86	1.28	2.17	1.03	2.06	1.00	1.71	1.00	5.60	2.92	2.29	1.53	1.88	1.20	1.88	1.26
	Crystalloids		1.49	1.17	.54	.88	.56	.94	.51					–	–	–	–	.91	.69
	Colloids, etc.		2.28	1.69	.74	1.29	.47	1.12	.49					–	–	–	–	.97	.57
Per cent. reduction calculated on	Shaken sample		26	44	75	58	80	60	80	67	80	–	48	59	73	67	79	67	78
	Settled sample		–	24	66	42	73	45	74	55	74	–	–	22	48	36	59	36	57
Free and saline ammonia		2.78	2.78	2.28	1.80	2.14	1.07	2.14	.64	2.21	.09	2.29	1.86	1.36	1.29	1.40	.26	1.36	nil
Per cent. reduction		–	–	18	35	23	62	23	77	21	97	–	19	41	44	39	89	41	100
Albuminoid ammonia		.815	.50	.405	.15	.405	.08	.38	.08	.42	.07	.70	.30	.285	.15	.23	.06	.15	.05
Per cent. reduction calculated on	Shaken sample	–	39	50	82	50	90	53	90	48	91	–	57	59	79	67	91	79	93
	Settled sample	–	–	19	70	19	84	24	84	16	86	–	–	5	50	23	80	50	83
Nitrite and nitrate (in terms of NH_3)				.23	.50	.215	1.31	.06	1.50	.09	1.72			nil	.46	nil	1.09	nil	1.37
Per cent. of ammonia oxidised				8	18	8	47	2	54	3	62			nil	20	nil	48	nil	60

A remarkable separation of the water from the sludge can be readily obtained by treatment of fine grade strainers with the production of a sludge of the consistency of a stiff jelly.

Gelatine counts have shown a bacterial content of at least 30 million organisms per cubic centimetre. In addition, the sludge by reason of its nitrifying power must of necessity contain a large number of nitrifying organisms.

It should also be noted that a fairly large number of a variety of protozoa are to be found and we are indebted to Mr. James Crabtree for assistance in regard to the enumeration and identification of these higher forms of life. It does not however contain any algal growths.

The chemical analysis of an average sample of the activated sludge is as follows:

	Percentage
Organic matter	64.7
Mineral matter	35.3
Total nitrogen (N)	4.6
Phosphate (P_4O_3)	2.6
Matter extracted by CCl_4	5.8

Attention should be drawn to the abnormally high percentage of nitrogen as compared with ordinary un-oxidised sewage sludge.

TABLE IX
Oxidation of Various Sewages

Results in parts per 100,000		Gorton						Macclesfield							
		Raw sewage		After aeration for				Raw sewage		After aeration for					
				3 Hours		9 Hours				3 Hours		6 Hours		9 Hours	
		Shaken	Settled	Alone	+ sludge	Alone	+ sludge	Shaken	Settled	Alone	+ sludge	Alone	+ sludge	Alone	+ sludge
4 Hours Oxygen absorption	Total	15.43	11.70	9.49	2.57	6.86	1.28	12.57	9.10	8.50	2.72	7.30	1.66	6.50	1.37
	Crystalloids		6.28	4.57	1.54	2.52	.80		4.06	3.66	1.12	2.51	.80	2.46	.74
	Colloids, etc.		5.42	4.92	1.03	4.34	.48		5.04	4.84	1.60	4.70	.86	4.04	.63
Per cent. reduction calculated on	Raw sewage		24	38	83	55	92		27	32	78	42	87	48	89
	Settled sewage			19	78	41	89			7	70	20	82	29	85
Colloids, etc., removed				.50	4.39	1.08	4.94			.20	3.44	.25	4.18	1.00	4.41
Free and saline ammonia		5.72	5.72	5.72	4.26	4.57	1.43	3.80	3.80	3.71	3.00	3.71	2.21	3.71	1.00
Per cent. reduction				0	25	20	75			2	21	2	42	2	74
Albuminoid ammonia		2.01	1.50	1.37	.42	1.03	.15	1.62	1.16	–	.50	–	.265	–	.18
Per cent. reduction calculated on	Raw sewage		25	31	79	48	92		28		69		84		89
	Settled sewage			9	72	31	90				57		77		85
Nitrite and nitrate (in terms of NH_3)				.03	.04	.06	1.22			nil	.10	nil	.50	nil	1.14
Per cent. of ammonia oxidised				1	1	1	21			0	3	0	13	0	30

TABLE X
Effect of Sterilisation of Sludge

					Sewage (diluted)* alone				Sewage + sterile sludge				Sewage + active sludge			
		Raw sewage		Diluted* raw sewage	Original	After aeration for			Original	After aeration for			Original	After aeration for		
		Shaken	Settled	Shaken	Settled	3 Hrs.	9 Hrs.	18 Hrs.	Settled	3 Hrs.	9 Hrs.	18 Hrs.	Settled	3 Hrs.	9 Hrs.	18 Hrs.
4 Hours oxygen absorption	Total	11.77	8.10	8.20	6.12	5.92	5.43	3.77	10.00	10.52	10.17	7.20	4.12	1.63	1.20	1.14
	Crystalloids			3.88	4.00	3.54	2.86	5.63	5.76	5.26	3.40	2.50	.94	.77	.77	
	Colloids, etc.			2.24	1.92	1.89	.91	4.37	4.76	4.91	3.80	1.62	.69	.43	.37	
Free and saline ammonia		3.30	3.30	2.95	2.86	2.86	2.36	2.07	2.95	2.86	2.64	2.50	2.95	2.71	1.72	.57
Albuminoid ammonia		.87	.42	.61	.315	.305	.33	.26	2.50	2.23	2.04	1.81	.215	.105	.12	.105
Nitrite and nitrate (in terms of NH_3)					.06	.06	nil	.03	.12	nil	nil	nil	.09	.12	.58	1.14

*Original sewage diluted with a volume of water equivalent to the volume of sludge employed in the experiment.

NATURE OF REACTION

Up to the present the authors have not seriously investigated the actual mechanism of the process and consequently no attempt has been made to differentiate between the part played by physical, chemical and biological agencies, all of which are doubtless, in varying degrees responsible for the total purification change. As to whether the protozoa content has any influence or not on the extent of the purification has yet to be determined, although it would appear that they rather indicate a particular condition of the activated sludge than play an important part in the changes effected.

While as previously stated no serious attempt has been made to determine to what extent bacterial agencies are concerned with the purification process, an experiment has been made on the effect produced by the aeration of sewage in contact with activated sludge both before and after steam sterilisation.

The results of this experiment are given in Table 10, from which it will be seen that activated sludge when sterilised under these conditions had no purification effect whatever (see p. 533*).

It must be borne in mind, however, that the physical characteristics of the activated sludge may be seriously altered by the steam process and consequently some other method of sterilisation, e.g., by means of ultra-violet rays might yield somewhat different results.

SUMMARY AND CONCLUSIONS

The foregoing investigations have established:

1. That the resultant solid matter obtained by prolonged aeration of sewage, which has been termed activated sludge, has the property of enormously increasing the purification effected by simple aeration of sewage, or in other words it greatly intensifies the oxidation process.
2. The extent of the accelerating effect depends upon the intimate manner in which the activated sludge is brought into contact with, and upon its proportion to, the sewage treated.
3. That in order to maintain the sludge at its highest efficiency it is necessary that there should not be at any time an accumulation of unoxidised sewage solids.
   It is not necessary that the sewage should be kept in contact with the activated sludge until such conditions obtain, as its activity may be maintained by suitable aeration of the activated sludge alone.
4. That temperature exerts a considerable influence on the oxidation process. The purification effected is seriously diminished at temperatures constantly below 10°C. Up to 20-24°C. no material difference in the clarification effect and general purification has been observed although the nitrification change proceeds more rapidly as the temperature rises. At higher temperatures the clarification effect is somewhat interfered with during the earlier period of aeration, with a consequent delay in the establishment of nitrification. Subsequently the rate of nitrification somewhat increases.
5. That under the conditions of experiment a well oxidised effluent can be obtained by the aeration of average strength Manchester sewage in contact with activated sludge for a period of from six to nine hours. The percentage purification effected as measured by the usual tests is

at least equal to that obtained by the treatment of sewage on efficient bacterial filters.

The period of aeration naturally depends upon the strength of the sewage treated and the degree of purification required.

6. That the activated sludge differs very considerably in character and composition from ordinary sewage sludge.

It is in a well oxidised condition and consequently entirely innocuous, can be readily drained on straining filters and possess a high nitrogen content.

The scope of the inquiry has been up to the present largely confined to laboratory investigations and while the results obtained have shown conclusively that the purification process can be readily maintained, a large amount of the further research is required in order to obtain a thorough knowledge of the character and mechanism of the changes taking place, which will be essential for the efficient control of the process.

The method employed in producing a satisfactory purification of sewage is however of so simple a nature, that there would not appear to be any insuperable difficulties in translating the experiments described, on to a working scale.

In view of the obviously great reduction in the area of works required and capital expenditure involved, the available data in regard to the probable cost of aeration is such as to lend encouragement to the idea that the adoption of aeration methods on the lines of these experiments would result in a considerable reduction in the total cost of sewage purification. In this connection it may be reasonably anticipated that the enhanced value of the resultant sludge should at least cover all costs incidental to its disposal.

In conclusion the authors wish to express their sincere thanks to Dr. Fowler for the suggestion which originated this inquiry, and for the keen interest with which he has followed the whole series of experiments.

They are indebted to the Rivers Committee of the Manchester Corporation for permission to publish the results of this investigation, which has been carried out in the laboratory at the Corporation Sewage Works, Davyhulme.

DISCUSSION

Dr. J. Grossman said that the sludge question had entered upon a phase in which, thought it was not expected to produce a large profit, it was to a certain extent capable of commercial treatment. Where the present processes of purification might be barred by local circumstances the process described in the paper if successful would be greatly in advance of what was being done at present. No doubt, in some instances it would become a commercial question as to whether aeration by means of activated sludge be more economical than any of the other processes of purification and the mechanical element would enter very largely into this question. He had been very much struck with the amount of nitrogen in the sludge. Was this partially due to the elimination to a greater extent of the detritus matter than was usual with ordinary sludge? Perhaps the authors could give them some information as to the average amount of nitrogen in ordinary Manchester sludge. Assuming even as much as two per cent of nitrogen on the dry sludge then the 4 or 4 ½ per cent of nitrogen shown could not be accounted for by a larger quantity of detritus having been taken out. Even if they took into consideration the ammonia being utilised by the bacterial, he could not understand how an increase of nitrogen could be obtained because the bacteria were supposed to oxidise the ammonia into nitrates which were soluble, unless the bacteria took up the nitrogen from the air and used it for building up their own bodies which afterwards remained in the sludge.

Mr. F. R. O'Shaughnessy regarded the paper as an epoch-making one, provided that the process experimentally established by the authors could ultimately be applied on the large scale at a reasonable cost. After all, from the point of view of the man-in-the-street - the man who paid the rates - the financial question was one of the first questions. The process suggested by the authors would greatly reduce the area of the works and would probably go far to eliminate nuisance, and these too were very important considerations from the public point of view. In Germany sewage was often merely precipitated or sedimented and the sewage liquor then passed through open channels for many miles to the nearest river. The Germans seemed to have no objection to this, but in England such a procedure would not be tolerated.

Apart, however, from such general and practical considerations, the scientific interest of the paper could not be over-estimated. So far as he could judge, the main principle at work did not differ substantially from that which obtained in an ordinary bacteria bed, viz., exposure to the necessary organisms in presence of an excess of oxygen. The experiments demonstrated that there must be considerable surface contact between the liquor to be purified and the “activated” sludge. The action was undoubtedly a very complex one. Merely physical effects in the way of flocculating the colloidal and finely divided suspended solids would be obtained which would help in clarifying the liquor. The destruction of the colloidal character of the sludge was no doubt brought about by biological agents and it was interesting to note than at a temperature of 30°C. a process of deflocculation went on.

Recently he had read a paper before the Institute of Sanitary Engineers giving a number of observations bearing on these points. Many engineers apparently held the view that the so-called “colloiders” precipitated colloidal matter by virtue of their physical action. This view was erroneous, for these “colloiders” were efficient only because they provided a habitat for the micro-organisms which were the effective “colloiders.” Not till the sewage liquor had an enormous surface presented to it, as in a bacteria bed, did physical forces remove any appreciable quantity of impurities from the liquor. The great advantage inherent in the process outlined by the authors of the present paper was that aerobic conditions prevailed and foul products were thereby eliminated.

His observations on these phenomena extended over many years and the following figures which were the averages of many analyses over a lengthy period made on the Birmingham sewage under working conditions on the large scale were correspondingly very reliable. He had taken the “oxygen absorbed in four hours” figure on the liquor freed from visible suspended solids as an index as to what happened. This figure for the crude sewage liquor was 17.10 parts per 100,000, and after passing through a plain rectangular sedimentation tank where the time of sojourn was four to five hours the liquor then gave the figure 13.71. A remarkable point was that 20 per cent of the dissolved impurities were removed by this simple means. Further treatment of the liquor for six hours in a septic tank reduced the figure to 12.53. After that the liquor passed through a five-mile-long sewer and the above figure was reduced by a six hours sojourn in this sewer to 9.11 parts per 100,000. The surface to which the liquor was exposed in this sewer was very considerable and the colloidal matter was precipitated to an appreciable extent on this journey, whilst the suspended matter was correspondingly increased. This suspended matter was arrested in upward flow conical tanks and the figure for the clear liquor issuing from these tanks fell from 9.11 (above) to 8.71 parts per 100,000. Passage through a percolation bed then reduced the figure to about two parts per 100,000 in ½ to 1 hour.

If the above observations were set out as rates per hour of elimination of impurities in solution the result became very striking. These rates were as follows:

On the sedimentation tank	0.68	parts per hour
“ “ septic “	0.20	“ “ “
“ “ five-mile sewer “	0.70	“ “ “
“ “ upward flow tank	0.28	“ “ “
“ “ percolation bed, about	10.00	“ “ “

The total purification of dissolved oxidisable impurities by 22 hours tank treatment was about 50 per cent. And was greater under “septic” than under “non-septic” conditions.

In another set of experiments on the large scale the sewage was divided into two portions each portion passing through two separate sets of tanks. One portion was treated with two parts per 100,000 of bleaching powder and the other untreated. The chlorinated liquor was sterilised by the treatment, and no change took place in the figure of “oxygen absorbed” owing to passage through the tanks, whilst on the other hand an appreciable drop in the dissolved oxidisable impurities occurred in the liquor passing through the other set of tanks to which no bleaching powder had been added. These observations had a bearing on the process brought forward by Messrs. Ardern and Lockett, for they throw some light on the nature of the action. Broadly, his conclusions were that the grosser colloidal matters held by sewage liquors came down readily in ordinary continuous flow sedimentation tanks, that the great bulk of the colloidal matters - say 70 - 80 per cent - were held very tenaciously by the sewage liquor and were only removed by either biological agents, or physical forces suitably applied such for instance as in a well constructed and properly worked bacteria bed. In ordinary modern works practice probably the biological factors were the most potent, and the experiments carried out by the Authors indicated that this held good with respect to the new process they described.

One other point he wished to refer to was the part played by the nitrogen in these phenomena. He agreed with the authors that this behaviour was rather puzzling, and much work remained yet to be done on this most important aspect of the question.

Mr. S. E. Melling thought the process described was ideal inasmuch as it resolved itself into a single-tank treatment. The greatest bugbear to the sewage problem had been the question of sludge disposal. By means of the new system the sludge, activated in the manner described, became the friend rather than the enemy of the sanitary scientist. Had there been any estimation of the percentage of nitrogen during the different stages of the development of activity of the sludge it would be interesting to learn by what stages the fixation of the nitrogen took place. He observed that the carbon tetrachloride extract was put down as grease. Had any approximate examination been made of that extract, as it would be distinctly against the value of the sludge as a manure if the grease was left in? The whole scheme appeared to be one of great value for communities with very small available spaces of land at their disposal. If it was possible to have the carbonaceous fermentation carried out successfully in a preliminary tank, whether it was in the nature of a "roughing" tank or filter, or similar existing device, and so bringing the effluent to the stage where, by passing it through aerating-filters the necessary nitrification could be attained, a great saving could be effected. The filters could be fed four to six times their usual speed. An interesting point occurred in connection with the disappearance of nitrogen, where in some cases the oxidised product did not at all correspond with the free ammonia. According to one of the tables shown it would seem that the best dilution for the oxidation-cycle to proceed, regularly and completely, was 1:12. Might there not be some feasible explanation of the loss of nitrogen when the ratio of activated sludge to sewage was much higher?

Mr. Percy Gaunt said that the method of treatment suggested might offer advantages sufficient to compensate for any additional power required for the aeration process, in view of the reduced area required, and the possibility of reduction of the nuisance from smell and from flies. Under the present system, even when circumstances favoured a fairly compact scheme, an area of ten acres would usually be required for the disposal works of a town of about 40,000 inhabitants, when due allowance had been made for the selection of a site providing the fall of several feet, necessary for a filtration process. The experiments described suggested the possibility of reducing the area by about eighty per cent., and the necessary fall to a few inches. A suitable site under existing conditions might be two or three miles from the town, entailing an independent power installation, whereas with the reduced area and diminished fall requirements of the suggested method, full advantage might be taken of any cheap power (such as a town gas, or electricity supply) in choosing the position of the works. Interesting information as to the relative importance of the physical and biological factors in purification might be obtained from comparative aeration experiments conducted (a) under ordinary conditions; (b) in the presence of ultra-violet rays.

Mr. Johnson inquired whether the sludge contained any ammonia, and also what quantity of air was required.

Mr. J. T. Thompson said that one striking feature of the new process was that it was aerobic from beginning to end, and it was probable that the amount of smell would be negligible. If these laboratory results could be economically obtained on a large scale the present elaborate system of dealing with sewage would be simplified; the cost of pressing sludge, depositing it in the sea or in trenches on land would be avoided, for activated sludge evidently dries rapidly and would yield good manure. This process might also reduce the area of bacteria beds needed. What volume of air was it necessary to blow through the mixture, for this would be a costly item in practice? He presumed there would be some limit below which the sludge would not be sufficiently mixed with the supernatant liquid to complete the oxidation in a reasonable time. With regard to the high nitrogen figure in the activated sludge, if possible, he would like to have an analysis of ordinary Manchester sludge to compare with the sample of activated sludge.

Mr. Hart (Leeds), speaking as an engineer, thought the process would resolve itself into a question of the relative cost of manipulation of the sludge either as liquid or solid matter. He admitted that the difficulty from the engineering side at the present time was to find a satisfactory method of manipulating the sludge for useful manurial purposes at a reasonable cost. At the moment he could not see that there was a probability of there being any great saving in costs of manipulation. The present experiments were, however, laboratory experiments, and it would be necessary to deal with sewage and sludge in bulk before any reliable data could be furnished as to cost.

Dr. G. J. Fowler said that a considerable time ago Mr. Ardern and himself read a paper before the Society on suspended matter in sewage and effluents, which raised in a simple way a question which had found its final expression in the paper they had heard that night, that was to say the flocculation of colloidal matter. The end had not been reached at once. There had been a number of stages, and a great many minds had been at work on the question. When he had the honour of delivering the Chairman's address before the Section he mentioned the idea of Dr. Maclean Wilson of an enzyme which might clot out sewage and produce the effect which now took place into a percolating filter, and ventured to suggest that it might be possible to find something of the kind. An experiment was tried with some of the deposit from a filter, blowing it up in sewage, with apparently little result. Other chemists had tried the same experiment. It was only right to admit that the illuminating idea which originated the work was really due to a visit he had paid while in the United States, to the Mecca of sewage purification, namely, the experimental station at Lawrence in the State of Massachusetts, where he saw the bottle, described in the paper, in which sewage had been completely purified by 24 hours' aeration. The idea at that time, and subsequently in the experiments which had been published from that laboratory, involved the principle of surface. He discussed some of the possibilities of the method with the President of the New York Sewage Commission, and that gentleman was of the opinion that the idea of surface should be abandoned if possible if the matter was to be really advanced. They also discussed the question of the clarification of sewage. The problem at New York was to deal with some 1,000 million gallons of sewage per day and the idea of sprinkling such a large quantity about in the atmosphere in the hot American summer did not seem to be altogether practicable. In the intervening time other experiments had been made by Mr. Mumford and himself with regard to the clarification of sewage bacterially, and they had succeeded in clarifying altogether about 10,000 gallons by means of a process which had already been published. As Dr. Grossmann had observed, local conditions had to be taken into consideration. It was also necessary to consider the process of sewage purification on the one hand and the utilisation of the nitrogen and other constituents on the other. The process described in the paper aimed at purifying the sewage as rapidly and as simply as possible. He, for his own part, believed that the process was practicable on a large scale, and they would have some idea of what that meant when he mentioned that the settling tanks at Davyhulme were constructed to hold 21 millions gallons. The results indicated in the paper showed that some six hours' blowing would produce an effluent equal to the final effluent at present obtainable; that was to say, complete purification in six hours. Assuming that the operation was only carried out twice in the 24 hours, allowing six hours to blow and six hours for the manipulation Mr. Hart had spoken of, aerating the sludge and so forth, it meant that in the tanks available 42 million gallons per day could be purified. The consequent saving of space and expenditure on filters would be something enormous, and would allow for quite a large expenditure on power and otherwise for the provision of air. He would not commit himself to figures that evening. It would not be a wise proceeding at that stage. The question of cost had been very carefully considered, and the whole matter had been approached from a number of points of view. Estimates had been obtained for large scale-work in blowing and so forth. He had consulted Mr. S. L. Pearce, the Chief Engineer of the Manchester Corporation Electricity Department, with reference to the amount of power required for providing a certain amount of air, estimating for the greatest quantity of air conceivable for the purpose, and recent work which had been begun showed that there had been an over-estimation in that direction. Taking everything together he was convinced that the process was a practical proposition. In order to carry it out by the most economical method possible it was, of course, necessary to call in the aid of their friends the engineers. Figures as to cost had been published by experimenters in America. In a paper by Messrs.Clark and Adams, published in the "Engineering Record" the figure for electricity was placed at 2d. per unit, which was not very cheap, and on that basis the cost of air was given at 8s. 4d. per million gallons. The American sewage was rather dilute. There was also cost of the slate surfaces. Still, if it was possible to carry on the process at the cost of 8s. 4d. per million gallons the matter appeared to be quite practicable. It was necessary to get the principle right in the first place, and on that point he had no doubt. The idea was really nothing new in a way. All that was happening was that instead of running the stream of sewage over a filter bed with imperfectly oxidised sludge one took activated sludge and moved it about with complete aeration. In the same way that a percolating filter was a concentration of land treatment so the treatment described was a further concentration on the percolating filter. No really new principle was involved, and for that reason it appeared to him the thing was on right lines. Regarding the question of nitrogen which had been raised, his view was that the organisms collected a certain amount of nitrogen from the products present in solution and built up a certain amount of protoplasm thereby. He was confirmed in this opinion by experiments made at the Manchester University, where a deposit was obtained containing even more nitrogen than was indicated in the paper. The amount of mineral matter in activated sludge was not high. It would be necessary in order to secure success that very careful means be taken to remove the grit, and considerable engineering skill would be required to design really satisfactory grit chambers. There were no such things in existence in the world at the present time, but no doubt the problem was capable of solution. The complete removal of grit would materially assist the working of the process. The research work carried out by Messrs. Ardern and Lockett opened out possibilities which would re-awaken the public interest in the sewage problem, which, perhaps, to some of them had latterly become somewhat of a bore by being standardised to such an extent that the whole question had become one of routine. The authors of the paper had now fired a bombshell into the camp, and perhaps they would all start on new ways in the future.

Mr. Ardern, in reply, said that no means had been taken to remove the detritus from the sewage which was generally the average 24 hours' sample. An inspection of the analysis would show that the percentage of organic matter in the resulting sludge was 65 per cent. or thereabouts, wheras the usual percentage of mineral matter in sedimented sludge in the case of Manchester would be about 50 per cent., so that there was a considerable increase in the organic content. With regard to the high percentage of nitrogen, the figure given was the mean of several determinations. It would appear that the high nitrogen content was due to a large extent to the flocculation of the fecal emulsion. There had been no determinations of nitrogen at different stages of the accumulation of the sludge. There were still a number of points requiring elucidation, and it was not suggested that investigation had been made into every operation that actually took place. What had been done was to endeavour to obtain results which could be readily maintained under conditions in which apparently there should be no serious difficulty in translating to a practical working scale. The scientific side of the matter had only been dealt with in a limited manner. The authors agreed with Dr. Fowler in regard to the principle of the process which he had dealt with in the course of his remarks. As stated by Mr. O'Shaughnessy, with a temperature of 30° Cent. there was apparently a slight deflocculating action on the sludge, but it was not maintained, the effect being observable in the initial stages, flocculation subsequently occurring. No examination had been made of the grease extract, as at the time the determination was made the activated sludge was rather a valuable product from the experimental point of view. He was of opinion, however, that the percentage of fatty matter present was not sufficient to militate against the use of the sludge as a fertiliser. It was a considerably lower percentage, as Dr. Grossmann would be aware, than in the case of ordinary sewage tank sludge, even counting the whole carbon tetrachloride extract as grease. It was quite common for ordinary tank sludge to contain 10 to 15 per cent. of grease extract, and possibly in some cases a greater quantity. There was no definite explanation to offer in connection with the loss of the nitrogen, and there was no doubt that with regard to the conservation of that constituent further information was required. In the earlier experiments almost quantitative nitrification of ammonia was obtained. This did not apply to the later experiments where there was a greater loss of nitrogen. It may be mentioned that during the later experiments a greater volume of sludge was employed, and nitrification proceeded at a more rapid rate which might possibly have some influence on the liability to losses of nitrogen. The question of the effect of waste liquor from sulphate of ammonia plants had not been investigated. The Manchester sewage dealt with, however, contained from 0.5 to 1.0 per cent. of this trade effluent, and in this proportion no serious retarding effect on the oxidation process was apparent. If, as appeared probable, the process was essentially bacterial, there was no doubt that any serious amount of inhibiting matter, of whatever type, as long as it was bactericidal, would doubtless have to some extent a deterrent effect. The volume of air required was a point which obviously was connected with the cost of the aeration process. They had not gone very deeply into the matter. As a matter of fact the laboratory experiments had been aerated without consideration of the question of cost. They had determined the volume of air used in the experiments, which was evidently much in excess of that actually required; the quantity amounting to something about one-fifth of a cubic foot per square foot of tank area per minute. While Dr. Fowler naturally refrained from giving any figures, one could say without hesitation that the quantity of air required was very much less than that allowed in any calculations he had made. In the laboratory experiment the air was used not only for aeration but also as a means of agitation, and it was quite conceivable that a combination of mechanical agitation with the use of air for aeration purposes only would be more economical. That, of course, remained to be seen. A question had been raised as to the effect of grease, concerning which he could not give any information. Whatever grease there was in the average sample was in the sewage when they treated it, and there was no apparent hindrance to the oxidation process. At no time was there an excessive quantity of grease, but he was of opinion that some simple means would be adopted for removing any actual grease from the sewage before subjecting it to any such treatment.

The main feature of the experimental work was the satisfactory purification of sewage by tank treatment alone, with the production of a sludge which, owing to its oxidised and flocculent condition, could be readily dealt with and converted into a valuable fertilising agent.

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THE SLUDGE AGE CONCEPT AND THE ACTIVATED SLUDGE PROCESS: A 45 YEAR RETROSPECTIVE COMMENTARY

Alonzo W. Lawrence, Ph.D., P.E., BCEE, and Andrew C. Middleton, Ph.D., P.Eng., BCEE[1]

INTRODUCTION

In 1962, when the senior author of this article, Lawrence, entered the doctoral program in sanitary engineering at Stanford University, the prevailing approach to the design and operation of suspended-growth biological wastewater treatment processes was based on experience-based, empirically-derived parameters. Foremost among these parameters were: 1) hydraulic retention time for anaerobic digestion of sewage sludge and 2) a weight of wastewater organics applied, e.g., BOD or COD, per unit volume of aeration basin capacity per unit time for the activated sludge process. There was also, evolving with respect to the activated sludge process, a research-based focus on an organic loading parameter, which became known as the food to microorganism (F/M) ratio. The F/M ratio was defined as the weight of wastewater organics applied per unit weight of aeration tank mixed liquor volatile suspended solids (MLVSS) per unit time, e.g., mg BOD/mgVSS/day. The parameter was deemed to be particularly useful in the treatment of industrial wastewaters in the completely mixed activated sludge process. While the F/M parameter was focused on the biological mechanism of waste removal, it had a number of design and operational short comings. In particular, it did not lend itself to a reaction-rate based mathematical process model of the activated sludge process, from which the entire design or operation could be calculated and optimized in a least cost design.

Also, in the summer of 1962, prior to entering Stanford, Lawrence had conducted a field study of extended aeration package sewage treatment plants at motels and other remote locations for the New York State Department of Health. The goal of that study was to develop guidelines for the design of such plants. That experience further heightened his intellectual curiosity in the search for a more fundamental biokinetic-based approach to the design and control of activated sludge and other biological wastewater treatment processes.

Fortunately, Lawrence was privileged to have the opportunity to study under Dr. Perry L. McCarty at Stanford. Lawrence's doctoral research led to the development of a microbial based kinetic approach to the design and control of the rate limiting step in anaerobic treatment processes, i.e. methane fermentation (Lawrence and McCarty, 1967; Lawrence and McCarty, 1969). Based on his extensive review and familiarity with wastewater treatment literature and the microbiological literature on chemostat-based continuous culture of pure cultures of microorganisms, Lawrence believed that the kinetic model approach could be extended to all microbial slurry-based biological waste treatment processes including activated sludge. Subsequently, Lawrence and McCarty developed a unified basis for biological treatment design and operation (Lawrence and McCarty, 1969; Lawrence and McCarty, 1970). In this approach, biological solids retention time, or more broadly sludge age, was identified as the key independent variable for process design and control.

This biological kinetic model is briefly reviewed in the next section of this article. Then, research studies conducted by Lawrence and his associates designed to develop information on the kinetics of activated sludge are described. Next, studies describing the application of the kinetic approach to design and control of industrial waste treatment activated sludge processes are presented. The article concludes with an assessment of the current status of the sludge age concept in the design and control of the activated sludge process.

THE UNIFIED BASIS FOR BIOLOGICAL TREATMENT AS APPLIED TO ACTIVATED SLUDGE

The information contained in the original Lawrence and McCarty 1970 "Unified Basis" has been widely disseminated in the 44 years since its original publication. The biokinetic models described in the original paper are included in the activated sludge design chapters of a widely used textbook on wastewater treatment (Metcalf and Eddy, 2003). Therefore, only a brief review of the unified basis concepts and the process kinetic models are discussed here.

Lawrence and McCarty (1970) described a unified basis for design and operation of biological waste treatment systems employing suspensions of microorganisms based on microbial kinetic concepts and continuous culture of microorganisms theory. Biological Solids Retention Time (SRT), or Sludge Age or Mean Cell Residence, i.e., the average time period a unit of biological mass (and by extension associated suspended solids of non-biological origin) is retained in the system was identified as the key independent variable for biological process design and operation. This is true because once a value of SRT is selected for a given wastewater treatment situation, all microbiological aspects of process design and operation are fixed, including the F/M ratio. This is shown by the kinetic relationships for the major process variables in Table 1 for the three process configurations shown in Figure 1. Operationally, the chosen SRT is achieved by the daily wasting of the daily production of activated sludge matrix solids (MLTSS). The parameter, P_x, in Table 1 identifies the daily production of excess biosolids (MLVSS) for a soluble wastewater situation, e.g., lb/day. For completeness, it should be noted, that for a soluble wastewater, the F/M ratio used by others, is equal to the Unified Basis parameter Specific Utilization, U, divided by the waste removal efficiency, E, when E is stated as a decimal.

In the case of the activated sludge process, the Unified Basis presented a mass balance around the aeration tank which described the mathematical steady-state relationship between SRT; hydraulic retention time (HRT); clarifier underflow rate (q) to wastewater flow rate (Q) ratio, i.e., the recycle ratio (r); and, clarifier underflow solids concentration (X_r) and mixed liquor suspended solids concentration (X). While the microbial aspects of the system are fixed, once a design value of SRT is selected, including the daily wasting rate of activated sludge solids (1/SRT times the system total solids), it is necessary to specify two additional system parameters to complete the overall design. While values of HRT, r, or X_r could be chosen, it is customary to choose design

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[1] Alonzo W. Lawrence and Andrew C. Middleton are Senior Consultant and President, respectively, in Corporate Environmental Solutions LLC, 1348 Beulah Rd., Pittsburgh, PA 15235-5068 (Mailing address: P.O.Box 427, Cecil, PA 15321). http://www.solutions-by-ces.com/

values for HRT and r. Then the clarifier component of the system is designed based on the uniquely determined zone settling velocity and thickening characteristics of the activated sludge mixed liquor suspended solids. Consideration of tradeoffs among HRT, r, and X_r provides an approach to determining least cost design of the activated sludge system. The importance of the activated sludge settling and thickening characteristics to the overall system performance is discussed in the next section.

Estimates of process performance and SRT for various activated sludge process options are shown here in Table 2.

BIOKINETIC BASED ACTIVATED SLUDGE RESEARCH STUDIES

During the first half of the decade of the 1970s, Lawrence and his associates performed a number of research studies to improve the state of the art of design and control of the activated sludge process. The performance of the secondary clarifier and its ability to separate and return activated sludge solids to the aeration tank was not as well understood as the microbial waste assimilation aspect of the process. In a published discussion of the Unified Basis (Lawrence and McCarty, 1970), Dick and Javaheri (1971) correctly pointed out that clarifier performance was critically important to overall process efficiency and, unless properly controlled could make it impossible to achieve the performance specified by the biokinetic model. Settling and thickening characteristics of activated sludge mixed liquor solids in the clarifier were identified as critical design information.

Bisogni and Lawrence (1971) performed a laboratory study using a synthetic wastewater to determine the relationship between SRT and activated sludge settling characteristics. They observed that the zone settling velocity (ZSV) of the activated sludge liquors, adjusted to a common value of MLTSS, plotted as a straight line versus SRT (Figure 2) over a 2-12 day range of SRTs. The best zone settling characteristics occurred in the 4-9 day SRT range. The zone settling characteristics are the fundamental parameters for design of the upflow clarification and downflow thickening zones of the final clarifier.

Milnes (1972) conducted doctorial research on the dynamic modeling of the completely mixed activated sludge process. His dynamic mathematical model described a nitrifying complete-mix activated sludge reactor in series with a gravity clarifier-thickener. The biological component of the model was based on Unified Basis microbial-kinetic equations for the growth of the heterotrophic microbial mass and the nitrifying bacteria mass. An empirical, dynamic model was developed to describe the operation of the secondary clarifier. The mathematical form of the clarifier model was based on results of laboratory studies performed on a 150-liter, completely mixed reactor in series with an 8-foot deep, 6-inch inside diameter, Plexiglas clarifier equipped with a sludge scraper and continuous sludge underflow return. The clarifier model contained four functional blocks, i.e. clarification, separation, zone settling and sludge blanket (Figure 3). The sludge thickening zone was modeled on the basis of an observed empirical relationship that described clarifier underflow suspended solids concentration (X_r) as a function of the weight of solids in the sludge blanket and the solids retention time in the blanket. After attaining steady state operation, the laboratory system was subjected to a series of organic and hydraulic non-steady state loading changes. Good agreement was achieved between the laboratory experimental results and the simulation model predictions.

TABLE 1
Summary of Steady State Relationships for Biological Waste Treatment with Suspensions of Microorganisms after Lawrence and McCarty (1969)

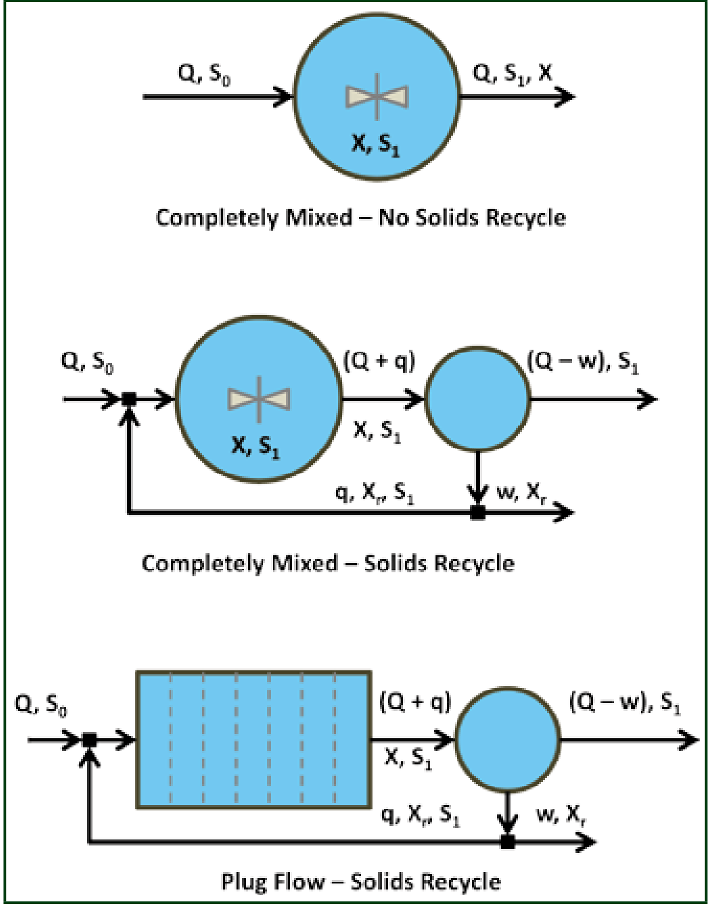
Characteristic	Complete-Mix System		Plug Flow System with Recycle [1]
	Without Recycle	With Recycle	
Specific Efficiency	$E_S = \frac{100\,(S_0 - S_1)}{S_0}$	$E_S = \frac{100\,(S_0 - S_1)}{S_0}$	$E_S = \frac{100\,(S_0 - S_1)}{S_0}$
Effluent Waste Concentration (M/L^3)	$S_1 = \frac{K_S\,(1 + b(SRT))}{SRT\,(Yk - b) - 1}$	$S_1 = \frac{K_S\,(1 + b(SRT))}{SRT\,(Yk - b) - 1}$	[2]
Microorganism Conc. in Reactor (M/L^3)	$X = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)}$	$X = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)} \left(\frac{SRT}{HRT}\right)$	$\bar{X} = \frac{Y\,(S_0 - S_1)}{1 + b(SRT)} \left(\frac{SRT}{HRT}\right)$
Excess Microorganism Production Rate (M/T)	$P_X = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$	$P_X = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$	$\bar{P}_X = \frac{YQ\,(S_0 - S_1)}{1 + b(SRT)}$
Hydraulic Retention Time (T)	$HRT = \left(\frac{V}{Q}\right) = SRT$	$HRT = \left(\frac{V}{Q}\right) \neq SRT$	$HRT = \left(\frac{V}{Q}\right) \neq SRT$
Recycle Ratio	not applicable	$r = \left(\frac{q}{Q}\right)$	$r = \left(\frac{q}{Q}\right)$
Recycle Sludge Conc. (M/L^3)	not applicable	$X_r = \frac{X\,(1 + r - \frac{SRT}{HRT})}{r}$	$X_r = \frac{\bar{X}\,(1 + r - \frac{SRT}{HRT})}{r}$
Solids Retention Time (T)			
General	$SRT^{-1} = \frac{YkS_1}{K_S + S_1} - b$	$SRT^{-1} = \frac{YkS_1}{K_S + S_1} - b$	$SRT^{-1} = \frac{Yk(S_0 - S_1)}{K_S \ln\left(\frac{S_0}{S_1}\right) + (S_0 - S_1)} - b$ [3]
Limiting Minimum	$SRT_{lim} = (Y_k - b)^{-1}$	$SRT_{lim} = (Y_k - b)^{-1}$	[4]

[1] For a situation in which reactor microbial mass concentration (X) is assumed constant
[2] No explicit solution for SRT
[3] For situation in which recycle ration (r) is less than one
[4] Not mathematically defined for this system

Sherrard and Lawrence (1975) reported the results of a laboratory research study designed to determine the impact on effluent quality (increase in COD) when completely mixed activated sludge units were subjected to a step increase of 250 percent in organic loading. As predicted based on biokinetic principles, the longer SRT units with higher mixed liquor suspended solids concentrations experienced less effluent quality deterioration than units operated at lesser values of SRT. This study provided further evidence that systems operated at "long" SRTs (>10 days) are perhaps the most effective method of maintaining stability in effluent quality and process efficiency.

Lawrence (1975) described the modeling and simulation of slurry biological reactors and proposed a SRT-based methodology for determining least cost design of a completely mixed activated sludge process including a secondary clarifier with recycle. This methodology incorporated the zone settling velocity (ZSV) as the clarifier design variable for clarification and the batch flux method suggested by Dick (1970) as the solids flux or clarifier underflow design variable. The maximum value of these two areas was chosen for clarifier design. In a series of computer-based design studies, Middleton and Lawrence (1973, 1974a 1974b, 1975, 1976) developed a comprehensive approach to the least cost design of the activated sludge process. They modeled wastewater treatment systems that included primary settling and waste sludge management. The final paper in the series included not only system capital cost minimization, but also present worth of operating costs. Middleton and other associates further developed the optimal design and operation of the activated sludge process using numerical algorithms (Craig, *et al.*, 1978; Hughey et al 1982; Kasprzak, *et al.*, 1982). None of these optimizations would have been possible without the underlying Unified Basis.

FIGURE 1
Schematic Representation of Three Continuous Flow Biological Waste Treatment Processes



Lawrence and Brown (1976) described a biokinetic based activated sludge treatability study of a municipal wastewater that included nitrification in both one and two sludge systems. The laboratory units were fed collected municipal wastewater effluent over a six month study period. The systems were operated on an 8 hour HRT and SRTs of 2, 4, 8, 20 days. Results showed that complete nitrification could be sustained at an 8 day SRT at 20°C and at a 20 day SRT at 8°C. Nitrification could not be sustained in the first stage of the two sludge system at a 2 day SRT at 20°C and a 4 day SRT at 8°. This study highlighted the temperature dependence of nitrifying activated sludge systems in cold northern climates.

TABLE 2
Process Loading Factors and SRT for Activated Sludge Processes after Lawrence and McCarty (1969)

Process Description	Normal Loading Range		Efficiency (E) [1]	Specific Utilization	SRT^d [2]	Safety Factor [3]
	Volumetric	Process Loading Factor (PLF)				
	lbs BOD$_5$/ 1000 ft^3/day	lbs BOD$_5$/lbs VSS/day	(assumed percent)	U = (PLF)/100	days	
Extended Aeration	20	0.05 - 0.2	85 - 95	0.043 - 0.19	14 - ∞	>70
Conventional Activated Sludge	35	0.2 - 0.5	95	0.19 - 0.48	4 - 14	20 - 70
Tapered Aeration	35	0.2 - 0.5	95	0.19 - 0.48	4 - 14	20 - 70
Step Aeration	50+	0.2 - 0.5	95	0.19 - 0.48	4 - 14	20 - 70
Contact Stabilization	70	0.2 - 0.5	90	0.18 - 0.45	4 - 15	20 - 75
Short-Term Aeration	100 - 400	0.5 - 3.5	60 - 85	0.43 - 2.1	0.8 - 4	4 - 20

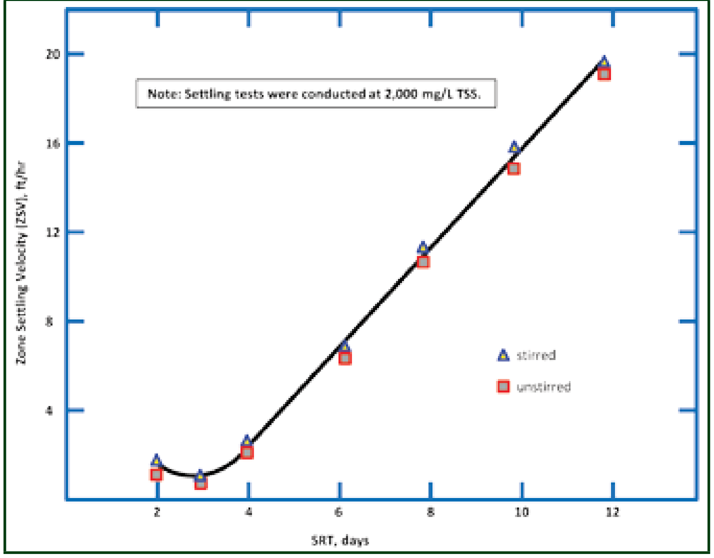
[1] Where a range is given, the higher efficiency is based on a soluble effluent waste concentration
[2] Assumed value of growth constants: Y = 0.65, b = 0.05 day^{-1}
[3] Safety Factor = SRT^d/SRT^{min} where SRT^{min} is the washout SRT

Lawrence (1975) had the privilege of working with the design team and discussing the simple elegance of SRT (sludge age) as the independent design and control variable during the time period that the team was involved in research and development of the PACT process, i.e., powdered activated carbon (PAC) mixed with activated sludge, for deployment as the secondary/tertiary treatment phase of the wastewater treatment expansion at the Chambers Works facility of the DuPont Company at Deep Water, NJ. The Unified Basis approach provided a means to calculate the mixed liquor concentrations of non-degradable suspended solids, like PAC, as a function of PAC addition rate, the SRT and HRT. Thus a rational, process based design for the PACT process was possible. From an operational perspective, since PAC shows up analytically as VSS, any VSS-based loading parameter, such as F/M, would have depended on the ability to separate the biological mass from the PAC mass. However, the SRT control system relies only on TSS measurement, regardless of the makeup of the TSS.

SRT BASED DESIGN AND OPERATION OF ACTIVATED SLUDGE TREATMENT OF INDUSTRIAL WASTEWATERS

In the late 1970s and for much of the 1980s, both authors worked together for a decade on industrial wastewater treatment where the wastewaters were typically of relatively high strength organically and often high in ammonia and other nitrogen compounds requiring nitrification to attain effluent limitations. The activated sludge process was applied to the predominant number of these industrial wastewater situations with great success due to the development of a new approach in employing the activated

FIGURE 2
Zone Settling Velocity as a Function of SRT after Bisogni and Lawrence (1971)



sludge process -- the use of very long SRTs, e.g., 50-500 days. The genesis of the long-SRT approach was the inability to achieve reliable nitrification of byproduct coke oven wastewaters, which typically had a relatively high concentration of phenolic compounds, ammonia and other nitrogen-containing compounds such as thiocyanate. By the late 1970s, BAT regulations required nitrification of these wastewaters to reduce ammonia to low concentrations. The breakthrough came in the late 1970s when it was demonstrated that generally SRTs of at least 50 days were necessary to achieve reliable nitrification of these wastewaters. (Bhattacharyya and Middleton, 1979, 1980a and 1980b) Around this time, others also began considering long SRTs, e.g., Grutsch (1980). Prior to this time, long SRT's had generally been confined to extended aeration systems and their consideration for use in industrial wastewater treatment was relatively new.

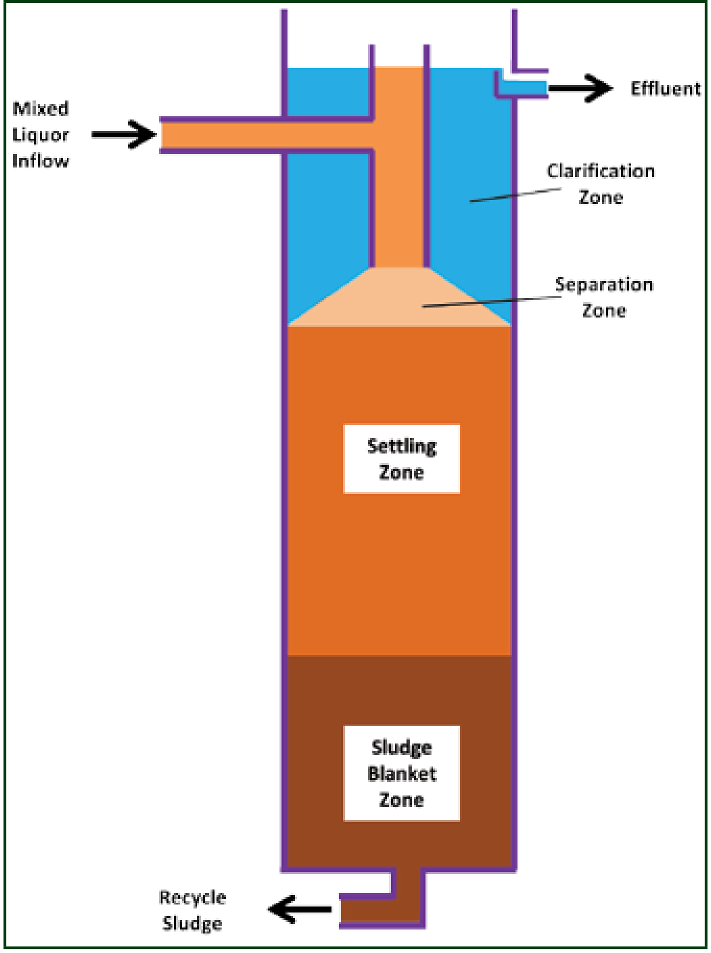
In Bhattacharyya and Middleton (1980b), the authors demonstrated that certain of the parameters in the Unified Basis had finite limits as the SRT approached infinity, in particular, the effluent degradable organic concentration, the bacterial concentration in the aeration tank, oxygen uptake rates and bacterial sludge production. The key parameter that did not have a limit was the aeration tank concentration of non-degradable suspended solids, which was infinite at an infinite SRT. This outcome pointed out the importance of the influent non-degradable suspended solids, e.g., fixed suspended solids, PAC or recalcitrant organic solids, and the need to consider enhanced pretreatment for their removal as a tradeoff for being able to use a long SRT system. Furthermore, this understanding provided a basis for designing "no waste" activated sludge systems where the incidental TSS in the secondary clarifier effluent, provided it was within permit limitations, could maintain a long SRT activated sludge system. In the 1980s Lawrence and Middleton oversaw the design, installation and operation of a number of long SRT activated sludge systems treating industrial wastewaters.

The equations resulting from the Unified Basis for aeration tank accumulation of non-degradable suspended solids was extended in the late 1980s to evaluate accumulation of recalcitrant compounds adsorbed to activated sludge (Smith, *et al.*, 1993).

All of these advances in the design and operation of the activated sludge process were made possible by the publication of the Unified Basis in 1970.

Of additional interest while not directly applicable to the activated sludge process, biokinetic research studies were conducted by Middleton and Lawrence (1977) to elucidate the biokinetics of microbial sulfate reduction and by Stensel, Loehr and Lawrence (1973) to elucidate the heterotrophic microbial denitrification process. Biokinetics of both these processes have applicability in odor prevention in sewers and equalization tanks; design of pre-aeration selector tanks for control of filamentous growth in return activated sludge; and, prevention of rising sludge due to denitrification in secondary clarifiers as well as for nitrate or sulfate removal from a wastewater.

FIGURE 3
Vertical Locations of Zones in the Secondary Clarifier after Milnes (1972)



THE SRT (SLUDGE AGE) APPROACH AND THE ACTIVATED SLUDGE PROCESS: TODAY AND TOMORROW

In the 45 years since Lawrence's first hand written draft of what became the Unified Basis paper (Lawrence and McCarty, 1970), the concepts presented in the paper have been widely accepted by the environmental engineering profession as the preferred methodology for the cost effective design and operation of the activated sludge process (Metcalf and Eddy, 2003: WEF & ASCE, 2010).

Simply stated, the idea of identifying microbial net specific growth rate (μ) and its reciprocal, SRT (Sludge Age) as the independent steady state design variable allows design and control of the activated sludge process by the daily wasting of the net accumulation of activated sludge mix liquor suspended solids regardless of their origin: i.e., active microbial mass; microbial cell debris; PAC; or, inorganic components of the waste water.

In conclusion, we believe the Unified Basis concepts and the identification of SRT (Sludge Age) as the independent design and control variable for the activated sludge process will continue to be the preferred approach employed by environmental engineers, not only today, but also tomorrow, and for many more tomorrows to come.

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The authors, also gratefully acknowledge the many contributions of our students and professional colleagues to our work on biological waste treatment and the activated sludge process over the past 40 plus years of our professional collaboration.

COMPLETE MIXING ACTIVATED SLUDGE

Ross E. McKinney[1]

Complete Mixing Activated Sludge (CMAS) is an old modification of conventional activated sludge systems. Anyone who has done laboratory studies on a continuously fed activated sludge pilot plant has already had experience with CMAS. Most people doing laboratory research on continuously fed activated sludge systems did not realize they were studying a CMAS process. It was simply activated sludge to them.

The first record of CMAS that I found in my research was at Bury, England (Martin 1927). Mr. Joshua Bolton, Chemist and Manager of the Sewage Works at Bury, was interested in seeing if he could develop activated sludge in his small sewage treatment plant. Initially, Mr. Bolton tried diffused aeration, the same as the system used at the Manchester wastewater treatment plant. It was a bust in the small aeration tank that Mr. Bolton had available. With the help of the Ames Crosta Engineering Company, the small tank was converted to a mechanical, surface aeration system with a center draft tube and a sludge settling zone with a circular baffle around the periphery of the tank. A slow speed motor and centrifugal sewage pump was located at the top of the draft tube. By submerging part of the pump blades into the sewage over the center draft tube, they had created one of the first surface aerators to treat domestic sewage in a single tank, combination aeration and sedimentation. The Bury CMAS treatment plant worked in 1919. Unfortunately, loss of suspended solids in the effluent resulted in a lower treatment efficiency than in the diffused aeration system of Ardern and Lockett. I was fortunate to visit Bury, England, in 1969 and saw the original CMAS tank (Photo 1) shortly before the tank was destroyed.

All the early activated sludge plants were designed for long, diffused aeration tanks followed by sedimentations tanks to allow the activated sludge to flocculate and settle out. The clarified effluent was discharged to the nearest river while the concentrated settled sludge was largely returned to the head end of the aeration tank to treat the incoming settled sewage. A small fraction of waste activated sludge was sent to the anaerobic digesters for further treatment with the settled primary sludge before being dewatered and applied to agricultural soil. Small communities in the United States used trickling filters rather than activated sludge plants to treat their domestic sewage. Trickling filters did not produce an effluent quality as good as activated sludge plants, but were much easier to operate.

After World War II, many communities in the United States were faced with housing booms that produced subdivisions beyond the city limits. Most of the subdivisions used septic tanks in the back yards for sewage disposal. As the soils became saturated with sewage, the subdivisions used sanitary sewers to collect the sewage from each resident and trickling filters to treat their sewage with final discharge of the treated effluent into a nearby creek or stream. A few equipment companies developed packaged activated sludge plants for small communities or isolated industries.

When I started my doctoral studies at M.I.T. in 1949, I was fortunate to be asked by Professor Clair Sawyer to be his laboratory assistant for a year while I finished my classes in Sanitary Engineering, took my language requirements in German and French, and began my minor in Chemistry. I quickly learned more Sanitary Chemistry from Professor Sawyer than I had learned when I took the original course. He was an excellent teacher and expected the best from all students in his classes. I also helped Dr. Sawyer with his laboratory research on industrial waste treatment by activated sludge. In my spare time, I went to the M.I.T. Library, located under the dome, to find out as much as I could about activated sludge, especially about the microbiology and the biochemistry related to activated sludge.

The next year, I worked on a research grant from the National Institute of Health to study the *Biology and Biochemistry of the Zooglea Producing Organisms Involved in the Activated Sludge Process*. Professor M.P. Horwood was the faculty member responsible for the N.I.H. grant. Richard S. Engelbrecht worked on the project with me as a Research Associate. Our research helped us both learn more about the microorganisms that made up activated sludge. We isolated a number of pure culture bacteria capable of forming floc under normal activated sludge aeration conditions. I obtained my doctorate and left M.I.T in 1951. Richard S. Engelbrecht carried on the N.I.H. research project and received his Master of Science degree in 1952.

I returned to M.I.T. in the spring of 1953 and became an Assistant Professor of Sanitary Engineering. Because Professor Horwood was on leave of absence, I was put in charge of the Sanitary Bacteriology courses. I changed the emphasis of the Sanitary Bacteriology courses to a broader focus on Sanitary Microbiology and Biochemistry. Next, I worked with Richard S. Engelbrecht to complete his doctorate. He graduated in June 1954, and headed to the University of Illinois, where he had a long and distinguished career. I was very successful in attracting good students wishing to learn more about Sanitary Microbiology and Biochemistry and to do research with me on waste treatment systems.

In the spring of 1955, Professor Rolf Eliassen asked me to make a quick study of the treatability of the cotton kiering wastes from the Dale Brook Bleachery in HoHoKus, NJ. I built a small activated sludge plant out of plastic sheets, using small fish tank aerators to supply the oxygen and mixing energy. With pH adjustment, added nitrogen and phosphorus, it was possible to produce some activated sludge from the bleachery wastes. Microscopic examination of a sample of mixed liquor showed active bacteria and good free-swimming protozoa. I fed the small activated sludge system on a batch feed basis, 23 hours aeration and one hour settling. There were no problems treating the Dale Brook Bleachery wastes in that unit. Next, I needed to examine a continuous flow activated sludge unit. Continuous feeding for several days showed the development of stalked ciliated protozoa, indicating a high degree of bio-treatment. COD data confirmed the high degree of treatment. Next, Professor Eliassen requested that I prepare a set of plans for use in constructing a full-size activated sludge plant for the bleachery. His instructions included that it should be cheap, easy to build, and very easy to operate.

I constructed a small plastic model of an activated sludge plant with 10 aeration cells in series. I did not think that I would ever

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[1] Professor Emeritus, University of Kansas

PHOTO 1
The first CMAS unit at Bury, England, in 1919 as pictured in 1969 before plant expansion.

PHOTO 2
The four cell CMAS plant at Dale Brook Bleachery, HoHoKus, NJ.

need a 10 cell activated sludge plant, but I wanted to see how the activated sludge responded in multiple cells. Continuous feeding of adjusted Dale Brook Bleachery effluent to a laboratory activated sludge seed in the 10 cell system showed the wastewaters were well treated in a 24 hour retention period. Examination of each cell showed that the wastes were undergoing stabilization in the first three cells. As a result of the laboratory study, I designed a simple treatment plant to have four units in parallel since the bleachery operated sporadically when the demand from customers in New York City required it to operate. The four units would allow the system to handle variable waste loads.

The plant manager was not entirely convinced that my activated sludge design would work. He had his men construct one unit with three cells in series. The plant wastes were added to the first cell of the first unit and the aeration equipment turned on when the waste flow filled the first cell. The waste from the first cell flowed into the second cell and finally into the third cell. When the activated sludge concentration reached normal levels, data indicated that all of the stabilization of the raw wastes was occurring primarily in the first cell. The plant was then modified to give three cells operating in parallel rather than in series. Since the waste flow through each cell was less with parallel operation, the final sedimentation sections were made smaller and the aeration tank capacity was increased. Once continuous waste feeding was established to the first unit, the good effluent quality convinced the plant manager to finish the other three units to complete the treatment plant as designed. It was not long before all four units were completed, operating in parallel and the wastewater treatment plant was put into full operation (Photo 2).

After the treatment plant had been in operation for about six weeks, I collected samples of the effluent and found the raw wastes had a pH of 6, a COD of 860 mg/L and a BOD5 of 420 mg/L. The treated waste sample had a pH of 7.8, a COD of 65 mf/L and a BOD5 of 3 mg/L. The plant effluent from the waste lagoon to the wastewater treatment plant averaged about 125,000 gpd. The treated effluent was discharged directly into HoHoKus Creek, a small stream that flowed through the residential areas of HoHoKus, NJ McKinney, *et. al.*, 1958). As business expanded for the Dale Brook Bleachery over the years, the wastewater treatment facilities were expanded as needed until they ran out of space for more treatment units. As a result of the success of the CMAS system at the Dale Brook Bleachery, I received a number of requests to look at other industrial wastes. These requests gave me an opportunity to examine a number of different industrial wastes and their suitability for treatment by CMAS. For the most part, I helped a number of small industrial plants that were unable to connect to a sanitary sewer system.

In 1960, I left M.I.T. and went to Kansas University in Lawrence, KS. One of my first MS students, Ramesh Doshi from India, did his MS thesis on the *Mathematics of Complete Mixing Activated Sludge* (Doshi, 1961). Unfortunately, his mathematical equations were far too complex for practical use by consulting engineers. At least, he set me to thinking about developing a simpler set of mathematical equations to evaluate CMAS systems. My CMAS equations were published in the *Journal of the Sanitary Engineering Division of the American Society of Civil Engineers in 1962* (McKinney, 1962). Almost immediately, my students wanted me to simplify my equations. In the next few years, I made a couple of simplifications. That was not enough for my students. They wanted the equations even simpler. I made the CMAS design equations as simple as I could (McKinney, 1974). One of my computer-oriented students put my equations for CMAS on the Department computer, making it easy for the students to work with the equations. My students became the best advocates I had for CMAS designs and evaluations.

In addition to teaching and research at the University of Kansas, I was involved in a Kansas Outreach program to assist small communities and individuals with special problems. One of the most interesting problems I became involved with was to help Mr. Paul Smart with a problem he had. Mr. Smart wanted to build a pig farrowing house on his property that abutted the main road between Lawrence and Topeka, KS. Mr. Smart had travelled over Europe and England, as well as, the United States, looking for an odorless hog confinement building without success. The Kansas State Health Department told Mr. Smart that I might be able to help him. Mr. Smart gave me written information on the waste production characteristics of hog manure. One of the hog building manufacturers had designed a farrowing building 142 ft. long and 26 ft. wide, with windows that opened to give ventilation and some mechanical ventilation units. A farrowing house was placed on a concrete box foundation designed for Mr. Smart. There was a concrete wall down the middle of the box foundation with 10 ft open spaces at each end of the center concrete wall. Mr. Smart asked me to design a treatment system for his new farrowing house. I suggested a mechanical surface aerator to be located across the width of the channel at the head end of the farrowing house, to aerate and move the water in the channel around the farrowing building. The floor was a series of precast-

PHOTO 3
Inside Paul Smart's farrowing house, showing slotted floor.

PHOTO 4
Graduate students at KU pouring sodium sulfite in clean water for oxygen transfer test.

concrete slabs with thin slots at regular intervals in each slab. The urine produced by the pigs dropped through the slots into the flowing liquid below the slab floor. The movement of the pigs in the pens forced the manure through the slots into the moving water. Theory became reality when 50 pregnant sows arrived and were herded into their separate pens (Photo 3). It was not long before microorganisms began to grow in the rotating liquid under the slotted floor. In a few days, activated sludge formed in the liquid under the pigs. Everyone visiting the hog farm was amazed that there were no obnoxious odors in or around the hog building. The success of the aerobic hog building stimulated Mr. Smart to build more buildings for finishing hogs. All were relatively odor free when the aeration equipment functioned properly. At peak production, Mr. Smart had about 6,000 hogs in buildings on his property. Eventually, Mr. Smart closed his hog farm and sold his property, ending my fear Mr. Smart might over expand on the site.

Kansas was quite different than Massachusetts, as far as wastewater treatment plants were concerned. There was plenty of land for wastewater lagoons. A few plants used aerated lagoons ahead of oxidation ponds. The isolated industrial plants were not interested in CMAS plants for their waste disposal treatment. On the other hand, the City of Lawrence, Kansas, had a conventional primary wastewater treatment plant with discharge of the treated effluent into the adjacent Kaw River. The EPA decided all municipal wastewater plants in the 1970s should be upgraded to secondary treatment with possible chlorination of the final effluent. To meet EPA requirements, the Design Engineer decided to install two circular aeration tanks, 105 ft. in diameter. The inside water depth of each aeration tank was 14.5 ft. There were four 60 HP mechanical surface aerators and draft tubes to supply oxygen to each aeration tank. The primary settled effluent from one primary tank was discharged into the corresponding aeration tank through a single pipe at the bottom of the aeration tank between the surface aerators. A surface weir was located at the surface on the opposite side of the aeration tank to allow effluent discharge from the aeration tank to the final sedimentation tank. A wooden baffle was placed around the effluent weir to dampen the surface motion prior to discharge over the weir to the final sedimentation tank. The mixed liquor discharged from each aeration tank went to corresponding final secondary settling tanks to separate the settled activated sludge for return to the aeration tanks. The sedimentation tank effluent was discharged to the Kaw River after chlorination. The waste activated sludge was sent to two aerobic digesters in series. After aerobic digestion, the final activated sludge residues were placed on nearby agricultural land and turned into soil.

The EPA required the City to run a clean water aeration test to determine the maximum capability of the surface mechanical aerators to transfer oxygen from the air into the aerated liquid. The engineer for the project had a series of continuously plotting DO probes placed at different points in the tank to see how well the water mixed in the aeration tank. The tank was filled with tap water and the recorders were turned on to obtain initial equilibrium. The City asked some of my graduate students to help pour the sodium sulfite into the aeration tank. My students and some plant operators were located on the runways next to the four aerators. When the recorders were steady, a signal was given and each man began to pour large bags of sodium sulfite into the aeration tank to remove all the dissolved oxygen in the water (Photo 4). The submerged recorders showed when the dissolved oxygen in the water was removed. It was some time before the recorders began to show oxygen returning to the aeration tank. The data recordings showed the aerators transferred 3.3 lbs. oxygen/ HP-hr to the water in the tank (McKinney, *et. al.*, 1977). Over the next year, the rest of the wastewater treatment plant was completed. As most wastewater treatment plant operators have learned, plant expansion and replacement of equipment is never really finished. The Lawrence wastewater treatment plant demonstrated that the aeration tanks were simply large CMAS units.

There is nothing unusual about complete mixing activated sludge. It is based entirely on understanding the microbiology of wastewater treatment and how to apply microbiology and biochemistry to treatment plant design. As a design engineer, you have lots of tools to design the best treatment plant possible. You will spend lots of time on tank sizes and mechanical equipment. Do not forget that the microorganisms living in those tanks will do their best with your design. The best advice the microorganisms can give you is to keep the system simple.

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SOLIDS SEPARATION IN THE ACTIVATED SLUDGE PROCESS - THE FIRST 100 YEARS

Richard I. Dick, Ph.D., P.E., BCEE[1]

Those who translated Ardern and Lockett's research into full-scale, continuous-flow, activated sludge plants designed final clarifiers as they had been accustomed to designing plain sedimentation tanks. Their precedent persisted throughout the first half century of use of the process. Application of thickening concepts to final settling tank design gave recognition to the substantial solids loading on the tank and allowed rational integration of the biological and solids separation phases of the activated sludge process.

INTRODUCTION

Ardern and Lockett had it easy - they only had to invent the activated sludge process, and did not need to deal with continuous solids separation and recycle. In their initial experiments Ardern and Lockett (1914a) used draw-and-fill reactors so solids settled under quiescent conditions in the biological reactor.

The second publication on their pioneering work (Ardern and Lockett, 1914b) included a brief description of small-scale, continuous-flow, experiments, but they were not pleased with results. Part III (Ardern and Lockett, 1915) concerned only draw-and-fill experiments; preliminary thoughts about scale-up - also involving draw-and-fill reactors - were included.

THE EARLY YEARS

The first large-scale demonstration of the activated sludge process, at Salford, England, mimicked the draw-and-fill procedure used by Ardern and Lockett (Melling, 1914). The many full-scale installations that quickly followed (Alleman and Prakasam, 1983), however, were continuous-flow plants (with solids separation and recycle).

I am not aware of literature documenting the strategy of designers of the first settling tanks for activated sludge mixed liquor. It appears that they were strongly influenced by past experience with raw sewage sedimentation. Such experience was extensive at the time [see, for example, Dunbar and Calvert (1908) and a book on sewage clarification by Schmeitzner (1910)]. Theoretical understanding of factors controlling performance of settling tanks receiving dilute suspensions also was available at the time: Hazen (1904) presented basic sedimentation concepts that remain valid over a century later.

As design practices in early years of the activated sludge process became chronicled in textbooks it became clear that designers of final sedimentation tanks had, indeed, applied concepts appropriate to clarifiers for raw sewage. Metcalf and Eddy (1922) prescribed determining the area of final settling tanks based on hydraulic loading. Babbitt (1925) agreed, and referred to a final settling tank as "a plain sedimentation tank." In their second edition Metcalf and Eddy (1930) wrote that "The design of settling tanks in which activated sludge is removed from the aeration tank effluent does not differ materially from the design of plain sedimentation tanks". In the vernacular of the time, plain sedimentation tanks were primary clarifiers in which sewage solids settled without the aid of added chemicals (Kinnicutt, *et al.*, 1910).

Thus, even though the suspended solid concentration of mixed liquor is roughly an order of magnitude higher than that of raw sewage, and in spite of the importance of recycled sludge concentration to the efficacy of the biological process, final clarifier design practice developed without concern for thickening (Dick, 1976).

EVOLUTION OF SLUDGE THICKENING CONCEPTS

Basic understanding of mechanisms involved in thickening of concentrated slurries began to develop at about the same time as Ardern and Lockett's work. Coe and Clevenger (1916) demonstrated that each layer in a settling suspension has an associated capacity for discharging its solids to underlying, more-concentrated, layers. They were the first to show that the rational basis for sizing a continuous thickener is to provide sufficient cross sectional area to assure that the rate of solids application (mass of solids per unit area and time) is equal to, or less than, the capacity of the rate-limiting layer for transmitting solids downward. The rate-limiting layer is the one with the lowest total suspended solids transmitting capacity (the sum of gravity transport and convective transport due to thickened sludge removal from the tank bottom).

Kynch (1952) provided insight into mechanisms involved in both batch and continuous thickening. He showed that, in batch thickening, layers with less capacity to transmit solids downward than the rate at which solids are received from overlying layers propagate upward at a constant velocity. Thus the shape of an interfacial subsidence curve in batch thickening is explained by an initial slope representing the settling velocity of the original suspension followed by continuously diminishing slopes as layers of higher concentration propagate to the interface and display their slower settling rates. The implication for continuous thickening is that, under fully-loaded conditions, the layer that would limit solids transmitting capacity must be pulled down (by removal of thickened sludge) at the same rate as the layer tries to propagate upward. Kynch's paper stimulated additional fundamental thickening work by, for example, Talmage and Fitch (1955), Yoshioka, *et al.* (1957), and Shannon, *et al.* (1963).

Environmental engineers were slow to recognize developments in sludge thickening of importance to their field - none of the authors cited previously in this section were environmental engineers. Behn (1957) was amongst the first in our field to build upon the foundation from other disciplines. And, just before the end of the first half-century of the activated sludge process, basic thickening concepts appeared in environmental engineering texts [Rich (1961) and Eckenfelder and O'Connor (1961)].

SOLIDS FLUX IN FINAL SETTLING TANKS

In accordance with the continuous thickening concepts described in the previous section, the rate at which suspended solids can pass downward through a layer with solids concentration c_i (M/L^3) is

$$G_i = c_i v_i + c_i u \qquad (1)$$

where G_i (M/L^2T) and v_i (L/T) are, respectively, the solids flux and gravity sedimentation velocity of the layer and u (L/T) is the rate of bulk downward transport due to sludge removal from the tank bottom.

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[1] The Joseph P. Ripley Professor of Engineering Emeritus, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14850, rid1@cornell.edu.

FIGURE 1

Graphical representation of Eq. 1 illustrates the limiting flux, G_L, that establishes final settling tank capacity.

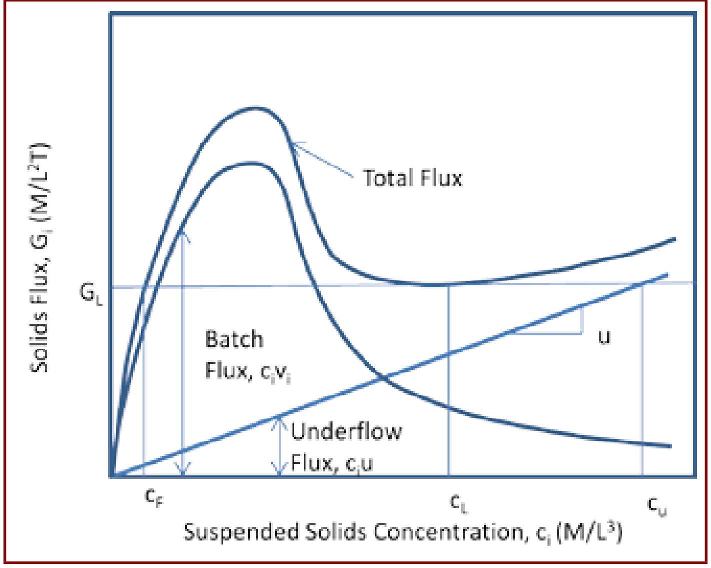
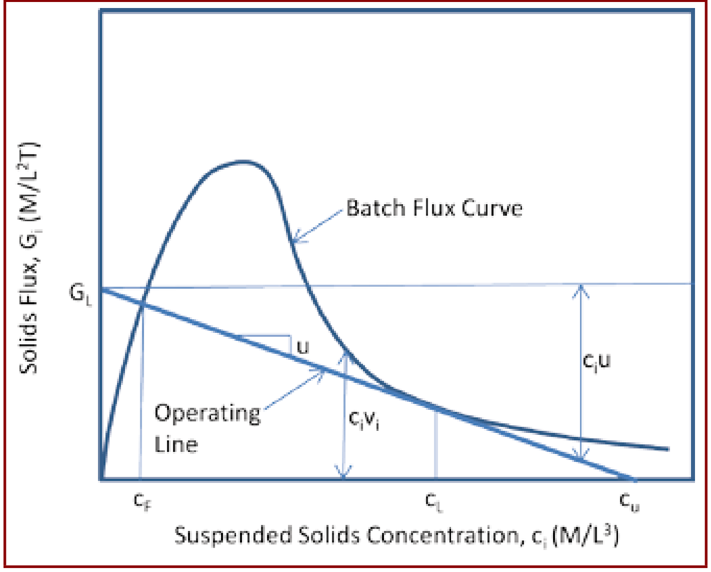


FIGURE 2

The operating line identifies the underflow concentration and the total solids flux



The c_iv_i term in Equation 1 is the solids flux due only to gravity subsidence, and it is established by the settling characteristics of the activated sludge solids. The c_iu term is the additional flux caused by removing thickened sludge. It is established by the rate of thickened sludge removal, Q_u (L^3/T), and the cross sectional area of the tank, A (L^2), or

$$u = Q_u/A \qquad (2)$$

Thus, solids transport due to sludge removal is independent of sludge settling characteristics: it is established by the designer (who fixes A) and the operator (who determines Q_u).

Graphical representation of Equation 1 as shown in Figure 1 is instructive (Dick, 1970). The batch flux curve is obtained by experimentally determining the subsidence velocity of activated sludge solids in batch settling tests over a range of suspended solids concentrations and multiplying velocities by their corresponding concentration. The shape shown is typical, for flux goes to zero at zero concentration, passes through a maximum at intermediate concentrations, and again approaches zero as settling velocity progressively diminishes at high concentrations. The linear line for solids flux caused by sludge withdrawal is established by selecting the underflow velocity, u. The point of Figure 1 is to illustrate that the total possible solids flux as given by Equation 1 passes through a minimum value - one concentration, c_L (L for limiting), has less total capacity for transmitting solids downward than all others[2], and the corresponding limiting flux, G_L, establishes the maximum rate at which solids can be applied. Any solids applied in excess of the limiting flux will accumulate above the rate-limiting layer awaiting their chance to pass through; if the condition is sustained, solids in excess of the capacity of the limiting layer will propagate upward and ultimately be discharged with the "clarified" effluent. The remedy for the overloaded situation is for the designer to provide more area (decreasing applied flux) or for the operator to increase the thickened sludge withdrawal rate (increasing underflow flux).

The rate of thickened solids removal from a final settling tank is the product of the underflow rate and the underflow concentration (c_u, M/L^3), and, if the tank is operating properly, this equals the applied solids flux (G_a, M/L^2T) times the area of the tank; thus

$$Q_uc_u = G_aA \qquad (3)$$

But, from Equation 2, $u = Q_u/A$, so

$$u = G_a/c_u \qquad (4)$$

Thus, as illustrated graphically in Figure 2, a line drawn from any underflow concentration with slope u identifies the corresponding applied solids flux (or a line drawn from any applied flux with slope u shows the corresponding underflow concentration). The line characterizes how a final tank is being operated and, hence, is called the "operating line".

The two terms on the right side of Equation 1 are identified in Figure 2. It may be seen that concentrations for which the batch flux curve lies above the operating line have capacity for transmitting solids in excess of the rate at which they are applied (and, thus will not exist in the tank). If the operating line is above the batch flux curve for a sustained period failure will occur, for solids are being applied at a rate faster than they can pass through some concentrations[2]. The operating line shown in Figure 2 illustrates the condition when the applied solids load exactly equals the limiting flux and identifies the rate limiting concentration as the point of tangency[3].

Constructing alternative operating lines with differing slopes allows designers to evaluate effects of varying settling tank area, and plant operators to determine effects of varying thickened sludge withdrawal rates. These opportunities are expanded in the following section.

FINAL SETTLING TANK AS PROCESS CONTROL CENTER

The applied solids loading may be expressed as

$$G_a = (Q/A)X + (R/A)X \qquad (5)$$

Where Q is the wastewater flow rate (L^3/T), R is the recycle rate (L^3/T), and X is the mixed liquor suspended solids concentration (M/L^3). Equation 5 is depicted graphically in Figure 3. The line emanating from the origin at slope Q/A (the hydraulic loading in clarifier parlance) - called the "loading line" - shows the flux attributable to solids conveyed by wastewater flow, and, as before, the distance between the ap-

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[2] Solids concentrations to the left of c_F in Figures 1 and 2 have less solids transmitting capacity than the limiting flux, but they are not of concern because such dilute concentrations do not exist in the thickening portion of final settling tanks. If the rate limiting layer is at a level below the inlet (as usual) incoming solids will be diluted to concentration c_F in a perfectly designed tank because it has capacity for transmitting solids at the same rate they are received.

[3] Kynch (1952) showed that the rate at which layers propagate upward in batch sedimentation is -dG/dc, the slope of a batch flux curve and of the operating line. Thus, under fully-loaded conditions in a continuous settling tank, the rate-limiting layer is held stationary because the rate of upward propagation equals the rate of downward convective transport.

FIGURE 3
The loading line and the operating line intersect at the mixed liquor suspended solids concentration

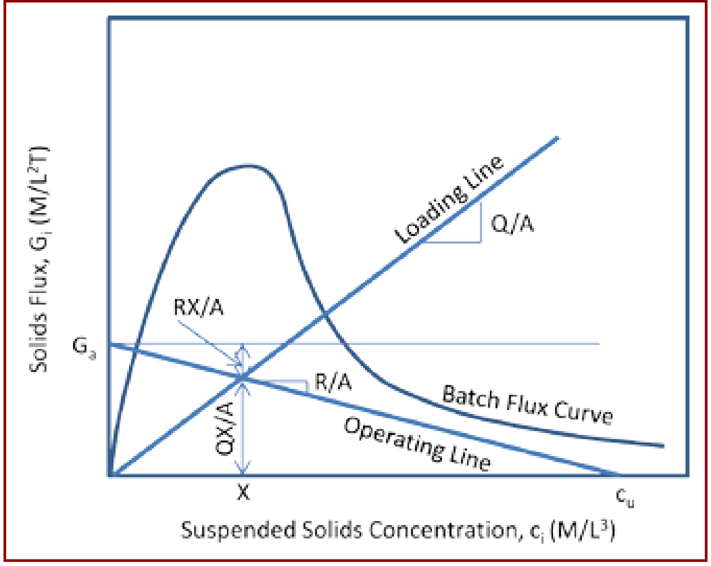
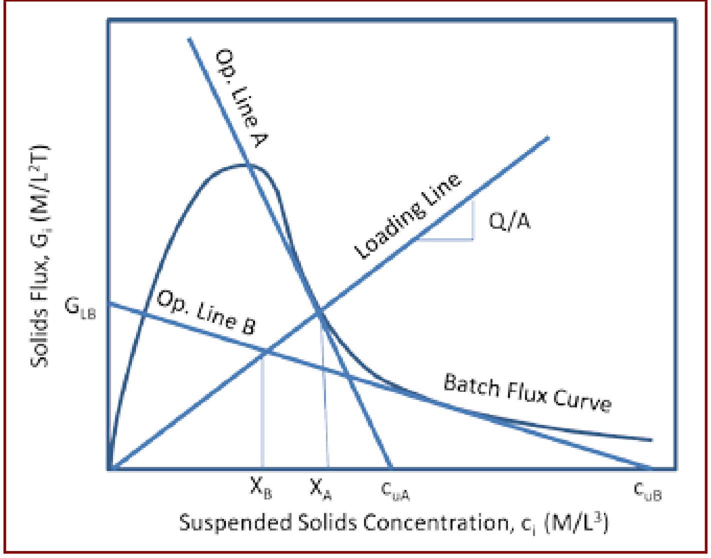


FIGURE 4
Final settling tanks can be operated under widely differing modes to accommodate optimal integration with the biological phase of the processThe operating line identifies the underflow concentration and the total solids flux



plied flux and the operating line (shown here with slope R/A) depicts the solids flux attributable to recycle flow[4]. As illustrated in Figure 3, the intersection of the loading line and the operating line, called the "state point", identifies the mixed liquor suspended solids concentration resulting from operation under the conditions depicted - no other concentration satisfies the relationship in Equation 5 (Dick, 1984).

Inspection of Figure 3 readily reveals not only the manner in which the final settling tank is being operated, but, also, the state of the entire activated sludge process: the final settling tank has reserve capacity (for the operating line is below the batch flux curve), and the aeration tank is operating far below its capacity (for the operating line slope could be increased to shift the state point to the right so as to increase the concentration of microorganisms in the biological reactor).

Figure 4 shows two extremely different operating lines and further illustrates the role of the final settling tank as the control center of the activated sludge process. Operating line A maximizes the capacity of the biological part of the process (it allows the highest possible mixed liquor solids concentration and, hence, maximizes sludge age). Selecting that strategy would require more recycle pumping capacity and energy, and increase oxygen requirements and decrease excess sludge production (both because of higher endogenous respiration). In contrast, selecting operating line B would, if aeration tank volume were adequate, reduce recycling and aeration costs, but increase waste sludge production.

A caveat: Changes in operating conditions as depicted in Figure 4 require monitoring of sludge settleability and any necessary adjustment of batch flux curves. Nevertheless, the analysis suggested by the figure aids in identifying optimal operating conditions. Predictive capability for estimating changes in the settling characteristics of activated sludge caused by operational adjustments remains for investigators in the second century of the process.

"RECENT" DEVELOPMENTS

It is difficult to identify significant improvements in activated sludge solids separation during the first half century of the process. In addition to recognition that the design of final settling tanks is guided by thickening concepts, as described herein, numerous developments occurred in recent decades.

Modeling of the process has been popular [for example, Henze, *et al.*, 2008] but with limitations for solids separation: usual modeling of the biological phase of the process does not assure effective bioflocculation, and estimating settling velocities based on empirical correlation with the sludge volume index, as is common, sacrifices accuracy.

Hydraulics of final settling tanks have been studied [by Zhou and McCorquodale (1992), for example], baffling arrangements have been advanced [see, for example, Tamayol, *et al.* (2010)], and inlets designed to promote flocculation have been introduced (Parker and Stenquist, 1986).

Some recent developments dramatically alter activated sludge solids separation as practiced during the first century of the process and as considered in this paper. The draw-and-fill configuration used by Ardern and Lockett has returned in the form of sequencing batch reactors (Irvine and Ketchum, 1989). Membrane separation of treated effluent, eliminating the use of gravity separation [Meng, *et al.* (2012), for example], and ability to create granular aerobic sludge (de Bruin, *et al.*, 2004)) significantly alter the activated sludge process. The volume of treated wastewater currently separated by these processes is a small fraction of the enormous volume discharged globally from final settling tanks, but, perhaps, after a century of gaining some understanding of final settling tanks, alternative options will emerge.

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[4] In previous figures the slope of the operating line has been shown, properly, as Qu/A; here, for convenience, it is taken as R/A. Qu is slightly greater than R because of sludge wastage. Under typical operating conditions, the error in ignoring sludge wastage is about 2 percent (Dick, 1984).

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DESIGNING ACTIVATED SLUDGE SYSTEMS FOR NITROGEN REMOVAL

Glen T. Daigger, Ph.D., P.E., BCEE, NAE[1]

Nitrogen is always present in domestic wastewater and can also be present in industrial wastewaters. Nitrogen discharges increasingly need to be reduced to protect ambient water quality and desired uses of water resources. Fortunately, activated sludge processes can be modified to accomplish both nitrification (conversion of ammonia-nitrogen to nitrate-nitrogen) and nitrogen removal. Conventional biological nitrogen removal is accomplished through autotrophic nitrification, which converts ammonia-nitrogen to nitrate-nitrogen, and heterotrophic denitrification, which uses nitrate-nitrogen as a terminal electron acceptor and reduces it to nitrogen gas. The principals of these biological processes and how they can be applied practically in activated sludge systems are well understood and widely applied. A well established set of biological nitrogen removal processes, such as Modified Ludzak-Ettinger (MLE) and Four-Stage Bardenpho, are available and are routinely applied in practice. Nitrous oxide (N_2O) is produced in biological nitrogen removal processes, including activated sludge, and estimates suggest that this is a nationally significant greenhouse gas emission source. Research is on-going and helping to elucidate both the mechanisms of nitrous oxide production and emission and control approaches. At the same time, biological metabolisms are being newly discovered and converted into practical activated sludge treatment processes which require significantly less oxygen and biodegradable organic matter. These processes, which require less resource consumption to achieve biological nitrogen removal, offer the potential for achieving wastewater treatment, including biological nitrogen removal, in a much more environmentally sustainable fashion.

INTRODUCTION

Nitrogen control was an essential component of the activated sludge process as originally developed 100 years ago (Alleman and Prakasam, 1983). At that time, complete nitrification was a key indicator of the completion of biological stabilization of the influent wastewater. Thus the process was initially operated to achieve complete nitrification. This was relaxed over the decades as the concept of providing just sufficient treatment to protect receiving water quality was introduced. It was found that activated sludge systems could be designed and operated to remove biodegradable organic matter without also converting ammonia-nitrogen to nitrate-nitrogen. As a consequence, when the activated sludge process was adopted as the model for secondary treatment of municipal wastewater in the United States, performance requirements specified effluent 5-day biochemical oxygen demand (BOD_5) limitations but not effluent nitrogen values. Thus, for many practitioners the activated sludge process became associated with the removal of BOD_5 and not nitrogen.

The requirements for environmental protection have changed over the past 100 years. The human population has grown significantly, and even greater economic growth has occurred, with a commensurate much greater generation of wastewater. Likewise, environmental protection requirements have grown significantly. In years past, the environmental protection objective was simply to avoid gross pollution of water bodies, whereas today we look to restore receiving water body quality to near-natural conditions. As ambient water quality expectations and requirements have become more stringent over the past several decades, the importance of nitrogen control, not only for ammonia-nitrogen but also total nitrogen, has become evident. In response, the activated sludge process has been adapted to provide significant nitrogen removal.

Significant interest in and practical application of biological nitrification (removal of ammonia-nitrogen by its conversion into nitrate-nitrogen) occurred beginning in the late 1970's and 1980's as the adverse impacts of ammonia discharges became evident. Research on biological nitrogen removal was also initiated in the 1960's but did not see significant full-scale application until the late 1980's. The implementation of biological nitrogen removal is still continuing, especially in coastal locations where discharges are to estuarine environments.

UNDER WHAT CIRCUMSTANCES IS NITROGEN CONTROL WARRANTED?

Nitrogen is present in municipal wastewater because it is in the diet of human beings and, as it is digested, it must be excreted. It is discharged in the urine as urea ($CO(NH_2)_2$), which is hydrolyzed relatively quickly in the sewer to ammonia-nitrogen, and in the feces as organic nitrogen (Metcalf & Eddy, 2013). Some household products also contain nitrogen compounds (although this is minimal these days). Municipal wastewater may also contain industrial wastewater which can also contain a wide variety of nitrogen-containing compounds. Some nitrogen is removed through conventional wastewater treatment as suspended solids, and the associated nitrogen is removed in primary treatment, and some nitrogen is used for biomass growth during secondary treatment. Municipal wastewater contains excessive quantities of nitrogen relative to biosynthesis needs however, and consequently, an effluent not treated for nitrogen removal will contain ammonia-nitrogen and some organic nitrogen. It will also contain nitrate-nitrogen if the biological treatment system is nitrifying.

Nitrogen is an essential nutrient for the growth of plant and animal life and, consequently, must be present in sufficient quantities in both terrestrial and aquatic environments. However, like most substances, there can be "too much of a good thing", and the presence of excessive quantities of nitrogen adversely impacts water quality and beneficial uses of water resources as outlined in Table 1.

Ammonia-nitrogen adversely affects ambient water quality in several ways. When discharged to waterways it can be nitrified, creating an oxygen demand which can deplete the oxygen resources of the receiving stream to below levels required by the desired aquatic organisms (generally fish). Ammonia is also a weak base and is present in two forms - un-ionized (NH_3-N) and ionized (NH_4^+-N) - depending on the ambient pH. The un-ionized fraction increases as the pH increases. Un-ionized ammonia is quite toxic to aquatic organisms, and ambient water quality standards limit un-ionized ammonia concentrations in receiving streams to quite low levels (generally about 0.1 mg-N/L). The pH of receiving waters is often higher than that of the treated water, leading to elevated un-ionized ammonia concentrations and the need for stringent control of total ammonia (un-ionized plus ionized) discharges. Ammonia-nitrogen can also interfere with water supply as it will combine with chlorine to form chloramines, which are a less effective disinfectant than free chlorine, and its presence in treated water distribution systems can lead to the growth of a nitrifying biofilm and the resulting deterioration in drinking water quality.

The presence of nitrate-nitrogen is also a drinking water concern as it can cause methemoglobinemia, also known as blue baby syndrome. As a result, the primary drinking water

[1] Senior Vice President and Chief Technology Officer, CH2M HILL, 9191 South Jamaica Street, Englewood, CO 80112. gdaigger@ch2m.com

TABLE 1
Nitrogen Species and Principal Water Quality Impacts

Constituent	Impact
Ammonia-Nitrogen (NH_3-N plus NH_4^+-N)[1]	Consumes oxygen when nitrification occurs in the ambient environment and can deplete available ambient dissolved oxygen (DO) concentration. Interferes with water treatment by formation of chloramines when chlorine added and can result in growth of nitrifying biofilms in water distribution system.
Un-ionized Ammonia (NH_3-N)	Toxic to a wide variety of organisms at relatively low concentrations. Un-ionized ammonia concentration depends on total ammonia concentration and water pH, with the un-ionized ammonia concentration increasing as the total ammonia concentration and water pH increase.
Nitrate-Nitrogen (NO_3^- N)	Concentrations over 10 mg-N/L cause methemoglobinemia (blue baby syndrome). Consequently, this concentration is a primary drinking water criteria
Total Nitrogen (NH_3-N, NO_2^--N, NO_3^--N, and Organic-N)	Can result in the growth of excessive quantities of aquatic plants and algae which consume oxygen during respiration. Also results in unsightly conditions which interfere with recreation and other uses. Cyanobacteria can produce toxic cyanotoxins. Excessive algae growth can adversely affect water supply by interfering with conventional water treatment and through products of their growth, such as geosmin, which impart unpleasant taste and odor to the water.

[1] Also referred to as total ammonia.

standard for nitrate-nitrogen is 10 mg-N/L. Of course, the discharge of any form of nitrogen can result in the presence of excessive quantities of nitrate-nitrogen if the discharged nitrogen is nitrified in the ambient environment, as it generally will be.

Nitrogen itself, can adversely impact ambient water quality if the concentration becomes sufficiently high to encourage the growth of excessive quantities of aquatic organisms, including algae. This process is called eutrophication and refers to the excessive growth of these undesirable aquatic organisms and the resulting adverse water quality impacts. Of course, other conditions conducive to this growth must be present, including clear water which will allow the necessary light for the growth of these photosynthetic organisms to penetrate the water column and the presence of other nutrients, including phosphorus. Phosphorus limitation is generally necessary to limit algae and aquatic plant growth in freshwater environments as nitrogen-fixing cyanobacteria (also referred to as blue-green algae), which can reduce atmospheric nitrogen gas into ammonia-nitrogen, are able to grow in these environments. In fact, achieving nitrogen-limiting conditions in such environments when excess phosphorus is present can result in the growth of cyanobacteria, using the excess phosphorus and obtaining nitrogen from the atmosphere through fixation. This is of consequence since they produce a variety of cyanotoxins which further adversely impact water quality. Nitrogen-fixing organisms do not generally grow in salt water environments; however, making nitrogen limitation a viable option to limit excessive growth of aquatic plants algae. Both nitrogen and phosphorus control strategies are generally required in estuarine environments both fresh and salt water environments are present.

Eutrophication adversely impacts water quality in several ways. While photosynthetic organisms produce oxygen when light is present, they respire heterotrophically and consume oxygen when light is not available, for example during the night. This can result in DO depletion during the nighttime. Algae also produces compounds such as geosmin, which impart an unpleasant odor and taste to water (thus interfering with its use as a water supply), and cyanotoxins which adversely affect aquatic organisms.

HOW DO BIOLOGICAL SYSTEMS REMOVE NITROGEN?

Biological nitrogen removal is traditionally accomplished by the combined processes of nitrification and denitrification (Grady, *et al.*, 2011; Henze, *et al.*, 2008). Nitrification is the conversion of ammonia-nitrogen first to nitrate-nitrogen and subsequently to nitrate-nitrogen. These are aerobic processes accomplished by two different groups of autotrophic microorganisms. The term "autotrophic" means that these organisms produce the energy needed for growth by the oxidation of inorganic substances and the carbon needed for biomass synthesis by fixing (reducing to the same oxidation state as in biomass organic matter) carbon dioxide (CO_2). The organisms that oxidize ammonia-nitrogen to nitrite-nitrogen are referred to as ammonia oxidizing bacteria, or AOBs. Ammonia-nitrogen is the electron donor in this oxidation and oxygen is the electron acceptor. Nitrite-nitrogen is subsequently oxidized by nitrite oxidizing bacteria (NOBs), with nitrite-nitrogen serving as the electron donor and oxygen serving as the electron acceptor.

TABLE 2
Synergy Between Nitrification and Denitrification

Item	Nitrification	Denitrification
Oxygen	4.6 mg O_2 Consumed/mg NO_3^--N Produced	2.86 mg O_2 Equivalent Produced/ mg NO_3^--N Removed
Alkalinity	7.6 mg as $CaCO_3$ Consumed/mg NO_3^--N Produced	3.6 mg as $CaCO_3$ Produced/mg NO_3^-N Removed

The nitrifying organisms (AOBs and NOBs) have generally similar growth characteristics. They grow significantly slower than the heterotrophic bacteria responsible for the removal of biodegradable organic matter, and only under aerobic conditions. Thus, the aerobic solids residence time (SRT) of the process is determined by that required to retain the nitrifiers in the system. Nitrifier grow is also relatively sensitive to temperature, and the required aerobic SRT increases significantly as the process temperature decreases. Nitrifiers are also relatively sensitive to pH, needing values ideally between 7.0 and 7.5 but certainly no lower than 6.5. The nitrifiers are generally more sensitive to a broad range of inhibitors and toxics than typical heterotrophs. The concentration of these compounds which affect nitrifiers is often an order of magnitude lower than the concentration which affects heterotrophs.

Denitrification is simply heterotrophic growth ("BOD_5 removal") using nitrate-nitrogen rather than oxygen as the terminal electron acceptor ("oxygen source"). Bacterial respiration (the demand for electron acceptor, either DO or nitrate) depends on the availability of biodegradable organic matter. Respiration is most rapid when dissolved, readily biodegradable organic matter is present, resulting in a high dentrification rate if DO is absent. The respiration rate is lower in the absence of dissolved, readily biodegradable organic matter but in the presence of colloidal and particulate biodegradable organic matter. This occurs because the particulate and colloidal matter must be first hydrolyzed (converted into a dissolved form) before heterotrophs can metabolize it. Hydrolysis is about three times slower than growth on dissolved readily biodegradable organic matter. Finally, if external biodegradable organic matter (dissolved, colloidal, and particulate) is absent, the organisms will respire at an even slower rate using internal carbon sources.

The relationship between electron donor and acceptor is fixed (stoichiometric). Consequently, a sufficient amount of biodegradable organic matter must be present to remove a particular amount of nitrate-nitrogen. Influent wastewater is fed first to the denitrification zone to provide the required biodegradable organic matter. DO is excluded by providing mixing (to retain settleable solids in suspension) rather than aeration. N is provided by directing mixed liquor from an aerobic portion of the process, where nitrate-nitrogen is produced by nitrification, to the denitrification zone. The denitrification zone is typically referred to as the anoxic zone, which refers to the condition where DO is excluded but nitrate-nitrogen is provided for heterotrophic respiration.

Nitrification and denitrification are complimentary processes. Nitrification requires the provision of oxygen (since it is an aerobic process). This requires a significant amount of energy cost since it is required to transfer oxygen into water. The produced nitrate-nitrogen is used to oxidize some of the biodegradable organic matter present in the influent wastewater however, thereby reducing the oxygen required for this purpose and, consequently, the net process energy requirement. Likewise, there is synergy with regard to alkalinity consumption. Alkalinity is the buffering capacity in water - the ability to resist unwanted changes in pH (remember the nitrifiers are sensitive to pH). Nitrification results in the consumption of alkalinity (buffering capacity) as the weak base ammonia is converted into nitrous (HNO_2) and nitric (HNO_3) acid. However, denitrification results in removal of these acids, although a base is not formed (nitrogen gas, N_2 has neither acid nor base properties). Table 2 summarizes these synergies. As noted, the oxygen equivalent saving and alkalinity production from denitrification are less than the oxygen and alkalinity consumption for nitrification, but a positive contribution is still indicated.

HOW ARE BIOLOGICAL NITROGEN REMOVAL PROCESSES CONFIGURED?

Figure 1 illustrates the familiar Modified Ludzak-Ettinger (MLE) biological nitrogen removal process. The initial anoxic zone is created by providing mixing but no aeration; introducing influent wastewater, with its biodegradable organic matter, into it; and providing nitrate-nitrogen through the recycle of mixed liquor from the downstream aerobic nitrification zone via the nitrified recycle (NRCY) and return activated sludge (RAS) streams. Denitrification occurs in this upstream zone, thereby removing a portion of the biodegradable organic matter in the influent wastewater and producing alkalinity. The denitrified mixed liquor, still containing most of the nitrogen from the influent wastewater, flows into the downstream aerobic zone where the ammonia-nitrogen is converted into nitrate-nitrogen. A swing zone (where both mixing and aeration facilities are provided), which can be operated either with mixing and no aeration (and thus be part of the anoxic zone) or with aeration (and can be part of the aerobic zone), is also illustrated.

The MLE process is capable of achieving significant biological nitrogen removal, but the extent of removal is limited because residual nitrate-nitrogen must be present at the end of the aerobic zone to be recirculated back to the aerobic zone for denitrification. Increasing NRCY recirculation increases the transport of nitrate-nitrogen back to the anoxic zone for increased denitrification, but with diminishing effect as the recirculation flow rate is increased. Effluent total nitrogen concentrations around 10 mg-N/L can typically be achieved with this process configuration, which represents 70 to 85 percent removal from typical domestic wastewater.

When further nitrogen removal is needed, another anoxic zone can be added downstream of the initial (or primary) aerobic zone. The rate of denitrification in this zone is significantly lower than in the initial anoxic zone because of the limited supply of biodegradable organic matter. The amount of nitrate to be removed is also significantly less, however, due to the large amount removed in the upstream anoxic zone. A small polishing aerobic zone is typically provided following the second anoxic zone to strip out dissolved nitrogen gas, which can interfere with settling in the downstream secondary clarifier, and to oxidize remaining biodegradable organic matter and ammonia-nitrogen. Supplemental biodegradable organic carbon, for example, purchased carbon sources like methanol, can be added to the second anoxic zone to accelerate the rate if needed. This process is commonly referred to as Four-Stage Bardenpho as it contains four stages (two anoxic and two aerobic), and it was developed by James Barnard.

FIGURE 1
Modified Ludzak-Ettinger (MLE) Process

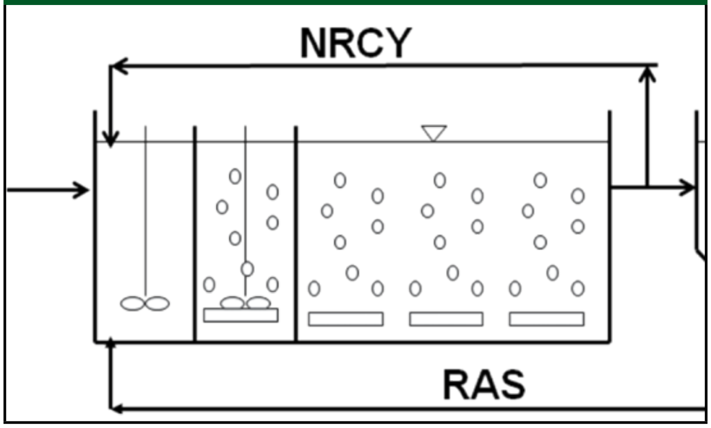
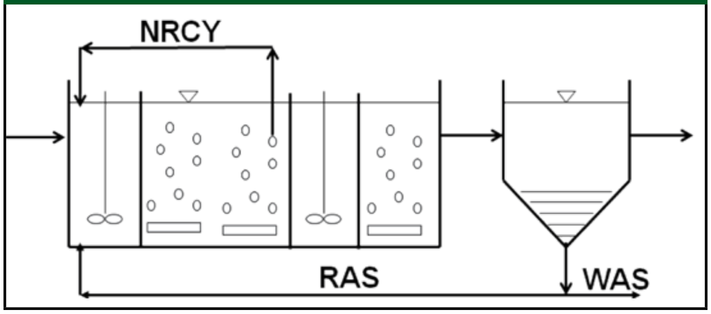


FIGURE 2
Four-Stage Bardenpho Process



Numerous other activated sludge biological nitrogen removal configurations are possible and have been implemented as documented in numerous textbooks and design manuals (WEF, 2013; Grady, *et al.*, 2011; WEF, 2009; Henze, *et al.*, 2008). Some typical examples include controlling oxygen input to oxidation ditches and step feed systems. All of these processes operate according to the principals outlined above.

IS GREENHOUSE GAS PRODUCTION AN ISSUE?

Nitrous oxide (N_2O) is an intermediate in heterotrophic denitrification and can be produced by nitrifying organisms. If produced it can be subsequently metabolized by heterotrophic organisms, but it can also be stripped from the water phase by aeration. This is of concern because nitrous oxide is a powerful greenhouse gas with a greenhouse gas potential 310 times that of carbon dioxide. The United States Environment Protection Agency (USEPA, 2013) estimates that nitrous oxide emissions from wastewater treatment plants were 5.2 million metric tons (MMT) of CO_2 equivalents in 2011 out of a total of 356.9 MMT CO_2 equivalents. This is further out of total greenhouse gas emissions from all sources of 6,702.3 MMT of CO_2 equivalents in 2011. Consequently, controlling nitrous oxide emissions from biological nitrogen removal processes is a significant objective.

Research on the production and emission of nitrous oxide from biological wastewater treatment plants is currently on-going and helping to unravel the relatively complex set of relationships involved (Chandran, 2012; GWRC, 2011). The factors that affect nitrous oxide production by heterotrophic bacteria are well known, and results to date generally indicate that this is not the principal source of activated sludge process emissions. Aeration of anoxic zones, where heterotrophs are denitrifying (and, consequently, producing nitrous acid), is limited to minimize DO transfer into the zone. Thus, stripping of formed nitrous oxide is minimized. Moreover, released nitrous oxide can be subsequently taken up by denitrifying heterotrophs when the conditions that lead to significant nitrous oxide formation are reversed. In contrast, current research suggests that nitrous oxide production by nitrifiers is the principal source of nitrous oxide emissions. It is becoming clear that maintaining stable, consistent, and complete nitrification, even on a diurnal basis, is one of the keys to minimize biological process nitrous oxide emissions. It may be expected that research, coupled with field-scale measurements and practical experience, will lead to full elucidation of the factors responsible for activated sludge process nitrous oxide emissions and methods for minimizing them.

WHAT ARE THE EMERGING NITROGEN REMOVAL OPTIONS?

Numerous historic biological nitrogen removal observations occurring in the apparent absence of sufficient biodegradable organic matter lead to speculation about potential novel nitrogen removal pathways and their significance for biological nitrogen removal process technology. Then, in 1988, microorganisms responsible for a biological metabolism first suggested in 1977 (Broda, 1977) were isolated, leading a few years later to the development and full-scale implementation of biological processes based on this metabolism (Kuenen, 2008). It was observed that, based on thermodynamics, sufficient energy is available for biological growth via the oxidation of ammonia-nitrogen with nitrite-nitrogen serving as the terminal electron acceptor and conversion of the nitrogen to nitrogen gas. It was further speculated that, since this is possible, it is likely that autotrophic organisms using this metabolism to produce the energy necessary for growth and using carbon dioxide as the carbons source for biomass production had likely evolved. This was confirmed in 1999 with isolation of bacteria using this metabolism (Strous, *et al.*, 1999). A small amount of nitrate-nitrogen is also produced which must be subsequently removed by heterotrophic denitrification if extensive nitrogen removal is required (Strous, *et al.*, 1998). The reaction is referred to as ANaerobic AMMonium OXidation (Anammox), and processes utilizing it are referred to as accomplishing deammonification.

The overall process requires conversion by AOBs of about half of the ammonia-nitrogen present in the subject wastewater to nitrite (referred to as partial nitritation), followed by utilization by Anammox bacteria of the produced nitrite-nitrogen as terminal electron acceptor with the remaining ammonia-nitrogen serving as electron donor. The net result is that the ammonia-nitrogen present in the influent wastewater is converted to nitrogen gas. Referred to partial nitritation/deammonification, this overall process can result in a significant reduction in process oxygen requirements when treating wastewaters with limited amounts of biodegradable organic matter. Process oxygen savings are provided because ammonia-nitrogen only needs to be oxidized to nitrite-nitrogen, which requires only three-quarters of the oxygen required to oxidize it to nitrate-nitrogen. Furthermore, only about half of the influent ammonia-nitrogen needs to be oxidized at all. Biodegradable organic matter requirements are minimized as it is only needed to denitrify the modest amounts of nitrate formed.

The energy savings potential offered by removing nitrogen by partial nitritation/deammonification has been a key component in the concept of achieving energy neutral biological nutrient removal wastewater treatment. The greatly reduced biodegradable organic matter requirement for biological nitrogen removal using this process allows influent carbon to be captured prior to biological nitrogen removal treatment, for example via chemically enhanced primary treatment (CEPT) or high-rate, non-nitrifying biological treatment. The captured carbon can subsequently be converted into energy, for example via anaerobic digestions and utilization of the produced biogas for combined heat and power production (CHP). This, coupled with the greatly reduced energy requirements for biological nitrogen removal, have proven crucial to achieving energy neutrality in full-scale plants.

Partial nitritation/deammonification has been applied full-scale to treat the high-strength recycle streams from solids processing systems, especially those employing anaerobic digestion which produces a recycle stream which is high in ammonia-nitrogen when the digested sludge is subsequently dewatered. These are commonly referred to as sidestream applications. Significant research and demonstration work is on-going to extend this process to the main liquid stream process, which is commonly referred to as mainstream treatment (for example, see WEF/IWA, 2013 and the results of the recent workshops at the Water Environment Federation Annual Technical Exhibition and Conference - WEFTEC). It appears that partial nitritation/deammonification is likely to become a much more widely used biological nitrogen removal activated sludge process in the future.

SUMMARY

In summary, the control of nitrogen discharges is of increasing importance and can be accomplished routinely and effectively using modifications of the activated sludge process. The fundamental and practical basis for activated sludge processes based on heterotrophic denitrification and autotrophic nitrification is well established, and these processes are widely applied in practice. Nitrous oxide emissions from biological nitrogen removal activated sludge processes can be a significant source of greenhouse emissions, and research is actively addressing the underlying mechanisms and providing an improved understanding to minimize these emissions. New biological nitrogen removal process technology is developing rapidly based on the Anammox biological nitrogen removal metabolism with processes commonly referred to as partial nitritation/deammonification. These technologies offer the potential for wastewater treatment plants to be energy-neutral while also achieving extensive biological nitrogen removal.

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PHOSPHORUS REMOVAL IN THE ACTIVATED SLUDGE PROCESS

James L. Barnard, Ph.D., BCEE, WEF Fellow, IWA Senior Fellow, Dist. MASCE[1]

INTRODUCTION

Limnological studies (Vollenweider, 1968) showed that phosphorus was the limiting nutrient for algae growth in inland water and led to an agreement between Canada and the USA to remove phosphorus from discharges to the Great Lakes (Great Lakes Water Quality Agreement of 1972). Widespread addition of chemicals such as ferric salts and alum followed to precipitate phosphorus where it could be removed with the waste sludge. The speedy recovery of Lake Washington in Seattle when wastewater was diverted convinced researchers that eutrophication could be curbed if the phosphates (P) discharged to the water bodies could be reduced.

EARLY HISTORY OF BIOLOGICAL PHOSPHORUS REMOVAL (EBPR)

Srinath *et al.* (1959) noted that P was released in the under-aerated upstream zone of a plug-flow reactor but thought of this as a problem that needed more oxygen, which the plant could not supply. Levin and Shapiro (1965) experimented in the laboratory with P uptake under aerobic conditions and release under anaerobic conditions and devised the first practical EBPR process called PhoStrip in which the P was taken up by organisms in a plug-flow high rate plant that did not nitrify (Figure 2-A). The return activated sludge (RAS) was retained in a thickener for more than 30 hours where fermentation resulted in the release of P to the supernatant from which it was precipitated with lime. The underflow, "stripped" of P, was returned to the aeration basin where P uptake occurred. More incidents were reported by Vacker *et al.* (1967), Witherow (1970), and Milbury *et al.* (1971). All of these plants were non-nitrifying plants with plug-flow configurations. Milbury *et al.* also reported problems with P release at the inlet zone because of the inability of the aeration system to supply enough air and noted that this "problem" was experienced at all the plug-flow plants that reported "luxury uptake" of P.

DEVELOPMENT OF BIOLOGICAL NUTRIENT REMOVAL (BNR)

The removal of both nitrogen and P from wastewater is referred to as BNR. The water reclamation project for the city of Windhoek, Namibia, and severe eutrophication in reservoirs around Johannesburg, South Africa, led to Barnard (1973) developing the 4-stage nitrogen (N) removal process now known as the Bardenpho process at the laboratories of the National Water Research Institute (NWRI) in Pretoria, South Africa. A 100 m^3/d pilot plant consisting of anoxic/aerobic/anoxic/aerobic stages was created by partitioning an existing structure using movable gates as shown in Figure 1. A "dead zone" with an incidental connection to the second anoxic zone resulted. Some mixed liquor which fermented in the "dead zone" passed back and forth to the 2nd anoxic zone where P was released to 32 mg/L. While nitrogen removal in excess of 90% percent was observed, P profiles through the plant showed that the effluent orthophosphates were consistently removed from about 9 mg P/L in the influent to less than 0.2 mg P/L in the filtered effluent. Noting that all plants that observed biological P uptake reported a release of P in a zone ahead of the main aeration zone, Barnard (1974a,b) postulated that for excess biological P removal to occur, it is necessary that the mixed liquor pass through an anaerobic phase free of nitrates and dissolved oxygen (DO) where P is released, followed by an aerated zone where it will be taken up. Unaware that the inadvertent connection between the second anoxic zone and the dead zone of the pilot plant provided this condition, Barnard (1976) proposed that anaerobic conditions could best be obtained ahead of the first anoxic zone, on the assumption that the 4-stage nitrogen N removal plant would leave few nitrates in the RAS. Nicholls (1975) experimented successfully with this concept at the temporary Alexandra Wastewater Treatment Plant (WWTP) in Johannesburg when switching off aerators near the inlet to create a low dissolved-oxygen (DO) condition similar to that observed in other full-scale plants, leading to the decision to add formal anaerobic stages ahead of the 750,000 population equivalents (PE) 4-stage Johannesburg Goudkoppies WWTP, then under construction. This rapid application of the BNR technology encouraged other authorities in the area to use the process because the need was evident, even though there was no regulation at that time that required the P removal of phosphorus.

The first application of BNR in North America was at the Palmetto, FL, plant in 1977, followed by the Kelowna plant in BC, Canada.

BIOLOGICAL MODEL

Based on the PhoStrip process, Fuhs and Chen (1975) suggested that certain bacteria - later collectively referred to as polyphosphate accumulating organisms (PAOs) - can take up excessive amounts of P in the aeration basin when supplied with acetate as feed in a preceding anaerobic zone free of nitrates and DO and store them as high energy phosphate bonds. When recycled back to the anaerobic zone, the PAOs obtain energy from these high-energy bonds to take up VFA and store it as an intermediate product such as Poly-β-alkoalates (PHA) in the anaerobic zone, releasing phosphorus to the liquid phase. When passing through the aerobic zone they metabolize the stored PHA to provide energy for the take up of all phosphorus released plus that in the influent. When sludge is wasted from the aerobic zone the accumulated P is removed. This hypothesis explained why nitrate or DO in the RAS could pose a problem that required the reduction of nitrates in the RAS. The model of Fuhs & Chen was further refined by Comeau-Wentzel model (Comeau *et al.*, 1986; Wentzel *et al.*, 1986), in which poly-P and PHA intracellular storage polymers played a central role, and the Mino model (Mino *et al.*, 1988), in which glycogen was identified as a third central intracellular polymer. Experimental work by Smolders *et al.* (1994) and others confirmed the role of glycogen in PAOs and opened the way to integrate the competition of glycogen-accumulating organisms (GAOs) that stored PHAs and glycogen but not poly-P.

PROCESS CONFIGURATIONS FOR BNR

Barnard (1976) proposed a number of BNR process configurations, such as the Phoredox (Figure 2B), for a non-nitrifying plant. The configurations illustrated on the other flow sheets would enable BNR by allowing for the reduction of nitrates in the return sludge to minimize interference in the anaerobic zone. The Modified Bardenpho plant (Figure 2C) was used for the original plant designs for the Goudkoppies WWTP in Johannesburg and the Cape Flats WWTP in Cape Town, South Africa, both of them treating 750,000 PE's. The 3-stage Bardenpho process (Figure 2D) was used with plants having surface aerators,

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[1] Global Practice & Technology Leader, Black & Veatch, Kansas City

which allowed a high degree of simultaneous nitrification and denitrification (SND), which reduced nitrates in the RAS (van Huyssteen *et al.*, 1990).

FIGURE 1
Pilot Plant Arrangement

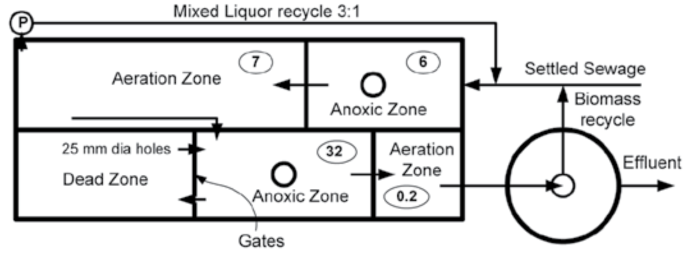
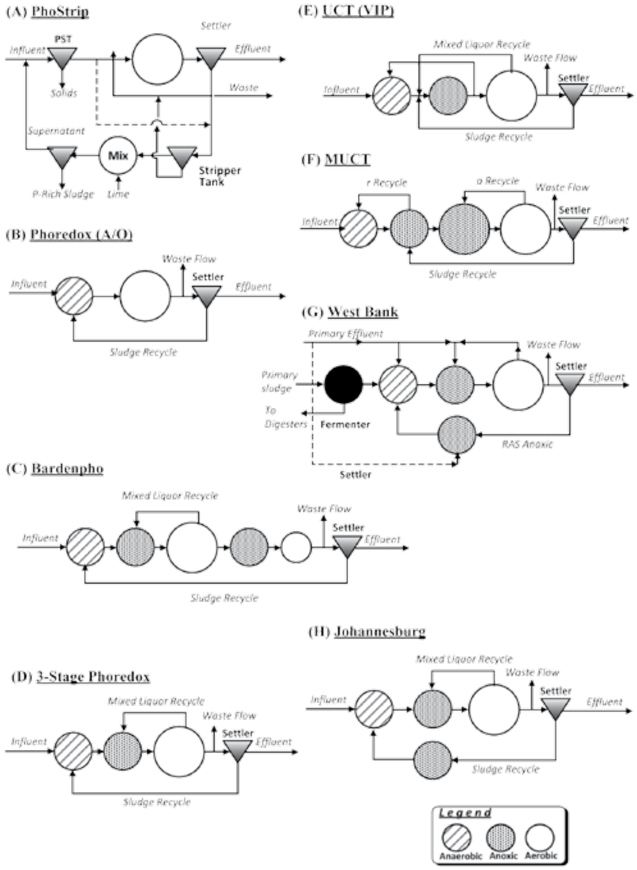


FIGURE 2
Process Schematics



The University of Cape Town (UCT) process (Figure 2E) was developed in the laboratory by Marais *et al.* (1983) using fine bubble aeration with little SND and, excessive nitrates in the RAS. In the UCT process, the RAS was returned to the anoxic zone for denitrification, and mixed liquor was recycled from the end of the anoxic zone, where the nitrate concentration could be reduced, prior to being returned to the anaerobic zone. This was improved by the Modified UCT (MUCT) process shown in Figure 2F. Due to the lack readily biodegradable chemical oxygen demand (rbCOD) or volatile fatty acids (VFAs) in the influent to the Westbank (now Westside Regional Wastewater Treatment Plant [WRWTP], British Columbia, Canada), primary sludge was fermented and supernatant passed to the anaerobic zone. Most of the influent was passed to the anoxic zone, while 5 to 10% percent of it was used to assist in the denitrification of the RAS in a pre-anoxic zone (Figure 2G). The city of Johannesburg (Nicholls *et al.*, 1987) proposed the Johannesburg process (Figure 2H) to reduce nitrates in the RAS by using a pre-anoxic zone for the RAS ahead of the anaerobic zone for RAS denitrification through endogenous respiration in the higher MLSS in this zone.

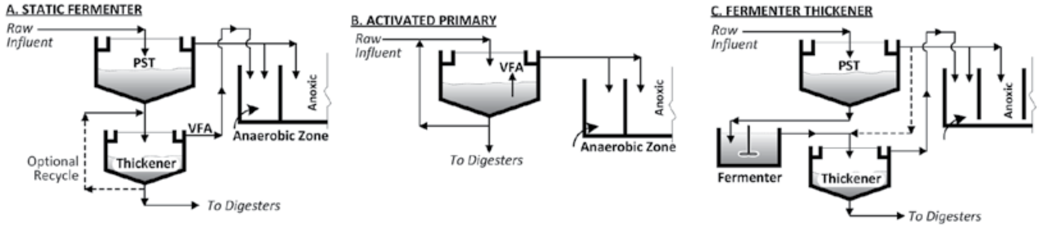
ACID FERMENTATION FOR PRODUCTION OF VFAS

Fermentation of Primary Sludge

During the design of the Kelowna B.C. Canada Wastewater Treatment Facility, an existing sludge holding tank with a solids retention time (SRT) of approximately 6 days was used to ferment primary sludge to produce the necessary VFA. The supernatant was discharged to the anaerobic zone of the main plant where it successfully augmented the supply of VFAs. This was later referred to as a Static Fermenter, which is shown in (Figure 3A). A study by Oldham and Stevens (1984) clearly showed that without a fermenter, there would be little P phosphorus removal in this plant. Studies by Rabinowitz and Oldham (1986) examined the design needs concerning the ideal SRT to for maximizing the fermentation of organic solids to VFAs without conversion to methane. Barnard (1984) suggested that primary sludge could be accumulated in primary tanks and allowed to ferment and release VFAs when some of the underflow was recycled to the influent, a concept referred to as Activated Primary tanks (Figure 3B).

Primary sludge could also be fermented in a dedicated fermenter, and the sludge then passed to a thickener where the sludge could be elutriated (Figure 3C). In the past 30 years, primary sludge fermenters have been used in BNR plants notably in Canada, the USA, Europe, South Africa, Australia, and New Zealand. At the Westside plant, in British Columbia, Canada, all of the primary effluent is passed to the anoxic zone, and only fermenter supernatant is passed to the anaerobic zone as shown in (Figure 2G). In the latest development at the Douglas L. Smith Middle Basin Wastewater Treatment Plant, in Overland Park, KS, USA, an upflow sludge blanket acid fermenter for primary sludge is being used with great success.

FIGURE 3
Types of Primary Fermenters



Fermentation of Mixed Liquor or RAS

Building on the model of the original pilot plant, the concept of fermenting some of the mixed liquor developed. This can take the form of passing mixed liquor equivalent to about 10% of the influent, to a fermenter with SRT of around 2 days. In some cases, a fraction of the RAS was fermented and fed to the anaerobic zone (Stroud, *et al.*, 2001). In other plants, it was found that switching of mixers in the anaerobic or anoxic zones for most of the time benefitted EBPR (Barnard, *et al.*, 2011). Some thickening takes place in such a tank and the fresh mixed liquor short-circuits over the top with some contact with the fermenting mixed liquor in the lower half. At the Henderson, NV, USA ,plant the orthophosphates was reduced to around 0.1 mg/L by using this technique. The technology was applied at about 10 plants in the USA with great success. In progress is a project to apply such fermentation at the 35 m^3/s (800 mgd) Stickney plant in Chicago which consists of a plug-flow nitrification plant, by merely switching off some aeration in the first pass.

SECONDARY RELEASE OF PHOSPHORUS

Barnard (1984) observed that P may be released in EBPR plants for cell maintenance in the absence of an electron acceptor, such as nitrates or DO, and of VFAs. It was not possible to take up P thus released by further aeration. This was referred to as secondary P release. Experience showed that additional VFAs would be required to take up the P again. Secondary release may happen in the anoxic zones when there are insufficient nitrates or when the zone is oversized relative to the required denitrification capacity or in final clarifier sludge blankets. Secondary release of phosphorus should be avoided in both design and operation of plants. Phosphorus may also be released through endogenous respiration (Oldham and Stevens, 1984) when the uptake is completed in a plug-flow aeration zone some distance before the end of the aerobic zone of the basin. This may indicate that the aerobic sludge retention time (SRT) is too long. Ideally, the uptake of P should be completed near the end of the aeration zone.

RELIABILITY OF EBPR

The reliability of the EBPR process has often been questioned. While EBPR can reliably reduce the orthophosphate concentration to well below 0.1 mg/L, some form of filtration with or without polymer would be required to coagulate and remove particulate and colloidal P. The reliability of P removal will depend on the availability of VFAs or rbCOD that can easily be fermented to VFA in the anaerobic zone and to absence of nitrates and dissolved oxygen in the anaerobic basin. Because of past patent issues, many plants were constructed in the USA without fermenters to augment VFAs and this resulted in inadequate P removal, leading to the assumption that the process was not reliable. The Kalispell, MT, USA, plant has fermentation of primary sludge and, although it is in a cold climate, can achieve annual average TP values of between 0.11 and 0.15 mg/L with filtration but no chemical addition (Neethling, *et al.*, 2005).

PHOSPHORUS RECOVERY

Phosphorus is a limited resource without which there can be no life and recovery goals are set in many European countries. EBPR allows the cost-efficient recovery of as much as 50% of the phosphorus in the influent by stripping the phosphorus and magnesium from the surplus sludge. The struvite formed is a pure crystal containing no organic matter and is a very valuable slow release fertilizer. In the process 10 to 15% of the nitrogen in the influent is also captured. Even when surplus sludge is incinerated the phosphorus is not lost but is available to plants if the ash is applied to land.

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THE FUTURE OF ACTIVATED SLUDGE

George Tchobanoglous, Ph.D., P.E., BCEE, NAE,[1] and H. David Stensel, Ph.D., P.E., BCEE[2]

The concepts and elements involved in the general design of the activated sludge treatment process have been presented and discussed in the previous sections. The purpose of this section is to consider and speculate on the evolution of the various concepts and design elements for the activated sludge process in light of the challenges and opportunities for wastewater management in the future. Topics considered include: (1) a brief review of what has driven activated sludge process designs for wastewater treatment, (2) factors that will affect future activated sludge design, and (3) some thoughts on the future of the activated sludge process.

OVERVIEW OF PROCESS DEVELOPMENT

Although the history of the activated sludge process has been discussed previously, some of the driving forces are repeated here, as they will continue to impact future process developments and implementation.

Early Developments - 1900-1970s

For most of the first 55 years of the activated sludge process, following its announcement in 1914 and the first large-scale continuous flow activated sludge plant at Milwaukee, WI, in 1916, treatment objectives were concerned with mitigating nuisance conditions caused by the uncontrolled discharge of municipal and industrial wastewaters. The primary concerns were with (1) the removal of suspended and floatable material, (2) the treatment of biodegradable organics, and (3) the elimination of pathogenic organisms (Stensel and Makinia, 2014).

RECENT DEVELOPMENTS - 1970-2014

The principal factors that have driven activated sludge process design and implementation since the early 1970s include: (1) effluent discharge standards and goals, (2) population growth, (3) sustainability concerns, (4) enhanced understanding through research, and (5) environmental concerns. These factors are reviewed briefly as they will continue to influence future designs (Stensel and Makinia, 2014).

Effluent Discharge Standards and Goals. Since the early 1970s with the formation of the U.S. EPA in 1970, and the passage of the Clean Water Act in 1972, the early treatment objectives, cited above, remain valid today; however, the required degree of treatment has increased significantly, and additional treatment objectives and goals have been added. To deal with the additional treatment objectives, treatment processes have evolved to deal with each new constituent of concern. Unfortunately, the approach of waiting to respond to the next new regulation has led to step-wise incremental process developments. In the future, it is anticipated that bridging or game-changing technologies will evolve.

Impact of Population Growth. Population growth has also influenced the development of the AS process. In many metropolitan areas, the need to intensify treatment has been brought about by urbanization, which has encircled treatment plants once thought to be in remote areas. As the municipal and urban population continue to increase, it has become necessary to intensify the treatment capacity of most urban treatment plants, as there is often little or no space for expansion. As treatment processes become more intense, greater operation skill is required for their operation. For small treatment plants where skilled help is difficult to support and land requirements are not limiting simplicity of process design and operation is the overriding concern. This situation small communities is not likely to change in the near future.

Sustainability Concerns. The need to be more efficient with the use of resources and the dispersal of anthropogenic constituents in the environment has become a central issue in nearly all aspects of society. Some notable examples of problematic current and past practices with respect to wastewater treatment include the discharge of nutrients and trace constituents, excessive headloss and pumping as a result of poor hydraulic design; inefficient aeration system design; lack of consideration for the importance of primary treatment systems; limited use of anaerobic processes for BOD removal and energy recovery; limitations in sludge reuse and ultimate disposal options, placement of wastewater treatment facilities without regard to water reuse, life cycle pumping energy implications, and the potential impacts of sea level rise.

Impact of Research Findings. The impact of research in the development of the AS process cannot be over estimated. So many research findings have changed the design of the activated sludge process to increase treatment capacity, stability and efficiency. Most have been discussed in the previous sections, a few are listed below to highlight some of these developments.

- Selector concept for filamentous bulking control, population selection
- Utilization of phosphorus accumulating organisms
- Identification of bacteria capable of micropollutant degradation to µg/L or ng/L concentrations
- Anammox bacteria capable of ammonia oxidation with nitrite
- Granular activated sludge can be selected and sustained
- Instrumentation and controls for use in sequencing batch reactors (SBRs) and simultaneous nitrification-denitrification (SNdN) processes

Environmental Concerns. As research into the characteristics of wastewater has become more extensive, and as the techniques for analyzing specific constituents and their potential health and environmental effects have become more comprehensive, the body of scientific knowledge has expanded significantly. New treatment methods are being developed to deal with health and environmental concerns associated with findings of this research. Many of these methods will involve modifications to the conventional activated sludge process.

FACTORS THAT WILL AFFECT FUTURE ACTIVATED SLUDGE DESIGN

In most wastewater treatment plants, the activated sludge process is one component, albeit a major one, of the overall wastewater management system. It is, therefore, important to examine what external factors will affect the future of the AS process and its implementation. Factors, in addition to those cited above, that will affect the future designs of the activated sludge process are summarized in Table 1. Two additional factors are highlighted in the following discussion.

New Approaches To Primary Treatment

Given the current emphasis on energy conservation and recovery, a number of alternative technologies are being developed (1) to reduce the organic loading to the biological treatment process to reduce the energy requirement for the oxidation of the carbonaceous organic material and (2) to alter the particle size distribution of the particles remaining in the pretreated

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[1] Professor Emeritus, Department of Civil and Environmental Engineering, University of California, Davis, California.
[2] Professor, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington.

TABLE 1
Factors that will influence future activated sludge process design and implementation[a]

Factor	Possible impact on activated sludge process
Climate change	As a result of climate change areas that are wet are getting wetter and areas that are dry are getting dryer. In both areas the intensity of rainfall has increased, dramatically in some locations. In wet areas with combined collection systems, surge flows are causing washout of the biological processes. In dry areas, exfiltration is resulting in increased wastewater constituent concentrations. The impact of climate change on biological process design is only now becoming appreciated fully.
Water conservation	In the past, per capita wastewater flowrates greater than 450 L/capita•d (120 gal/capita•d) were common. In the not so distant future, it is reasonable to assume the per capita flowrates could decrease to below 150 L/capita•d (40 gal/capita•d). Such a decrease would have a significant impact on wastewater collection system and the biological treatment process design and operation.
Source control/collection changes	Impacts of urine separation on biological treatment. Greater use of satellite plants for water reuse will increase solids in wastewater.
Interest in sustainable environmental engineering	WWTPs will strive to be energy self-sufficient. Conflict will develop over best use of influent organic matter (e.g., methane production, denitrification and/or phosphorus removal).
Use of existing facilities	Because of the significant in place investment, most existing wastewater treatment plants will have to be modified to meet future standards and needs.
Instrumentation and automation	Improved instrumentation will result in energy and chemical savings. Smaller plants will be automated to provide greater performance and reliability.
Nutrient removal	Continued interest in achieving extremely low N and P concentrations will lead to new process modifications. Extremely low not-to-exceed discharge limits may not be achievable due to inherent instability as predicted by "Chaos Theory."
Micropollutant treatment goals	Removal of endocrine disruptor compounds in WWTP effluents to better protect fish and the aquatic environment, and water reuse quality (see discussion to treatment process endpoints) will involve process changes.
Research and molecular biology tools	New ideas, approaches, operational tools, and knowledge of microbial capabilities will lead to the development of new variations of the activated sludge process.
Major technology changes leading to totally different designs	New mixing and aeration technologies for existing and new tankage. Changes in membrane technology. Use of membranes in conjunction with granular sludge reactor designs may overcome persistent fouling problems.
Changes in wastewater characteristics	Increased strength due to reductions in per capita water use will lead to the development of new process modifications to address higher constituent concentrations.
Solids management	New methods and directions for solids reuse may affect future activated sludge process designs.
Direct potable reuse	The implementation of direct potable reuse will affect future activated sludge process designs. In some cases, treatment systems for potable reuse may rely only on physical/chemical treatment.
Impact of uncontrollable events	Wastewater treatment plants are subject to the effects of uncontrollable events such as natural disasters and the price of chemicals and supplies.
Impact of unintended consequences	Even beyond all of the factors considered above unintended consequences must be anticipated, as resources and cost for wastewater management become more restrictive.

[a] Adapted in part from Tchobanoglous et al., 2014.

wastewater to optimize treatment. Solids removed from the raw wastewater could be sent to the solids processing facility or utilized for denitrification or phosphorus removal. Three technologies that have been demonstrated successfully are: (1) microscreening of raw wastewater, (2) charged bubble flotation of raw wastewater, and (3) primary effluent filtration with various cloth and synthetic media filters (Tchobanoglous, *et al.*, 2014). Because the filtered primary effluent typically contains a BOD concentration of 50 to 70 mg/L, with altered BOD/N and BOD/P ratios, a number of modified activated sludge processes can be developed. For example, a process in which the carbonaceous oxidation step is either eliminated or significantly reduced and the BOD is used for denitrification, would result in a considerable savings in aeration energy.

Alternative Treatment Process Endpoints

For the first 100 years, the endpoint of conventional wastewater treatment has been the production of a treated wastewater effluent suitable for discharge to the environment. In the future, with the emphasis on direct potable reuse, a more appropriate end point for wastewater treatment might be the production of a treated effluent with chemical characteristics optimized for treatment with membranes, reverse osmosis, and advanced oxidation. The chemical characteristics of such an optimized effluent could be quite different from those required for discharge to the environment.

THE FUTURE OF ACTIVATED SLUDGE

The future of the activated sludge process design is intertwined with the following 21st century paradigm shift in the view of wastewater, that is: "wastewater is renewable recoverable source of potable water, energy, and resources, and " (Tchobanoglous *et al.*, 2010). In light of this view of wastewater and the factors cited in Table 1, and discussed above, it is appropriate to consider briefly some challenges as well as the opportunities that will become increasingly important in the future.

Utilization of Existing infrastructure

Due to the extensive infrastructure now in place in most communities and the fact that individual wastewater flowrates are decreasing, it is anticipated that much of existing treatment tankage it will be operating for many decades in the future and that excess capacity will be available. The challenge will be how to modify the existing tankage to address operations/reliability, sustainability, nutrient removal, and new treatment needs, such as producing an effluent suitable for processing by other technologies to produce potable water.

Conflicting Views in the Application of Technology

Although wastewater is increasingly viewed as a resource and the profession is shifting to one of sustainable environmental engineering, sustainability concepts are not being applied uniformly. For example, for small systems, the focus is on what do they "have to do" whereas for larger facilities the concern is with enhanced treatment and energy sustainability.

Other important conflicting views are how to best utilize the organic content (e.g., BOD) of wastewater and the removal of micropollutants. Should more methane be produced or is it better to utilize more BOD for enhanced biological phosphorus removal (EBPR) processes and optimize the recovery of phosphorus? Should less emphasis be placed on energy recovery versus the need to direct more BOD for the growth of heterotrophic bacteria capable of biodegrading micropollutants? Is the removal of nitrogen more compelling?

Can the advancements being considered in large facilities (anammox treatment at ambient temperature, P recovery, increased methane) be used in smaller facilities and how will such treatment technologies be implemented?

Short Term View - Next 10 to 20 Years

For the short term, the following process modifications to the conventional activated sludge process seem likely:

- The use of improved SNdN processes will be favored over N removal systems with discrete nitrification and anoxic denitrification zones.
- The implementation of granular sludge reactors will increase due to space savings and nutrient removal ability.
- The use of EBPR process for phosphorus recovery will increase.
- Water reuse applications will increase and methods to reduce cost of membranes, reduce energy demands of MBRs and better control fouling will be found.
- Advances in instrumentation and controls will be used to provide better reliability, energy, and chemical savings.
- Micropollutants and endocrine disruptors will be addressed in new process designs, especially for direct potable reuse applications and for environmental water quality stewardship.
- Greater emphasis will be given to integrating the management and utilization of community wastes with the local WWTP sustainability and energy self sufficiency goals.
- Improved home food waste grinders and waste collection systems will be used to deliver food waste to wastewater treatment plants along with other waste constituents.
- Greater incorporation of local community food waste into WWTP carbon management strategies.
- New process designs will be developed to deal with higher wastewater constituent concentrations.
- A number of new bacteria will be identified for the treatment of specific constituents, which will lead to the development of new and the modification of existing processes

Long Term View - Greater Than 20 Years

Because no one could have predicted in the 1920s the activated sludge process developments that have occurred in the last 30 years, the following speculations are offered for the long term.

- Direct potable reuse will be commonplace with the AS process optimized for advanced treatment.
- Urine separation and recovery will be an important element of wastewater treatment.
- Complete membrane treatment systems will replace a number of conventional activated sludge processes.
- Greater population and diminishing resources may force people to: (1) retain their own solid waste (feces and food waste) for use in home anaerobic digesters to get heat and (2) sell their urine. A portion of the wastewater may still be transported a WWTP; the wastewater could be more dilute maybe or more concentrated, depending on the application of onsite technologies.
- Some form of activated sludge will still be in operation.

SUMMARY

Due to the ongoing unprecedented development of biological science and the need to remove an ever-increasing number of constituents from wastewater, the activated sludge process will continue to evolve over the next 10 to 20 years. The need to produce an effluent suitable for further treatment for the production of potable water will result in a renaissance in the development of biological treatment. The need to utilize existing treatment tankage will spur the development of new treatment technologies to replace existing activated sludge process technologies. The new biological treatment technologies may or may not be called activated sludge, but will trace their lineage to the original activated sludge continuous flow process put into operation by early investigators in Milwaukee, WI.

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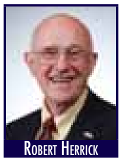
MEMBER NEWS

AWARDS AND RECOGNITION

Dr. Paul F. Boulos, BCEEM, Hon.D.WRE, Dist.D.NE, F.ASCE, has assumed position of President and Chairman of the Board of Trustees of the American Academy of Water Resources Engineers (AAWRE) of the American Society of Civil Engineers (ASCE). Dr. Boulos, President and Chief Operating Officer of Innovyze, is an expert on water resources and navigation engineering and has received numerous national and international scientific and engineering honors including the U.S. Ellis Island Medal of Honor, the Lebanese American Foundation's Pride of Heritage Award, the Lebanese American University Alumni of the Year Award, and induction into the University of Kentucky College of Engineering Hall of Distinction.

In addition to AAEES, Dr. Boulos is an Honorary Diplomate of the American Academy of Water Resources Engineers, has Distinguished Diplomate status in Navigation Engineering by ACOPNE, and is a Fellow of the American Society of Civil Engineers. He has been a Board Certified Environmental Engineering Member in Water Supply and Wastewater Engineering since 2011.



Robert Herrick

Robert A. Herrick, P.E., CIH, BCEE, was named the 2013 Linton E. Grinter Distinguished Service Award recipient. Mr. Herrick was the 36th recipient of the Grinter Award, ABET's highest honor. The award was named for engineering and engineering technology education pioneer Linton E. Grinter, and it recognizes ABET volunteers who follow Grinter's example and surpass even the highest service expectations of the organization.

Mr. Herrick has served as an ABET evaluator for more than 30 years. He is a Life Member and has been a Board Certified Environmental Engineer in Air Pollution Control since 1966.

ON THE MOVE

Dr. Arijit Pakrasi, P.E., BCEE, has been named Partner of Environmental Resources Management, Inc. (ERM). With over 30 years experience of air quality consulting, Dr. Pakrasi will focus on the air quality practice in the power and oil and gas sectors. He has been a Board Certified Environmental Engineer in Air Pollution Control since 2005.

Fernando Sarmiento

Fernando Sarmiento, P.E., PMP, BCEE, has been appointed to Managing Director of Greeley and Hansen's Latin American Operating Group. Originally from South America, he has been instrumental in continuing to advance the firm's strategy for expanding business operations in high-growth Latin American Markets. Mr. Sarmiento has been a Board Certified Environmental Engineer in Water Supply and Wastewater Engineering since 2011.

IN MEMORIAM

James F. Braithwaite, P.E., BCEE, passed away April 17, 2013. Mr. Braithwaite received his BS in Mechanical Engineeering from Michigan State University and was a practicing engineer for more than 44 years. He most recently served as Chairman of Vector Resolutions, LLC. (Tucson, AZ). Mr. Braithwaite had been a Board Certified Environmental Engineer in Solid Waste Management since 1987.

Donald E. Eckmann, P.E., BCEE, passed away July 4, 2013. Mr. Eckmann, a Partner in Alvord, Burdick & Howson, received his BS in Civil Enginering from University of Illinois. He was a Past President of the American Society of Civil Engineers (Illinois Section) and a past Director of the National ASCE. He was a Life Member and had been a Board Certified Environmental Engineer in Sanitary Engineering since 1971.

Roald "Ralph" Haestad, P.E., BCEE, F.ASCE, passed away May 27, 2013. Mr. Haestad was a Past President of the National Society of Professional Engineers (Connecticut Section) and a Life Member of the American Society of Civil Engineers and the American Water Works Association. He most recently served as Chairman Emeritus of Roald Haestad, Inc. and received his BCE in Civil Engineering from City College of New York. Mr. Haestad was a Life Member and had been a Board Certified Environmental Engineer in Water Supply and Wastewater Engineering since 1980.

Francis Eugene Soloducha, P.E., BCEE, passed away September 21, 2012. Most recently with Greeley and Hansen, Mr. Soloducha received his BS in Civil Engineering from NJIT and his MS in Manufacturing Systems from Unviersity of Maryland. He had been a Board Certified Environmental Engineer in Water Supply and Wastewater Engineering since 2002.

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