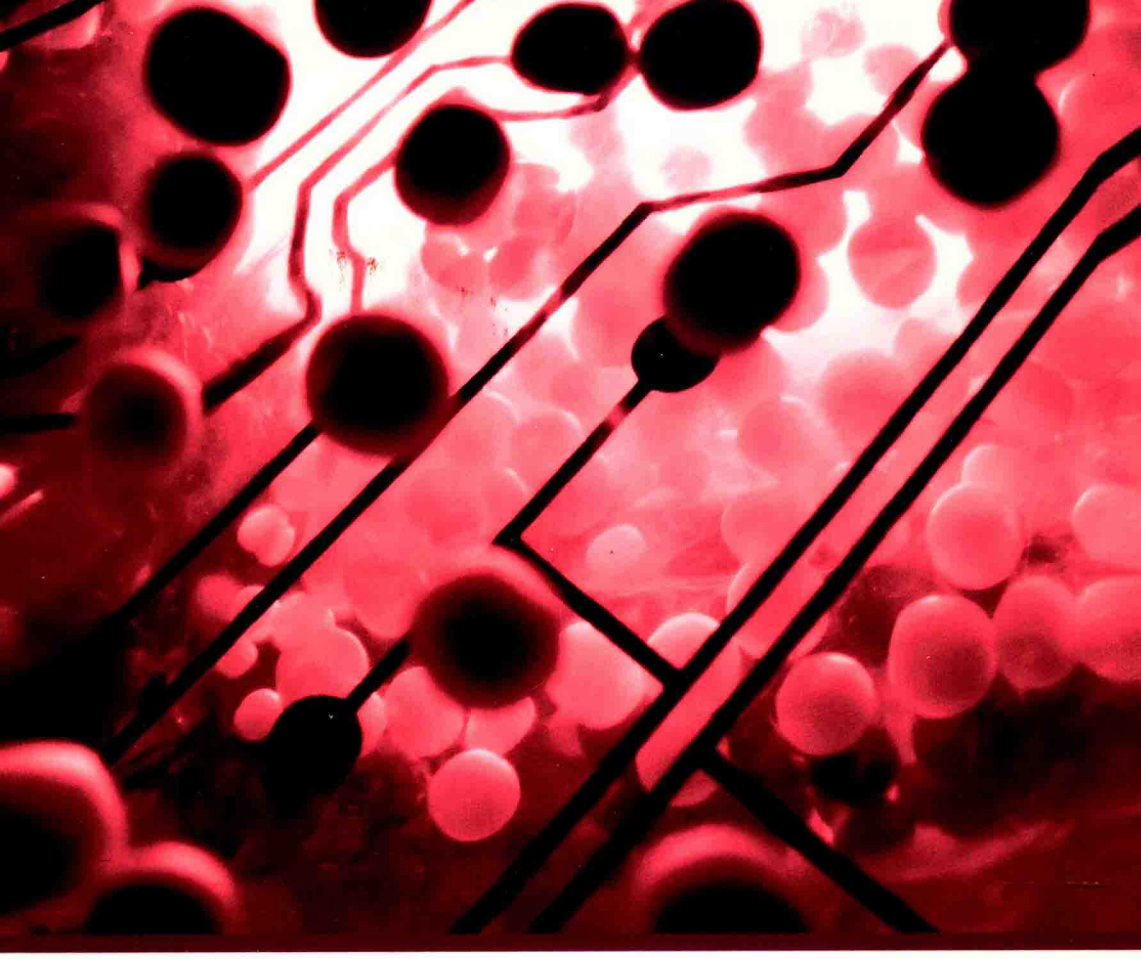

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Chapter 1
Introduction

1.1 HISTORY OF THE ACTIVATED SLUDGE PROCESS

1.1.1 Initial period

The activated sludge process currently represents the most widespread technology for the secondary treatment of municipal wastewater and constitutes "*the heart*" of many wastewater treatment plants (WWTPs) (Lessard and Beck 1991). The scale of activated sludge plants ranges from package plants [for single houses] to huge plants serving large metropolitan areas with flows up to $5 \cdot 10^6$ m^3/d (Grady *et al.* 1999). With regard to the invention and initial development of the activated sludge process, various workers in both the USA and UK contributed useful results and ideas (Cooper and Downing 1998).

Even though the last two decades of the nineteenth century research efforts had concentrated on treatment by the promising biological filtration theories, experiments on the aeration of sewage had been carried out since the early 1880's (Cooper 2001). It is now generally accepted that Dr R. Angus Smith initiated in 1882 the earliest research in "*blowing air*" into sewage tanks to minimize undesirable odour problems associated with putrefying sewage (Lester and Birkett 1999; Metcalf and Eddy

2003). According to Martin (1927), these were the first tests leading to development of activated sludge. The aeration of wastewater was investigated subsequently (1884-1897) by several workers in the UK including Dupre and Dibdin, Hartland and Kaye-Parry and Fowler. At the same time (1891-1894), similar research were also conducted in the USA by Drown, Mason and Hine, Lowcock and Waring (Ardern and Lockett 1914; Mohlman 1917). All these attempts were derived from the idea that aeration "*per se*" could provide the desired oxidizing effect on sewage. Poor experimental results (little improvement in effluent quality) revealed, however, that this approach could not be considered "*a practicable adjunct in the process of sewage purification*" (Ardren and Lockett 1914).

In the following years, the most notable work in the aeration of sewage was that performed by Black and Phelps for the Metropolitan Sewerage Commission of New York (1910), and by Clark and his colleagues at the Lawrence, Massachusetts, Sewage Experiment Station of the Massachusetts State Board of Health in 1912 and 1913 (Babbitt 1922). Black and Phelps studied in 1910 the possibility of aerating sewage for the Metropolitan Sewerage Commission of New York (Black and Phelps 1914). The sewage was aerated for varying periods up to twenty four hours in tanks filled with closely spaced, wooden laths in order to achieve a higher surface area for desired slime accumulation. The effects of oxidation were practically insignificant in terms of ammonia removal, although some reduction in putrescibility was indicated by the incubation tests. Black and Phelps had recommended the process for a full-scale installation but eventually the idea was not adopted (Mohlman 1917). A similar unit with wooden laths had earlier been used as an anaerobic contact chamber and called Travis "*Colloider*" or "*Hydrolytic*" Tank (Alleman and Prakasam 1983).

According to Metcalf and Eddy (1922), the idea from which the activated sludge process for the treatment of sewage has been developed appears to originate from a series of experiments during 1912 and 1913 at the Lawrence Experimental Station of the Massachusetts State Board of Health. Clark, Gage and Adams conducted there a series of successful experiments on using aeration for preliminary treatment of sewage prior to filtration. The aeration of sewage was conducted in both bottles, in presence of algal growths on the walls, and in a tank with vertical slate walls placed one inch (25 mm) apart. The attention of the investigators was focused on the attached growth on the walls of the aeration vessels and they did not claim that the aeration would entirely obviate filtration (Mohlman 1917). At this point, however, it is important to note that the "*adherent growths and heavy deposit*" were not thrown out from the bottles but were retained to assist in treating the next dose of raw sewage (Fowler 1934). Vesilind (2003) noted that "*the researchers at the Lawrence Experiment Station did all the right research, but they did not understand the significance of their results*".

In November 1912, Dr. Gilbert J. Fowler of the Manchester University was called to the USA along with other specialists to report upon the proposals of the Metropolitan Sewerage Commission of New York for disposing of the sewage of greater New York which amounted to the enormous volume of 1,000 million gallons per day (Fowler 1934). Under such conditions, the current methods including tricking filters or chemical treatment seemed impractical solutions. While considering the problem of New York pollution, Fowler also visited the Lawrence Experimental Station and saw the on-going experiments on the aeration of sewage in the presence of green organisms. The results of the experiments in Lawrence impressed Fowler so much that, shortly after his return to the UK, Fowler described them to two chemists, Edward Ardern and William T. Lockett, from the Rivers Committee of the Manchester Corporation, and suggested to his colleagues that similar experiments should be carried out at the Davyhulme Sewage Works of Manchester. However, the objective was a process which could be operated in an open tank, without the aid of filters (Fowler 1934).

The remarkable results which Ardern and Lockett had obtained during the course of their experiments (1913-1914) were presented to the society of the Chemical Industry at the Grand Hotel, Manchester on 3 April 1914 (Ardern and Lockett 1914). During the discussion their paper was called an "*epoch-making one*" and a "*bombshell fired into the camp*". They first continuously aerated sewage in glass bottles until complete nitrification was achieved. In comparison with the other investigations, the investigation in Manchester considered two novel aspects. Firstly, the bottles were protected from light by covering with brown paper to prevent the growth of algae. Secondly, the bottles were not emptied completely after each aeration period but the deposited solids were mixed with a new portion of raw sewage. This procedure was repeated several times. In the first run, aeration for about five weeks was required to achieve complete nitrification. The amount of solids deposited in the bottles was gradually increasing and the time required for complete nitrification was eventually reduced to twenty four hours. Once having accumulated a sufficient volume of the deposited solids, a series of tests were carried out to determine the effects of aeration of various samples of the Manchester sewage. In general, a proportion of one volume of the solids to four volumes of sewage was used and a well oxidized effluent was obtained within a period of 6-9 hours. The deposited solids resulting from the oxidation of sewage were indeed a suspension of viable microorganisms and named "*activated sludge*". Ardern and Lockett reported that:

> *"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. (...) Gelatine counts have shown a bacterial content of at least 30 million organisms per cubic centrimetre. 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 protozoa are to be found (...)"

In conclusions, the authors were convinced that the new method, because of its simplicity, would find widespread applications:

"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 August, 1914, Dr. Edward Bartow, professor of chemistry and director and chief of the State Water Survey in Illinois, visited Fowler's group in Manchester and saw the work in progress. Upon his return to the USA Bartow and Floyd William Mohlman started their own bench- and pilot-scale experiments with activated sludge at the University of Illinois (November, 1914) (Mohlman 1917). Activated sludge was built up in the manner suggested by Ardern and Lockett (1914). The main finding was that during the aeration of sewage in contact with activated sludge, ammonia was oxidized to nitrate during 4-5 hours, whereas nitrite was evidently oxidized to nitrate almost as rapidly as it was formed. Furthermore, satisfactory activated sludge could be obtained with 6-hour aeration periods without complete nitrification needed from the beginning of the operation. In addition to the time of aeration, the study addressed several far-reaching issues, such as the required area for air diffusion, required amount of sludge for purification, quantity of sludge formed, composition of sludge including the content of nitrogen, dewatering of sludge and cost of the activated sludge process.

Indeed, within the period of a few years, development of the activated sludge process was proceeding very rapidly and an enormous amount of experimental work was initiated throughout the world. Carpenter and Horowitz (1915) reported that the literature on the subject of activated sludge was "*so recent, and so well known to the sanitary engineers*". Porter's bibliography (Porter 1921) contains over 600 abstracts of the papers written between 1914 and 1920. Buswell (1923) noted that the bibliography listed over 80 experimental plants and 17 municipal activated sludge plants which had been completed or under construction. The first pilot and full-scale applications of activated sludge were based on a fill-and-draw operational mode (a precursor of the modern sequencing batch reactors), which was soon converted to continuous flow through aeration tanks, followed by

sedimentation and biomass recycle (Grady *et al.* 1999). Babbitt (1922) described an activated sludge reactor as a rectangular tank with a depth of about 15 feet and a width of channel not to exceed 6 to 8 feet. According to the author, such proportions would allow better air and current distribution than larger tanks, and the level bottom should insure an even distribution of air.

The pioneering fill-and-draw laboratory studies of Ardern and Lockett were shortly thereafter successfully repeated in a pilot scale at Manchester's Davyhulme sewage treatment works. The first full-scale activated-sludge plant in England was put into operation in Worcester in 1916 (Cooper 2001). However, the major activated sludge plants, such as Mogden in London (which served 1.25 million people), Davyhulme in Manchester and Coleshill in Birmingham, were not built until mid-1930's. There were two principal reasons for this delay. Firstly, capital for investment was very limited in the UK after the First World War. Secondly, all the major cities had already invested in the biological filter technologies for sewage treatment in the period between 1890 and 1910 (Cooper 2001).

In the USA, by contrast, the development was more rapid and many of the activated sludge plants were the first form of sewage treatment ever used (Cooper 2001). Full-scale installations began to appear at about the same time as the experiments of Bartow and Mohlmann at the University of Illinois. In Milwaukee, a plant with the capacity of 1,600,000 gallons per day was erected in December, 1915. The plant was used for experimental purposes and was closed by 1922 Babbitt (1922). Platt (2004) noted that over a relatively short period of three years, Manchester (Fowler's group), Urbana (Bartow's group) and Milwaukee had become international leaders. They established the new method which became far superior to all previous methods of sewage treatment and disposal. By 1927 there were several full-scale systems in the US spread throughout the country (Table 1.1). Among them, Chicago North was largest with the capacity of 660,000 m^3/d. Stickney, another Chicago plant, went into operation in 1930 and was expanded in 1939. With the design capacity of over 4,500,000 m^3/d (1,200 MGD), Stickney is currently the largest activated sludge facility in the world. Due to litigations on patent infringements, a really widespread use of the activated sludge process in the US did not begin until the 1950s (Alleman and Prakasam 1983).

During the 1920's, the activated sludge process was gradually commenced in other countries. In 1924. Ontario, Canada had 7 municipal and 11 institutional activated sludge plants with a total capacity of 10,235,000 gallons per day (Wolman 1924). The first application in the continental Europe (outside the UK) took place in Denmark in the Soelleroed Municipality in 1922 (Cooper 2001). The first experimental plant in Germany was built and run in Essen by Karl Imhoff in 1924. It was a rectangular glass container with the volume of 0.5 m^3 which was divided into aerating and settling compartments in the ratio 6:1 (Miller 1927). Soon, the first full-scale plants

in the country were built in Essen-Rellinghausen (1926) and in Stahnsdorf near Berlin (1929–1931) (Seeger 1999). The latter one was designed and operated as an experimental plant for the study of different sedimentation tank options. Miller (1930) reported brief descriptions of eight "*interesting*" plants in Germany. In 1927, an abattoir effluent at Apeldoorn (Holland) was treated using an activated sludge process equipped with a brush aerator developed by Kessener (Cooper 2001).

Table 1.1 List of early activated sludge installations in the UK and USA (Alleman and Prakasam 1983)

Year	Location	Flow rate, m^3/d	Operational mode	Aeration system
	UK			
1914	Salford	303	Fill-and-draw	Diffused
		45	Continuous-flow	Diffused
1915	Davyhulme	378	Fill-and-draw	Diffused
1916	Worcester	7 570	Continuous-flow	Diffused
1917	Sheffield	3 028	Fill-and-draw	Mechanical
1917	Withington	946	Continuous-flow	Diffused
1917	Stamford	378	Continuous-flow	Diffused
1920	Tunstall	1 104	Continuous-flow	Mechanical
1920	Sheffield	1 340	Continuous-flow	Mechanical
1921	Davyhulme	2 509	Continuous-flow	Diffused
1921	Bury	1 363	Continuous-flow	Diffused
	USA			
1916	San Marcos, Texas	454	Continuous-flow	Diffused
1916	Milwaukee, Wisconsin	7 570	Continuous-flow	Diffused
1916	Cleveland, Ohio	3 785	Continuous-flow	Diffused
1917	Houston, Texas	20 817	Continuous-flow	Diffused
1917	Houston, Texas	18 925	Continuous-flow	Diffused
1922	Des Plaines, Illinois	20 817	Continuous-flow	Diffused
1922	Calumet, Indiana	5 677	Continuous-flow	Mechanical
1925	Milwaukee, Wisconsin	170 325	Continuous-flow	Diffused
1925	Indianapolis, Indiana	189 250	Continuous-flow	Diffused
1927	Chicago, Illoinis	662 375	Continuous-flow	Diffused

Yet before the World War II, the number of full-scale activated sludge plants could be counted in hundreds and was steadily increasing (Cooper and Downing 1998). For example, the number of U.S. activated sludge facilities raised to 203

in 1938 (Alleman and Prakasam 1983). The process reached other continents then Europe and America. For example, the Japanese city of Nagoya installed an activated sludge plant in December, 1924 and the daily volume of sewage treated was 15,600 ft^3 (440 m^3) (Miller 1927). While reviewing the initial twenty-five-year history of the activated sludge process for the Federation of Sewage Works Association in the USA, Mohlman noted that the process had been applied in five continents (cited in Cooper (2001):

> *"In 1938, the activated sludge process is in operation in hundreds of full-scale sewage treatment works and more than a billion gallons of sewage are treated every day. Activated sludge plants are now operated all over the world, extending from Helsinki, Finland to Bangalore, India; from Flin Flon, Manitoba, Canada to Glenelg, Australia; and from Golden Gate Park, San Francisco to Johannesburg, South Africa. Huge plants are in operation at London, New York, Chicago, Cleveland and Milwaukee."*

Almost 30 years later, Sawyer (1965) reviewed the developments and updates in the activated sludge process ("*as Dr. Mohlmann did similarly*") and "*this new knowledge has shown the process to be extremely adaptable and, as a result, many modifications have been proposed to meet certain requirements or condition*". In the period from the 1930s to the early 1950s, the major operational problems that motivated these modifications were sludge bulking, and oxygen transfer and utilization (McKinney, 1957). Lawrence and McCarthy (1970) summarized the ranges of process loading factors and SRTs for most common modifications of the conventional activated sludge process, such as extended aeration, tapered aeration, step aeration, contact stabilization, short term aeration (high loaded). More detailed descriptions of these systems can be found in Orhon and Artan (1994) (including the flow sheets) and Jeppsson (1996). It should be noted that not all modifications are recognized nowadays. For example, the so-called "Z" process, invented in 1944, faded into obscurity as it used asbestos fibers in the aeration tank to enhance floc sedimentation properties (Alleman and Prakasam 1983).

In the initial period of application of the activated sludge process, the discharge requirements were mainly to meet standards for suspended solids (SS) and 5-day Biochemical Oxygen Demand (BOD_5), e.g. the so-called "*Royal Commission 30:20 Standard*" in the UK. By the 1950s, effluent limits for ammonia concentration were started to be imposed for plants discharging into rivers providing water for public supply systems. Those limits were subsequently becoming more widespread and more stringent (Downing and Cooper 1998). In the 1970s, discharge requirements for nitrite and nitrate started to be enacted as well (Gujer 2010).

1.1.2 Biological nitrogen removal

Nitrification and denitrification were observed in the 19th century before the invention of the activated sludge process. Pasteur was first who suggested that the oxidation of ammonia to nitric acid taking place in nature was really due to microorganisms, and two French chemists, Schlösing and Muntz, actually proved that hypothesis (Fowler 1934). In their pioneering experiments, Ardern and Lockett (1914) reported the occurrence of complete nitrification after 10-18 hours when aerating normal Manchester sewage. The aeration time was reduced to 6 hours when treating wet weather sewage. In the early investigations of the activated sludge process considerable attention was paid to the degree of ammonia oxidation, but nitrification was not considered to be "*essential to the success of the [activated sludge] process*" (Buswell 1923). Until the early 1960's, nitrification was not reliable or predictable in activated sludge systems (Cooper 2001).

Skinner and Walker (1961) were among the first to investigate nitrification in continuous culture and obtained steady-state cultures of *Nitrosomonas europea* in an ammonia-limited chemostat. Boon and Laudelout (1962) studied the effects of different environmental conditions on the kinetics of the nitrite oxidation by Nitrobacter. A "*landmark*" work, as called by Barnard (2006), was performed by Downing *et al.* (1964) at the Water Pollution Research Laboratory (WPRL) in Stevenage (UK). The authors demonstrated that for consistent nitrification (i.e. preventing the washout of the slowly growing autotrophic microorganisms), the period of aeration of mixed liquor in the fully aerobic bioreactors would have to greater than the retention time in the bioreactor, t_m, defined as:

$$t_m = \frac{\Delta X}{\mu_N X} \tag{1.1}$$

where

ΔX - increase in concentration of activated sludge (X) during transit through an assumed plug-flow bioreactor

μ_N - specific growth rate of *Nitrosomonas spp* (assumed to be the organisms converting ammonia to nitrate), T^{-1}

The concept and results of the study of Downing *et al.* (1964) were later incorporated into design methods and mathematical models of activated sludge systems (Cooper 2001).

Denitrification was first studied in 1882 by Gayon and Dupetit who found that when a solution containing potassium nitrate together with sewage and a little

urine was allowed to stand in absence of air the nitrate was reduced. Moreover, positive effects of the addition of organic compounds, such as carbohydrates, tartrates, were observed. It was concluded that denitrification was essentially the "*combustion*" of organic material by the nitrate oxygen and thus the process proceeded "*best*" in presence of a minimum air supply (Fowler 1934). In the early experiments with activated sludge, Buswell (1923) observed that the nitrate oxygen was utilized as a source of oxygen by the microorganisms in the sludge when low quantities of air were added while treating nitrate rich sewage. Fowler (1934) noted that the subject of denitrification has been investigated by numerous workers, notably Percy, Frankland and Beyerinck. Cooper and Downing (1998) found the studies of Kershaw and Finch (1936) and several years later by Edmondson and Goodrich (1943, 1947) as particularly significant in terms of the subsequent development of activated sludge systems. In both studies, the effluent from nitrifying biological filters was diverted into second-stage activated-sludge units where the oxidized nitrogen was effectively removed. Moreover, in the case of the latter study, sludge settleability in the activated-sludge unit significantly improved in comparison with the previously overloaded biological filter. Barnard (2006) reported another early study on denitrification while investigating sludge rising problems in final clarifiers (Sawyer and Bradney 1945).

Biological nitrification/denitrification as a process for nitrogen removal from wastewater gained attention during the early 1960s. Wuhrmann (1962, 1964) proposed a configuration of two tanks in series in a one-sludge system, known as the Wuhrman (or post-denitrification) process (Figure 1.1). A separate denitrification (anoxic) compartment was added after the aerobic compartment for denitrification using stored carbon in a high-rate process (Barnard 2006). As the process depended upon internal carbon sources, therefore its potential was limited. In fact, the original process configuration was not applied in full-scale without supplemental carbon addition (USEPA 1993). In Sweden, for example, WWTPs for carbon and chemical phosphorus removal (pre-precipitation) were commonly extended with post-denitrification where methanol was added for denitrification (Nyberg *et al.* 1992). A similar concept was also demonstrated in full-scale at the Blue Plains WWTP in the District of Columbia (Bailey *et al.* 1998). Ludzack and Ettinger (1962) introduced the "*semi-aerobic activated sludge process*", called the Ludzack-Ettinger process (Figure 1.1), to reflect simultaneous nitrification and denitrification observed in channel systems. The raw wastewater entering the "*semi-aerobic*" zone provided organic (readily biodegradable) carbon for denitrification. As the two zones ("*semi-aerobic*" and aerobic) were only partially separated, recycling of dissolved oxygen to the "*semi-aerobic*" compartment was induced, resulting in a low efficiency of nitrogen removal (35-50%) with weak sewage (Barnard 2006).