# CHEMISTRY OF SEWAGE TREATMENT

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A recent conversation between an eminent scientist and a successful business man, which the speaker chanced to overhear, will serve to introduce the subject of this paper and to emphasize the need for greater general enlightenment in educated circles. Asked the scientist, "Is it possible to purify sewage?" "Oh yes," the business man replied, "We are building a sewage treatment plant for our town. I think it is to be some sort of an incinerator!"

Almost every chemical graduate has a general notion of how leather, rubber or Portland cement is manufactured, and even high school students of chemistry are likely to know how gas is produced and how water may be softened. These and other chemical processes are discussed both in the elementary and advanced texts on industrial chemistry. But the treatment of human and industrial wastes, while essentially a chemical process, is almost wholly neglected. Naturally, therefore, the scientifically trained student knows nothing about sewage treatment unless he has taken a special elective course.

In introducing the subject of sewage treatment I want therefore to say a few words about the amount and composition of sewage. Sewage may be defined as the combined water carried wastes of a city or community. In addition to the human and household wastes it may contain the by-products from almost any variety of industry; it may contain the washing from streets, and unless separate drains are provided it will include the surface run-off during rain.

In amount, the sewage includes the ordinary water consumption plus what is contributed from rain and other sources. The dry weather flow usually approximates rather closely the water consumption. This amount varies greatly between different localities. In Europe the sewage flow in dry weather will run from 20 to 40 gallons per capita per day. In this country it will be from

80 to 100 gallons for smaller residential communities and on up to 200 gallons per capita per day in some larger cities. This flow is not uniform throughout the day but rises and falls with the tide of human activities.

The amount of organic matter which is present in sewage is relatively small. Some notion of the concentration can be gained by imagining the total daily bodily wastes of one person plus his share of the industrial wastes diluted with from 100 to 200 gallons of water. Yet small as this amount of organic matter is, it must in general be reduced by 70% to 95% before the sewage may be discharged without offense.

The number of urban districts in the United States which have sewage treatment plants, or rather the number of those which do not have such plants will, I think, surprise you. Mr. Langdon Pearse, of the Sanitary District of Chicago, has compiled some interesting data in this connection which appeared as a committee report to the Society for Municipal Improvements. He states that of 68 cities in the United States of 100,000 population or over, including a total population of 27½ million, only 17 cities or a total population of 8¾ million have sewage treatment works. In other words, less than one-third of our larger cities treat their sewage. In the next group, in cities of 25,000 to 100,000, with a total population of 10 1/3 million, only about 12 per cent have treatment work.

As in the case in most young industries, the importance of technically trained operating personnel is not generally realized. The larger cities with treatment works employ a regular staff of chemists or at least a chemical consultant employed intermittently. Of the 26 cities of from 25,000 to 100,000 population with sewage plants, only six employ trained operators, while in cities under 25,000 anybody from the Mayor to the dog catcher may be detailed to look after the sewage works. This condition cannot long continue. Sewage treatment is a complex process and cannot be carried out successfully except under the supervision of trained chemists.

In discussing the manufacture of relatively pure water from the combined water carried wastes of a modern city

I want to invite your attention, first, to the raw material and the final product which must be produced; second, to typical factory layouts in which the process may be carried out; and third, to some of the chemical reactions which take place.

1. *Raw materials.* A general idea of the raw materials may be gained from the statement that the amount of sewage is very close to the cities' total water consumption. This ranges from 75 to 150 gallons in American cities per capita per day. In Chicago, due to the enormous waste of water, the consumption is over 300 gallons per capita per day. When the wastes from one person, even including his share of factory and trade wastes, are diluted with such a large volume of water it is apparent that the amount of organic matter per gallon of sewage is comparatively small. And yet it is exceedingly objectionable.

Sewage is most concentrated and the flow is greatest during the day. It drops off both in concentration and flow, reaching a minimum about midnight to 1:00 or 2:00 o'clock A. M. In addition to the hourly variation in concentration and flow, sewage also varies with the days of the week and the seasons of the year. In fact, so great is the variation in sewage that it is impossible to make a sufficiently reliable laboratory analysis of it. Where any considerable sewage treatment work is contemplated it is necessary to erect an experimental plant to try out various methods on a sufficient scale to allow for the effect of the numerous variables.

(2) *Typical factory layouts.* Although each plant must be designed to handle the particular local problem, there are certain steps that are usually made use of in purifying sewage. Time will permit us to mention only the two most important methods.

The new plants being built at Decatur and Urbana-Champaign may be taken as typical Imhoff tank and sprinkling filter installations. The sewage flows first through bar screens which remove larger debris of more than 2 to 3 inches in size. Next it passes through grit chambers in which large gravel, cinders, and grit particles settle out. Next it may be passed through some sort of fine screen. Screens do not happen to be used in the two new installations referred to. The sewage, still flowing at a fairly high velocity and carrying considerable matter in suspension, flows now into tanks where the velocity is reduced and sedimentation takes place. The tanks are of the so-called Emscher or Imhoff design, invented by Dr. Karl Imhoff and first used in the Emscher district of Germany.

The tank is a sort of two story affair in which the sedimentation takes place in the upper chamber. The sludge slips through the slot into the lower compartment where it is subjected to septic digestion. One of the features of this tank is the separation of a biolytic or digestion chamber. The vents at the sides allow the escape of gaseous products of digestion without stirring up the sedimentation chamber. This separate digestion of the sludge prevents the fouling of the liquor in the sedimentation chamber so that the effluent has a mild musty odor rather than the septic odor of the older septic tanks.

The effluent, now very materially improved and having no large floating particles but still with a distinct milkiness, may in some cases be discharged into the stream if the stream has sufficient volume. In most cases, however, it is passed through sprinkler nozzles on to a so-called filter in which the action is not one of filtering or straining at all, since the medium is broken rock of 2 to 3 inches in size. A slimy film soon develops on the surface of the stone, which acts in some way or other to take up all of the milky colloidal organic matter and oxidize much of the nitrogen to nitrate. The effluent of a trickling filter is perfectly clear, and it not only does not contain any putrescible organic matter but the nitrate constitutes what might be called an excess stability. The effluent is really of better quality than the water in many of our muddy prairie streams.

From time to time these filters "unload" a sort of black humus which usually is caught in secondary tanks of the Imhoff type. This process has for its net effect the digestion, liquifaction and oxidation of the organic matter, the end products being $(NH_4)_2CO_3$, $NH_4NO_3$ and a black humus containing 95% or more of water, and known as the sludge. This sludge is siphoned off from the digestion chamber of the tanks from time to time, drained on gravel or sand beds and hauled away. It is comparatively poor in nitrogen, most of that element having been converted into soluble salts. In some cases it is sold for as high as $2.00 per load.

The activated sludge process which is rapidly coming into favor substitutes an aeration tank and settling tank for Imhoff tanks and filters and is very much more compact.

The sewage, together with about 25% by volume of returned sludge, enters one end of the tank and the two are thoroughly mixed and aerated by means of air blown in through porous plates at the center and bottom of the tank. In from three to six hours the sewage is completely clarified, considerable nitrates are produced and the mixture passes on to settling tanks. The settled liquor is clear and stable and is discharged into the stream. The sludge, which contains 97-99% moisture, is partly returned to maintain the process while the remainder is dried and sold for fertilizer.

The sludge differs radically from Imhoff sludge. Activated sludge has practically the same chemical composition as microbial protein, containing from 7 to 10% of nitrogen. It is a very valuable fertilizer, but unfortunately no cheap method of drying it has been worked out. Much progress is being made by the Sanitary District of Chicago and elsewhere at the present time and the problem appears far from insoluble.

I have purposely avoided discussing the question of sludge drying from lack of time.

## CHEMISTRY OF SEWAGE PURIFICATION

Two rather opposing theories have been proposed for the explanation of the reactions in sewage treatment, more especially the clarification and nitrification which takes place in the activated sludge tank or on the trickling filter.

The one is the Hampton Doctrine of Travis which Ardern summarizes as follows: "According to this theory the purification process is primarily and essentially a de-solution effect brought about purely by physical causes, and any bacterial or biological action is definitely ancillary." Dr. Remsen is quoted as saying that the value of a theory is to be judged by the experimental work which it stimulates. Judged on this basis the Hampton doctrine does not make much of a showing.

The other theory is that of Dunbar, with perhaps some modifications, and holds that the results are brought about largely by biological catalysts which produce biochemical reactions.

If one examines particles of activated sludge under the microscope he is impressed immediately with the fact that there is practically no adsorbed, precipitated or coagulated amorphous matter in these sludge particles, but that they are composed entirely of active growing microscopic organisms of varieties ranging from true bacteria up through the giant bacteria, with occasionally molds and yeasts, and including as well, a variety of free swimming and attached protozoa. These communities of microorganisms must obtain food, and this food must be supplied from the colloidal and dissolved matter and salts in the sewage. From what we know of the metabolism of microorganisms it is probable that the unicellular forms are absorbing through their membrane such soluble forms of organic matter as are able to pass through this membrane, and that they are also secreting enzymes which are capable of peptizing or liquefying colloidal particles too large to be directly absorbed. Protozoa, on the other hand, can easily be seen to approach and ingest visible particles of organic matter. This biological theory of the action of activated sludge might be summarized and emphasized by proposing what seems to be a rather striking analogy, namely, that the purification of sewage effected by microscopic communities appearing as flocs is entirely similar to that of disposal of garbage by feeding it to hogs. It does not seem probable that adsorption of colloids or mechanical precipitation plays any greater part in the metabolism of microorganisms than they do in the digestion of the larger animals. One serious objection to the colloidal theory of coagulation is that the colloidal particles in sewage and the activated sludge particles are, so far as we are able to determine, both negatively charged. Since adsorption of colloids is most effective between oppositely charged particles it should not be applied to the conditions of the activated sludge particles without reservation. Furthermore, adsorption is an almost instantaneous action, while considerable time is required for the activated sludge reaction.

The biological theory suggests a somewhat different notion of the importance of oxidation in sewage purification than that ordinarily expressed. When garbage is disposed of by feeding to hogs, only as much oxidation takes place as is required to furnish energy for the life processes of the hogs. Final oxidation does not take place until the pork chops are eaten and burned up in the body to furnish human energy. If the analogy of this process to sewage disposal is admitted, oxidation appears as an incidental reaction. Biochemical precipitation of colloids would appear to be the important phase of the reaction.

*The Sludge-Digestion Spiral*—In nature organic matter is worked over by succeeding generations and races of micro-organisms until a large percentage of it has been broken down to ammonia, nitrates and carbon dioxide, leaving a relatively small amount of black humus as a residue. The course of this reaction might be represented by a spiral. Suppose at a point A we start out with the dissolved and colloidal organic matter in sewage. Microbial spores then develop, producing bacteria, molds and sometimes even higher forms whose nourishment is drawn from the organic matter, until when we arrive at point B all of the organic matter has been taken up to form the living substances of the growths which develop. If these growths continue their life processes they produce a certain amount of carbon dioxide and ammonia, and then eventually die and decompose, bringing us to the point A′, where we again have dead and more or less liquefied organic matter. The distance from A to A′ would represent what some authorities refer to as the "wet-burning" or "moist combustion" which has taken place during the first lap around the spiral. If we continue to go round and round this spiral we eventually arrive in nature at a condition where a fairly considerable portion of the organic matter has been mineralized and a black stable humus substance remains.

Sewage treatment by means of biolytic tanks, sprinkling, or contact filters and subsequent secondary tanks gives us practically the result indicated by the spiral. The heavy solids are attacked and worked over by certain groups of bacteria in the sludge digestion chamber of the biolytic tank until practically nothing but a black humus remains. The liquefied product, together with the collodial and dissolved organic matter in the sewage, is taken in by the organisms of the biological jelly on the sewage filter. In this jelly the same spiral of activities goes on. A cross-section cut with a knife through the growth on the sewage filter stone shows on the outside the new whitish growth composed of various types of bacteria and protozoa. Just below this new growth there is a layer of less active dying or dead bacterial filaments upon which varieties of protozoa are feeding. These protozoa in turn die, and various forms follow, undoubtedly, including some of the same anaerobic forms which are active in the sludge digestion chamber of the tanks, which produce immediately adjacent to the stone a black stable humus. From time to time this humus sloughs off and is finally worked over in the digestion chamber of the secondary tanks. As a result of allowing this process to go on to the limit we obtain a relatively small amount of comparatively inoffensive sludge of low $N_2$ content, the $N_2$ having been largely converted into ammonium salts. The process, however, requires rather a large area for its practical application.

In the Activated Sludge Process, we start out with the idea that the sludge is a valuable fertilizing material, and therefore for the most economical operation of the process we should try to get as much sludge as possible. Since it is a biological process the course of the reaction will be along the course of the same spiral described above. But since we are going to considerable expense in order to provide a condition favorable for the growth of the microscopic life, namely, by blowing air into the sewage, we will waste considerable effort if we allow the process to proceed very many laps around the spiral. The most efficient process would seem to be one which removes the sludge as near the point B as possible; that is, as soon as a luxuriant growth has been developed and before any of this growth begins to die and decompose. This fact is the fundamental distinction between tank-and-filter treatment and activated-sludge treatment, the object of the former being to go round the spiral approaching the center as nearly as possible, that is with the maximum of wet-burning, while the latter should go only to the point B.

There is also a mechanical difference between the activated-sludge process and the tank-and-filter system. Hering has shown that the amount of purification is proportional to the surface exposed. Since it is necessary to use rather large stone in filters to avoid ponding or clogging, it is obvious that the ratio of surface to volume, that is the efficiency per cubic foot, is comparatively low, while in the activated-sludge process the floc surface is relatively enormous, being in the neighborhood of 500 sq. ft. of surface area per cubic foot of aeration tank volume.

It will not be possible to discuss all of the chemical changes which take place, but I want to consider briefly the nitrogenous compounds and the changes which they undergo. In this field we find that the chemistry of soils and fertilizers and the chemistry of sewage have gone hand in hand. Chemists in one line apply freely the advances made in the other. Although the chemistry of nitrogen and the changes which it undergoes in nature is one of the oldest subjects of chemical investigation we find that there is much misinformation in the literature and much still to be learned.

When bacterial enzymes attack the organic matter of sewage, progressive hydrolysis takes place with the formation of ammonia. This is known as ammonification and is brought about by a variety of organisms.

If aerobic conditions prevail, the nitrifying organisms oxidize nitrogen to nitrites and nitrates and the mineralization of nitrogen is complete.

These reactions are pretty well understood and in fact a matter of common knowledge among chemists. The fact that these reactions can take place in the reverse direction has, however, but recently been demonstrated.

If we start with nitrates we find that under anaerobic conditions they are reduced. This process is generally referred to as denitrification and most authorities state that denitrification results in loss of nitrogen. Experiments in our laboratory and elsewhere indicate that this is not true. Nitrates when reduced are synthesized into protein, the living protein of micro-organisms and bacteria. Likewise free ammonia in some cases decreases during the process of sewage treatment, but here again nitrogen is not lost but protein is formed. Thus we see that in sewage treatment we may have protein compounds undergoing hydrolysis, liquefaction and oxidation, or the reverse action may take place and protein may be precipitated.

The carbon and sulfur cycles are equally interesting but would be beyond the limits of the time alloted this paper.