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Strong oxidant waste water conditioning of allentown wastewater sludge

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by

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OF ALLENTOWN WASTEWATER SLUDGE

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CHAPTER ONE

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The extensive hydrogen peroxide and ozone experiments for evaluation of these strong oxidants included the application of the strong oxidants as the sole sludge conditioning agents on Allentown Wastewater Treatment Plant anaerobically digested sludge and in combinations with ferric chloride and lime. The strong oxidants both exhibited a tendency to reduce specific resistance and thus increase dewaterability of the sludge, but these effects were much less marked in comparison to conditioning with ferric chloride and lime. Many combinations of hydrogen peroxide, lime, and ferric chloride were tested for sludge conditioning effectiveness with varying degrees of success. The overall trend observed was that lime seemed to have the most marked effect on dewatering characteristics. Hydrogen peroxide addition was inconsistent in increasing dewaterability, but lower doses of between 200 mg/ℓ to 500 mg/ℓ seemed to be most effective in sludge dewatering improvement when the sludge solids were less concentrated, around 30 grams per liter (g/ℓ). When sludge solids concentrations were around 40 g/ℓ or more, the addition of hydrogen peroxide was not significantly effective and in some cases was counterproductive with respect to increasing dewaterability.

Effective ozone doses were found to be in the 25 mg/ℓ to 100 mg/ℓ concentration range when combined with ferric chloride and lime. Higher doses of ozone in combination with ferric chloride and lime were undesirable and decreased dewatering effectiveness. On a preliminary basis, addition of ozone also seemed to show a relationship to lower sludge solids concentrations and conditioning effectiveness. However, sufficient supporting data is not available to support this observation with certainty.

The effects of the strong oxidants on the filtrate strength were to increase soluble filtrate strength. However, effective conditioning under any of the chemical applications increased the soluble filtrate strength as measured in the Büchner funnel filtrate but decreased the overall filtrate strength in terms of chemical oxygen demand in the filter leaf filtrate.

The results of these tests show that both strong oxidants can be applied with some success to Allentown Wastewater Treatment Plant sludge. However, in terms of sensitivity, the success of those oxidants, especially hydrogen peroxide, are very dependent on sludge solids concentrations being low, i.e., around 30 g/ℓ. The test results also indicate that lime is the most desirable chemical conditioner to change, and that increased lime dosages generally result in better dewaterability throughout the sludge solids concentration ranges investigated.

A preliminary economic evaluation for hydrogen-peroxide indicate that the dosages required for effectiveness would not be competitive to lime and ferric chloride at the current costs. Ozone dosages in the 50 mg/ℓ range would be competitive to excess lime based on operating costs.

Conclusions

From the above summary of results, the following is concluded:

1. Strong oxidants do affect the dewaterability of anaerobically digested wastewater sludge.
2. Strong oxidants tested are not as effective as conventional chemicals, such as lime and ferric-chloride, in sludge conditioning.
3. When used in small doses, e.g., 200 to 500 mg/ℓ hydrogen peroxide or 25 to 100 mg/ℓ ozone, enhancement of dewaterability can be attained in conjunction with lime and ferric chloride sludge treatment.
4. The effectiveness of strong oxidant conditioning seems to have an inverse relationship to sludge solids concentration, i.e., lower sludge solids concentrations respond more favorably to strong oxidant conditioning.
5. The most effective chemical variation occurred due to lime. Better sludge conditioning resulted with increased lime dosages.
6. Total filtrate strength, based on COD, decreased when effective conditioning was achieved. This effect was observed for all conditioning agents. Soluble filtrate strength increased under these same conditions.
7. Hydrogen peroxide dosages were not economically competitive even when used in combinations with ferric chloride and lime.
8. Ozone costs, less capital equipment expenditures, were competitive for use in conjunction with lime and ferric chloride.

Recommendations

The test results indicate that the use of strong oxidants on the anaerobically digested sludge has potential as a sludge conditioning agent. The variability of effectiveness, as related to sludge solids concentration, has a limiting aspect for application of the oxidants for this purpose. The following recommendations are the results of this study:

1. Because of the variability of effectiveness of the strong oxidants and the relative consistency of lime effects, the addition of lime is recommended for increasing dewaterability of this sludge.
2. The current practices of ferric chloride and lime addition for sludge conditioning, as currently performed at Allentown's wastewater treatment plant, is effective and should continue. Other methods and chemicals, e.g., polymers, may be useful additives and may be worthwhile to investigate in the future.
3. The relationship of sludge solids concentration and strong oxidant conditioning effects should be more thoroughly investigated.

CHAPTER TWO

ALLENTOWN WASTEWATER SLUDGE CONDITIONING PROJECT

The conditioning of wastewater sludges is important so that a separation of water-solids content can be achieved. The net results of this is the production of a drier solids fraction which directly relates to lower total volume and weight of material for hauling and ultimate disposal. Sludge solids can tenaciously hold water, and many methods of sludge conditioning are available (1,2). Each method has its advantages and disadvantages, and each sludge may respond differently to any one method. The quest for optimal conditioning agents and techniques is open for much investigation and innovation.

The sludge at Allentown's wastewater treatment plant is conditioned using ferric chloride and lime after anaerobic digestion and elutriation. The conditioned sludge is dewatered by vacuum filtration, resulting in a dried cake for disposal and a sludge filtrate which is returned to the mainstream of the treatment plant. The objective of this research was to investigate the effects of using strong oxidants, specifically ozone and hydrogen peroxide, as sludge conditioners. These conditioners were applied as the only chemical additive, and they were also added in combination with ferric chloride and lime in varying dosages.

The effectiveness of sludge conditioning was measured by determining specific resistance of conditioned samples of Allentown wastewater sludge using Büchner funnel filtration tests. From physical parameter measurements and the volume of filtrate obtained versus time under a given vacuum, the specific resistance was measured. The results of the specific resistance measurements indicated the ease of dewaterability and the effectiveness of the conditioning agents. Lower specific resistance values result when better conditioning is achieved.

The specific resistance parameter is theoretical. A practical simulation parameter of actual expected vacuum filter performance is the filter leaf test. The filter leaf is an actual vacuum filter media of known area on which conditioned sludge may be collected, and the actual operation of a vacuum filter may be simulated with respect to form and dry times. The resulting measure of effectiveness is termed filter yield, with higher filter yields indicating better dewaterability, i.e., better conditioning effectiveness.

Sludge conditioning tests were performed using hydrogen peroxide, ozone, ferric chloride and lime. Extensive testing of various combinations of these conditioning agents was performed and evaluated. Each of the sets of tests were generally compared to two control samples, one control being an unconditioned sludge sample and a second control simulating the average dosages of chemical conditioners used in daily operation at Allentown's wastewater treatment facility. Specific resistance and filter yield tests were performed, and characterization of the sludge filtrates in terms of pH and chemical oxygen demand (COD) was investigated. Initial sludge characteristics were measured for assessment of sludge conditioning effectiveness, as well.

The experiment program lasted nine months in which a variety of sludge samples were obtained and used in the testing. The sludge, all from the Allentown wastewater treatment plant, was found to vary in composition during the experimental program. This variation resulted in different responses to conditioning agents, adding an additional interesting problem for evaluation and investigation. This also helped to illustrate the complexity of the sludge conditioning problem.

CHAPTER THREE

WASTEWATER SLUDGE CONDITIONING PROJECT METHODOLOGY

Processing of wastewater solids presents a major treatment and disposal problem. Wastewater sludge solids consist of original wastewater solids plus any chemical precipitates or biological solids generated in various treatment processes. These solids may be handled in numerous ways depending on overall system parameters, wastewater treatment facility location, and governmental and regulatory agency limitations. In many cases, it is desirable to reduce the sludge to dry cake form for purposes of easier handling and reducing total sludge volume. This may be accomplished by a number of dewatering techniques, e.g., vacuum filtration, sand drying beds, etc. The ease and effectiveness of dewatering techniques depend upon the water-holding characteristics of the sludge in question. When the tenacity of the sludge for the bound water is great, as is often the case, the sludge may be physically or chemically conditioned to decrease attraction between the solid and liquid phases. In order to provide good dewaterability, many sludge conditioning techniques have been developed and applied with varying effectiveness (1,2). Typical physical conditioning techniques used are heating or freezing. Common chemical conditioners are lime, iron salts, aluminum salts, and polymers. An alternative chemical conditioner method which may prove beneficial is the use of strong oxidants such as ozone or hydrogen peroxide. These oxidants are known to readily and rapidly react with wastewater solids, but their effectiveness on increasing dewsterability of sludge solids remains unknown. Principal mechanisms postulated in potential increasing of sludge dewaterability are the strong oxidant attack on the sludge colloidal constituents and the breakup of filamentous biological growths (3).

The Allentown Wastewater Treatment Plant is presently at design capacity and is undergoing active expansion of facilities. Plant capacity may also be increased by improving treatment efficiency in any of the unit operations, which would result in larger throughput volumes without decreasing effluent quality. The focus of this research was to determine if greater capacity of dewatering units can be achieved using strong oxidant sludge conditioning methods and to determine the feasibility of such sludge conditioning practices.

Allentown wastewater sludge is currently thickened and then stabilized by anaerobic digestion. The digested sludge is elutriated and chemically conditioned prior to vacuum filtration. Comparison of effectiveness of present conditioning practices at the Kline's Island facility versus the use of strong oxidants for conditioning Allentown wastewater sludge in order to ascertain if indeed strong oxidants are effective sludge conditioning agents was investigated and the results are reported herein. The dosages of strong oxidant needed to effect increased dewaterability were determined and provide the basic data for an economic comparison to the present conditioning practices at the Kline's Island facility.

Hydrogen peroxide and ozone were the strong oxidants used as sludge conditioners. These oxidants were selected based on their strong oxidizing characteristics and the innocuous end products generally produced. A simple contrast to other oxidants illustrates this point; e.g., the end products of ozone and hydrogen peroxide include water and oxygen, whereas oxidants such as permanganate result in a precipitous oxide. Chlorine may result in only partial oxidation of organics and undesirable chemical species. Salt content of the water may also increase from addition of other chemical oxidants, and this is not a direct consequence of hydrogen peroxide or ozone reduction. Hydrogen peroxide and ozone are also readily available for sludge conditioning applications so that that factor would not be a limiting consideration.

Thickened stabilized elutriated sludge from the Allentown Wastewater Treatment Plant was used in investigating the feasibility of strong oxidant sludge conditioning versus the current chemical conditioning practices used. These studies focused on four major categories of investigation: the determination of strong oxidant dosages to effect dewatering improvement, the determination of dewatering characteristics, the determination of filtrate characteristics, and a preliminary economic feasibility analysis of strong oxidant conditioning.

Sludge samples were obtained from the Allentown Wastewater Treatment Plant for the conditioning tests. The sludge samples were characterized as to solids concentration before conditioning tests were performed. During the course of the experiments the sludge sample characteristics were observed to vary with respect to concentration and also with respect to dewatering characteristics when a given sample was used on consecutive days. The latter condition was monitored in the testing procedure and eliminated by test scheduling when sets of conditioning parameters so dictated. The former aspect presented some problems in selection of a standard conditioning technique to use as a baseline for comparison to strong oxidant conditioning, as well as in experimental data handling and interpretation. It was decided to keep the concentration of chemicals which represented standard operating procedure at the Allentown Wastewater Treatment Plant constant, rather than adjusting dosages on some parameter, e.g., solids content.

Allentown operations use ferric chloride and lime as sludge conditioners. For laboratory comparisons the sludges were conditioned using reagent grade ferric chloride and lime with a standard dosage of ferric chloride as 1.05 grams per liter of sludge (g/ℓ) and lime at 4.5 g/ℓ. These dosages were derived as an "average" based on Allentown Wastewater Treatment Plant operational records. The standard dosage was determined from conversion of dry weight of conditioners to dry weight of sludge and average sludge concentrations. The range of iron dosage in terms of dry weight was 1.8% to 4.4%, and the lime dosage range was 6.7% to 21.3%, with average values of 3.5% and 15%, respectively. The corresponding average sludge concentration used was 3.0%.

A thirty percent hydrogen peroxide (ACS grade) stock solution was used to prepare sludge conditioning dosages ranging from zero to 6000 mg/ℓ. The solutions were prepared such that 20 milliliters of hydrogen peroxide solution would yield the desired concentration when added to one liter of sludge, thus eliminating any dilution effect between the different dosages used. The hydrogen peroxide was added to a rapidly agitated sludge sample in order to provide completely-mixed conditions, thereby minimizing strong concentration areas within the sample.

Ozone was generated using dry air passed through a Welsbach Model T-23 Laboratory Ozonator. A fritted glass diffuser dispersed the ozone through a one liter sample of sludge. An overflow for the foam which was produced was provided. The gas flow rate was set at 0.03 cubic feet per minute and the voltage was set at 115 volts. These values were found to be optimal for ozone transfer in these experiments. A 500 mℓ gas washing bottle containing potassium iodide trapped non-reacted ozone. Figure 1 represents the ozone contacting setup. Sludge samples were contacted with ozone based on calibration work performed on early samples. Because of short retention times in the experimental contacting units, efficiencies of ozone utilization were low - on the order of 60 percent - but no special techniques were employed to utilize unreacted gas to improve this situation. Ozone dosages reported are lower than dosages applied and represent the approximate quantities of ozone reacted with the sludge.

The conditioned sludges were tested for dewaterability using two techniques, the Büchner funnel filtration test for specific resistance and the filter leaf test. The Büchner funnel filtration test is used for determining the specific resistance of the sludge, a theoretical parameter indicating the ease of dewaterability of sludges. The Büchner funnel filtration test was run using Whatman No. 2 filter paper and a controlled vacuum of 7 to 10 psig. The volume of filtrate obtained measured versus filtration time allowed for the development of the specific resistance.

The specific resistance parameter is a function of sludge properties and has its theoretical basis in the Kozeny filtration equation. As modified by Coakley (4) the Kozeny equation becomes

$$\frac{dV}{dt} = \frac{a^2 \Delta P}{\mu(\xi C_s V + R_m a)} \tag{1}$$

in which V = volume of filtrate

a = area of cake under filtration

ΔP = pressure difference across cake

μ = viscosity of filtrate

ξ = specific resistance of cake

C_s = initial dry weight concentration of solids

R_m = resistance of unit area of filter medium

Integration yields

$$\frac{t}{V} = \frac{\mu \xi C_s}{2a^2 \Delta P} V + \frac{\mu R_m}{a \Delta P} \quad (2)$$

A plot of t/V versus V gives the specific resistance as the slope of the line, i.e.,

$$\text{Slope} = m = \frac{\mu \xi C_s}{2a^2 \Delta P} \quad (3)$$

or

$$\xi = \frac{2a^2 \Delta P_m}{\mu C_s} \quad (4)$$

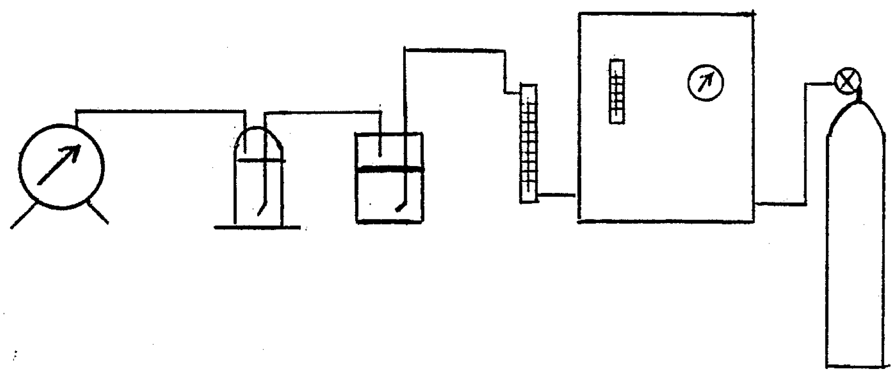
Values of specific resistance are indicative of sludge dewaterability, e.g., low specific resistance indicates good dewaterability. Specific resistance obtained in the experiments provided one basis for comparison of chemical conditioning and oxidant conditioning effectiveness.

Filter leaf tests simulate actual filter performance and provide more reliable data for design purposes in terms of filter yield for given form time and operational conditions. The filter-leaf method applies a controlled vacuum to an actual filter medium which is submerged in a conditioned sludge sample for the desired form time, and then removed with vacuum still applied for the desired drying time. Dry weight of sludge retained is measured and expressed in terms of filter yield. The filter leaf method uses different combinations of form time and drying times for the conditioned sludges and provides design information of the vacuum (power) requirements for given conditioning procedures to obtain satisfactory dewatering and solids capture. The filter leaf tests in this program used a filter leaf on loan from Dorr-Oliver, and this had the same filtration media as is used at the Allentown Wastewater Treatment Plant.

The filter leaf tests may also be applied for determination of specific resistance, but there is some difficulty in measuring time response for filtrate collection. Theoretical constants for quantification of filterability are more readily obtained from Büchner funnel tests and thus those tests provide the theoretical basis for evaluating the effects of conditioning on dewaterability and performance. The filter leaf tests provide better information for design and actual filter performance requirements to achieve satisfactory filter yields with the various sludge conditioning methods studied in this research program. The effectiveness of strong oxidant conditioning methods with regard to the solid fraction of the sludge can therefore be adequately defined by these dewaterability tests.

Filtrate resulting from sludge dewatering was analyzed and compared for the various conditioning methods investigated because of the importance of this sludge fraction on the overall performance of a wastewater treatment facility. The filtrate was characterized on COD, pH, and solids. Partial oxidation of sludge solids yielding a high strength filtrate may be detrimental to overall treatment operations either in overloading biological treatment units or resulting in an increase in solids to be handled. A total solids balance must be performed to adequately determine solids handling requirements, and the returned liquid fraction from dewatering operations plays an important role in that solids balance. Comparisons of Büchner funnel filtrate to filter leaf test filtrate indicated the relative distribution between soluble and total COD.

Figure 1 Experimental Ozone Contacting Apparatus



1. Wet test gas flow meter
2. 500 mℓ gas washing bottle, KI solution for ozone determination
3. Ozone-sludge contacting reactor
4. Flow meter
5. Ozone generator
6. Dry air supply

CHAPTER FOUR

~~RESULTS AND DISCUSSION OF WASTEWATER~~
SLUDGE CONDITIONING TESTS

The wastewater sludge conditioning tests results are presented in Tables 1 through 22 in Appendix A. These tables represent the range of experiments performed in the evaluation of strong oxidants as sludge conditioners. The experimental program included the investigation of the effects of the strong oxidants as the sole conditioning chemical and the effects of various combinations of the strong oxidants with ferric chloride and lime. The latter was prompted after initial experiments with hydrogen peroxide and the results of additional information regarding other work previously performed in evaluating hydrogen peroxide as a sludge conditioner (5). A summary of the earlier work is found in Appendix B.

Hydrogen Peroxide Tests and Results

Hydrogen peroxide tests were run in four stages. The first stage was a preliminary investigation of the effects of hydrogen peroxide effectiveness for sludge conditioning. The preliminary testing purpose was to investigate and determine what dosages of oxidant might be effective in improving the dewaterability characteristics of the wastewater sludge as measured by the Büchner funnel filtration test method for specific resistance determinations.

The preliminary results are not at all encouraging with respect to hydrogen peroxide as a sludge conditioner. Table 1 indicates that there was a slight decrease in specific resistance between the control (no chemical conditioners added) and the addition of hydrogen peroxide in very low dosages ranging from 0.2 to 20 mg/ℓ. In all cases of hydrogen peroxide addition, a slight decrease in specific resistance - from 2.1×10^{10} sec^2/g for the control to 1.6×10^{10} sec^2/g - was observed. Table 2 and Table 3 represent the results of specific resistance determinations for hydrogen peroxide dosages of 10 to 1000 mg/ℓ versus a control sample. Again, small changes in specific resistance were observed, with most dosages of hydrogen peroxide decreasing specific resistance, except for 10 mg/ℓ and 600 mg/ℓ in both cases. Because of the small changes involved, the increases, and for that matter the decreases, observed in specific resistance are not conclusive in indicating effectiveness of hydrogen peroxide as a sludge conditioner.

The results in Table 4 represent a comparison of specific resistance values of hydrogen peroxide dosages of 10 to 1000 mg/ℓ versus a conditioned sample obtained from the Allentown Wastewater Treatment Plant. While all samples conditioned with 100 mg/ℓ or more of hydrogen peroxide showed a decrease of specific resistance from the 3.7×10^{10} sec^2/g for the control to 2.2×10^{10} sec^2/g for the best hydrogen peroxide result, the conditioned sludge sample from the wastewater treatment plant had a specific resistance of 0.1 x 10^{10} sec^2/g, better than the hydrogen peroxide sludge conditioning by an order of magnitude. However, since the sludge solids concentration differed significantly between the two sludge samples obtained, the validity of the comparison is questionable. Table 5 and Table 6 represent further comparisons of hydrogen peroxide versus ferric chloride and lime. The Büchner funnel experimental technique was changed slightly in testing for specific resistance between the experiments represented in Tables 1 through 5 and Table 6, with all subsequent experiments following the procedure used in determining dewaterability in the latter table. In both Table 5 and Table 6, the ferric chloride-lime combinations as conditioned in the laboratory were more effective than hydrogen peroxide and lime with respect to decreasing specific resistance.

The results of the first six sets of tests pointed out that hydrogen peroxide in dosages from 0 to 6000 mg/ℓ had some positive effects in decreasing dewaterability of the sludges, but were much less effective than the ferric chloride-lime conditioning combination. The next phase of the experimental program focused on the effects that hydrogen peroxide has in combination with ferric chloride and lime. Comparisons to control samples of unconditioned sludge and sludge conditioned by the average dosages of ferric chloride and lime were performed.

Table 7 represents the results of the first series of comparisons of the conditioning chemical combinations. A constant value of 200 mg/ℓ of hydrogen peroxide was combined with various percentages of ferric chloride and lime. The results show that as ferric chloride and lime dosages increased, there was a continual decrease of specific resistance from 6.4 x 10^9 sec^2/g for the unconditioned sample to 0.45 x 10^9 sec^2/g for the maximum ferric chloride-lime sample with the hydrogen peroxide added. Hydrogen peroxide alone resulted in a small decrease of sludge specific resistance to 6.3 x 10^9 sec^2/g. Ferric chloride and lime at the average conditioning dosage decreased the specific resistance to 0.52 x 10^9 sec^2/g - almost as effective as the best combination of the three chemical conditioners.

The effects of hydrogen peroxide plus ferric chloride without lime are shown in Table 8. A dosage of 200 mg/ℓ of hydrogen peroxide was again used as a constant and ferric chloride dosages ranged from zero to 100 percent of the average dosage. The unconditioned control had a specific resistance of 1.7 x 10^{10} sec^2/g and 200 mg/ℓ of hydrogen peroxide alone only decreased the specific resistance to 1.5 x 10^{10} sec^2/g. Increasing dosages of ferric chloride in combination with the 200 mg/ℓ of hydrogen peroxide showed a trend of decreasing specific resistance to a minimum of 0.2 x 10^{10} sec^2/g for the 80 percent ferric chloride plus 200 mg/ℓ hydrogen peroxide case. The 100 percent ferric chloride plus 200 mg/ℓ hydrogen peroxide case and the 100 percent ferric chloride alone had the same specific resistance of 0.3 x 10^{10} sec^2/g. This indicates that the hydrogen peroxide had no benefit in decreasing sludge dewaterability at the 100 percent dosage. When lime was added with the ferric chloride at the 100 percent average dosage, the specific resistance was decreased to 0.09×10^{10} sec^2/g.

Additional comparisons of hydrogen peroxide-ferric chloride-lime combinations are shown in Tables 9 and 10. In this series, various dosages of 200 to 3000 mg/ℓ of hydrogen peroxide were added to 50 percent and 75 percent of average ferric chloride-lime, respectively and compared for conditioning effectiveness. Table 9 shows that increasing dosages of hydrogen peroxide with 50 percent ferric chloride-lime resulted in increasing specific resistance as compared to the 50 percent dosage without hydrogen peroxide. The hydrogen peroxide in this case seemed counterproductive. The 100 percent average dosage of ferric chloride and lime again showed the greatest effect in decreasing specific resistance to 1.2×10^9 sec^2/g as compared to 10.2×10^9 sec^2/g for the unconditioned sample.

Specific resistance and filter yield values are shown in Table 10 for dosages of hydrogen peroxide up to 3000 mg/ℓ with 75 percent of average ferric chloride and lime. The same observations as in Table 9 cannot be made with respect to specific resistance, except at the 3000 mg/ℓ level of hydrogen peroxide addition. No benefit is observed for hydrogen peroxide addition, however, when filter yields are compared. A slight decrease in filter yield seems to occur with hydrogen peroxide addition as compared to the 75 percent ferric chloride-lime dosage. Filter yields for the latter were 2.22 lb/ft^2hr as compared to 1.73-2.03 lb/ft^2hr for the combinations of the three conditioners. The 100 percent ferric chloride-lime conditioning showed the lowest specific resistance at 0.95×10^9 sec^2/g and the best filter yield at 3.04 lb/ft^2hr.

Additional test results to illustrate the effects of hydrogen peroxide - ferric chloride-lime combinations are shown in Table 11. In this series of tests, lime and hydrogen peroxide variations with a constant 75 percent ferric chloride dosage were investigated. Hydrogen peroxide dosages varied from 0 to 2000 mg/ℓ and lime dosages ranged from 20 to 60 percent of average. The general trend in the experiments suggested that at lower lime dosages, hydrogen peroxide had a positive effect on lowering specific resistance and increasing filter yields. This general trend occurred when the lime dosages were in the 20 to 40 percent range. However, when the lime dosage was in the 60 percent range, hydrogen peroxide did not seem to provide positive effectiveness in specific resistance changes or in filter yields. In addition, the higher lime dosages resulted in lower specific resistances and higher filter yields. And as had been repeatedly seen, the 100 percent ferric chloride-lime dosage was most effective in both measures of dewatering effectiveness. These results were confirmed in additional tests as shown in Tables 12, 13 and 14. The values for filter yield in Table 14 are relative because of experimental problems in clogging of the filter leaf. Specific resistance values show the same trends observed earlier.

Table 15 represents a significant deviation from earlier results. In this test, combinations of 100 percent ferric chloride were tested with different dosages of lime and hydrogen peroxide. In this test series, 500 mg/ℓ of hydrogen peroxide improved both filter yield and specific resistance in all cases as compared to ferric chloride-lime without hydrogen peroxide. This was true also for the 100 percent average ferric chloride-lime dosage. For 100 percent ferric chloride, 10 percent lime the values for specific resistance were 2.47×10^8 and 1.59×10^8 sec^2/g without hydrogen peroxide and with 500 mg/ℓ hydrogen peroxide, respectively. The corresponding values for filter yield were 1.63 and 1.91 lb/ft^2hr, respectively. Similarly, for 100 percent ferric chloride and 20 percent lime, the specific resistance was 1.87×10^8 sec^2/g and the filter yield was 1.36 lb/ft^2hr without hydrogen peroxide. When 500 mg/ℓ of hydrogen peroxide was added with these same doses, the specific resistance value was decreased to 1.82×10^8 sec^2/g and the filter yield increased to 1.53 lb/ft^2hr. In the case of 100 percent ferric chloride and 100 percent lime, specific resistance decreased from 1.70×10^8 sec^2/g to 1.57 sec^2/g and filter yield increased from 1.61 lb/ft^2hr to 2.29 lb/ft^2hr when 500 mg/ℓ of hydrogen peroxide was added.

The major difference in the series of experiments represented by Table 15 from most of the earlier work was the lower solids concentration of the unconditioned sludge. The unconditioned sludge was on the order of 29 g/ℓ as compared to most of the earlier sludges being around 40 g/ℓ or more. With lower solids sludges, normal plant operation at Allentown is to add more lime to increase dewaterability. In this case, hydrogen peroxide produced effective results. For this case, as well, approximately equivalent treatment was obtained at the 10 percent lime and 100 percent lime with the 500 mg/ℓ of hydrogen peroxide and 100 percent ferric chloride.

In Table 16, three major points were focused on. First was the effect of the 500 mg/ℓ dosage of hydrogen peroxide on dewatering characteristics with varying doses of lime and 100 percent ferric chloride. Secondly was the effect of lime in varying doses, including excess of normal average doses, and third was the comparison of lime to an excess ferric chloride dosage. As is evident in Table 16, the solids concentration was at the normal levels observed most frequently during the experimental program. In all cases, the ferric chloride-lime treatment was superior to the hydrogen peroxide-ferric chloride-lime conditioning. When above normal dosages of lime (120 percent) were added specific resistance decreased and filter yields increased with or without hydrogen peroxide. Excess ferric chloride (120 percent) resulted in better conditioning than the 100 percent value when hydrogen peroxide was used but did not match the performance of the 100 percent values without hydrogen peroxide. Specifically, the specific resistance of the excess lime treatment was 0.72×10^8 sec^2/g and the filter yield was 4.33 lb/ft^2hr with 500 mg/ℓ hydrogen peroxide and 100 percent ferric chloride. Without hydrogen peroxide, these values were 0.46×10^8 sec^2/g and 5.93 lb/ft^2hr, respectively. The values for excess ferric chloride, 100 percent lime, and 500 mg/ℓ dosage of hydrogen peroxide were 0.74 x 10^8 sec^2/g and 3.31 lb/ft^2hr as compared to 0.83 x 10^8 sec^2/g and 5.24 lb/ft^2hr without hydrogen peroxide. The 100 percent treatment with lime and ferric chloride yielded values of 0.93 x 10^8 sec^2/g and 2.99 lb/ft^2hr with 500 mg/ℓ hydrogen peroxide, and 0.46 x 10^8 sec^2/g and 5.93 lb/ft^2hr without hydrogen peroxide. When excess lime was added the values of specific resistance were 0.72 x 10^8 sec^2/g with 500 mg/1 hydrogen peroxide and 0.30 x 10^8 sec^2/g without, and the values for filter yield were 4.33 lb/ft^2hr with 500 mg/ℓ hydrogen peroxide and 6.90 lb/ft^2hr without. The excess ferric chloride with 500 mg/ℓ hydrogen peroxide had a specific resistance of 0.74 x 10^8 sec^2/g and a filter yield of 3.31 lb/ft^2hr. Without hydrogen peroxide the values for excess ferric chloride treatment without hydrogen peroxide were 0.83 x 10^8 sec^2/g and 5.24 lb/ft^2hr. The best conditioning in this set of experiments was obtained by excess lime treatment.

Two other aspects were investigated with respect to hydrogen peroxide conditioning. Table 17 presents the results of studies to determine what approximate dosage of hydrogen peroxide would be most effective. Lime and ferric chloride dosages were held constant at the normal average concentration and hydrogen peroxide doses varied from zero to 800 mg/ℓ. Tests were also run to evaluate the effect of solids concentration and hydrogen peroxide effectiveness, and these results are shown in Tables 17 and 18. In Table 17, the results indicate that approximately 500 mg/ℓ of hydrogen peroxide results in the lowest specific resistance and highest filter yield - as compared to treatment at lower and higher doses and without hydrogen peroxide as well. The initial solids concentration was low again (30 g/ℓ). When the same sludge was diluted to approximately 75 percent of its original concentration, 100 mg/ℓ of hydrogen peroxide was most effective in terms of filter yield and approximately the same as no hydrogen peroxide treatment in terms of specific resistance.

Table 18 further evaluates the effect of solids concentration and hydrogen peroxide effectiveness. The initial solids concentration was 37.9 g/ℓ. When treated with 100 percent ferric chloride-lime conditioning dosages, the specific resistance of the sludge was 0.83 x 10^8 sec^2/g and the filter yield was 3.60 lb/ft^2hr. When 500 mg/ℓ of hydrogen peroxide was used in conjunction with the normal treatment, specific resistance increased to 1.00 x 10^8 sec^2/g and filter yield decreased to 3.05 lb/ft^2hr. The sludge was diluted to approximately 75 percent of its original concentration and treated as above. Without hydrogen peroxide, the specific resistance was 0.63 x 10^8 sec^2/g and the filter yield was 3.26 lb/ft^2hr. With peroxide the specific resistance was 0.53 x 10^8 sec^2/g and 3.49 lb/ft^2hr. Further dilution to approximately 50 percent of the original concentration yielded specific resistances of 0.40 x 10^8 sec^2/g and 0.36 x 10^8 sec^2/g and filter yields of 2.43 lb/ft^2hr and 2.69 lb/ft^2hr, without and with hydrogen peroxide treatment, respectively. These tests indicate a definite relationship of solids concentration to hydrogen peroxide effectiveness.

The other important aspect which has been observed in the analysis of the experimental results relates to the effect of the conditioning technique on strength of the filtrate. In general, as the dewaterability increases, the filtrate strength of the Büchner funnel tests increases and the filtrate strength of the filter leaf test decreases. In the Büchner funnel test, the COD determined is principally a filtered or soluble COD, whereas the filter leaf test COD is representative of total COD which would be returned to the mainstream of the treatment plant. The increase in soluble COD with decreased specific resistance is logical in that the bound water is released during conditioning. Due to its proximity to the solids, this bound water can have a microconcentration gradient which is in excess of the normal solution concentration. Upon release, this stronger strength bound water will exhibit its strength in the bulk solution. The decrease in filter leaf COD was evident in examining the physical appearance of the filtrate. Better solids capture was obvious in the higher filter yield results. The general trend with respect to COD values held for the three conditioning agents used. The hydrogen peroxide only seemed to affect the soluble COD when dosages in excess of 1000 mg/ℓ were applied. The soluble COD then increased.

Ozone Tests and Results

Ozone conditioning tests presented special problems with respect to adequate contacting and transfer of ozone. Calibrations for approximate ozone transfer versus time were made and used as a constant rate of transfer. This represented a first approximation and, although not completely accurate, allowed for a reasonable estimate of ozone utilized by the sample. Another problem which developed in the ozone experiments was a foaming problem as the gas was dispersed through the sludge sample. The foam would be carried out of the reactor containing the sludge sample. A second vessel to capture this foam was incorporated into the experimental setup and the foam was used with the sludge remaining in the reactor in the dewaterability tests for specific resistance and filter yield.

The results of the ozone testing are presented in Tables 19 through 22. These tests represent investigations of ozone as the sole conditioning agent and as an adjunct to lime and ferric chloride. The results given in Table 19 represent the effects of ozone alone and in conjunction with lime. The ozone was applied in dosages ranging from zero to 3000 mg/ℓ. As the concentration of ozone increased, the specific resistance decreased and the filter yield increased slightly. The unconditioned sample specific resistance of 3.79×10^9 sec^2/g and filter yield of 0.49 lb/ft^2hr was changed to 1.54×10^9 sec^2/g and 1.10 lb/ft^2hr with a 50 mg/ℓ dosage of ozone alone. Increasing the ozone dosage to 3000 mg/ℓ decreased the specific resistance to 0.64×10^9 sec^2/g and increased the filter yield to 1.32 lb/ft^2hr. The addition of lime to a 1000 mg/ℓ dosage of ozone increased the dewatering characteristics of the conditioned sludge, with higher dosages of lime being more effective.

The sequence of lime-ozone addition was investigated on one set of dosages and when lime was added after ozone contacting, the specific resistance decreased by approximately a factor of two to 0.28×10^9 sec^2/g and the filter yield doubled to 2.92 lb/ft^2 hr when compared to lime added prior to ozone contacting. Ozone-lime was more effective than ozone or lime alone, but the ozone alone was only slightly better than lime alone with respect to specific resistance or filter yield. When compared to the 100 percent average dosage of ferric chloride and lime, however, only the lime after ozone conditioning was significant with respect to specific resistance. The specific resistance using the normal average conditioning technique was 0.22×10^9 sec^2/g and the filter yield was 5.29 lb/ft^2 hr. These latter results were superior to any of the other conditioning methods in this set of experiments with ozone.

The results in Table 20 represent the effects of ozone in conjunction with 100 percent dosages of ferric chloride and lime. Except for one case of 500 mg/ℓ of ozone, ferric chloride and lime were added after chemical addition.

With the lowest dosage of ozone, i.e., 50 mg/ℓ, and normal average ferric chloride and lime, the specific resistance was reduced from 38.0×10^9 sec^2/g for the unconditioned sludge to 0.25×10^9 sec^2/g and the filter yield increased to 6.48 lb/ft^2hr from 0.46 lb/ft^2hr. As ozone dosages increased, specific resistance values increased in a regular fashion. Filter yields were lower with the increasing ozone dosages when compared to the 50 mg/ℓ conditioning dosage of ozone but not in a regular fashion with increasing ozone for ozone contact before ferric chloride-lime addition. When these latter conditioners were added before the 500 mg/ℓ ozone conditioning test comparison, specific resistance values were essentially the same but the filter yield was the largest value observed in this set at 6.87 lb/ft^2hr. The sequence of better conditioning was reversed in comparison to the earlier results previously discussed in reference to Table 19.

The final comparison of results from Table 20 is the normal average dosage of ferric chloride and lime. The specific resistance after this conditioning was 0.38×10^9 sec^2/g which was only exceeded by the unconditioned sample and the highest ozone dosage of this set. The filter yield was 6.21 lb/ft^2sec which is somewhat less than all but the 500 mg/ℓ ozone conditioning before chemical addition. The general trend of better yield with decreasing specific resistance is observed in these experiments.

Ozone dosages in the lower range of 25 mg/ℓ to 500 mg/ℓ were examined in the next set of experiments. The samples were conditioned first by ozone contacting and then with the 100 percent average ferric chloride and lime. The results of this set of experiments are given in Table 21. The lower dosages of ozone, specifically 25 mg/ℓ and 100 mg/ℓ resulted in filter yields of 6.29 lb/ft^2hr and 7.44 lb/ft^2hr, respectively, and specific resistances of 0.30 x 10^9 sec^2/g and 0.33 x 10^9 sec^2/g, respectively. The higher dosages of ozone resulted in decreased dewaterability with increasing dosage. Comparison to no ozone treatment and 100 percent ferric chloride-lime showed the normal operation gave values of 0.26 x 10^9 sec^2/g and 7.44 lb/ft^2hr for dewaterability parameters. This latter value of specific resistance was the best, as was the filter yield value. The solids levels in this set of experiments was higher than the earlier experiments represented in Table 20 in which ozone proved effective in increasing dewaterability, suggesting a relationship between solids concentration and strong oxidant conditioning effectiveness.

Table 22 presents additional ozone conditioning experiments using various combinations of ozone, ferric chloride, and lime. Ozone concentrations varied from zero to 1000 mg/ℓ and were used in conjunction with 100 percent ferric chloride plus 25 percent lime, 100 percent ferric chloride plus 50 percent lime, 25 percent ferric chloride plus 100 percent lime, and 75 percent ferric chloride plus 100 percent lime. For the experiments in which the ferric chloride was at the 100 percent average dosage, a general decreasing trend in specific resistance was observed with increasing dosages of ozone and lime. In terms of filter yield, however, little improvement was observed by the use of ozone for those two groups of tests. The samples without ozone were the best for the 25 percent level of lime and essentially equal for the 50 percent level of lime in terms of filter yield. The specific resistance decreased from 4.33 x 10^8 sec^2/g for the 100 percent ferric chloride, 25 percent lime, and no ozone to 2.84 x 10^8 sec^2/g for 100 percent ferric chloride, 50 percent lime, and 1000 mg/ℓ ozone. The filter yields however were 1.94 lb/ft^2hr for the 100 percent ferric chloride, 25 percent lime and no ozone with a minimum of 1.61 lb/ft^2hr occurring when 50 mg/ℓ of ozone was added at that level of lime and ferric chloride. Most filter yield values were around 1.90 lb/ft^2hr in these two sets of conditioning experiments.

When lime was added at the 100 percent dosage and ferric chloride was used at the 25 percent level the best filter yield occurred with no ozone contacting. That yield was 3.16 lb/ft^2hr, with a corresponding specific resistance of 1.73 x 10^8 sec^2/g. As ozone conditioning was applied, the specific resistance initially decreased to 1.54 x 10^8 sec^2/g for 50 mg/ℓ ozone with a filter yield of 2.96 lb/ft^2hr. Increased ozone dosages to 500 mg/ℓ and 1000 mg/ℓ caused the specific resistance to increase and the filter yield to decrease beyond the lower dosage results. By increasing the ferric chloride to 75 percent of the normal average dosage and using lime at 100 percent, the 50 mg/ℓ dosage of ozone resulted in the lowest specific resistance, 1.28 x 10^8 sec^2/g, and the best filter yield at 3.36 lb/ft^2hr. Increasing ozone dosages caused specific resistance values to increase and filter yield values to decrease.

From an overall viewpoint of conditioning, increased dosages of ferric chloride and lime resulted in increased dewaterability. The application of a low dose of ozone (50 mg/ℓ) resulted in increased dewaterability as well when viewed from both specific resistance measurements and filter yield values.

Preliminary Economic Analysis

At a bulk rate of approximately $25 per 100 weight for 50 percent hydrogen peroxide, a 500 mg/ℓ dosage would cost approximately $2.10/1000 gallons for sludge conditioning. Increasing the lime dosage by 20 percent based on this experimental work at a cost of $52 per ton of substance which is 70 percent calcium oxide would cost approximately 20¢/1000 gallons for sludge conditioning. Total ozone costs are not calculated because of economies of scale dependent on the size of the ozone generator required, but capital expenditures would be significant. Efficiency in ozone contacting would need to be assured, e.g., by use of special contacting techniques (6) to minimize overall costs of ozone treatment. With air feed and power requirements of 8 kilowatt hours per pound (3), a 50 mg/ℓ dosage of ozone would require 4170 kwh per million gallons of sludge at 80 percent transfer efficiency or an operating cost of 16¢/1000 gallons based on $0.0376/kwh. Operating costs are more favorable for ozone than hydrogen peroxide and about the same order of magnitude for 20 percent excess lime.

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APPENDIX A

Experimental Results

Table 1. Preliminary Hydrogen Peroxide Conditioning Results: Set 1.

Peroxide Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g)x10^{10}$
0 (Control)	36.3	2.1
0.2	36.3	1.9
1.0	36.3	1.7
4.0	36.3	1.8
12	36.3	1.6
20	36.3	1.7

Table 2. Preliminary Hydrogen Peroxide Conditioning Results: Set 2.

Peroxide Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g)x10^{10}$
0 (Control)	16.9	7.6
10	16.9	8.0
50	16.9	6.5
400	16.9	6.3
600	16.9	7.8
1000	16.9	7.2

Table 3. Preliminary Hydrogen Peroxide Conditioning Results: Set 3

Peroxide Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g)x10^{10}$
0 (Control)	38.0	2.0
10	38.0	2.0
50	38.0	1.6
100	38.0	1.7
400	38.0	1.7
600	38.0	2.1
1000	38.0	1.8

Table 4. Preliminary Hydrogen Peroxide Conditioning Results: Set 4

Chemical Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g)x10^{10}$
0 (Control)	57.4	3.7
10 H_2O_2	57.4	3.7
100 H_2O_2	57.4	2.8
600 H_2O_2	57.4	2.2
1000 H_2O_2	57.4	2.8
100%($FeCl_3$+$Ca(OH)_2$-(AWTP)	41.0	0.1

Table 5. Preliminary Hydrogen Peroxide Conditioning Results: Set 5

Chemical Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g) \times 10^{10}$
0 (Control)	44.8	1.3
50 H_2O_2	44.8	1.3
400 H_2O_2	44.8	1.4
1000 H_2O_2	44.8	1.4
6000 H_2O_2	44.8	1.5
100%($FeCl_3$+$Ca(OH)_2$)	42.5	0.9

Table 6. Hydrogen Peroxide Conditioning Results: Set 1

Chemical Dosage (mg/ℓ)	Solids Concentration (g/ℓ)	Specific Resistance $(sec^2/g) \times 10^{9}$
0 (Control)	11.4	1.3
10 H_2O_2	40.7	1.4
400 H_2O_2	40.7	1.0
1000 H_2O_2	40.7	1.0
100%($FeCl_3$+$Ca(OH)_2$)	40.7	0.2

Table 7. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 1. Büchner Funnel Tests

Chemical Dosage	C_s (g/ℓ)	ξ $(sec^2/g)x10^9$	COD (mg/ℓ)	pH
0 (Control)	33.9	6.4	165	7.2
200 mg/ℓ H_2O_2	32.3	6.3	204	7.4
200 mg/ℓ H_2O_2+20%($FeCl_3$+$Ca(OH)_2$)	32.7	3.6	173	8.5
200 mg/ℓ H_2O_2+40%($FeCl_3$+$Ca(OH)_2$)	32.5	1.4	94	9.9
200 mg/ℓ H_2O_2+60%($FeCl_3$+$Ca(OH)_2$)	33.1	0.74	125	10.9
200 mg/ℓ H_2O_2+80%($FeCl_3$+$Ca(OH)_2$)	33.2	0.54	179	11.8
200 mg/ℓ H_2O_2+100%($FeCl_3$+$Ca(OH)_2$)	38.7	0.45	218	12.2
0 mg/ℓ H_2O_2+100%($FeCl_3$+$Ca(OH)_2$)	35.5	0.52	204	12.3

Table 8. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 2. Büchner Funnel Tests

Chemical Dosage	C_s (g/ℓ)	ξ $(sec^2/g)x10^{10}$	COD (mg/ℓ)	pH
0 (Control)	57.4	1.7	176	8.2
200 mg/ℓ H_2O_2	57.4	1.5	299	8.2
200 mg/ℓ H_2O_2+20%$FeCl_3$+0%$Ca(OH)_2$	57.4	1.0	260	7.8
200 mg/ℓ H_2O_2+40%$FeCl_3$+0%$Ca(OH)_2$	57.4	0.7	253	7.7
200 mg/ℓ H_2O_2+60%$FeCl_3$+0%$Ca(OH)_2$	57.4	0.4	322	6.9
200 mg/ℓ H_2O_2+80%$FeCl_3$+0%$Ca(OH)_2$	57.4	0.2	260	6.3
200 mg/ℓ H_2O_2+100%$FeCl_3$+0%$Ca(OH)_2$	57.4	0.3	290	6.8
0 mg/ℓ H_2O_2+100%$FeCl_3$+0%$Ca(OH)_2$	57.4	0.3	222	6.5
0 mg/ℓ H_2O_2+100%($FeCl_3$+$Ca(OH)_2$)	57.4	0.09	222	10.6

Table 9. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 3. Büchner Funnel Tests

Chemical Dosage	C_s (g/ℓ)	ξ $(sec^2/g)x10^9$	COD (mg/ℓ)	pH
0 (Control)	40.7	10.2	15.3	7.9
200 mg/ℓ H_2O_2+50%($FeCl_3$+$Ca(OH)_2$)	41.6	1.5	38	9.0
500 mg/ℓ H_2O_2+50%($FeCl_3$+$Ca(OH)_2$)	38.8	1.8	92	9.0
1000 mg/ℓ H_2O_2+50%($FeCl_3$+$Ca(OH)_2$)	37.2	1.7	206	9.0
3000 mg/ℓ H_2O_2+50%($FeCl_3$+$Ca(OH)_2$)	41.6	2.3	343	8.7
50%($FeCl_3$+$Ca(OH)_2$)	34.4	1.4	-	9.1
0 mg/ℓ H_2O_2+100%($FeCl_3$+$Ca(OH)_2$)	37.3	1.2	473	11.5

Table 10. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 4. Buchner Funnel Tests and Filter Leaf Tests

Chemical Dosage	C_s (g/ℓ)	ξ $(sec^2/g)x10^9$	COD (mg/ℓ)	pH	Filter Yield $(lb/ft^2 hr)$
0 (Control)	41.2	15.6	182	6.6	--
200 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	43.2	1.4	174	9.5	2.03
500 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	45.6	1.4	206	9.6	1.88
1000 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	44.2	1.3	316	9.7	1.97
2000 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	46.1	1.2	418	9.2	1.73
3000 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	47.0	1.7	498	9.2	1.91
0 mg/ℓ H_2O_2+75%($FeCl_3$+$Ca(OH)_2$)	46.7	1.3	158	9.8	2.22
0 mg/ℓ H_2O_2+100%($FeCl_3$+$Ca(OH)_2$)	47.7	0.95	273	10.5	3.04

Table 11. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 5. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage			C_s	ξ	COD_{BF}	pH_{BF}	Filter Yield	COD_{FL}	pH_{FL}
H_2O_2(mg/ℓ)	$FeCl_3$(%)	$Ca(OH)_2$(%)	g/ℓ	$(sec^2/g)x10^9$	mg/ℓ		$(lb/ft^2 hr)$	(mg/ℓ)	
0	0	0	37.1	15.5	270	8.1	0.57	23,200	7.7
100	0	0	36.5	13.7	270	8.1	0.57	22,500	7.7
400	0	0	38.1	18.4	339	8.2	0.48	27,000	7.8
0	75	20	42.0	4.0	203	7.4	1.11	16,800	7.5
100	75	20	38.1	3.4	250	7.4	1.21	11,460	7.5
200	75	20	35.4	3.9	281	7.4	1.09	-	7.6
400	75	20	34.8	4.2	274	7.3	1.12	15,810	7.3
600	75	20	40.5	6.4	336	7.5	1.35	10,200	7.2
1000	75	20	35.2	11.2	406	7.6	1.12	17,790	7.2
2000	75	20	38.8	2.5	625	7.6	1.05	11,070	7.4
0	75	40	42.8	2.8	211	7.8	1.03	9,880	7.6
100	75	40	37.3	3.6	585	7.7	1.06	12,250	7.4
200	75	40	40.3	3.2	198	7.9	1.11	10,280	7.6
400	75	40	45.1	2.2	253	7.9	1.23	12,650	7.7
600	75	40	47.3	2.3	277	7.9	-	7,120	7.6
1000	75	40	39.2	3.1	364	7.9	2.11	10,670	7.6
2000	75	40	41.7	2.7	348	8.0	1.14	11,950	7.7
0	75	60	46.3	1.5	194	9.2	1.72	6,770	9.2
100	75	60	40.2	1.8	242	9.0	1.52	8,370	9.1
200	75	60	43.2	1.8	208	8.9	1.44	8,360	8.9
400	75	60	54.0	1.3	235	8.9	1.35	9,560	9.0
600	75	60	44.5	1.9	291	9.1	1.46	9,560	9.0
1000	75	60	49.2	1.7	346	8.9	1.28	9,160	8.9
2000	75	60	45.2	1.5	353	8.9	1.54	7,560	8.8
0	100	100	39.0	1.2	637	10.0	2.55	8,650	11.1

Table 12. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 6. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ (sec^2/g)x10^9	Filter Yield (lb/ft^{2}hr)
0	0	0	54	14.0	-
0	75	20	57	5.8	-
200	75	20	60	3.5	0.7
400	75	20	62	2.3	0.7
600	75	20	59	1.7	0.7
1000	75	20	54	1.7	0.6
2000	75	20	63	1.3	0.7
3000	75	20	55	1.2	0.9
6000	75	20	56	0.7	1.0
0	100	100	44	1.0	1.8

Table 13. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 7. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage			C_s	ξ	Filter Yield	COD_{BF}	COD_{FL}
H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	(g/ℓ)	$(sec^2/g) \times 10^8$	$(lb/ft^2 hr)$	(mg/ℓ)	(mg/ℓ)
0	0	0	49	49.5	0.16	360	14,000
0	75	20	49	2.1	0.80	280	3,700
200	75	20	48	7.1	0.37	380	10,000
400	75	20	48	6.6	0.34	-	-
600	75	20	48	6.5	0.37	520	9,600
1000	75	20	49	6.4	0.36	580	11,000
2000	75	20	47	5.8	0.40	690	9,100
3000	75	20	50	5.8	0.40	700	8,600
6000	75	20	50	3.9	0.71	820	4,300
0	100	100	53	2.0	1.02	320	2,400

Table 14. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 8. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ $(sec^2/g) \times 10^8$	Filter Yield $(lb/ft^2 hr)$
500	100	10	40	2.67	2.12
1000	100	10	41	2.69	1.47
2000	100	10	40	2.62	1.25
3000	100	10	40	2.27	1.10
6000	100	10	40	2.69	0.99
0	100	10	42	3.89	1.08
500	100	20	41	3.70	0.80
1000	100	20	40	4.01	0.77
2000	100	20	40	4.23	0.59
3000	100	20	41	3.70	0.58
6000	100	20	39	4.30	0.57
0	100	20	40	5.49	0.66
500	100	10	38	-	0.86
500	100	100	44	1.16	0.66
1000	100	100	44	1.55	1.07
2000	100	100	43	2.18	0.74
3000	100	100	43	2.28	0.72
6000	100	100	44	2.03	1.10
500	100	10	38	-	0.58

Table 15. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 9. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ (sec^2/g)x10^8	Filter Yield (lb/ft^2 hr)	COD_{FL} (mg/ℓ)
0	0	0	29.0	48.9	0.25	15,500
0	100	10	30.0	2.47	1.63	3,400
250	100	10	30.0	2.12	1.64	3,600
500	100	10	30.0	1.59	1.91	3,200
750	100	10	30.0	1.73	1.69	-
1000	100	10	29.0	1.48	1.64	3,600
0	100	20	32.0	1.87	1.36	3,500
500	100	20	31.0	1.82	1.53	3,600
0	100	100	34.0	1.70	1.61	4,000
500	100	100	34.0	1.51	2.29	2,800

Table 16. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 10. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage			C_s	ξ	Filter Yield
H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	(g/ℓ)	$(sec^2/g)x10^8$	(lb/ft^2hr)
500	100	10	42	2.43	1.68
500	100	20	43	4.08	1.34
500	100	40	44	2.67	1.81
500	100	60	46	1.89	2.09
500	100	80	47	1.17	2.41
500	100	100	47	0.93	2.99
500	100	120	47	0.72	4.33
500	120	100	47	0.74	3.31
0	0	0	40	20.81	-
0	100	10	43	1.58	2.66
0	100	20	44	2.40	2.29
0	100	40	44	2.31	2.30
0	100	60	46	0.83	3.22
0	100	80	46	0.76	4.49
0	100	100	45	0.46	5.93
	100	120	46	0.30	6.90
	120	100	46	0.83	5.24

Table 17. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set 11. Büchner Funnel Tests and Filter Yield Tests

Chemical Dosage H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ (sec^2/g)x10^8	Filter Yield (lb/ft^2 hr)
0	100	100	35	1.50	2.64
100	100	100	36	1.15	2.67
500	100	100	34	1.03	3.05
800	100	100	35	1.11	2.80
0	0	0	30	42.5	-
0	100	100	28	0.75	2.80
100	100	100	28	0.80	3.16
500	100	100	29	1.03	2.50
800	100	100	27	1.14	2.13
0	0	0	32	45.2	-

Table 18. Hydrogen Peroxide-Ferric Chloride-Lime Combinations for Sludge Conditioning: Set . Büchner Funnel Tests and Filter Yield Tests

Chemical Dosage H_2O_2 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ (sec^2/g)x10^8	Filter Yield (lb/ft^2 hr)
500	100	100	46.7	1.00	3.05
0	100	100	44.4	0.83	3.60
500	100	100	35.2	0.53	3.49
0	100	100	35.1	0.63	3.26
500	100	100	24.8	0.36	2.69
0	100	100	24.2	0.40	2.43

Table 19. Ozone Conditioning Test Results Set 1. Büchner Funnel Tests and Filter Leaf Tests

O_3 (mg/ℓ)	Chemical Dosage $FeCl_3$ (%)	$Ca(OH)_2$ (%)	ξ (sec^2/g)x10^9	Filter Yield ($lb/ft^2 hr$)
50	0	0	1.54	1.10
500	0	0	1.52	1.06
3000	0	0	0.64	1.32
1000	0	25	1.01	1.06
1000	0	75 (1)	0.52	1.41
1000	0	75 (2)	0.28	2.92
0	0	75	1.89	1.06
0	100	100	0.22	5.29
0	0	0	3.79	0.49

(1) Lime added before O_3

(2) Lime added after O_3

Table 20. Ozone Conditioning Test Results Set 2. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage O_3 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ $(sec^2/g) \times 10^9$	Filter Yield $(lb/ft^2 hr)$
0	0	0	28.7	38.0	0.46
50	100	100	35.0	0.25	6.48
500	100	100(1)	33.0	0.30	5.42
500	100	100(2)	36.0	0.31	6.87
1000	100	100	30.5	0.40	6.34
0	100	100	33.4	0.38	6.21

(1) Ozone contact before chemical addition

(2) Ozone contact after chemical addition

Table 21. Ozone Conditioning Test Results Set 3. Büchner Funnel Tests and Filter Leaf Tests

Chemical Dosage O_3 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	C_s (g/ℓ)	ξ $(sec^2/g) \times 10^9$	Filter Yield $(lb/ft^2 hr)$
0	0	0	45.6	24.2	0.86
25	100	100	48.4	0.30	6.29
100	100	100	53.0	0.33	7.40
250	100	100	49.9	0.36	4.85
500	100	100	46.6	0.49	4.93
0	100	100	50.9	0.26	7.44

Table 22. Ozone Conditioning Test Results Set 4. Büchner Funnel Tests and Filter Yield Tests

	Chemical Dosage		C_s	ξ	Filter Yield
O_3 (mg/ℓ)	$FeCl_3$ (%)	$Ca(OH)_2$ (%)	(g/ℓ)	$(sec^2/g) \times 10^8$	$(lb/ft^2 hr)$
0	0	0	43	23.1	-
0	100	25	44	4.33	1.94
50	100	25	42	4.79	1.61
500	100	25	42	3.43	1.81
1000	100	25	39	3.54	1.70
0	100	50	46	3.54	1.87
50	100	50	44	3.14	1.90
500	100	50	39	3.79	1.67
1000	100	50	41	2.84	1.91
0	25	100	46	1.73	3.16
50	25	100	42	1.54	2.96
500	25	100	41	2.16	2.42
1000	25	100	40	2.12	2.40
0	75	100	46	1.57	2.92
50	75	100	45	1.28	3.36
500	75	100	43	1.45	2.81
1000	75	100	42	1.64	2.75

APPENDIX B

Summary of Early Work

Earlier work (5) results are generalized below:

1. Greatest densification occurs with secondary clarifier return sludge and aerobically digested sludge. Anaerobically digested sludge did not respond.
2. Treatment ranges that proved effective were 1-3% hydrogen peroxide (100% basis), 4-7% trivalent iron, pH maintained at 6.0. (Concentrations are based on dry weight of solids.)
3. Advantages claimed:
   a. Filtration efficiency increased 50%.
   b. Filter cake solids increased 22%.
   c. Filtration frequency halved. Working hours decreased 36%.
   d. Chemical costs dropped 3%.
   e. Filter cake weight decreased 45%.
   f. Sludge freight costs decreased 45%.
   g. Operation became odor free.
   h. A clear filtrate of pH 5-7. Prior yellow filtrate at pH 11 required downward pH adjustment with H_2SO_4.
   i. Simplified chemical handling.