A BENCH-SCALE EVALUATION OF THE REUSE OF WATER AT HIGHWAY REST AREAS

by

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Many individuals, state agencies, and personnel from an engineering design firm have been involved with this project over the past three years. Dr. Clinton E. Parker, the originator of this wastewater reuse concept, was the primary advisor and director of this research which was a funded project of the Virginia Highway and Transportation Research Council. Michael Ritz supplied many ideas and recommendations which were utilized in this research and Austin Brockenbrough and Associates, the consulting design engineers for the field project, supplied pertinent information on several occasions.

SUMMARY

A pilot laboratory treatment system was successfully employed to investigate the reuse of wastewater for flushing toilets at highway rest areas. This extended aeration unit used a synthetic waste to determine if the biological system could operate efficiently at high dissolved solids concentrations produced by effluent recycle rates of up to 95 percent. Effluent quality and sludge accumulation rates were monitored and biological solids control methods were studied. Results from pilot plant performance with and without recycle show that treatment efficiency, in terms of a biologically degradable effluent, will not be adversely affected by high recycle ratios.

The use of dye to distinguish recycle water from potable water was explored. Included in this research was the selection, quantification, and removal of this artificial color from recycled effluent. Sodium fluorescein was found to be susceptible to biological attack and sunlight, and to be readily removable by carbon adsorption.

The small volumes of effluent water produced by a recycle system have the potential to be impounded and either partly or completely disposed of by solar evaporation, depending on the rest area location. Climatological data were used to predict net evaporation rates for a recycle facility installed at Fairfield, Virginia.

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INTRODUCTION

This study was a continuation of research, begun in 1971, dealing with the possibility of reusing water at highway rest areas. It had been found that this type of water reuse would be of significant benefit by greatly reducing both the effluent discharged and the volume of water needed to maintain the rest area. The later benefit is important because several rest areas in Virginia presently experience water shortage problems during peak highway travel periods such as the Fourth of July and Memorial Day.

Research by Ritz(1) had led to the conclusion that at 90 percent effluent recycle, water from rest areas could be treated and reused for flushing toilets where extended aeration treatment is employed. The current research was directed toward higher recycle rates with the possible attainment of zero discharge. A part of this investigation was to determine if the biological system would yield an acceptable water at 95 percent effluent recycle without decreased efficiency or failure. In addition, the application of certain advanced treatment processes to further reduce in volume or better treat the discharged portion of the recycled effluent was studied.

The Fairfield rest area on Interstate 81 just north of Lexington, Virginia, had been selected as an initial field test site. The existing facility is a standard biological package plant, extended aeration arrangement. The treatment scheme consists of a comminutor box, an aeration basin (aerated 15 minutes every hour), a secondary clarifier with overflow side weirs, a sludge storage tank, a 15-day holding pond, a V-notched weir for flow measurement, and a chlorine contact unit (Figure 1).

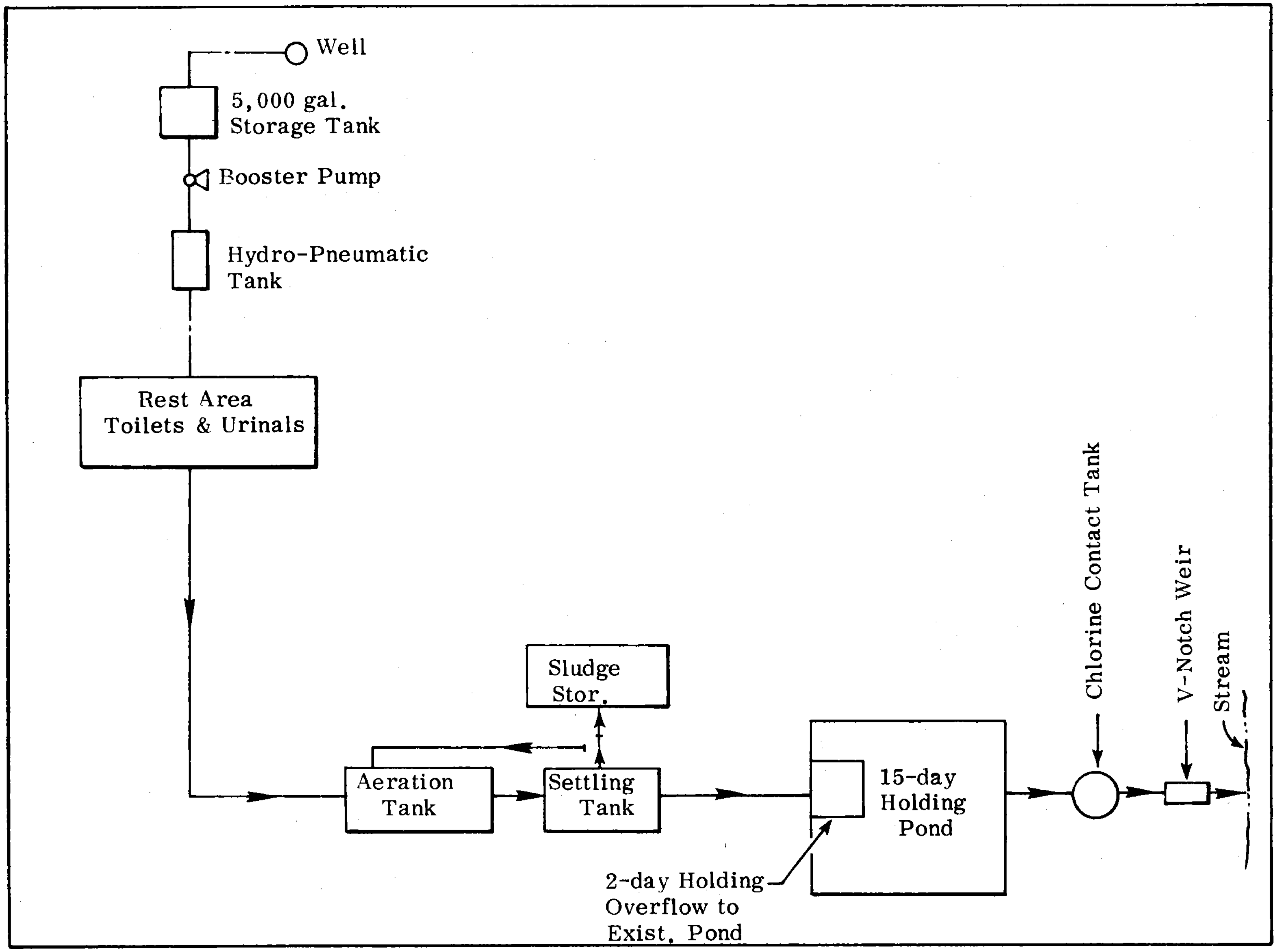


Figure 1. Schematic flow diagram of the existing wastewater treatment system at the Fairfield rest area.

The effluent from this rest area averages approximately 10,000 gallons per day (gpd), and is discharged into White Sides Run, a tributary of the South River that flows into the Maury River. The rest area effluent must meet water quality standards outlined by the Virginia State Water Control Board. The receiving stream falls under section IV B of the upper James River Basin, and is classified as water generally satisfactory for use as a public or municipal water supply and primary contact recreation.(2)

The proposed recycle facilities to be constructed include sand filtration, water storage and equalization tanks, and pump controlled dye addition. The plant has been designed with cut-off valves and multiple connections to provide the flexibility necessary for a demonstration facility (Figure 2). If these modifications can be successfully used to provide acceptable wastewater treatment over a given test period, a statewide expansion of the concept to include other rest areas using similar extended aeration treatment would be evaluated. The cost of installing the demonstration facility cannot be compared to the cost of future application of this concept because of the addition of numerous controls to provide flexibility. It is anticipated that statewide use of this concept would prove economically feasible when compared with other alternatives to meet both water and wastewater needs at the rest areas.

A delay in construction has taken place primarily as a result of coordination among the state agencies involved. Such agencies as the Virginia Department of Highways and Transportation, State Department of Health, State Water Control Board, the University of Virginia, and Austin Brokenbrough Consulting Engineers have carefully reviewed the plans and have considered all aspects of the project to ensure the success of the modifications. As of January 1, 1975, the field demonstration project plans and specifications had received final approval from all agencies, and the project was waiting for construction bids.

The work reported here completes all preliminary laboratory investigations of the wastewater reuse concept for highway rest areas. After completion of the proposed recycle modifications at Fairfield, further research will be directed toward assisting plant start-up, and monitoring performance and effluent quality.

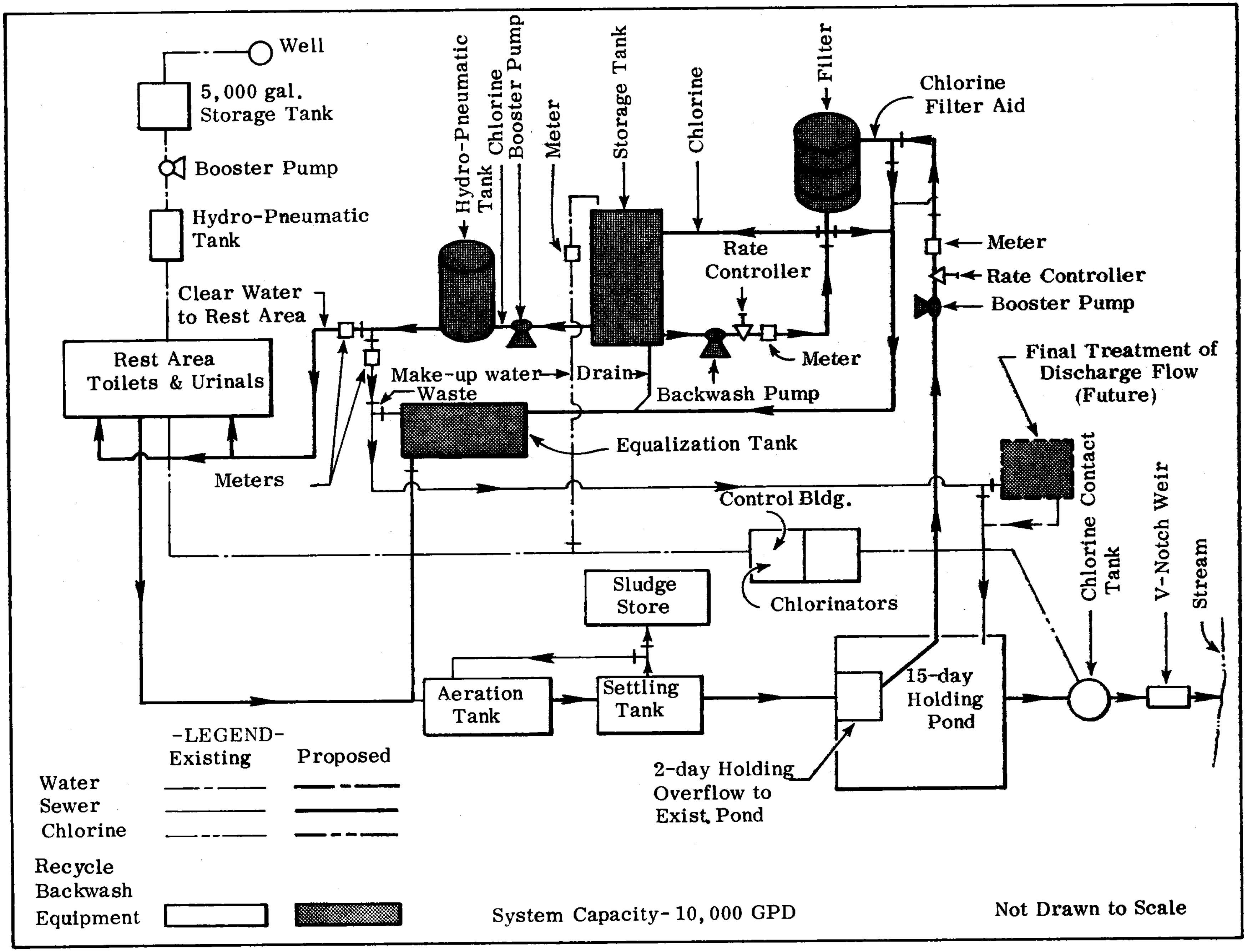


Figure 2. Schematic flow diagram for the proposed field installation.

PURPOSE AND OBJECTIVES

The intent of this study was to conduct further research toward the development of a successful wastewater recycle-reuse system for highway rest areas. The proposed treatment system should have the twofold benefit of alleviating water shortage problems and greatly reducing effluent volumes discharged to receiving streams.(3) The investigation was to determine some of the limitations and methods of control for the recycle treatment system. In this regard, two basic questions were to be answered. First, what effect would a recycle ratio greater than 90 percent have on the efficiency of biological treatment? Second, what would be the best or most practical method of treatment and disposal of that fraction of waste not to be recycled?

It was initially hoped that experimental evidence could be gathered both through the continued use of the laboratory pilot plant and through a coordinated field investigation of an installed recycle treatment system at the Fairfield rest area.(4) However, continued delays in approval from state agencies postponed construction. Efforts were therefore directed toward the accomplishment of the following objectives by means of laboratory research, literature review, and manufacturer's equipment review.

1. Using a pilot plant, determine if steady state can be achieved and maintained at 95 percent effluent recycle without sludge wastage.

2. Evaluate the use of a dye to distinguish recycled water in the toilets from potable water used elsewhere at the rest area. Once a suitable dye has been selected, evaluate its effect on the final released effluent (if any), and its effect on the biological treatment system.

3. Through laboratory analyses, evaluate the use of activated carbon for color removal and general improvement of the final effluent to be discharged.

4. Investigate suitable means of biological solids control and waste sludge handling.

5. By means of a current manufacturer's equipment review and literature study, suggest a course to be taken for the ultimate disposal of the effluent volume not recycled.

PREVIOUS RESEARCH AND APPLIED TECHNOLOGY

Summary of Previous Water Reuse Studies at Virginia Highway Rest Areas

The concept of recycling water at highway rest areas was originated by Dr. Clinton E. Parker, Associate Professor of Civil Engineering at the University of Virginia. His idea was an outgrowth of the fact that the two major problems experienced at rest areas in Virginia are insufficient potable water supplies to meet peak period water demands and the necessity for treating effluents to meet state standards.(5)

The first phase of Parker's work on recycling water was to assess the feasibility of reclaiming wastewater and reusing it for flushing toilets.(6) Bott investigated water quality and quantity needs at rest areas, and concluded that 90 to 95 percent of the water at rest areas throughout the state of Virginia was used for flushing toilets.(7)

Based on conclusions from the preliminary study by Bott, Ritz(8) operated a pilot plant to study the recycle of treated wastewater using plant modifications that could be applied in the field. The pilot plant was operated at various effluent recycle rates to determine if recycle was possible without adverse effects on the biological treatment unit. Ritz found that the extended aeration treatment process could effectively operate at the elevated dissolved solids levels (6000 mg/l) produced by high recycle rates. He further found that the efficiency of the process was dependent on the system's ability to retain biological solids. A proper food-to-mass ratio was considered imperative to the operation of the biological unit, and hence provisions should be made in the field design to assure the return of biomass to the aeration vessel.(9)

The research reported here was an extension of all previous work and was stimulated by recommendations arising from the pilot plant study by Ritz. One such recommendation was the need to investigate color removal, which is necessitated when recycled effluent is purposely colored by dye addition to distinguish it from potable water at the rest area. Further research was needed to examine possible methods to completely eliminate discharges from the rest area. In addition, an insight into effective activated sludge control, wastage, and handling techniques for the recycle system was needed.

Conceptual Evaluation of Applying Advanced Treatment Technology

Tertiary or advanced treatment normally includes any operation or process used to remove refractory contaminants or inorganic nutrients not removed in primary or secondary treatment.(10) Some of these pollutants not taken out by conventional means can accumulate to high levels through recycle.(11) Upon discharge they may adversely affect stream biological life, accelerate eutrophication of lakes, and hinder domestic water reuse.(12) There are currently only a limited number of processes available which are capable of removing refractory organic compounds from wastewater. These include reverse osmosis, distillation, and carbon adsorption.(13)

In respect to a recycle treatment system at highway rest areas, advanced waste treatment will refer to any final treatment of the discharge flow as shown by Figure 2. The treatment may include some unit process for the removal of color, dissolved salts, or soluble organics remaining in the discharged portion of the recycled effluent. Coagulation and precipitation could be used as an advanced treatment method for removal of suspended solids. However, they have been ruled out as a possible alternative for treating wastewaters at highway rest areas because of operational and sludge production problems. Also included as advanced treatment would be final effluent evaporation of the 5 to 10 percent daily water wastage. If such treatment could be economically provided by currently available equipment, the complete elimination of discharges at rest area recycle facilities ultimately may be accomplished.

Color Removal

Any effluent discharged from a rest area recycle treatment facility will undoubtedly contain significant color. This color will be from two organic sources. First, pilot plant results have shown that recycling at high ratios with a synthetic wastewater inherently builds up apparent color caused by colloidal vegetable or organic extracts which remain in the system.(14) Secondly, the application of dye to the recycle line prior to its return to the toilets will result in an increase in color. Artificial coloring may be removed to some extent by the biological treatment system through incorporation in the activated sludge floc. However, this removal may not be sufficient to meet state regulations, which currently place an upper limit on discharged effluents of 75 total color units.(15) Future consideration should thus be given to the subsequent removal of residual color by some economical means.

"The use of activated carbon for the adsorption of color and organic materials from wastewater has been established as a practical, reliable, and economical unit process for water pollution control."(16) In order to make proper use of the activated carbon process for the treatment of recycled effluent, an appropriate carbon and mode of operation must first be selected. Laboratory pilot tests can be used to provide a means of determining the treatability of the waste by carbon and developing design criteria.(17)

Activated carbon is generally best suited for the adsorption of dissolved organics.(18) Basically, these can be broken down into two categories, biodegradable and refractory. Biodegradable dissolved organics are those which can be broken down by the biomass in a biological treatment system. These are most effectively measured by the standard BOD test. In contrast, refractory dissolved organics are not amenable to biological action, and will remain in solution and accumulate in the recycled effluent. Refractory dissolved organics show up as contributing to the total oxidizable organic matter in the COD test.(19) In effluent from a recycle system, this latter group of dissolved organics is by far the most prevalent, especially at high recycle ratios.

Removal of organic materials by activated carbon can be characterized as a three-step sequence.(20,21)

1. Diffusion of solute molecules to the carbon surface through the liquid film surrounding the carbon particle.

2. Intraparticle diffusion of the solute within the channels of the carbon particle.

3. Adsorption to the internal carbon surface.

"The adsorption process can be pictured as one in which molecules (such as color) leave solution and are held on the solid surface by chemical and physical bonding. Physical adsorption is the process that occurs most frequently in the removal of wastewater constituents by activated carbon."(22) Here, weak bonds caused by van der Waal forces form between the dissolved organic molecules and the carbon. Molecules adsorbed in this manner are easily removed or desorbed through a reversible process of changing the influent solution concentration.(23)

With the basic knowledge of adsorption phenomena and the recycled effluent waste characteristics, a particular carbon can be selected based on any one of its physical properties such as surface area, apparent density, bulk density, and effective size.(24) Since adsorption is a surface phenomenon, surface area is perhaps the most important criterion for determining the carbon's capability. Powdered activated carbon obviously provides the greatest available surface area, but has several drawbacks, among which are handling and dust problems and difficulty in retention due to its small size.(25) Adsorption of dissolved color and refractory organics on granular activated carbon would appear to be a more acceptable solution for once-through use and disposal at a rest area recycle facility.

It was assumed from the beginning that granular carbon to be applied at the rest area would be used only on a once-through basis with no consideration being given to regeneration, because the typically low flow rates and low carbon requirements do not justify expensive regeneration equipment. Fresh carbon would be used on a single run until a breakthrough concentration of color appeared in the effluent, at which time it would be discarded and replaced with new carbon.

Utilization of the granular activated carbon could be via some form of a columnized bed contact unit. In this dynamic system, recycled effluent would be continuously passed through the carbon bed. It has been found that granular carbon columns have the adsorptive capacity to handle shock loads with no apparent loss in efficiency.(26) Either a replaceable, cartidge type, gravity flow packed column or an upflow, expanded column could be used. For granular carbon column applications, surface film mass transfer diffusion is the rate limiting step.(27) The removal efficiency will then be affected not only by the equilibrium adsorption properties of the carbon, but also by the rate of adsorption.(28) The particular flow rate and bed depth required for optimum color removal depend on the rate at which dissolved organic impurities and color are adsorbed from the recycled effluent by the carbon.(29) In other words, preferential adsorption occurs in a contaminated colored water such as recycled effluent. Color may be adsorbed initially, but a portion of the carbon is spent in adsorbing refractory organics.

The Freudlich adsorption isotherm shown below is an empirical relationship commonly used for calculating approximate carbon dosages:(30,31,32)

$$\frac{X}{M} = KC_t^{1/n} \tag{1}$$

where

X = amount of impurity adsorbed

M = weight of carbon

X/M = amount of impurity adsorbed per unit weight of carbon

C_t = residual equilibrium concentration of impurity left in the solution

K, 1/n = constants to be determined experimentally

In logarithmic form:

$$\log X/M = \log K + 1/n \log C_t \tag{2}$$

where 1/n = slope of straight-line isotherm
K = intercept

This adsorption isotherm relates the amount of impurity such as color or COD in solution to that adsorbed by the carbon at a given temperature and contact time. The logarithmic isotherm normally yields a straight-line plot for dilute solutions such as a wastewater.(33) The practical usefulness of the Freudlich isotherm is recognized by its simplicity in predicting the exchange capacity of a particular carbon in grams of impurity per cubic centimeter of carbon.(34) This information cannot be used in column design but it does provide a basis for evaluating the effectiveness of the carbon.

Where carbon adsorption is a concern, the Freudlich isotherm can be evaluated from a graph plotting residual color in the recycled effluent against color adsorbed per gram of carbon. Figure 3 shows the isotherms for two types of carbon. A point on these isotherm lines represents the amount of color adsorbed per unit weight of carbon. This information is essentially the carbon adsorptive capacity at a particular contact time and water temperature. The isotherm for Carbon A is at a high level with only a slight slope indicating that adsorption is high over the range of concentrations studied. The isotherm for Carbon B, having a much steeper slope, suggests improved adsorption at higher concentrations.(35) Generally, the steeper the isotherm slope, the greater the efficiency of the carbon. Carbon B should be better suited than Carbon A to a countercurrent column operation since it has a higher capacity at the influent concentration. By the same token, Carbon A should be better suited for batch decolorization treatment since the capacity is relatively constant over a range of concentrations.(36)

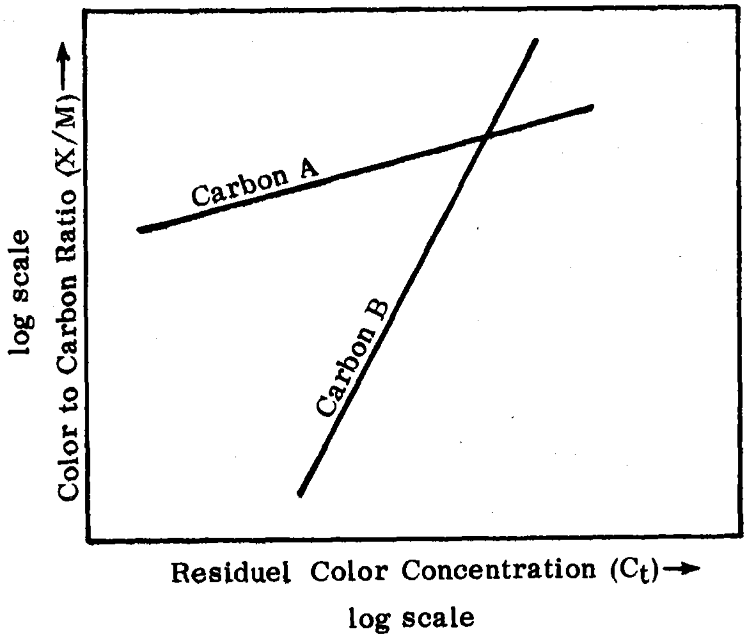


Figure 3. Typical Freudlich color adsorption isotherms for two different carbons.

When a color solution passes through a fixed bed of carbon, the concentration of color is reduced as the solution contacts successive portions of the bed.(37) However, there is no sharp demarcation between purified liquid and the feed.(38) Instead, there is an adsorption zone in which the concentration of adsorbable color varies from a maximum at the top of the zone to near zero at the bottom.(39) This color concentration gradient or adsorption exchange zone travels downward, expending the upper layers of carbon as it goes. As long as the adsorption zone remains entirely within the carbon column, the effluent will stay nearly void of color. When the adsorption zone reaches the effluent end, breakthrough occurs and the concentration of color in the effluent rapidly increases to approach the influent concentration.(40) At this point effluent quality has drastically decreased and the carbon is said to be saturated. The carbon has reached a maximum loading for the operating conditions.(41) The adsorption capacity of the carbon is usually established at the point of breakthrough rather than the point of exhaustion.(42) Selection of this breakthrough color concentration is arbitrary, but normally the desired residual color concentration will be the governing factor.

Determination of the height of the adsorption zone can be made from an analysis of a breakthrough color curve similar to that shown in Figure 4. This curve is obtained by passing a colored fluid through a packed bed of carbon. The concentration of color in the effluent stream from the bed is plotted against the volume of fluid passed through. The slope of the breakthrough portion of the curve is dependent on both the rate of color adsorption and the fluid flow rate.(43) Contact or residence time is the major design parameter for the column.(44) The steeper the slope the greater the rate of adsorption, or the lower the flow rate.(45) Conversely, the more gradual the slope of the breakthrough curve, the lower the rate of adsorption or the higher the flow rate. Generally, greater rates of adsorption are desired for maximum efficiency of carbon. The carbon with the steepest breakthrough curve will, therefore, have the longest service life even though the capacity of two carbons at equilibrium may be the same. Thus, for selecting carbons and designing adsorption systems, the rate of adsorption as reflected in the breakthrough curves is an important consideration.(46)

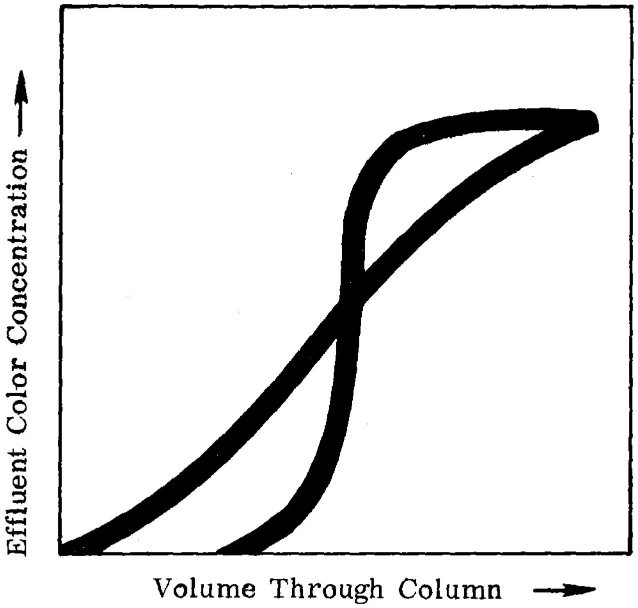


Figure 4. Two idealized breakthrough curves.

The specific design of a preliminary laboratory carbon column for the removal of dissolved color is based on the idea that the height of the adsorption exchange zone remains constant for a given set of conditions. This zone will descend through the bed a distance equal to its height during the time it takes to collect the effluent volume between the breakthrough and exhaustion points. Empirically, the amount of color removed from this volume (V_E) as it passes through the adsorption zone equals the amount of color retained in the zone.(47)

$$V_E C_o = ZS\ (Q + E\ C_o) \tag{3}$$

where

V_E = effluent volume in cm^3 collected between the point of breakthrough and the point of exhaustion

C_o = initial concentration of color to be removed in mg/l

Z = height of adsorption zone

S = cross-sectional area of the bed in cm^2

Q = adsorptive capacity of the carbon in mg of color per cm^3 of carbon. This is determined from previous isotherm data by multiplying the desired X/M (gm color/gfn carbon) loading by the density of the carbon (gm/cm^3)

E = bed porosity = ratio of the volume of voids to the total volume

The height of the exchange zone is then:

$$Z = \frac{V_E C_o}{S\ (\ Q + E\ C_o)} \tag{4}$$

This height can be evaluated in the laboratory for a specific fluid flow rate and a given set of column conditions. At breakthrough, the carbon column has reached its total adsorptive capacity and can be divided into two distinct sectors. First, the adsorption zone at the bottom contains carbon which is only partly utilized. This utilization is determined as $\bar{X}$, the average of the percentages of influent color at breakthrough and the exhaustion color concentrations. The second sector is the remainder of the bed above, containing carbon that has been completely utilized. Therefore the total adsorptive capacity of the carbon column can be written as:(48)

$$C = \bar{X}SZQ + S(L-Z)Q \tag{5}$$

where

C = adsorption capacity required = color content of adsorption zone plus color content of the remainder of the bed in mg or grams

$\bar{X}$ = the average of breakthrough and exhaustion color concentrations expressed as percentage of influent color

L = depth of submerged carbon column (cm) bed

On the basis of the superficial approach velocity, the cross-sectional area of the carbon column can be estimated. Using this estimation in the rearranged form of the above expression, the total column height required is then:(49)

$$L = \bar{X}Z + C/SQ \tag{6}$$

Under certain conditions, the capacity of granular carbon columns is sometimes increased by biological activity on the carbon, because carbon adsorbs organics from the wastewater and thus provides a highly enriched substrate for biological growth.(50) Theoretically, the carbon traps organics for subsequent utilization by the microorganisms. As a result there may be a slight improvement of the carbon adsorption service life.(51) On the other hand, the biological activity may be such that it covers the carbon and prevents efficient utilization of its adsorptive properties. Biological activity on a carbon column at a rest area facility would not be expected to significantly increase the removal of the degradable organics in the biological reactor. Frequent replacement of the carbon should preclude the establishment of growth on the column.

In summary, "A test program to evaluate the economic and technical feasibility of granular activated carbon treatment should consist of two parts. Batch isotherm tests should first be made to determine if the desired degree of color removal could be attained. Continuous flow column tests should then be conducted to establish operating capacities as well as to obtain column design data".(52)

Evaporation and Desalination

General

Even though a recycle-reuse system has the potential to greatly reduce the volume of effluent discharged, a buildup of dissolved materials will occur in both the recycled and discharge waters. At high recycle rates, in the range of 90 to 95 percent, the quality of effluent expected from a rest area recycle facility may be classified as brackish, containing total dissolved solids (TDS) in the range of 5000-10000 mg/l. This is an intermediate value between municipal wastewater containing less than 1000 mg/l TDS and seawater with over 30,000 mg/l TDS. The dissolved solids in a recycle system can be estimated by a materials balance multiplying factor at each percentage recycle level. For example, at 90 percent recycle, the effluent solids concentration could be expected to be approximately 10 times that of the influent. Both refractory organics (non-biodegradable) and inorganic salts make up the majority of dissolved solids in recycled water. The concentrations of these compounds will be in excess of the amounts usable by the bacterial cells, and for practical purposes they can be considered inert to biological activity.(53) Since the function of recycled effluent is the transportation of wastes from the toilet to the treatment plant, reuse of the brackish effluent for this purpose should be acceptable as long as scaling is not a significant problem.

Effluents from rest area treatment plants are often released into small receiving streams. During summer months the stream flow may periodically approach zero, and the treatment plant discharge may make up nearly all of the stream flow. Under these conditions, high recycle rates could result in undesirable dissolved solids being released to the stream. Controlled discharge or dilution of effluent are possible solutions to this problem. If these are ruled out, then some means of effluent improvement by desalination would have to be considered.

Within the limits of practicality, only membrane and distillation processes for desalination of recycled effluent have been considered in this evaluation. These general processes have shown some potential for small-scale separation of dissolved material from effluents with recycle concentrations. It should be mentioned that both processes will produce a small, highly concentrated waste stream which must ultimately be disposed of.

Membrane Processes

Ultrafiltration, electrodialysis, and reverse osmosis are all membrane processes used for desalting water.(54,55,56) These methods are based on the principle that selective membranes allow some ions or molecules to pass through them while rejecting others.(57) The principal driving force and the function of the membrane in each process differ. In ultrafiltration, the driving force is pressure and the membrane discriminates on the basis of molecular size.(58) The process is applicable for the separation of solutes with high molecular weights (above 500) such as bacteria, viruses, proteins, and clays.(59)

Electodialysis uses electrical potential as the driving force and a pair of ion-selective membranes.(60,61) Although, this process seems best adaptable to desalination of brackish water with a lower concentration than salt water, electrodialysis may have problems with both chemical precipitation of salts on the membrane surface and clogging of the membrane with residual colloidal organic matter. Prior removal of these substances by extensive pretreatment may be required.(62)

Reverse osmosis is a more promising advanced concept for saline and brackish water conversion.(63) Water is separated from dissolved salts in solution by filtering through a semipermeable membrane by the application of mechanical pressure greater than the osmotic pressure caused by the dissolved salts in the wastewater.(64,65,66,67) The fresh water component flows through the membrane to the pure water on the other side. This process leaves the dissolved salts in increasing concentrations on their original side of the membrane.(68) Considerable developmental work on a small-scale has proven that reverse osmosis has potential for the renovation of wastewater.(69) The main emphasis has been directed toward obtaining suitable semipermeable membranes which are durable and selective and permit water to pass at high rates under reasonable pressures. It has been documented that the selection of a proper membrane is dependent on a knowledge of the chemical nature of the individual wastewater constituents.(70,71) The advantages of a reverse osmosis desalination system include:

1. Low energy requirements; no phase changes are involved and thus there is a low thermodynamic energy requirement. The only energy input is mechanical energy.

2. Simplicity of the system with respect to equipment.

3. Operation at ambient temperature, which results in minimal corrosion and scaling problems.

4. Application to brackish water with a range of dissolved solids concentrations similar to that of recycled effluent (5000-10000 mg/l TDS).

Pretreatment by activated carbon may be needed to prevent salt precipitation on the membrane. Should activated carbon already be employed for color removal at a highway rest area the two processes may complement one another for final water quality improvement.

Evaporation and Distillation Processes

Distillation is a general desalination process in which water is separated from the dissolved salts by evaporation and condensation. This separation can be accomplished by several methods including multistage flash evaporation and solar distillation. In the former, the brackish water is preheated and then introduced into a series of low pressure flash chambers. Here some of the water immediately flashes to vapor leaving the salt and some of the other impurities behind. The vapor rises and comes in contact with condenser tubes carrying cool influent water to the heater. The droplets formed fall into a separator and are carried away as a desalinated product water.(72) This method has wide application from small shipboard marine evaporators to the largest of desalination systems.(73,74) Corrosion and scale formation are major problems of the multistage flash process.(75) In addition, the product water produced by the distillation of biologically treated effluents may have odors caused by the carryover of organic compounds and ammonia. This problem has been shown to increase with operating temperature, and may necessitate subsequent treatment by activated carbon. Recently, a feasibility study was conducted by the Environmental Protection Agency on the treatment of wastewater by distillation.(76) It was concluded that multistage evaporation of extended aeration effluent followed by activated carbon treatment produced a demineralized, odor-free product suitable for high quality reuse.(77)

In solar distillation, the heat energy of the sun is used to cause evaporation under circumstances where the condensate can be recovered. Recycled effluent is introduced into a shallow basin with a dark bottom to absorb the sun's heat. A transparent roof covers the basin, allowing the sun to heat the water beneath. Vapor rises and condenses on the underside of the covering and then drains into collection troughs as demineralized water. Fresh recycled effluent is pumped nightly into the lined pond, and the concentrated brine is automatically flushed to storage. This process is severely limited by the large area that must be covered. Solar distillation is useful only where sunshine and open space are plentiful and fuel is scarce. An output of one gallon per square foot per day of surface area can be expected on days of good sunshine.(78)

Solar evaporation would be a final means of effluent volume reduction. With the high recycle rates to be employed, only small volumes (500 to 1000 gallons) will remain to be discharged daily. The natural process of evaporation from the final holding pond would most probably provide the key to an economical and practical solution for zero discharge at highway rest areas.

Rates of solar evaporation depend on a combination of factors including temperature, vapor pressure, wind speed, relative humidity and water quality.(79) Vapor pressure is a measure of the activity of the molecules at the water surface.(80) Large differences between the vapor pressure of the water and the partial pressure of the overlying air produce conditions for rapid evaporation. Since vapor pressure is temperature dependent, more molecules can be forced to leave the surface as the heat content of the water body is increased.(81) Normally the vapor pressure is nearly doubled for every 10 degree centigrade rise in temperature.(82) Where relatively shallow holding ponds, such as those at rest areas, are responsive to the warming and cooling process, temperature has the most profound effect on evaporation. For example, monthly variations in evaporation can be expected to closely correspond to fluctuations in mean monthly temperature. In some instances, an artificial heat source can be used to raise the pond temperature to enhance evaporation, as in the submerged combustion process. To a smaller extent, winds also stimulate evaporation by displacing saturated air over the pond and replacing it with fresh dry air.(83) With all conditions equal, the evaporation of recycled effluent should occur at a somewhat slower rate than that for pure water, because the accumulation of dissolved salts in the effluent tends to lower the vapor pressure and thus makes the escape of water molecules more difficult.

The total volume of water evaporated from a solar pond in a given period of time will also depend on the size of the pond and the net energy received during the period. Having a lot in common with the phenomena of gas transfer, evaporation is related to the interfacial area between air and water. Broad shallow ponds with some agitation therefore favor evaporation. The net energy received by the pond is from two sources, direct radiation from the sun, and indirect radiation from the atmosphere.(84) This net energy is then divided by reflection, absorbtion, and transmission to the pond bottom. Part of the radiation received by the pond bottom is reflected and the rest is absorbed by the surrounding soil.(85) In a solar pond the energy balance is constantly shifting. During daylight hours heat is lost by conduction into the ground, while at night this heat is regained. The overall daily difference between energy gain and loss is accounted for primarily by the evaporation of water.(86) Using this principle for pond design, evaporation can be increased by providing for shallow depths with a darkened bottom to absorb more heat. It has been found for instance that the effect of heat transfer with the pond bottom is significant for pond depths less than two feet.(87)

Effluent volume reductions realized by solar evaporation could, of course, be offset by precipitation depending on the climate. In an area such as Virginia, the average annual precipitation is approximately 80 percent of the average annual evaporation.(88) Although there is considerable variation from month to month and year to year, it is expected that evaporation will exceed rainfall in at least six of the warmer months. The natural trend throughout the region is concentration of impounded water during the summer and dilution during the winter. At highway rest areas, the winter months are typically low traffic periods, and as a result, low water use periods. In contrast, receiving stream flows are generally at a maximum during this winter period. Possibly the small discharges from a recycle plant could be stored and partly evaporated in the existing holding pond during the warmer months and discharged in a controlled manner in the winter. This controlled discharge scheme would not only take advantage of seasonal evaporation, but would provide for protection of the receiving stream during the critical summer months.

A study is being conducted by the Alabama Department of Highways on the evapotranspiration of wastewater from highway rest areas.(89) Their plans are to distribute treated wastewater in a drainfield containing numerous phreatophytic trees. Since these trees are capable of consuming and transpiring enormous amounts of water, the need for continuous discharge may be eliminated.

Biological Solids Control and Handling

General

The activated sludge process uses a continuous culture of mixed microorganisms grown on a combination of organic and inorganic substrates found in wastewater. The process inherently produces large quantities of waste biological material in the form of dilute suspended solid mixtures known as sludge.

The characteristics and solids content of these sludges will vary depending on the strength of the influent waste material and the form of activated sludge treatment.(90,91) In most cases organic substrate is the limiting factor, and an increase in influent waste in terms of BOD results in an increased production of biological mass. This fact is confirmed by a simple material balance for substrate utilization as presented by Ritz,(92) and also by the familiar Monod equation for the growth rate of biological cultures.(93)

$$\mu = \mu_{max} \frac{S_1}{K_s + S_1} \qquad (7)$$

where

μ = unit rate of cellular increase, $hr.^{-1}$

μ_{max} = maximum rate of cellular increase, $hr.^{-1}$

K_s = constant

S_1 = substrate concentration in the reactor in terms of organic loading mg/l

This relationship describes the curve shown in Figure 5 and indicates that as the substrate concentration (BOD) becomes large, the cellular growth rate approaches a maximum until it is no longer substrate dependent.(94)

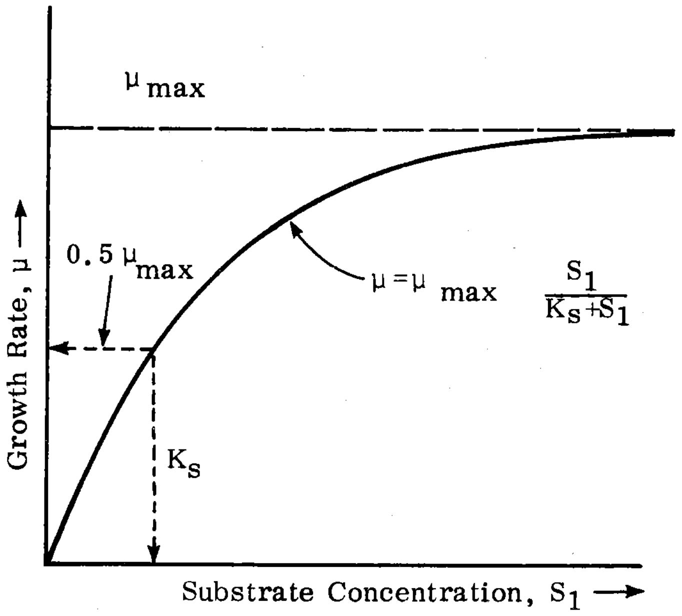


Figure 5. The rate of pure culture growth on substrates.

The amount of excess sludge produced depends on the degree of sludge oxidation, and is governed by the loading criteria and oxygen requirements for the particular process. Loading criteria are normally measured in terms of a food-to-mass ratio, which may be expressed in several ways. The most common expression is food removed per day per mass of microorganisms in the system (pounds of BOD removed per day per pound of volatile suspended solids in the system). Efficient operation of any activated sludge process depends on maintaining a fairly constant food-tc-mass ratio. An appropriate biological mass is thus needed to meet fluctuations in influent loading. Oxygen requirements depend on both the growth phase and number of organisms present; the more active, and the greater number present, the more oxygen consumed.

Extended aeration is a modification of the conventional activated sludge process and is used primarily for high efficiency treatment of small volume wastes.(95,96) It is well suited for biological treatment of wastes at highway rest areas. "The extended-aeration process operates in the endogenous respiration phase of the growth curve, which necessitates a relatively low organic loading and long aeration time".(97) This low organic loading coupled with a higher range of MLSS (3000-6000 mg/l) yields the lowest food-to-mass ratio of the activated sludge variations.(98) The most important characteristic of this process is that the excess sludge is generally not wasted continuously from the system.(99) Rather, the cells are allowed to accumulate to high levels for the purpose of aerobically digesting or destroying the majority of the biological sludge produced.(100) Only infrequently is a portion of the biological solids wasted from the system. The large, completely mixed volume of highly concentrated mixed liquor in the extended-aeration process allows it to accept intermittent loadings, including both periodic shock loads and occasional periods without feed.(101) During the periods without feed, the major organic loading is the sludge itself.

Biological Solids Accumulation

The conversion of organic waste in the activated sludge process can be shown as three reactions which occur simultaneously. In the first and second reactions, as shown by Figure 6, the organic waste is partly oxidized for energy and partly synthesized into new bacterial cells.(102) Thirdly, the bacterial cells formed are transformed via self-oxidation into simple end products and more energy. Temperature has a marked effect on the ratio of cell synthesis to oxidation of waste material. Higher temperatures shift the ratio in favor of oxidation, thereby causing less sludge to accumulate.(103) In endogenous respiration, the active solids use oxygen to oxidize the degradable portion of themselves to carbon dioxide and water. This oxidation results in a decrease in sludge mass. The net daily increase in cell mass is then equal to the amount of new cellular material produced each day minus the quantity of existing cellular material oxidized for endogenous respiration.(104)

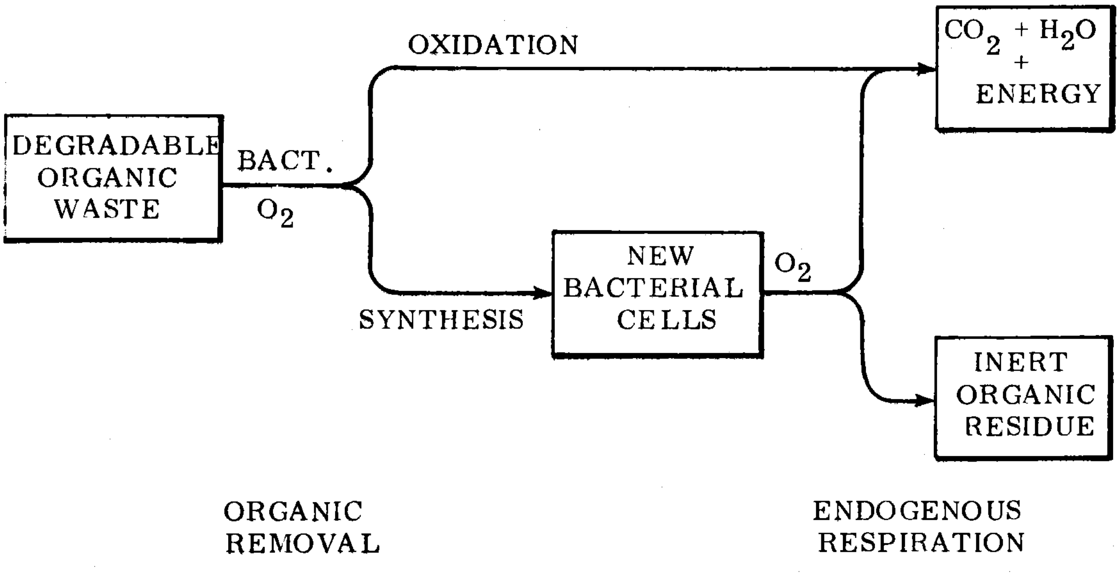


Figure 6. Conversion of organic wastes in activated sludge.

There are two opposite theories regarding the long-term accumulation of solids in extended aeration.(105) One theory supports occasional sludge wastage, contending that roughly one-fourth of the cells produced are inert to biological oxidation, and therefore accumulate in the system.(106) In contrast, a second theory (total oxidation) maintains that cell wastage is unnecessary.(107) However, with or without cell wastage, "the total accumulation of sludge in an extended aeration activated sludge plant will be equal to the accumulation of biological solids plus the accumulation of biologically undegradable suspended solids which were originally present in the influent waste".(108) The undegradable materials consist of lignin, cellulose, and other biologically resistant organics.(109) Any long-term growth curve for activated sludge will have irregular cycles of solids accumulation and deaccumulation which cannot be predicted.(110)

Biological Sludge Characteristics

Biological sludges are those produced as a result of secondary biological treatment processes. These are in contrast to primary sludge, which is accumulated solids on the bottom of a primary clarifier. It is generally conceded that biological sludge is the most variable in nature of the wastewater sludges. It is therefore the most costly to process and troublesome to dispose of, because secondary sludges contain an enormous number of extremely tiny microorganisms which are much finer than discrete particles found in primary sludge.(111) Normally secondary sludges contain 60 to 90 percent more cellular organic material than does primary sludge.(112) In high concentrations such as 10^{10} per ml, the organisms form a biomass as a result of a bioflocculation phenomenon. Bacteriological cells contain a large volume of hydrated water that is tightly bound within the cell. The greater the net cell surface area, the larger the water of hydration.(113) When flocculated, these cells form a gel-like structure which leads to increased resistance to dewatering and settling since the flocculated cell mass has a high affinity for the bound water. When subjected to pressure, this gelatinous sludge tends to compress and cause more clogging.

The characteristics of waste activated sludge from extended aeration are similar to those of sludges from aerobic digestors. Both methods use continuous long-term aeration to achieve solids reduction, however, the objectives of the two processes differ slightly. In aerobic digestion, the main intent is to reduce the five-day BOD and volatile portion of the suspended solids. This differs from extended aeration, which has treatment of the soluble fraction of wastewater as the main function. During both processes there is cellular destruction through endogenous respiration. Waste sludges from extended aeration are, therefore, particularly well adapted to aerobic digestion, since the required organisms are already developed and in the proper growth phase.(114)

Aerobic digestion may serve as a potential alternative for the reduction of the biological solids which are occasionally wasted at a highway rest area. For instance, sludge holding tanks could possibly be converted to aerobic digestors in which accumulated sludge would be aerated continously for several weeks to lower the organic fraction. The pollutional load of the supernatant from aerobic digestion is significantly less than that from conventional anaerobic digestion in which organic material is decomposed in an atmosphere devoid of oxygen. Even though the energy requirements are much higher for aerobic digestion, it has the following advantages over anaerobic digestion:(115)

1. A humus-like, biologically stable end product is produced which is free of odors and easily facilitates land disposal or lagooning.
2. Volatile solids reduction equivalent to that of anaerobic digestion is possible.
3. The aerobic digestion system is less complex than anaerobic digestion, and therefore, unskilled labor could be employed to operate the facility.
4. Although operating costs would be slightly higher, capital investment would be significantly less than for anaerobic digestion.

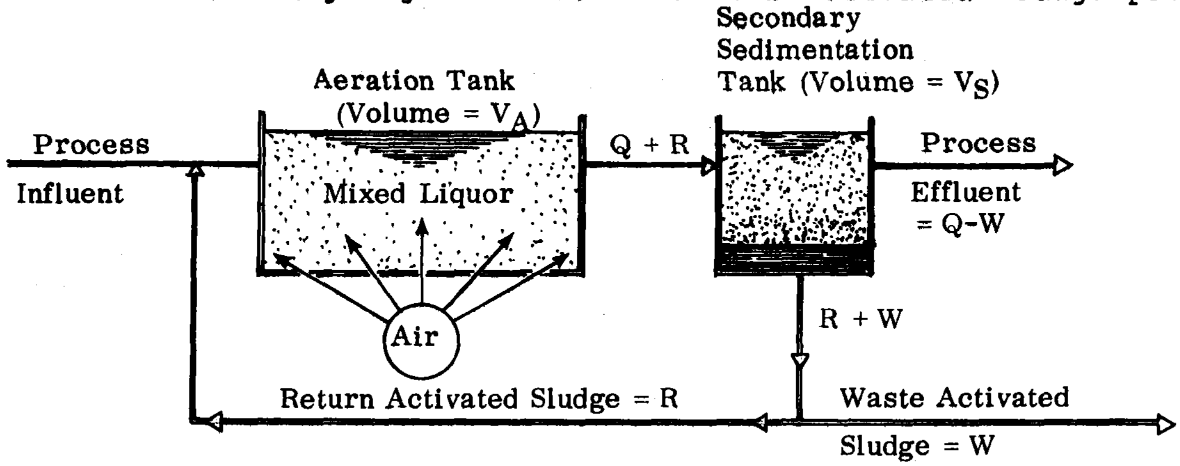
Biological Solids Control

The BOD removal efficiency of any activated sludge system is largely dependent on the operational control of the biological solids level. However, the advantage of small extended aeration plants, such as at the Fairfield rest area, is a minimum of operator attention. This plant currently requires little operational control, produces a minimum of excess solids, and attains good BOD removal. For instance, the daily procedure includes only the monitoring of the settleable solids level in a 1000 ml graduated cylinder. Semiannually, a large volume, approaching half that of the aeration vessl, is wasted to a separate sludge holding tank. From here, the solids are pumped to a truck and hauled away for disposal. One objective of an extended aeration plant with effluent recycle would be to maintain the simplicity of operational control. With a recycle plant, it will be critical to minimize daily fluctuations in treatment efficiency. For example, untreated soluble BOD could cause odor problems when returned to the toilets. Therefore, it may be necessary to utilize a more effective means of solids control than is presently employed.

Three methods may be employed to control solids levels in activated sludge.(116) In the first method, the operator maintains a constant MLSS level to treat the incoming wastewater. Although this method is simple, it requires some laboratory work, and it ignores the important food-to-mass ratio.(117,118) The current settling column method is similar, yet not as effective because sludge settling characteristics vary with sludge age.

The second method calls for the maintenance of a constant food-to-mass ratio. In this method, the operator daily determines the influent strength in terms of either BOD_5 or COD, and wastes solids to achieve the desired food-to-mass ratio. Although theoretically sound, this operation requires continuous laboratory analysis and, in the case of BOD_5, does not give immediate results.(119,120)

A third method for controlling solids levels in activated sludge is to keep a constant sludge age. Sludge age, θ_c, is defined as the ratio of the mass of organisms in the system to the mass of organisms wasted per day.(121) In extended aeration, the sludge age is in the range of 20-30 days to insure endogenous cells.(122) Two procedures exist for controlling sludge age. In one, the operator wastes daily a certain percentage of the total suspended solids in the system.(123) This method is very much similar to the constant food-to-mass procedure, however, it requires only a daily measurement of suspended solids. The other constant sludge age method requires no laboratory work and only a knowledge of the daily wastewater flows. Figure 7 shows the parameters required for hydraulic control of sludge age in a conventional activated sludge process.(124)



$$\text{Continuous Wasting Rate W as \% of R + W} = \frac{100}{\theta_c(P)}$$

where P = No. of Passes per day by the Solids $= \dfrac{Q + R}{V_A + V_S}$

$$W(\text{as \% of } R + W) = \frac{100(V_A+V_S)}{\theta_c(Q + R)}$$

Figure 7. Hydraulic control for the activated sludge process.

Q = influent flow rate in gallons per day (gpd)

R = return rate of activated sludge in gpd

V_A = volume of the aeration basin in gal

V_S = volume of the settling basin in gallons

X = continuous wasting rate as percentage of gross return sludge, $R + W$

θ_c = sludge age in days

T = detention time in settling basin (hours)

W = daily sludge wastage in gpd

For sludge age control it is necessary to waste $100/\theta_c$ percent of the total biological solids in the system each day. For a continuous wasting rate, this ratio must be divided by the number of passes the sludge makes through the return line daily. This number of sludge passes is equal to the total flow through the process, $Q + R$, divided by the total process volume, $V_A + V_S$. Therefore, the wasting rate, X, is dependent only on the hydraulic flow through the process:(125)

$$X = \frac{100\ (V_A + V_S)}{\theta_c (Q + R)} \tag{8}$$

Knowing the volume of the secondary clarifier and the detention time, T, the return sludge flow rate, R, can be determined:

$$R = \frac{V_S}{T} - Q \tag{9}$$

It is observed that R is solely dependent on the influent flow, Q. From equations 8 and 9, the amount of sludge wasted daily may be expressed as:

$$W = X(R + W) \tag{10}$$

In the extended aeration process, the vast majority of cells are returned, and R would be much greater than W. Therefore, equation 10 may be closely approximated by

$$W = XR \tag{11}$$

For the operator to maintain a constant sludge age, all he needs to do is monitor the influent flow, Q, and waste sludge accordingly. The operator could record the daily flows and amounts of sludge wasted based on equations 9 and 11. Once enough data has been collected, he could waste according to a chart of the historical flow record. The basic assumption for this control process is that the strength of the influent waste in terms of BOD_5 is proportional to the flow rate. The advantages of this method of control over that currently used at the rest area are as follows:

1. Small volumes of sludge are wasted according to daily variations in flow. This allows a more constant treatment efficiency.
2. This daily withdrawal of small volumes of sludge is not the drastic shock to the biological system that the large semiannual withdrawal is. This latter technique requires a growth period to return to peak treatment efficiency.

An alternate approach to maintaining a constant sludge age is wastage directly from the aeration basin. The amount of mixed liquor to be wasted daily, Q_W, is:

$$Q_W = \frac{V_A + V_S}{\theta_c} \tag{12}$$

If sludge wastage is done from the mixed liquor, the operator need only waste a constant percentage of the total volume ($V_A + V_S$) each day to maintain a constant θ_c.(126) However, this method neglects variations in daily flow.

Cell Hydrolysis

As previously discussed, the major organic loading in an extended aeration system is the sludge itself. Since the cells represent a complex carbon source which is difficult to break down, a long aeration time is desirable.(127,128) Even so, excess cells gradually build up, and some form of sludge wastage is required. It is possible that this wasted material could be solubilized and reused as substrate, thereby eliminating the need for separate sludge disposal facilities. Since protein is the major macromolecular constituent of the cells, the breakdown of these large molecules to the liquid phase is possible through cell hydrolysis. Gaudy has reported the successful use of cell hydrolysis as a method for handling waste activated sludge by a technique employing the return of hydrolyzed material as substrate to an extended aeration unit.(129,130) A three-step process was used to treat the wasted sludge. In the first stage, sludge was acidified to pH 1.0 with 0.5N sulfuric acid. This mixture was then autoclaved for five hours at 15 psi and 121°C. Using this procedure he was able to solubilize the majority of suspended biological solids. The hydrolyzed sludge was finally neutralized to pH 7.0 with sodium hydroxide, and then combined with the normal influent feed. This "hydrolytic assist" technique was successful in initiating solids deaccumulation periods.

Gaudy's detailed results can be further summarized as follows:(131)

1. The neutralized cell hydrolysate used by itself proved to be a complete feed.

2. With freshly grown cells, hydrolysis provided nearly complete solubilization of the biomass. However, with old cell suspensions, only 75 to 80 percent solubilization occurred.

3. Increasing the acid concentration had no effect on the degree of solubilization.

4. Lower acid concentrations were desirable because high concentrations destroyed some of the carbohydrate compounds.

5. This method did not interfere with the nitrifying characteristics of the extended aeration process.

Because sludge hydrolysis requires a continuous supply of acid in addition to necessary equipment for elevating the pressure and temperature, its application for use at small facilities is limited, and as yet unproven.

Thermal Reduction of Sludge

Thermal processes are most effective for the reduction of sludge solids.(132) One form of sludge reduction is incineration. "Incineration is a two step process involving drying and combustion."(133) It is a sludge volume reduction method rather than a means of sludge disposal.(134) Only the organic fraction of the sludge undergoes ultimate disposal during combustion.(135) An inert ash is produced as a final product of incineration which subsequently requires final disposal. Prior to initial drying in the incineration process, sludge must undergo some type of dewatering operation to attain 25-30 percent solids.(136,137) Drying and combustion processes may be done in the same or successive units and consist of three phases:(138)

1. Elevating the temperature of the incoming sludge to the boiling point of water (212°F)

2. Evaporating water from the sludge

3. Increasing the air temperature of the gaseous fuel, and thereby raising the temperature of the dried sludge organics to the ignition point.

For a complete reaction not only fuel and air but time, temperature, and turbulence are essential.(139) Excess air is introduced in controlled amounts to provide oxygen in quantities greater than theoretically required to completely oxidize the sludge.(140) This has the effect of controlling temperature and increasing heat losses from the furnace.(141,142) The two most commonly used types of equipment for sludge combustion are multiple hearth furnaces and fluidized bed reactors. The operation of these is described in detail elsewhere.(143,144,145)

Most wastewater sludges contain three principal combustion elements: carbon, hydrogen, and sulfur, which determine the caloric fuel value.(146) The heat balance for sludge combustion is dependent not only on the proportion of these elements, but also on the moisture content of the particular sludge.(147,148) When comparing biological sludges with the same moisture content, digested sludges will have the lowest fuel value, because the volatile content is reduced and the inert noncombustible portion is increased during digestion.(149) Waste sludges from extended aeration thus have a lower range of heat values because of their greater sludge age. This fact, along with the requirement for dewatering equipment, would have to be considered for the development of an efficient incineration process.

PROCEDURES AND ANALYSIS

Pilot Plant Operation

The procedure for pilot plant operation was basically the same as that used by Ritz.(150) The biological unit was operated at 90 percent recycle over a five-month period as a continuation of his work. The recycle system was then shut down and restarted at zero percent recycle. The intent of this reversion to zero percent recycle was to achieve steady state, and then go directly to 95 percent recycle. However, after steady state was reached, problems with pH and alkalinity forced the unit to be shut down until synthetic feed modifications could be made. Upon the completion of these feed modifications, the unit was started using raw sewage as seed, and was operated at 95 percent effluent recycle over a six-month period.

The laboratory recycle equipment for all pilot plant operations was identical to that previously used with only minor modifications (Figure 8):

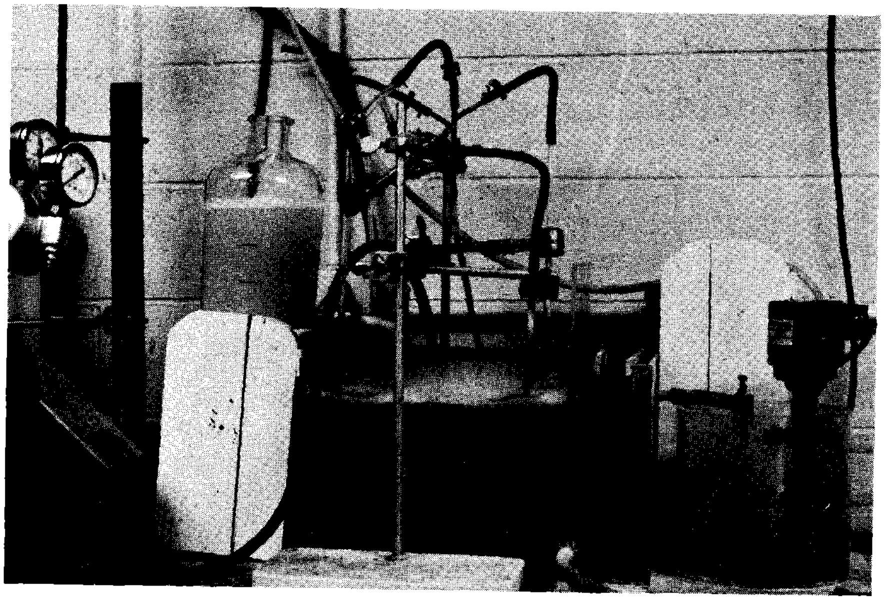


Figure 8. Laboratory pilot plant.

1. Only one refrigerated storage container (21 l) was used. Filtered recycled effluent was drained into this container, and was periodically pumped into the aeration unit to complete the recycle loop. The recycled effluent was continuously mixed by a magnetic stirrer to ensure a representative sample was delivered during each pumping interval. While operating at zero percent recycle, the container was used only as a collection vessel for treated effluent in order that a composite sample could be collected over the 24-hour period.

2. The synthetic waste material was added daily by means of a 4 l gravity container. The feed was continuously mixed by a magnetic stirrer and dripped in a slurry form into the aeration unit over a four- to eight-hour period.

The daily procedure was slightly altered at 90, 0, and 95 percent recycle by changing the contents of the feed and storage tanks. These changes ensured the daily balance of water for the treatment system as outlined below.

1. <u>At 90 percent recycle</u>, the synthetic feed was diluted with 2 liters of tap water. This volume constituted the 10 percent make-up fresh water for an average flow of 20 l/day for the system. To account for this addition, the level in the recycled effluent storage tank was

lowered to 18 l each morning. Any losses to evaporation were thus accounted for. The filter backwash was completely wasted from the system each day.

2. At zero percent recycle, the synthetic feed was also diluted with 2 liters of tap water. Eighteen liters of additional tap water were delivered via the influent pump to the aeration unit. The equalization basin was used as a supplemental clarifier, and effluent water flowed by gravity into a 20 l storage tank. The sand filter was not utilized.

3. At 95 percent recycle, the synthetic feed was diluted with 2 liters of recycled effluent plus the first liter of filter backwash. This last liter constituted the 5 percent make-up fresh water for the 20 l/day flow system. It also ensured the return of any biological solids caught on the filter. During the first three months of operation, the liter wasted from the system daily was supernatant from the mixed liquor. This procedure caused the inadvertent loss of biological solids. Since the objective was 95 percent effluent recycle without sludge wastage, the daily wastage was changed to withdrawal of 1 liter of recycled effluent from the refrigerated storage tank. A daily log was kept of evaporation, and losses were made up with the addition of tap water directly to the effluent storage tank.

The synthetic waste used at 90 and zero percent recycle was the same as that used by Ritz.(151) It was found in both these phases of operation that severe pH and alkalinity problems developed which required modification of the feed. A detailed laboratory analysis of the individual feed constituents was conducted. As a result, three changes were made in the recipe for the preparation of the synthetic waste.

In each phase of pilot plant operation, periodic analyses were conducted to document the unit's performance. These included tests on mixed liquor and recycled effluent such as:

1. Mixed liquor suspended solids (MLSS)

2. Mixed liquor volatile suspended solids (MLVSS)

3. Total dissolved solids (TDS)

4. Total dissolved fixed solids (TDFS)

5. pH
6. Total alkalinity
7. Sludge volume index (SVI)
8. Chemical oxygen demand (COD)
9. Biochemical oxygen demand (BOD)
10. Volatile acids (95% recycle only)

All of these were run in accordance with the 13th edition of Standard Methods for the Examination of Water and Wastewater, with the exception of volatile acids, which were estimated using a direct distillation procedure outlined in the 10th edition of the same reference. In addition, a procedural change was made from 90 to 95 percent recycle for the determination of dissolved oxygen. Interferences rendered the Winkler method ineffective, so the dissolved oxygen membrane probe was substituted. Another analysis run periodically was the determination of the rate of oxygen uptake by the mixed liquor. This was done to determine the activity of the biomass. A 300 ml BOD bottle was filled completely with mixed liquor and stirred magnetically with the DO probe inserted. Levels of oxygen were recorded at increments of time, and the rate of oxygen uptake was computed.

During each phase of pilot plant operation the biological treatment system was allowed to reach a condition of "steady state". This condition was defined for the purpose of this work as a period of relatively constant treatment efficiency. At steady state, effluent strength in terms of COD and dissolved solids did not increase significantly with time. Once this state was reached final analyses were run to conclude the phase of operation. These analyses included all those tests listed above, as well as Total Kjeldahl Nitrogen (TKN), Ammonia Nitrogen (NH_3-N), and Chlorides (Cl^-). The Micro-Kjeldahl Nitrogen was run using a procedure presented by McKenzie.(152) While at steady state with 95 percent effluent recycle, a biological analysis of the organisms present was conducted to determine their acid producing characteristics. Using the streak plate method outlined in the General Microbiology Laboratory Manual, colonies were separated and Gram stains of each were made. The characteristics of each colony were noted and innoculations from each colony were made onto separate sucrose and lactose substrates. In each case, growth, acid production, motility, and gas production were observed.

Operation of the pilot plant at 95 percent effluent recycle was concluded with a six-week period of dye addition to observe its effect on biological treatment efficiency. Routine tests were continued during this period to observe acclimation and ascertain any changes that may have occurred as a result of dye addition. Dye selection and analysis were done previous to this phase of operation, as described in the following section of this report. The entire system was initially dosed with dye to bring the unit's color level up to the desired base concentration. Thereafter, color was added daily in proportion to the 5 percent volume removed from the system each day.

The final separation of biological suspended solids from the effluent was accomplished by a sand filter. A sieve analysis was made on the sand used in this column to determine the grain size distribution. This analysis, performed in accordance with the American Society for Testing Materials (ASTM) standards, was used to determine the effective size, the coefficient of nonuniformity, and the log normal distribution for the sand.(153)

Color Analysis

Color Selection

A recycle system would require the addition of artificial coloring to the recycled effluent before its return to the toilets. The selection of color may be arbitrary, however, it was felt that blue probably would be the most pleasing color in the toilets. In addition, it was thought the color to be used should meet the following criteria:

1. It should not cause additional odor or contribute significantly to the strength of the wastewater.
2. It should not cause permanent staining or corrosion.
3. It should be biologically degradable and have a mininum of residual color after treatment.
4. Any residual color should be readily removed by a simple unit operation.

Three dyes were studied for potential use. A dosage was selected for each one based on visual comparison of a range of concentrations diluted with tap water. A desired base color concentration selected from this range was then used throughout further color analyses.

Since methylene blue dye was readily available in the laboratory, it was initially selected for testing. Only a visual comparison was made between 100 ml samples of uncolored and colored mixed liquor. Both samples were aerated and stirred overnight and then allowed to settle. The supernatants were then visually compared for residual color.

To expand the selection of dyes, Sauer's blue food coloring was also tested. In addition to tests similar to that mentioned for methylene blue, color quantifications and removal were studied.

Based on a recommendation from the State Health Department, sodium fluorescein dye was finally selected for study in detail. Although this dye is not the preferred blue color, it is known to be biologically degradable, and will fade when exposed to sunlight. The majority of color analyses were therefore done with the fluorescein yellow-green dye. Color quantification, biological color uptake and sunlight exposure were all investigated using this dye. Consideration was also given to the removal of this dye by activated carbon adsorption. Isotherm data were collected for estimating the amount of carbon required and both tap water and recycled effluent colored with sodium fluorescein were subjected to fixed bed carbon contact units.

Color Quantification

Color quantification was performed using a Bausch and Lomb Model 20 spectrophotometer. In this method, the color of the sample was considered to be the color of the light transmitted by the solution after the removal of suspended material. The first step in using this device was the selection of the most sensitive wavelength, found by scanning the range of wavelengths to determine the one with the greatest absorption. The wavelength determined by this method was subsequently used as the base wavelength for that particular dye, regardless of whether recycled effluent or tap water was being colored. Standard color curves were constructed by preparing bottle dilutions of the desired color concentration and plotting color concentration against percent transmission on semilog paper. The resulting graph was used to convert transmission readings to color concentrations during later analyses. Since the standard color curve was prepared with dye added to tap water, any color quantification done on samples other than tap water required a knowledge of the raw color present. For instance, it was readily apparent that samples such as recycled effluent, synthetic feed, and rest area influent wastewater contained appreciable raw color before the addition of dye. Uncolored filtered samples of these three were spectronically analyzed to determine an equivalent color concentration. In this manner, the contribution to total color from the raw sample was found.

Color units using the platinum cobalt standard were also determined using a Model 611 Hellige Aqua Tester and a standard calibrated color disc. A reference curve for the two color scales was prepared to readily convert quantified color to platinum cobalt units.

Color Removal

The final phase of color analysis involved removal of the applied artificial color. Varying degrees of color removal can be accomplished by both natural processes and unit operations. In the case of sodium fluorescein, applied color will deteriorate with exposure to sunlight. To document this, 1 liter of tap water was colored with the desired base dosage, capped to prevent evaporation, and allowed to stand in indirect sunlight for a two-week period. Daily percent transmission readings were taken to quantify the amount of color dissipated by the sun.

The artificial color will also be exposed to biological attack over the 24-hour period in the extended-aeration treatment system, and with recycle employed, this color will undergo repeated exposure to the biomass. Preliminary batch tests were made to observe either color uptake or biological toxicity. One-liter samples of mixed liquor from both the recycle pilot plant and the Fairfield rest area were dosed with the base color of sodium fluorescein. These were continuously aerated and stirred over a period of time, and daily percent transmission readings were taken on samples of filtered supernatant to estimate biological uptake of the color.

Carbon adsorption was considered to be the ultimate method for color removal from the recycled effluent after sunlight and biological attack. The preliminary step was the selection of a suitable carbon. Batch tests were first run using powdered activated carbon for the removal of food coloring from both tap water and recycled effluent. Flasks containing tap water samples with identical color concentrations were dosed with various amounts of powdered carbon and contacted for 15 minutes. The carbon was separated by centrifugation, and the supernatants were visually compared. The sample that appeared to have complete color removal with the minimum carbon dosage was selected for further quantification. Using this carbon dosage as a median concentration, a finer range of carbon concentrations were again visually analyzed in Nessler tubes to give a more precise estimate of the carbon requirement. The entire procedure was repeated using colored recycled effluent instead of tap water to find the additional carbon required for the adsorption of trace organics. In order to establish the most effective contact time, the powdered activated carbon dosage was held constant at the previously determined carbon to color ratio (mg carbon/ml food color), and contact time was varied. At five-minute intervals samples were taken, centrifuged, and analyzed for residual COD and color using the spectrophotometer. This rough estimate for optimum carbon to color dosage and contact time was used for subsequent column evaluation. Both a fixed bed gravity flow column and a reversed flow fluidized bed were operated using application rates typical for carbon columns and rapid sand filters.(154) No removal data were taken due to powdered carbon retention problems.

Color analyses were continued using grade 400 granular activated carbon (GAC 400). Specifications for this carbon are listed in Table 1. A known weight of GAC 400 was supported on a screen in a gravity flow column. Tap water containing the selected food color concentration was applied at a constant rate, and effluent samples were analyzed for percent transmission at five-minute intervals. Using the food color standard curve, percent transmission values were converted to residual color concentrations. With the flow rate known, this residual color concentration was then plotted against effluent volume collected to determine a food color breakthrough curve. Based on the percent transmission for the lower limit of visual food color, a color breakthrough concentration was determined from the standard color curve. The point at which the breakthrough curve reached this value was taken as the maximum effluent volume allowed before carbon replacement. Finally, a new carbon to food color ratio was calculated by dividing the total weight of carbon in the column by the food color concentration times the breakthrough effluent volume.

$$\text{Carbon to Color Ratio:}\quad \frac{\text{GAC 400}}{\text{ml food color}} = \frac{\text{total grams GAC 400 used in column}}{\left(\frac{\text{ml food color}}{\text{l tap water}}\right)\left(\frac{\text{l of filtered water}}{\text{at breakthrough}}\right)} \qquad (13)$$

A laboratory analysis for color removal was also made with sodium fluorescein and GAC 400 carbon. The procedure used was slightly different from that used for the removal of food color. Color and COD isotherms were developed to estimate the carbon dosages required for later column design. Blended, uncolored recycled effluent was initially analyzed for color and COD. Six liters of this blended recycled effluent were then colored with the base concentration of color and COD. Using a constant contact time of 20 minutes, varying amounts of carbon were applied to 1-liter samples. Color and COD determinations were performed on each, and Freudlich isotherm plots for both color and COD were made. These were log-log graphs with carbon loading on the vertical axis ($\frac{X}{M}$ = gm sodium fluorescein per gm GAC 400 carbon) plotted against residual color or COD concentration on the horizontal axis. Since removal of color was the primary concern, the color isotherm was used to approximate the color adsorption capacity of the carbon. The straight-line isotherm was extrapolated out to a residual color concentration which corresponded to the threshold of visual color on the standard color curve. At this concentration on the isotherm line, a color to carbon ratio was determined on the vertical axis. This ratio provided an estimate of the grams of carbon required to remove one gram of color, and was later compared to a similar ratio determined from pilot column breakthrough tests.

Pilot column tests were run with both tap water and recycled effluent colored with sodium fluorescein. GAC 400 was again used throughout these analyses. In the case of colored tap water, 10 grams of carbon were used, and the test was run until the carbon was exhausted. The slope of the breakthrough curve was analyzed for efficiency of carbon use. The pilot column run with colored recycled effluent was not taken to exhaustion since only a limited volume of recycled effluent was available. As before, the carbon was considered expired at the breakthrough of visual color in the effluent. At this point, a color to carbon ratio (X/M) was determined and compared with the isotherm value. Also during this column run, residual COD and dissolved solids were periodically monitored to determine if secondary water quality improvement or preferential adsorption occurred in addition to the removal of color.

Evaporation

To investigate the rates of natural evaporation, ten years of monthly rainfall and evaporation data were gathered from climatological records taken at Riverton, Virginia. Based on flow information data at the rest area and the volume of the existing holding pond, projections were made for annual evaporation with a recycle system.

Table 1. Characteristics of GAC 400. (From reference 17.)

Physical Properties	Calgon Filtrasorb 400
Surface Area, m^2/g (BET)	1000-1200
Apparent Density, g/cc	0.44
Density, backwashed	25
Real Density, g/cc	2.1
Particle Density, g/cc	1.3-1.4
Effective Size	0.55-0.65
Uniformity Coefficient	1.9 or less
Pore Volume, cc/g	0.94
Mean Particle Diameter, mm	0.9-1.1
Specifications	
Sieve Size (U.S.Std.Series)	
Larger than No. 8-Max %	--
Larger than No. 12-Max %	5
Smaller than No. 30-Max %	--
Smaller than No. 40-Max %	5
Iodine No.	1000
Abrasion No., minimum	75
Ash, %	8.5
Moisture as packed, Max %	2

PRESENTATION OF RESULTS

Pilot Plant Operation

This investigation began in February 1974 with an existing laboratory pilot plant already operating at steady state 90 percent effluent recycle. The unit was continued in this phase for a three-month period during which periodic analyses were run on mixed liquor and recycled effluent. The results of these analyses are shown in the Appendix in Figures A1 through A3. An operational concern during this period was a lack of buffering capacity. The total alkalinity for the three months averaged 20 mg/l as $CaCO_3$, and the pH fluctuated around a value of 5.0. Ten grams of sodium carbonate (soda ash) per day were used in an attempt to increase the acid neutralization capacity of the mixed liquor. The results of soda ash addition were:

1. A failure to raise the pH or increase the total alkalinity,
2. a dramatic increase in dissolved solids, as shown by Figure A2 of the Appendix, and
3. an adverse change in the sludge settling characteristics, as shown by the increase in Sludge Volume Index in Figure 9.

The same pH and alkalinity problems were experienced again at zero percent recycle; therefore, synthetic feed problems were suspected to be the cause. The results of an analysis of the individual constituents in the synthetic feed are listed in Table A1 of the Appendix. Three changes were made in the recipe and preparation of the synthetic feed to adjust pH and alkalinity as follows:

1. The daily dosage of lime was doubled to raise the pH and provide additional buffering capacity.
2. Sodium sulfite (Na_2SO_3) was replaced with sodium carbonate (Na_2CO_3) in an attempt to prevent the biological oxidation of sulfites to sulfuric acid (H_2SO_4). The latter, when in excess, can upset the process.
3. The addition of inorganic salts was changed from solution to a dry basis. This was required because the preparation of a 40-day supply necessitated the addition of approximately 100 ml of 1.0 N H_2SO_4 to dissolve the salts. This acid had a tendency to destroy the alkalinity. The modified procedure called for the daily addition of salts mixed in with the dry feed.

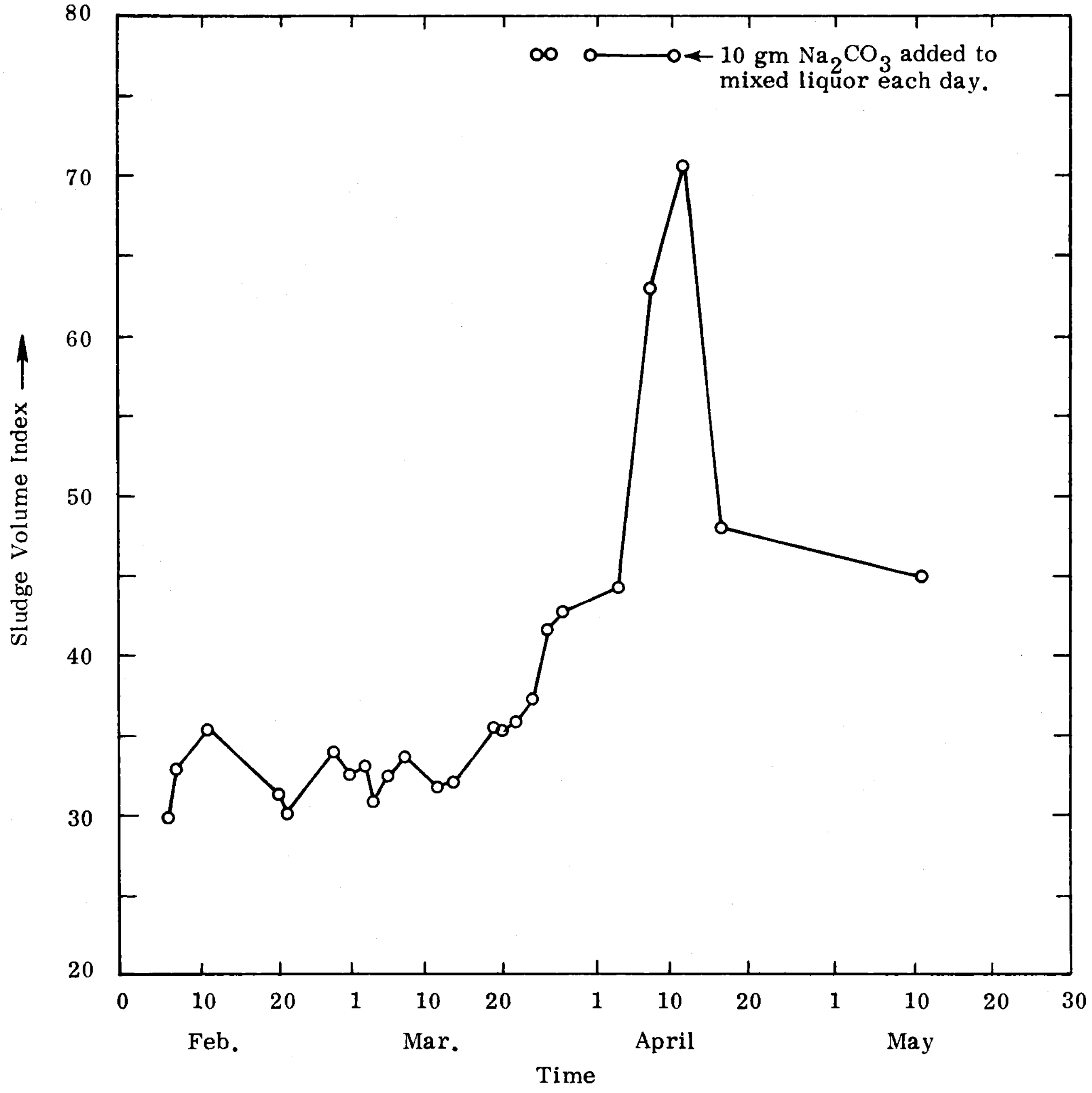


Figure 9. Sludge volume index at 90% recycle showing influence of soda ash addition.

The recipe shown in Table 2 reflects the changes made in the synthetic feed. In an effort to determine the oxygen demand of the synthetic wastewater, due to both nitrification and carbonaceous demands, an ultimate BOD (20 days) was made (Appendix Figure A4). From this curve, the ultimate carbonaceous demand was found to be approximately 400 mg/l, and the ultimate nitrification demand was approximately 650 mg/l.

With the new feed, the unit was restarted at 95 percent effluent recycle and monitored for steady state. Using TDS and COD of the recycled effluent (COD_{RE}) as the determining parameters, steady state was reached in approximately three months, as shown in Figures 10 and 11. Once this condition was attained, TDS had a mean value of 8191 mg/l with a fluctuation of ± 20 percent. COD_{RE} had a mean value of 887 mg/l with a fluctuation of ± 16 percent. The periodic analyses conducted during this recycle phase are shown in Appendix Figures A5 through A8. Figure 12 shows the buildup of MLSS for 95% effluent recycle. From this curve, a suspended solids accumulation rate of 1340 $\frac{mg}{l}$/month was calculated. The production of volatile acids, as shown by Figure 13, was thought to be caused by the particular organisms present.(155) Samples of mixed liquor taken during 95% recycle steady state were biologically analyzed and a summary of the results is presented in Table 3, which shows organisms capable of producing volatile acids.

Table 2. Revised Recipe for Synthetic Wastewater

Ingredient	Formula	Synthetic Wastewater Dosage (mg/l)
SUCROSE		160
PEPTONE		160
MONOSODIUM GLUTAMATE		15
UREA		32.5
YEAST EXTRACT		32.5
CALCIUM HYDROXIDE	$Ca(OH)_2$	100
CALCIUM SULFATE	$CaSO_4$	50
SODIUM BICARBONATE	$NaHCO_3$	5
AMMONIUM CHLORIDE	NH_4Cl	100
AMMONIUM NITRATE	NH_4NO_3	37.5
POTASSIUM PHOSPHATE MONOBASIC	KH_2PO_4	5
POTASSIUM PHOSPHATE DIBASIC	K_2HPO_4	20
DIBASIC SODIUM PHOSPHATE	$Na_2HPO_4 \cdot 7H_2O$	25
POTASSIUM NITRATE	KNO_3	100
SODIUM NITRITE	$NaNO_2$	50
SODIUM CARBONATE	Na_2CO_3	25
MAGNESIUM SULFATE	$MgSO_4$	25

Table 3. 95% Recycle Biological Analysis

Innoculations of mixed liquor were made onto nutrient agar and three distinct colonies were found present.

Characteristic	Colony #1	Colony #2	Colony #3
Color	Light yellow	White	White
Motility	Non motile	Non motile	Non motile
Shape & Arrangement	Large colony with coccoid rods arranged in pairs and bunches. Sticky on the slant.	Medium sized rods arranged in pairs and bunches.	Definite colony shape with two shoulders. Short coccoid shape occurring in singles, pairs, and bunches. Arranged in matrix form when in bunches.
Gram Stain	Negative	Positive	Negative
Growth on Sucrose Substrate	Positive	Positive	Positive
Growth on Lactose Substrate	Positive	Positive	Positive
Gas Production	Negative on both sucrose and lactose.	Negative on both sucrose and lactose.	Negative on both sucrose and lactose.
Acid Production	Negative on both sucrose and lactose.	Positive on sucrose; Negative on lactose.	Negative on both sucrose and lactose.

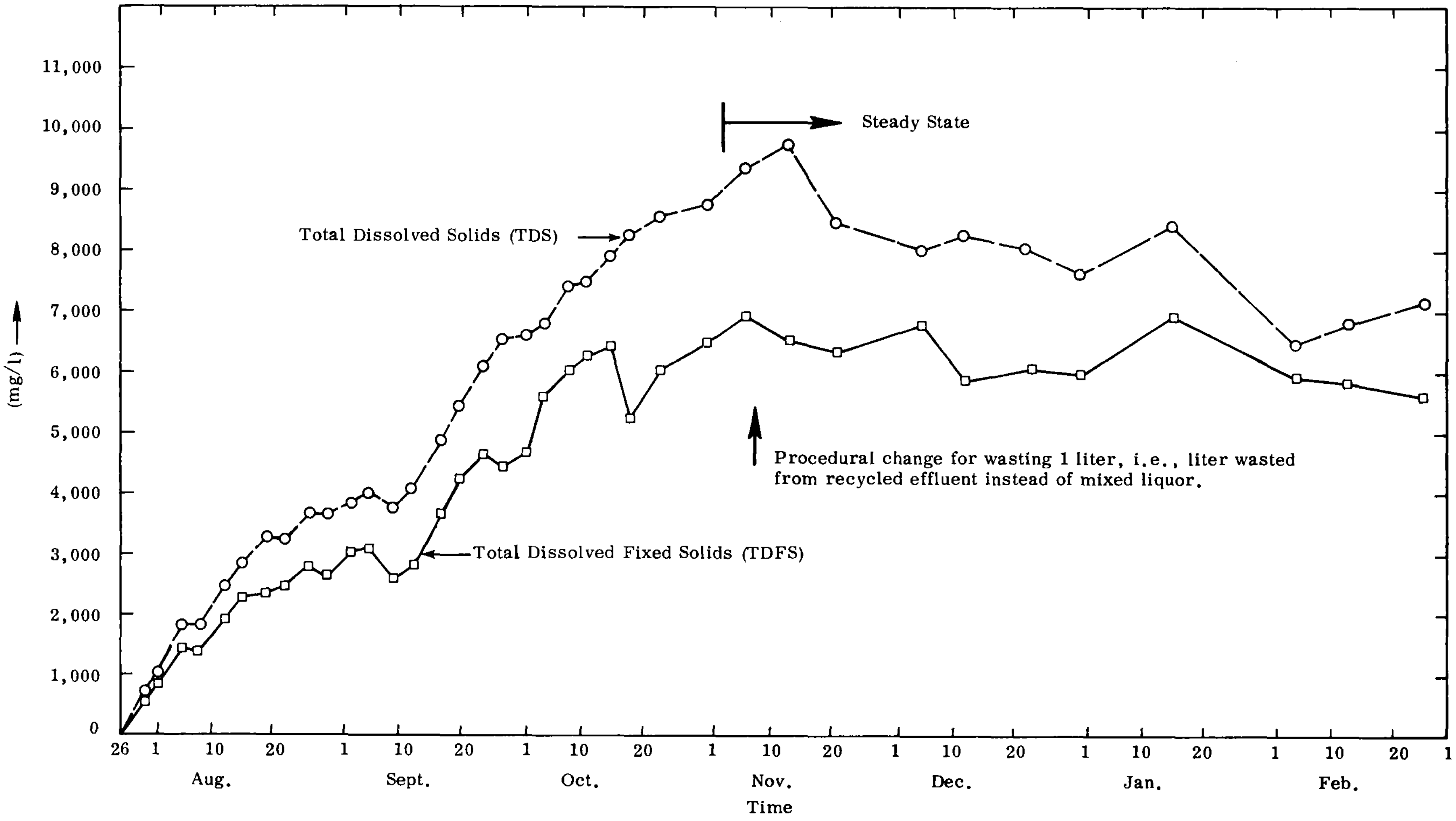


Figure 10. TDS and TDFS of mixed liquor at 95% recycle.

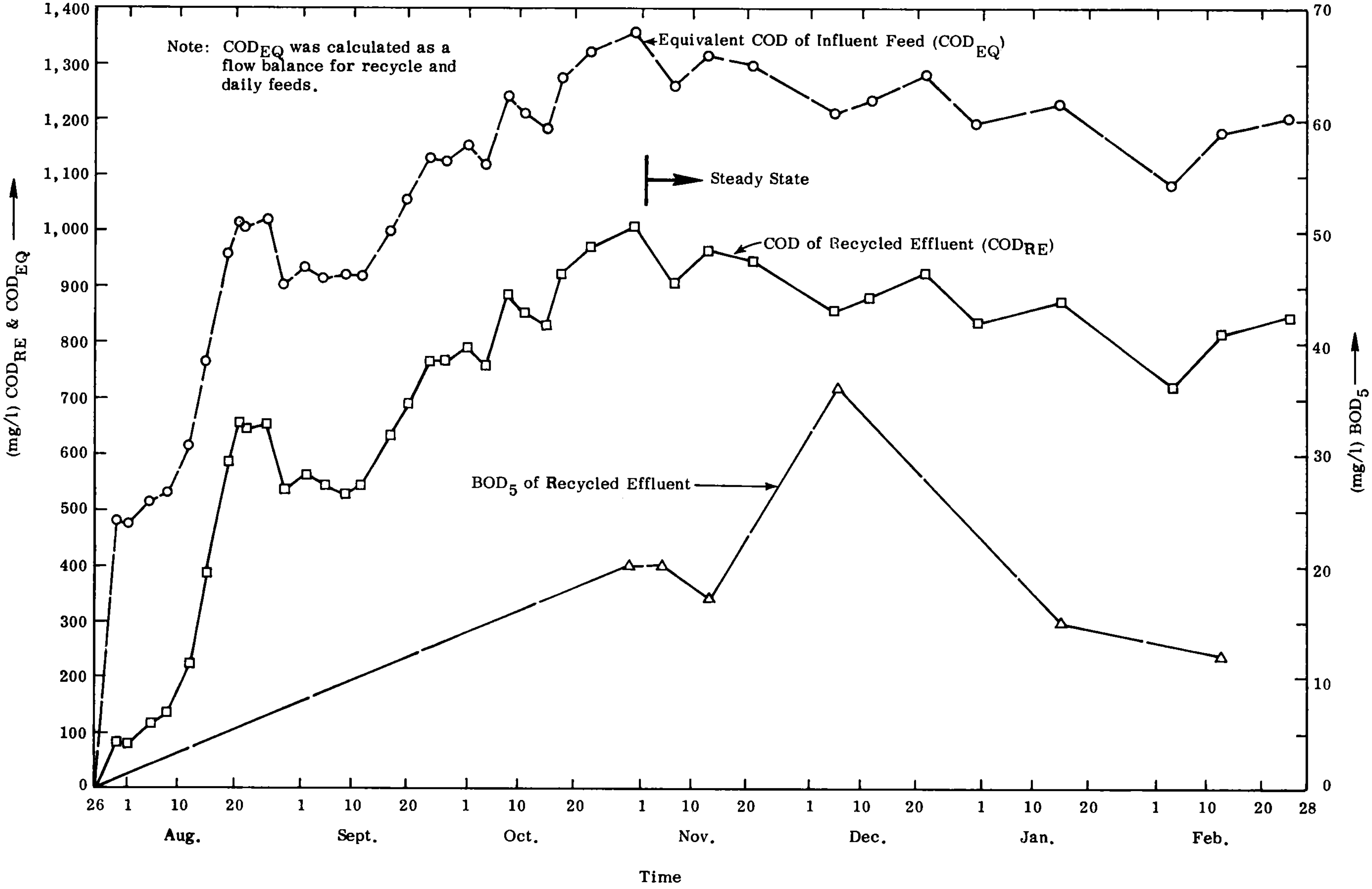
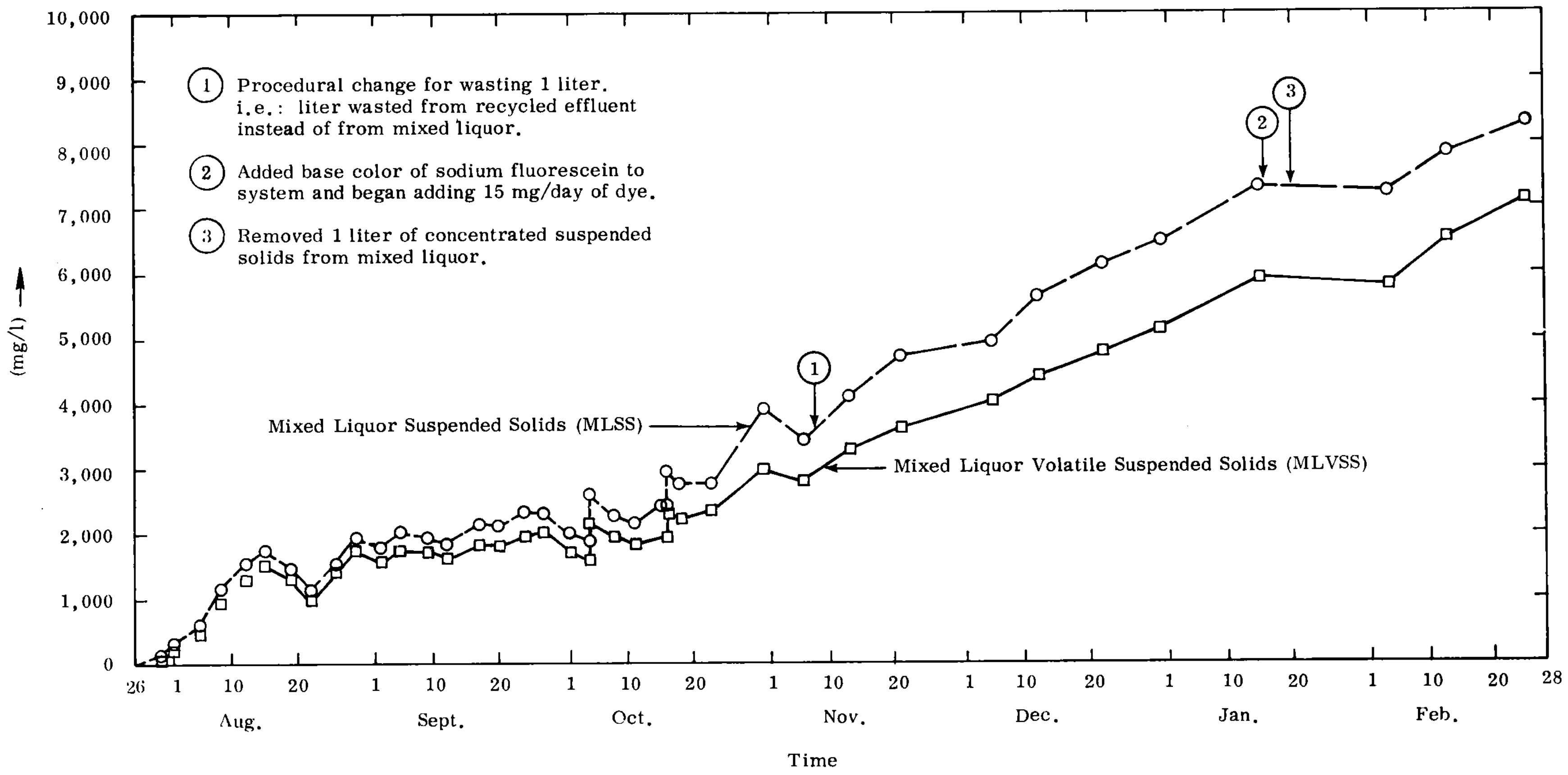


Figure 11. COD_{RE} and BOD_5 of recycled effluent at 95% recycle.



① Procedural change for wasting 1 liter. i.e.: liter wasted from recycled effluent instead of from mixed liquor.

② Added base color of sodium fluorescein to system and began adding 15 mg/day of dye.

③ Removed 1 liter of concentrated suspended solids from mixed liquor.

Figure 12. Mixed liquor concentrations at 95% recycle.

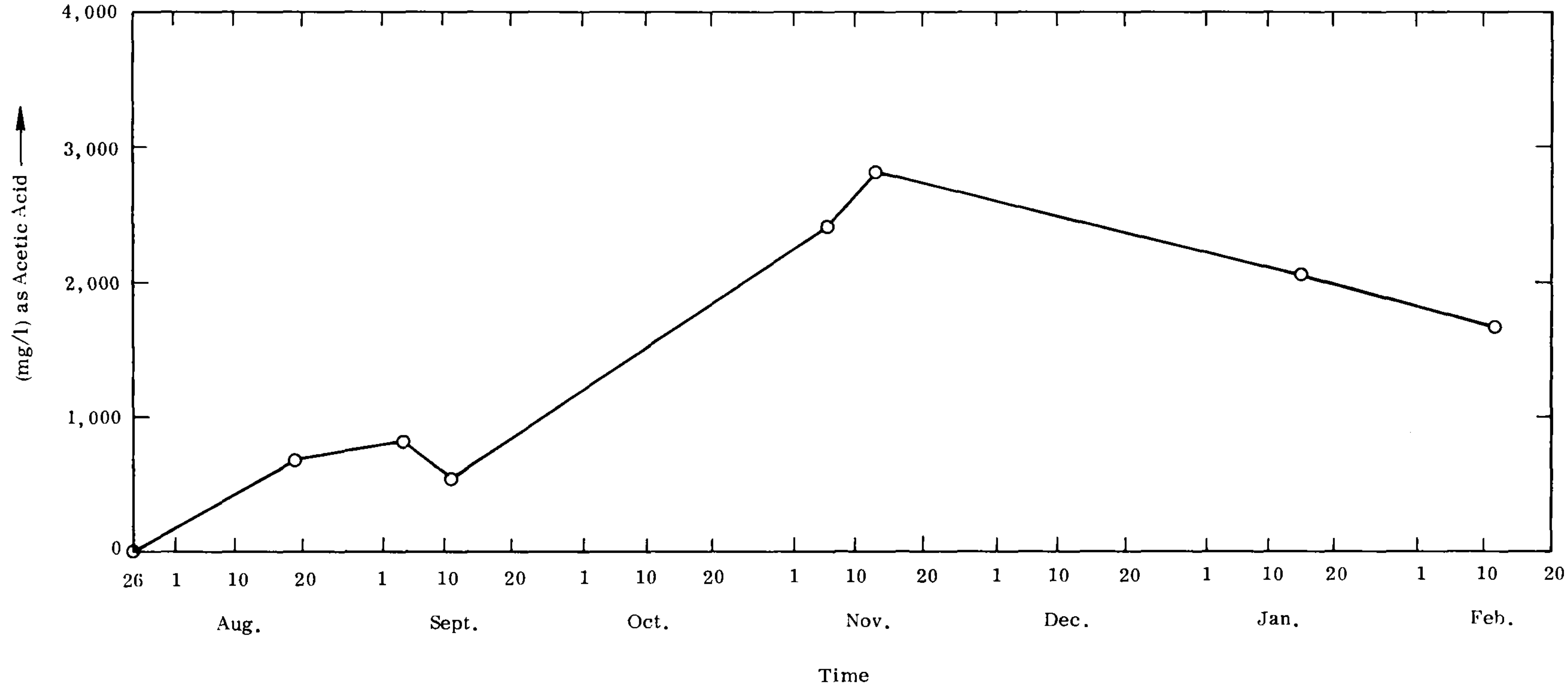


Figure 13. Volatile acids of mixed liquor at 95% recycle.

A comparison of steady state analyses for the various recycle phases of pilot plant operation is presented in Table 4. The range of treatment efficiencies for the unit in various recycle phases is compared against a typical Virginia rest area without recycle in Table 5.

The sand used for the filtration of recycled effluent was the same grade as that used by Ritz.(156) The grain size distribution for this sand is shown in Figure A9 of the Appendix. Hazen's Effective Size (E) was determined to be 0.029 cm. The coefficient of nonuniformity, also obtained from the graph of grain size distribution, was found to be 2.22.

Color Quantification and Removal

Methylene Blue

Color analysis was begun with the use of methylene blue. The results obtained were limited to visual color uptake by mixed liquor from the pilot plant. After 24 hours of aeration, it appeared that the entire 2 ml/l base dosage of methylene blue was taken up by the sludge, and no visible color remained in the supernatant.

Sauer's Blue Food Color

The first step after the switch to Sauer's blue food coloring was the selection of a base color dosage of 0.5 ml/l. The color standard curve prepared using a wavelength of 515 millimicrons (mμ) is presented in Figure A10 in the Appendix. The next step was the determination of the optimum powdered activated carbon dosage for the removal of food color (carbon to color ratio). This ratio along with the results for the determination of the optimum contact time are presented in Appendix Table A2. The concluding analysis with food coloring was a breakthrough curve run with colored tap water and GAC 400, as shown in Appendix Figure A11. From this curve, visible color breakthrough occurred at 4 liters with a carbon to color ratio of $\frac{\text{12.4 gm GAC 400}}{\text{ml food color}}$.

Sodium Fluorescein

The base color dosage selected for sodium fluorescein was 15 mg/l. The color standard curve (Figure 14) for the quantification of this dye was made using a wavelength of 486 mμ. A graph relating platinum-cobalt color units to color concentration is presented in Figure 15. Before any dye was applied, inherent color was quantified in terms of sodium fluorescein color concentration and platinum-cobalt color units (Table 6). The color uptake by mixed liquor from the Fairfield rest area and the dissipation of color from tap water with exposure to sunlight are shown by Figures 16 and 17.

Table 4. Laboratory Pilot Plant Effluent Quality
At Various Recycle Rates

PARAMETER[a]	SYMBOL	90%[b]	0%	95%	95% with color
1 Biochemical Oxygen Demand	BOD	14	8.5	15	12
2 Chemical Oxygen Demand	COD	155	109	875	846
3 Total Dissolved Solids	TDS	5920	486	7644	7152
4 Total Dissolved Fixed Solids	TDFS	3860	365	5980	5572
5 Percent Fixed of Dissolved Solids	% FIXED	65.2	75.1	78.2	77.9
6 Total Kjeldahl Nitrogen	TKN	128	45.5	--	210
7 Ammonia Nitrogen	NH_3-N	83	38.5	--	102
8 Mixed Liquor Suspended Solids	MLSS	7100	1726	7362	7846
9 Mixed Liquor Volatile Suspended Solids	MLVSS	5900	1505	5936	6528
10 % Volatile of Mixed Liquor	% VOL	83.1	87.2	80.6	83.2
11 pH		5.4	5.6	6.2	6.2
12 Alkalinity	ALK	10	26.3	346	314
13 Volatile Acids (mixed liquor)	VA	635	120	2032	1669
14 Sludge Volume Index	SVI	36.0	35.3	38.7	38.9
15 BOD (mixed liquor)	BOD (m/l)	--	--	676	684
16 COD (mixed liquor)	COD (m/l)	--	2355	8669	9962
17 Chlorides	Cl^-	597	--	1170	--
18 Efficiency BOD Removal	EFF. (BOD)	99.5	96.9	99.7	99.8
19 Efficiency COD Removal	EFF. (COD)	96.1	72.8	89.1	89.4

(a) All results except pH expressed in mg/l

(b) Analysis run before addition of sodium carbonate

Table 5. Comparison Table for Treatment Efficiencies.

	Typical Existing Rest Area Without Recycle (1)		Pilot Plant Without Recycle (2)		Pilot Plant at 90% Recycle (3)		Pilot Plant at 95% Recycle (4)	
	BOD_5	COD	BOD_5	COD	BOD_5	COD	BOD_5	COD
Influent Range $(\frac{mg}{l})$	105-240	202-945	270	400	270	400	270	400
Effluent Range $(\frac{mg}{l})$	1-4	4-101	8-26	37-109	8-28	135-225	15-36	830-1360
Efficiency Range (%)	98.3-99.0	89.3-98.0	90.4-97.0	72.8-90.8	99.0-99.7	94.4-96.6	99.3-99.7	83.0-89.6

(1) Information taken from summary data for wastewater quality rest station no. 21, Montgomery County: Table 5 of "The Feasibility of Recycling Grey Water at Highway Rest Stations" by William B. Bott, unpublished.

(2) Information gathered from extreme values obtained during two-month period of pilot plant operation at 0% recycle. June 1974 - July 1974.

(3) Information gathered from extreme values obtained during three month period of pilot plant operation at 90% recycle steady state. February 6, 1974 - May 13, 1974.

(4) Information gathered from extreme values obtained during three month period of pilot plant operation at 95% recycle steady state. October 15, 1974 - January 15, 1975

Table 6. Quantification of Inherent Color Before the Addition of Sodium Fluorescein

Base Wavelength = 486 mμ

Sample	Equivalent Sodium Fluorescein Color Concentration	Corresponding Platium Cobalt Color Units
1) Threshold of Visible Color	0.3 mg/l	60
2) Raw Influent Feed Fairfield Rest Area	0.2 mg/l	50
3) Synthetic Feed for Pilot Plant	0.4 mg/l	70
4) Recycled Effluent for Pilot Plant	0.8 mg/l	110

All samples were filtered to remove suspended material prior to spectronic analysis.

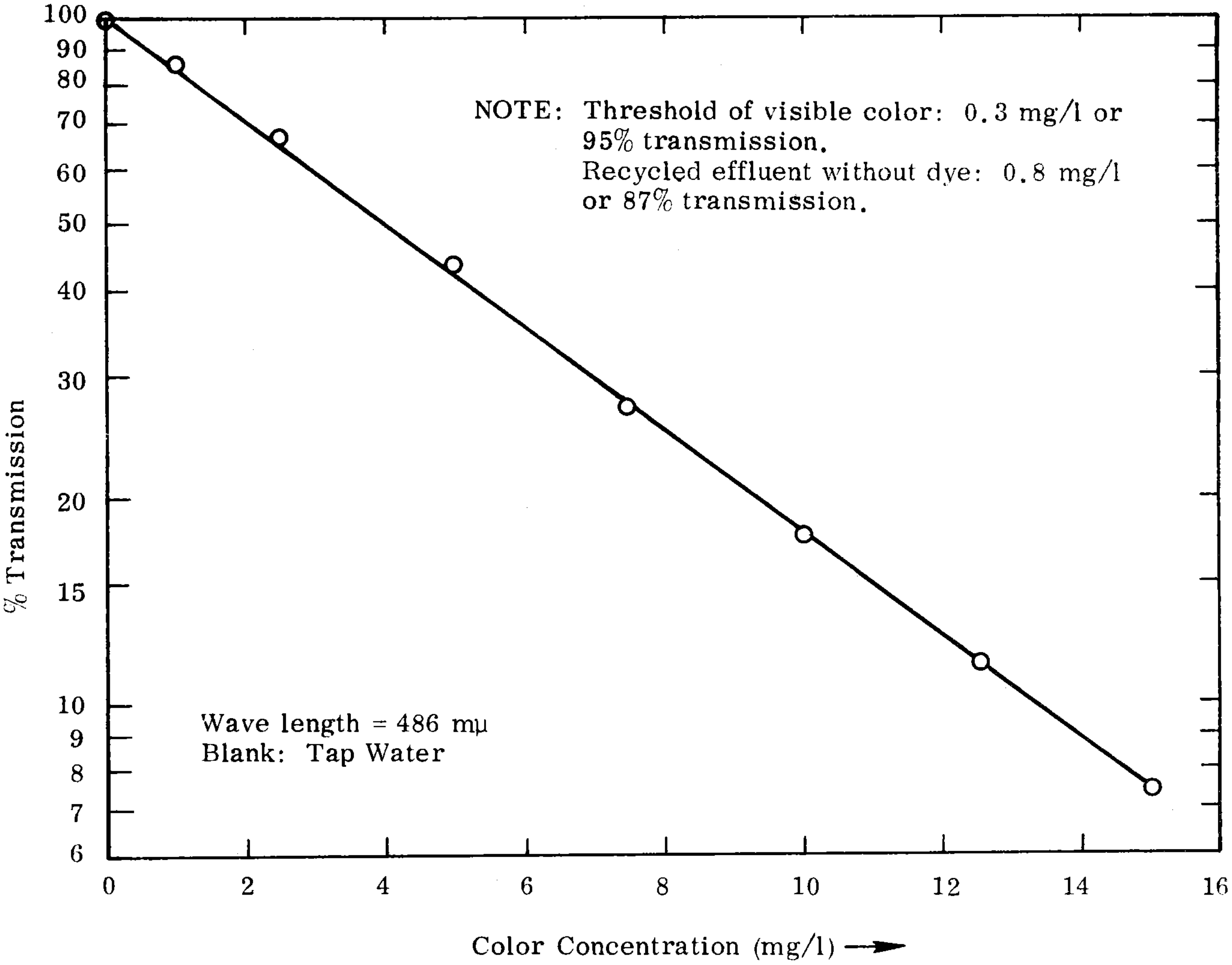


Figure 14. Color standard curves for sodium fluorescein.

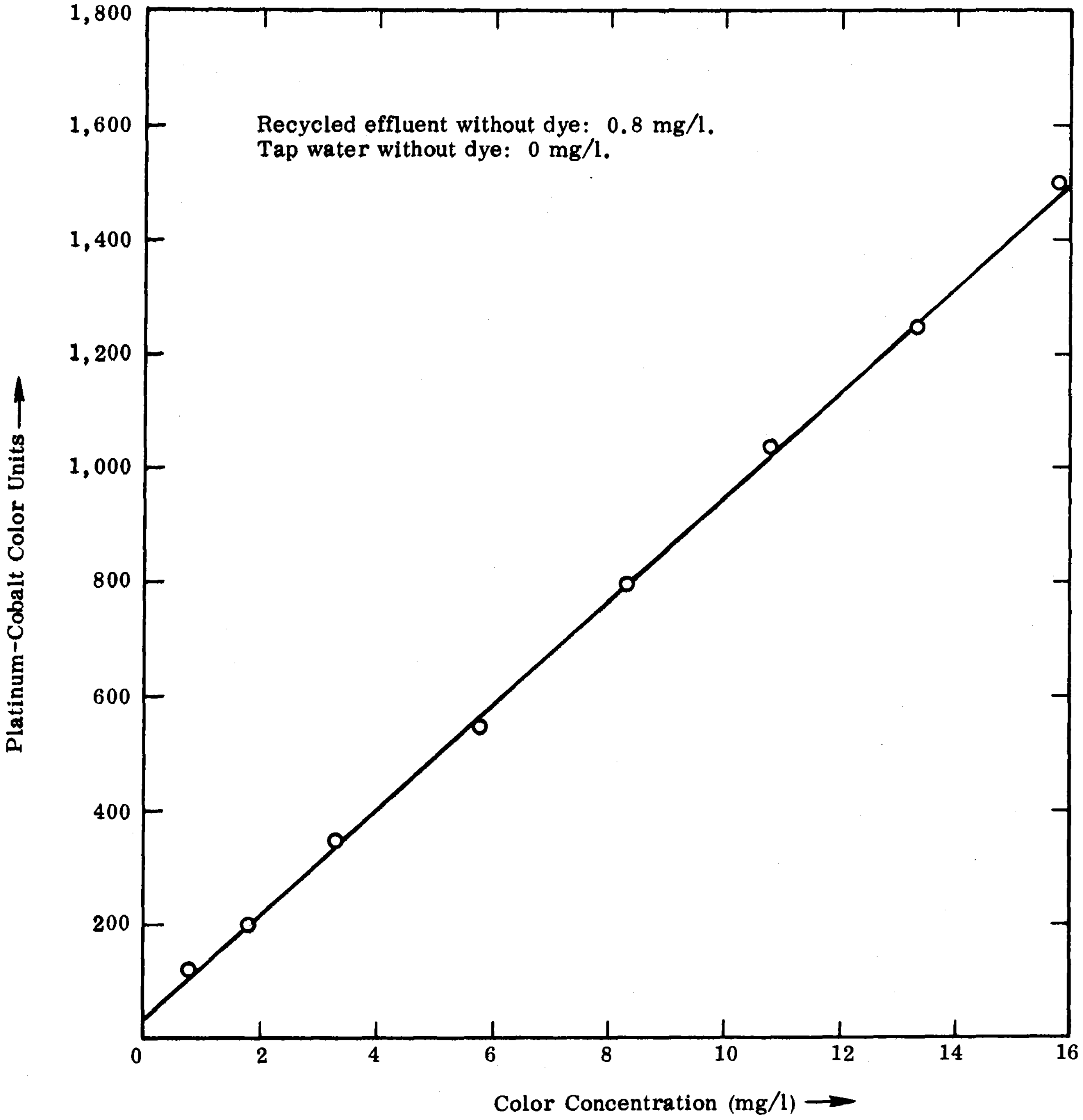


Figure 15. Sodium fluorescein color quantification scale.

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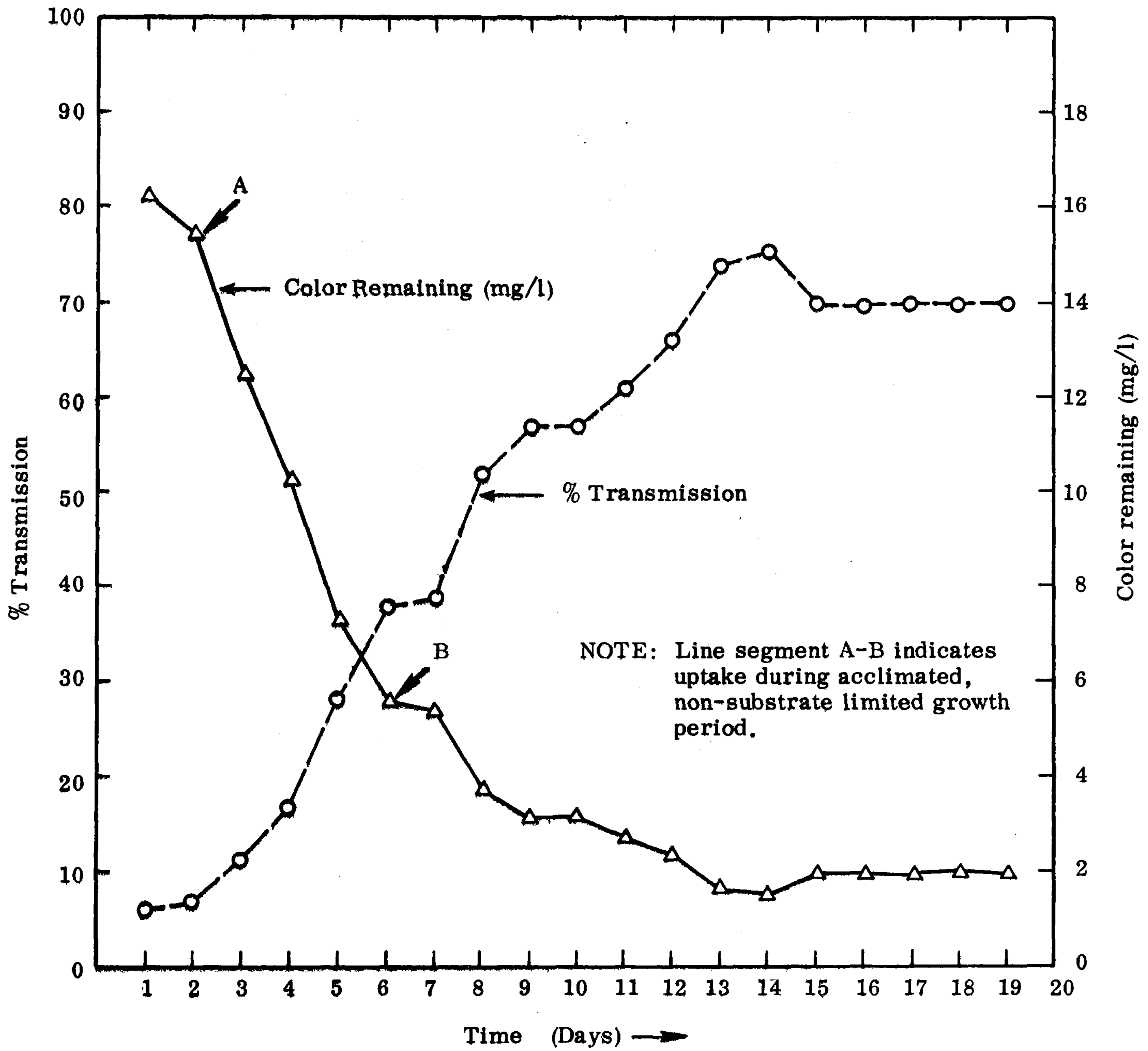

Figure 16, Sodium fluorescein uptake by Fairfield mixed liquor.

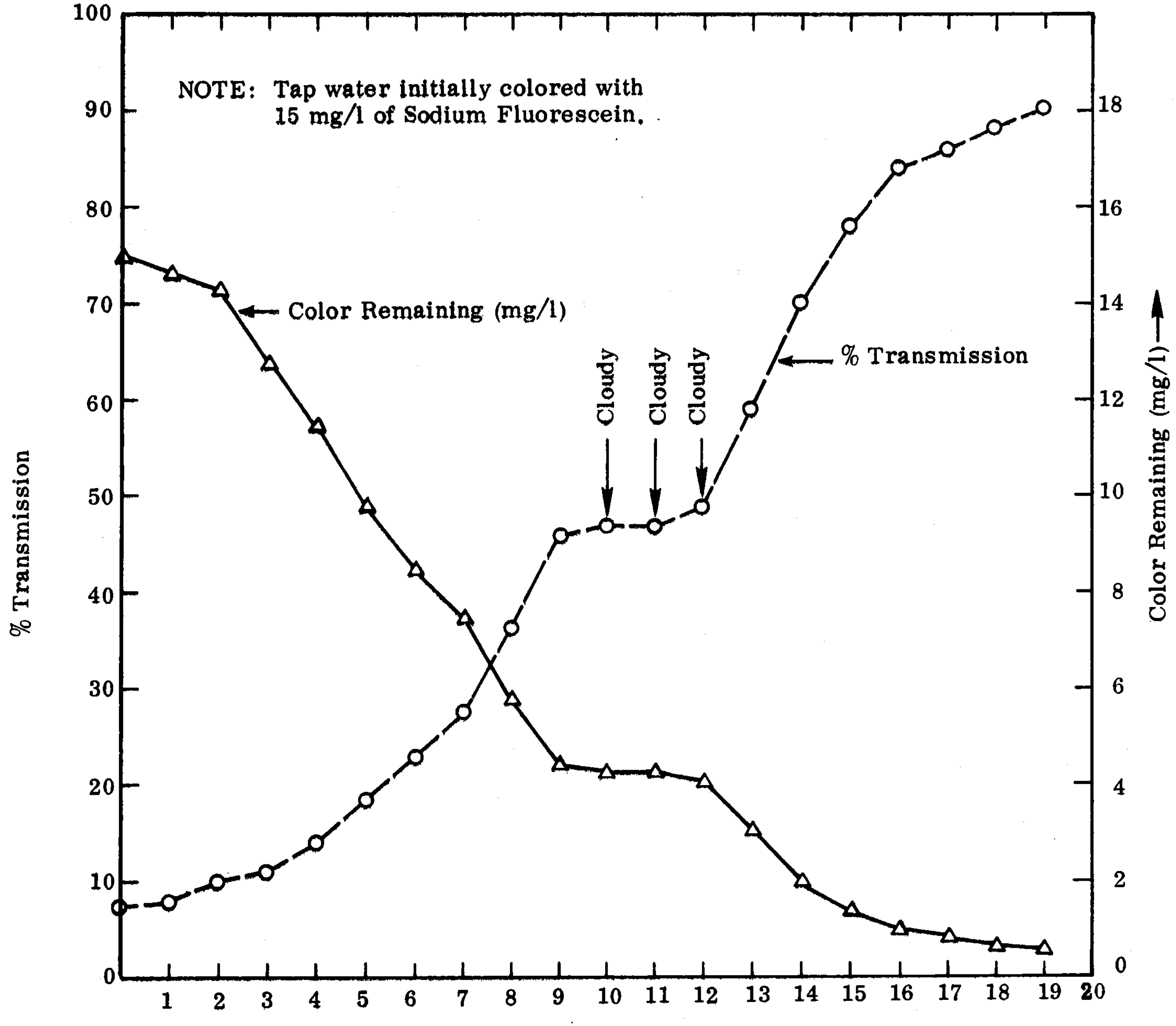

Figure 17. Sodium fluorescein fading with sunlight.

Freudlich isotherms were prepared for the removal of sodium fluorescein and COD from recycled effluent with GAC 400. The batch isotherm results for color removal are shown in Figure 18, and similar results for COD are presented in Figure A12 of the Appendix.

Sodium fluorescein breakthrough color curves were run with both tap water and recycled effluent passed through GAC 400. The breakthrough curve with tap water is presented in Figure A13 of the Appendix. Figure 19 is the breakthrough curve for recycled effluent colored with the base dosage of sodium fluorescein. Breakthrough occurred at a filtered volume of 5 liters, producing a color to carbon ratio (X/M) of 0.0042 $\frac{\text{gm color}}{\text{gm GAC 400}}$. During this same column run, breakthrough data for COD and dissolved solids were collected. These results are found in Figures A14 and A15 of the Appendix.

Evaporation Results

Table A3 in the Appendix is a summary of information collected by means of manufacturer's correspondence for evaporation desalination equipment. The climatological data used are listed in Table A4 of the Appendix. Projections for evaporation in the holding pond can be found in Table 7.

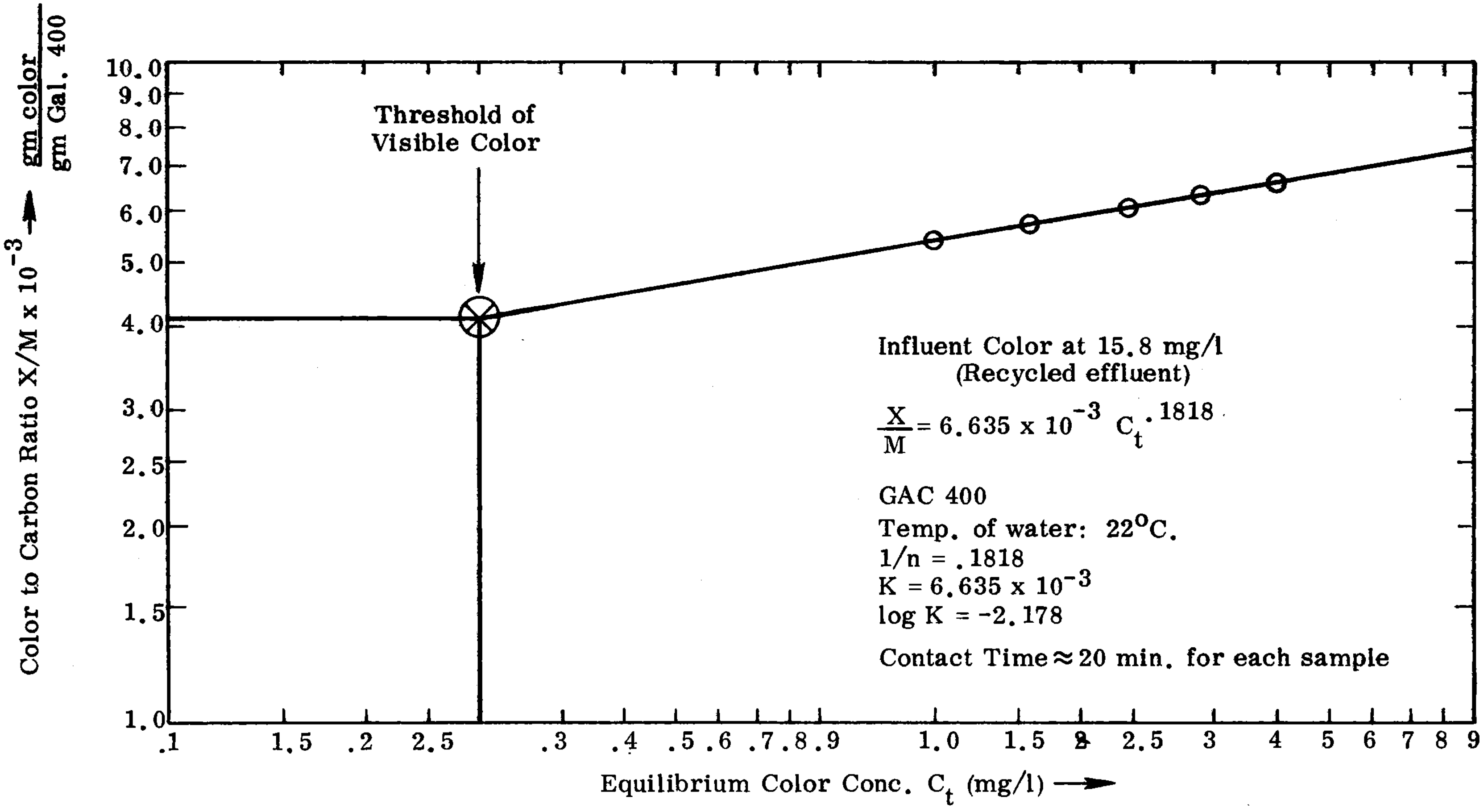

Figure 18. Freudlich isotherm for sodium fluorescein removal from recycled effluent.

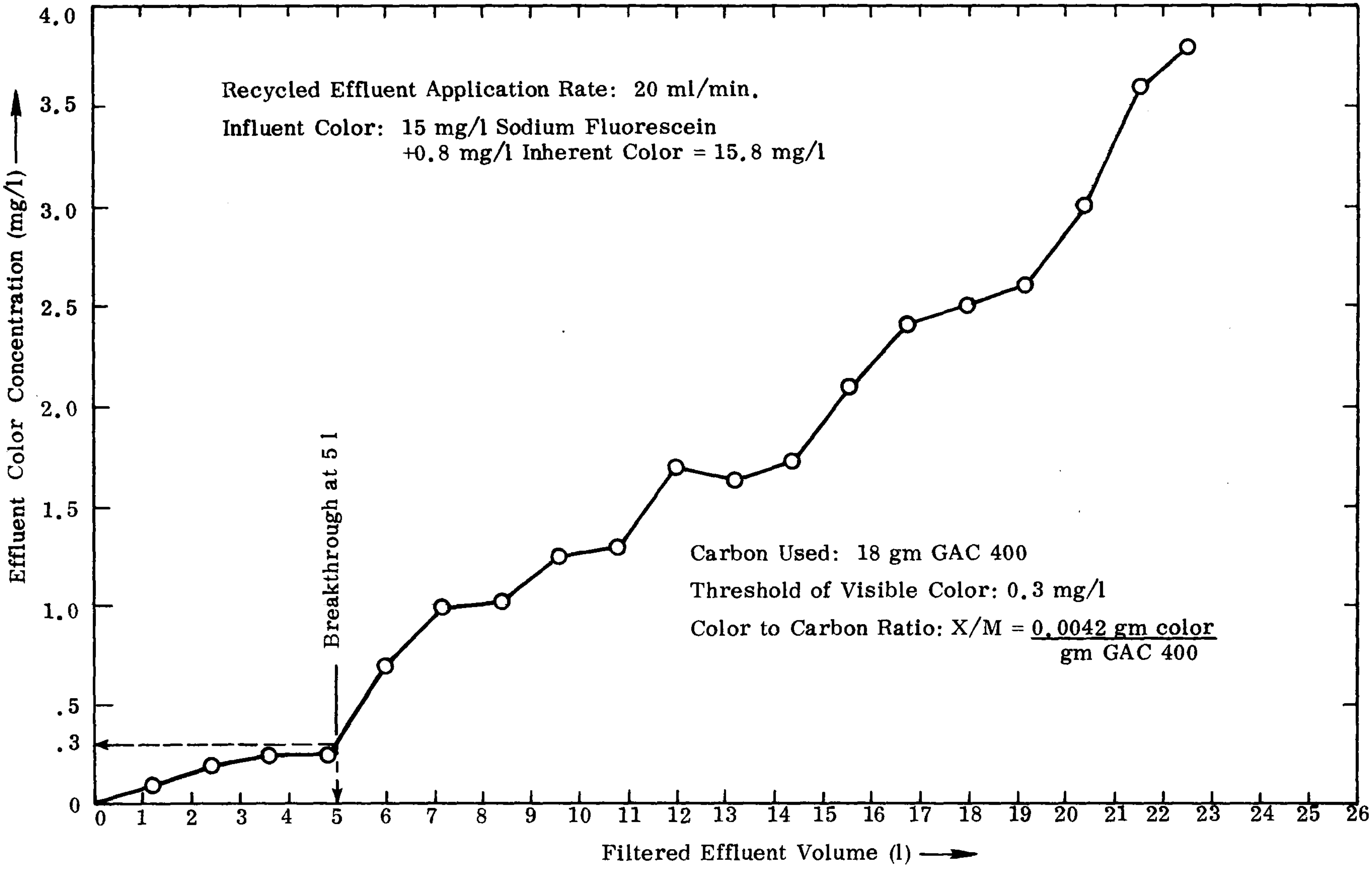

Figure 19. Sodium fluorescein color breakthrough curve.

Table 7. Projected Annual Evaporation Losses From the Fairfield Rest Area

1. Existing Water Surface Area of Holding Pond:

   $5400\ ft^2 = 777600\ in^2 = 496.8\ m^2$

   All calculations are based on the assumption that the pond remains filled so that this area remains available for evaporation.

2. Flow Rate Assumptions:

   1) Average daily flow for June-August is 10,000 gpd - 37,850 l/day
   2) Average daily flow for March-May and September-November is 6,000 gpd - 22,710 l/day
   3) Average daily flow for November-March is 3,000 gpd - 11,355 l/day

3. Evaporation Assumptions:

   1) Case 1: Holding pond remains uncovered and net monthly evaporation is difference between average evaporation less average rainfall
   2) Case 2: Holding pond is covered with a transparent roof: effects of rainfall neglected. Net monthly evaporation is average evaporation taken from Appendix Table A4

4. Sign Convention:

   (-) indicates surplus water accumulated in holding pond

   (+) indicates net evaporation loss in holding pond

5. Sample Calculation:

   using month of October

   $$777600\ in^2 \times (+)\ 0.54\ in = 419904\ in^3$$

   $$419904\ in^3 \times \frac{ft^3}{1728\ in^3} \times \frac{7.48\ gal}{ft^3} = (+)\ 1818\ gal\ evaporated$$

   for 90% recycle:

   monthly flow:

   $$31\ days \times \frac{600\ gal}{day} = (-)\ 18600\ gal\ surplus\ in\ pond$$

   net surplus water for the month of October

   $$-18600 + 1818 = (-)\ 16782\ gal\ surplus\ water\ for\ October\ at\ 90\%\ recycle$$

	Case One Uncovered Holding Pond			Case Two Covered Holding Pond		
Month	Net Evaporation (gallons)	Surplus Water (gallons)		Net Evaporation (gallons)	Surplus Water (gallons)	
		90% Recycle	95% Recycle		90% Recycle	95% Recycle
January	- 4914	- 14214	- 9565	+ 3433	- 5867	- 1217
February	- 4006	- 12406	- 8206	+ 5184	- 3216	+ 684
March	+ 505	- 18095	- 8795	+ 10839	- 7761	+ 1539
April	+ 3703	- 14297	- 5297	+ 14238	- 3762	+ 5238
May	+ 6126	- 12474	- 3174	+ 17840	- 760	+ 8540
June	+10435	- 19565	- 4565	+ 20297	- 9703	+ 5297
July	+10839	- 20161	- 4661	+ 20230	-10770	+ 4730
August	+ 9627	- 21404	- 5873	+ 18681	-12319	+ 3181
September	+ 2424	- 15576	- 6576	+ 14036	- 3964	+ 5036
October	+ 1818	- 16782	- 7482	+ 9391	- 9209	+ 91
November	- 1043	- 19043	-10043	+ 7775	-10225	- 1225
December	- 3568	- 12868	- 8218	+ 4780	- 4520	+ 130
Annual Totals	+31946	-196885	-82454	+146724	-82076	+32024

DISCUSSION OF RESULTS

Pilot Plant Operation

An important criterion for any activated sludge process is the ability to buffer itself from slug loads which might drastically alter the pH of the system. Without sufficient alkalinity to provide this buffering capacity, the biomass would be unable to withstand a sudden change in pH, and as a result, treatment efficiency would suffer. Although the pilot plant operating at 90% recycle did not receive any shock loads, the low range of pH and alkalinity values had the potential for upsetting the system. To adjust the pH and alkalinity, sodium carbonate was selected as a buffer primarily because the monovalent ion, sodium, would not increase the total hardness of the recycled water. Since no precipitate was visible, it was assumed that the 10 gm/day of soda ash went into solution. This assumption is substantiated by the rise in TDS as shown by Appendix Figure A2. A further consequence of soda ash addition was sludge bulking (Figure 9). The rising Sludge Volume Index (SVI) was indicative of future biomass retention problems. The higher the SVI, the lower the concentration of suspended solids that could be maintained in the mixed liquor without loss of biomass to the effluent. To bring the rise in SVI under control, the addition of soda ash was terminated, and within five days the SVI decreased to a value where the loss of suspended solids was no longer imminent. However, the pH and alkalinity problem remained unsolved.

With the revised feed, 95 percent recycle steady state values for total dissolved solids (TDS) approached the level predicted by the materials balance multiplying factor (MBMF).(157)

Example

Based on a daily flow rate of 20 l at 95 percent recycle, 5 percent of the flow is lost each day from the system and the MBMF = 20. From Appendix Table A1 the TDS added per day was 18.475 gm. The assumption is made that this entire mass of organics, nutrients, and salts goes into solution. The total system volume = 42 l, which includes the aeration vessel (20 l), secondary clarifier (2 l), and the storage or response volume (20 l).

The once-through value is determined by

$$\frac{18.475 \text{ gm TDS/day}}{42 \text{ l}} = 440 \text{ mg/l}_{\text{/day}}\text{TDS}$$

At 95 percent recycle the resulting TDS buildup should be approximately 20 times this value, i.e.:

400 mg/l TDS X 20 MBMF = 8800 mg/l TDS

The mean value achieved at steady state for 95 percent recycle was 8191 mg/l (Figure 10), which is comparable to the predicted value. The difference between the predicted and actual values is that portion of the TDS which is both used for respiration and transferred into cellular material. Regardless, this range of concentrations yields a water of brackish quality.

The COD of the recycled effluent (COD_{RE}) at 95 percent recycle is a good indication of the large buildup of refractory organics. Although these organics exert a chemical oxygen demand, they are virtually inert to biological activity as reflected by the much lower effluent BOD (Figure 11). Therefore, the major organic loading in terms of COD is from the non-degraded recycled effluent rather than the daily feed.

Example

The equivalent influent COD (COD_{EQ}) for the aeration unit is calculated from a flow balance for recycle and daily feeds.

COD_{RE} = 850 mg/l typical effluent value

$COD_{DAILY\ FEED}$ = 400 mg/l synthetic feed

For 95 percent recycle:

$$COD_{EQ} = \frac{(400\ \text{mg/l})(20\ \text{l daily flow rate}) + (850\ \text{mg/l})(19\ \text{l daily recycle flow rate})}{20\ \text{l total daily flow rate}}$$

COD_{EQ} = 1208 mg/l through the aeration unit.

this is roughly a 300 percent increase over the loading produced by the daily feed. The organic loading in terms of BOD_5, however, is reflected more in the daily feed.

Example

BOD_{RE} = 15 mg/l typical effluent value

$BOD_{DAILY\ FEED}$ = 270 mg/l synthetic feed

For 95 percent recycle:

$$BOD_{EQ} = \frac{(270\ \text{mg/l})(20\ \text{l daily flow rate}) + (15\ \text{mg/l})(19\ \text{l daily recycle flow rate})}{20\ \text{l total daily flow rate}}$$

BOD_{EQ} = 284 mg/l through the aeration unit.

It is seen that the equivalent BOD (BOD_{EQ}) loading produced by recycle is only 5 percent greater than that for the daily feed. As a result, the food to mass ratio (BOD_{EQ}/MLVSS) would be only slightly higher with 95 percent recycle. Therefore, the biomass growth rate in terms of suspended solids accumulation would also increase to only a small degree. To keep the level of suspended solids within a manageable limit, sludge wastage would then be required on only a slightly greater volume basis than without recycle. The following example illustrates this point.

Case 1: Without Recycle

Assume a flow rate (Q) of 10,000 gpd, a sludge return rate (R) of 5990 gpd, and a sludge age of 180 days. Using equations 8 and 11 previously presented a sludge wastage rate of 28 gal/day is determined.

Case 2: With 95 Percent Recycle

Assume an upper manageable limit for MLSS as 8000 mg/l, a sludge accumulation rate of 1340 mg/l/month (Figure 12), and a flow rate of 10,000 gpd. A sludge wastage rate of approximately 56 gal/day is determined. Although this figure is twice that without recycle, it is felt that this accumulation rate of 1340 mg/l/month obtained from the pilot plant represents an upper limit because of the characteristics of the synthetic feed. The strength of this feed was purposely designed to simulate the worst possible influent conditions, and for this reason, sludge wastage with 95 percent recycle in the field would probably not be as high as predicted above.

Color Quantification and Removal

Another characteristic of the synthetic feed was an inherent color (equivalent to 0.4 mg/l of sodium fluorescein dye) that was twice that of influent sewage sampled at the Fairfield rest area (Table 6). This higher concentration of inherent color again suggests that the pilot plant experienced the worst possible conditions for influent feed. It follows, then, that synthetic recycled effluent produced from this feed contained more inherent color (0.8 mg/l) than would be anticipated from recycled effluent produced in the field.

Once the biomass has become acclimated to the sodium fluorescein dye in the system, approximately 15 percent of the base color can be expected to be degraded during the 24-hour period in the reactor. This 15 percent reduction is approximated from Figure 16. The slope of line segment AB represents the rate of color uptake for an acclimated, nonsubstrate-limited growth period. If it is further assumed that field flow arrangements utilizing 15-day holding ponds will remain unchanged after the application of color and recycle modifications, it is anticipated that the residual sodium fluorescein present in the discharge portion will be only a small fraction of the base color. In 15 days, exposure to sunlight should deteriorate the color concentration by at least 80 percent (Figure 17). If the base dosage of 15 mg/l is used in the field, these two considerations combined will leave perhaps 1 to 2 mg/l of residual color to be removed by activated carbon.

The batch isotherm plot for the removal of sodium fluorescein from recycled effluent (Figure 18) suggests that GAC 400 is an efficient carbon for color removal. The gradual slope of the isotherm indicates it has a fairly constant loading (color to carbon ratio) over a wide range of residual color concentrations. The pilot column runs with both colored tap water and recycled effluent were subject to the following physical limitations during testing:

1. The column diameter used was too small to assume that short circuiting was negligible.

2. The height of the carbon in the column was less than that required for the absorption zone. This was because the availability of carbon was limited.

3. The supply of raw recycled effluent to be used as column influent was limited, and the breakthrough test could not be run to exhaustion.

Since these limitations may have led to unreliable results, the pilot column cannot be used for direct scale-up for field design. The results presented in Figure A13 and Figure 19 reflect the inadequacies of the pilot carbon column as seen from the gradual slopes for the breakthrough curve.

Considering these inadequacies, only a rough idea of the amount of carbon required daily can be determined from the breakthrough point for visual color.

Example: Worst Possible Condition

Assume:

1. No fading or biological uptake of sodium fluorescein occurs. (Short circuiting.) The base color concentration of 15 mg/l appears as the column influent.
2. A color to carbon ratio of 4.2 mg color/gm GAC 400.
3. Visible color breakthrough occurs at 5 l of filtered effluent 15 mg/l x 5 l = 75 mg of color removed before carbon is replaced.

$$75 \text{ mg color} \times \frac{\text{gm GAC 400}}{4.2 \text{ mg color}} = 17.9 \text{ gm GAC used for 5 l}$$

At 95 percent recycle 500 gpd (1893 l/day) would be treated daily

$$\frac{17.9 \text{ gm GAC}}{5 \text{ l}} = \frac{x \text{ gm}}{1893 \text{ l}}$$

$$x - 6775 \text{ gm} = 14.9 \text{ lb GAC 400/day}$$

at $0.15/lb GAC 400, the cost would be approximately $2.24/day to remove the color under these conditions.

The results of the biological analysis (Table 4) confirmed that acid producing (gram positive) bacteria were being grown on the sucrose base synthetic feed. These organisms, separated as Colony #2, were most predominant and were apparently the cause of pH and alkalinity problems experienced at 90 and 0 percent recycle. The majority of the carbohydrates in the synthetic feed, most notably sucrose, are readily converted to volatile acids (lactic acid) by lactic acid bacteria. This can partly explain the high production rate for volatile acids (Figure 13). However at 95 percent recycle, even though volatile acids were being converted from the synthetic feed, the doubled lime dosage was successful in buffering the biomass from pH changes caused by volatile acid production. Since these volatile acids are products of aerobic fermentation, they will show up as refractory compounds contributing to the effluent COD. In the field, the characteristics of the wastewater will be more variable and will not be primarily sucrose based, as was the synthetic waste. Consequently, it is anticipated that volatile acid production will not be as severe as in the pilot plant.

The addition of the base concentration of sodium fluorescein to the pilot plant had no significant effect on treatment efficiency (Table 4). Although minor fluctuations in dissolved solids and effluent COD persisted, no appreciable changes occurred. The summary of pilot plant performance with and without recycle (Table 5) shows that treatment efficiency, in terms of a biologically degradable effluent, will not be adversely affected by high recycle ratios. In fact, the range of effluent BOD_5 values with 95 percent recycle is closely comparable to values obtained from the pilot plant without recycle. The same relationship between the variance of BOD_5 and COD_{RE} is expected in the field, and the overall performance of the rest area recycle system once it has reached steady state should exceed that of the pilot plant.

Evaporation

The natural process of solar evaporation should be the most practical means of final effluent volume reduction from a recycle facility. Table 7 provides several predictions for annual water surplus at the Fairfield rest area under different evaporating conditions. It appears that with 95 percent recycle, it would take at least 18 months to fill an uncovered 15-day holding pond. In this case either controlled discharge or occasional withdrawal by tank trucks would alleviate the need for daily discharge, and permit the rest area to remain within state standards. However, if a cover is provided the natural solar evaporation process should completely eliminate all surplus water at the rest area, and with this transparent cover employed, even color removal would not be required. For complete zero discharge this alternative should therefore be considered.

Another means of handling the final 500 to 1,000 gallons per day of effluent remaining at a recycle facility is by a capital investment for evaporation-desalination equipment. Table A3 in the Appendix presents several systems which apply current technology to concentrate the waste stream and reduce the volume of effluent discharged. Although this summary is by no means comprehensive, it appears that a variety of capable equipment is available at a per unit cost of between $10,000 and $13,000. In addition, operating costs, which are not listed in the table, must be considered. The submerged combustion unit may be the system which is most compatible with the needs of a rest area. It could be used to supplement the natural solar evaporation process, and is the only process listed which produces no concentrated stream that ultimately must be disposed of.

CONCLUSIONS

1. Based on the use of synthetic waste, it is possible to produce a water of sufficient quality for toilet flushing purposes by recycling 95 percent of the effluent from rest area wastewater treated by the extended aeration process. This wastewater can be expected to be brackish in quality, containing dissolved solids in the range of 7,000 to 10,000 mg/l. Included will be refractory organic compounds which produce a high COD and cause inherent color accumulation.

2. Biological processes, such as extended aeration, can operate effectively at dissolved solids concentrations over 9,000 mg/l which are produced by recycle and reuse of effluent.

3. Based on the rate of sludge accumulation for the pilot plant, sludge wastage for an extended aeration system employing 95 percent recycle will be required on a slightly greater volume basis than without recycle.

4. The addition of sodium fluorescein dye had no significant influence on the biological treatment efficiency of the pilot plant while operating at 95 percent recycle.

5. The removal of any residual sodium fluorescein color remaining in the recycled effluent after biological attack and exposure to sunlight can be readily accomplished by granular activated carbon adsorption.

6. Solar evaporation of impounded recycled effluent will provide several feasible alternatives to the daily discharge of wastewater from rest areas once recycle modifications have been installed.

RECOMMENDATIONS

1. A full-scale demonstration facility should be constructed at an existing rest area and the recycle system should be closely monitored for:

    a) Rates of solids accumulation in the mixed liquor,

    b) the appearance of color in the final effluent, and

    c) efficiency of biological treatment in terms of BOD_5.

2. Full-scale pilot column tests for the removal of residual color should be conducted to determine the proper quantity of granular carbon per gallon of final effluent.

3. Operating at a constant recycle rate over a year's period, a full accounting of daily influent and effluent flow rates should be made to document the annual evaporation. From this record, the feasibility of a transparent cover for the holding pond could be determined.

4. Upon the completion of the demonstration facility, a complete monitoring program should be established to study public acceptance to the use of recycled water in the toilets and urinals.

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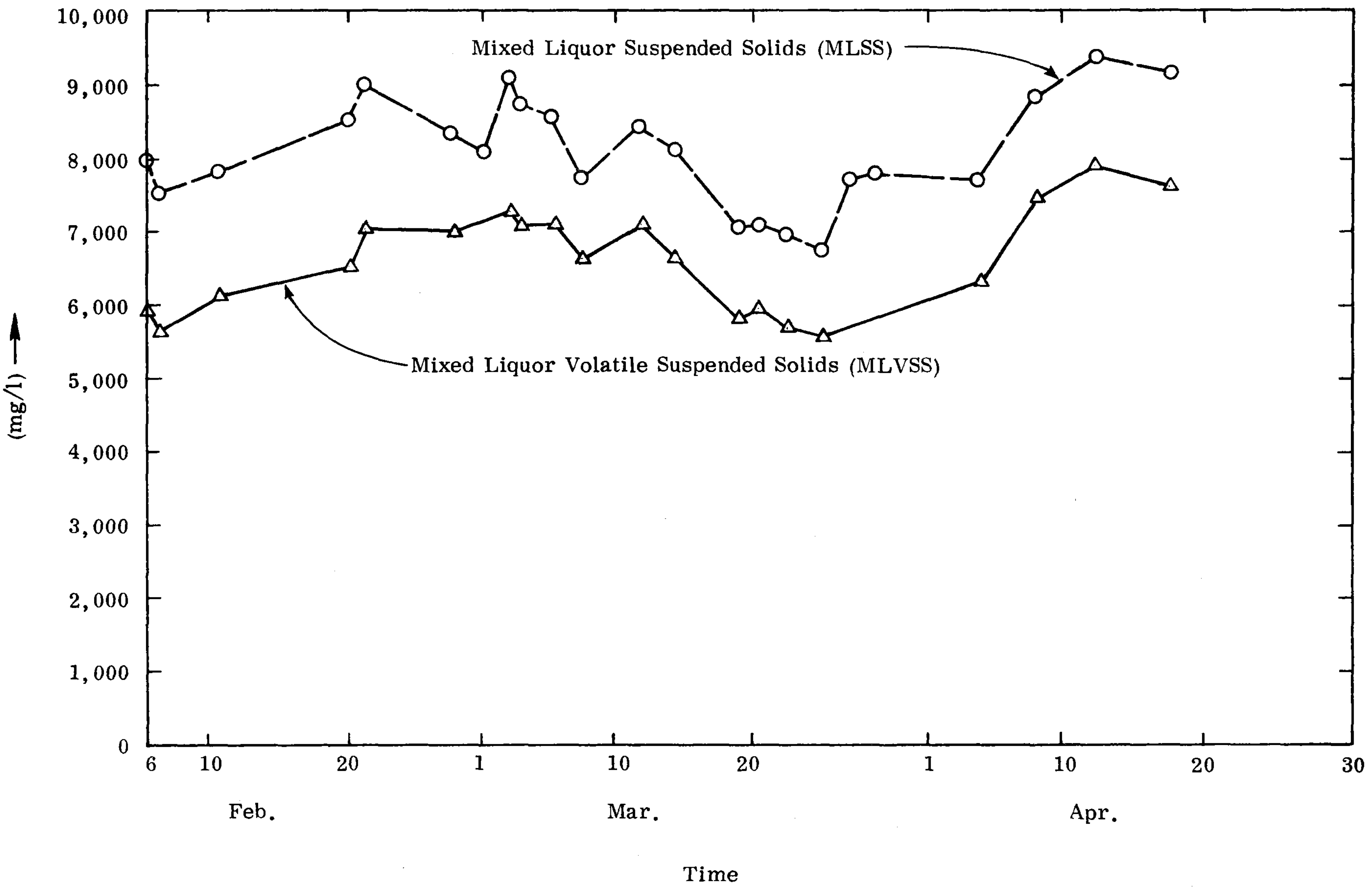

Figure A1. MLSS and MLVSS at 90% recycle.

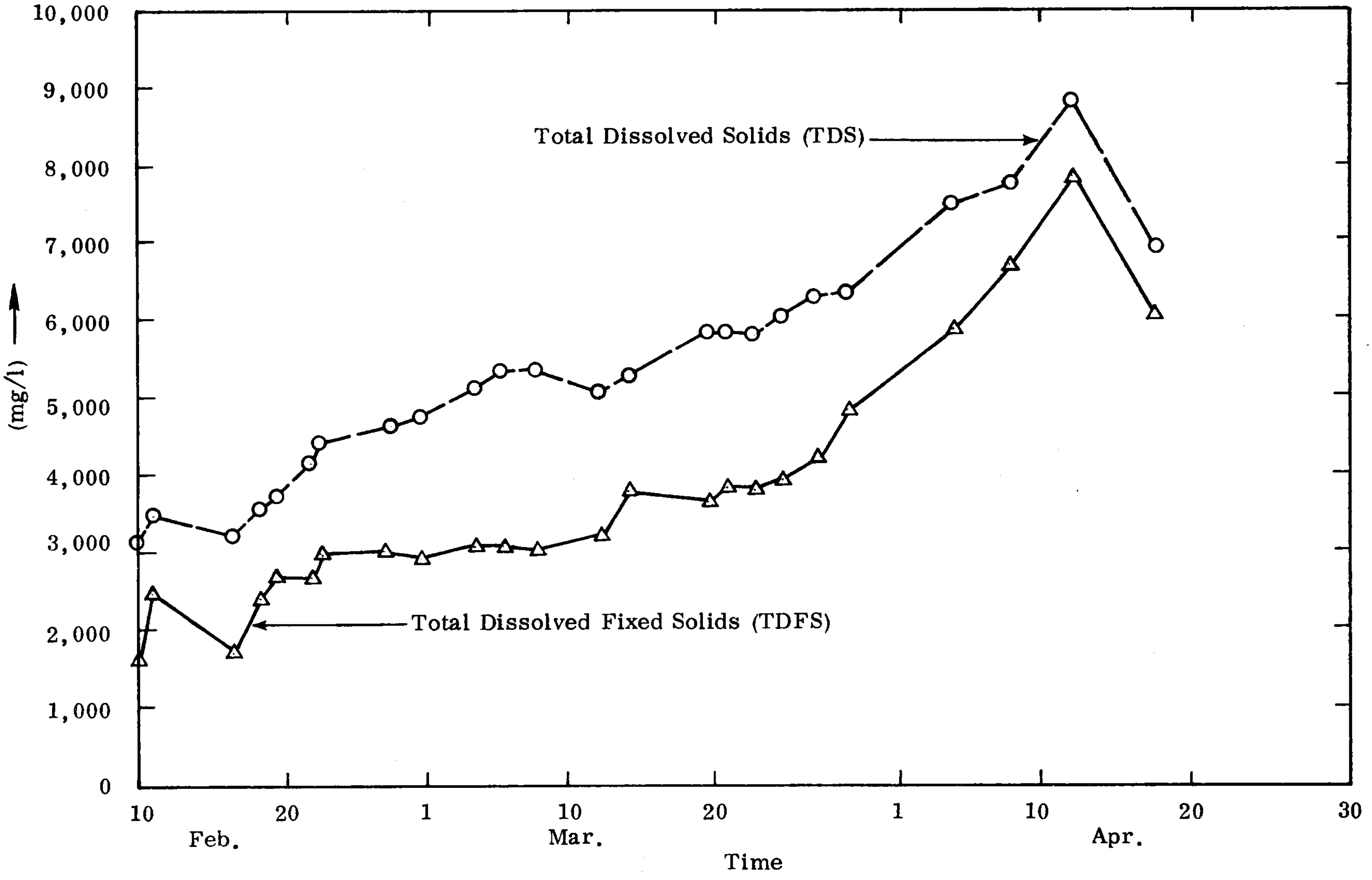

Figure A2. TDS and TDFS at 90% recycle.

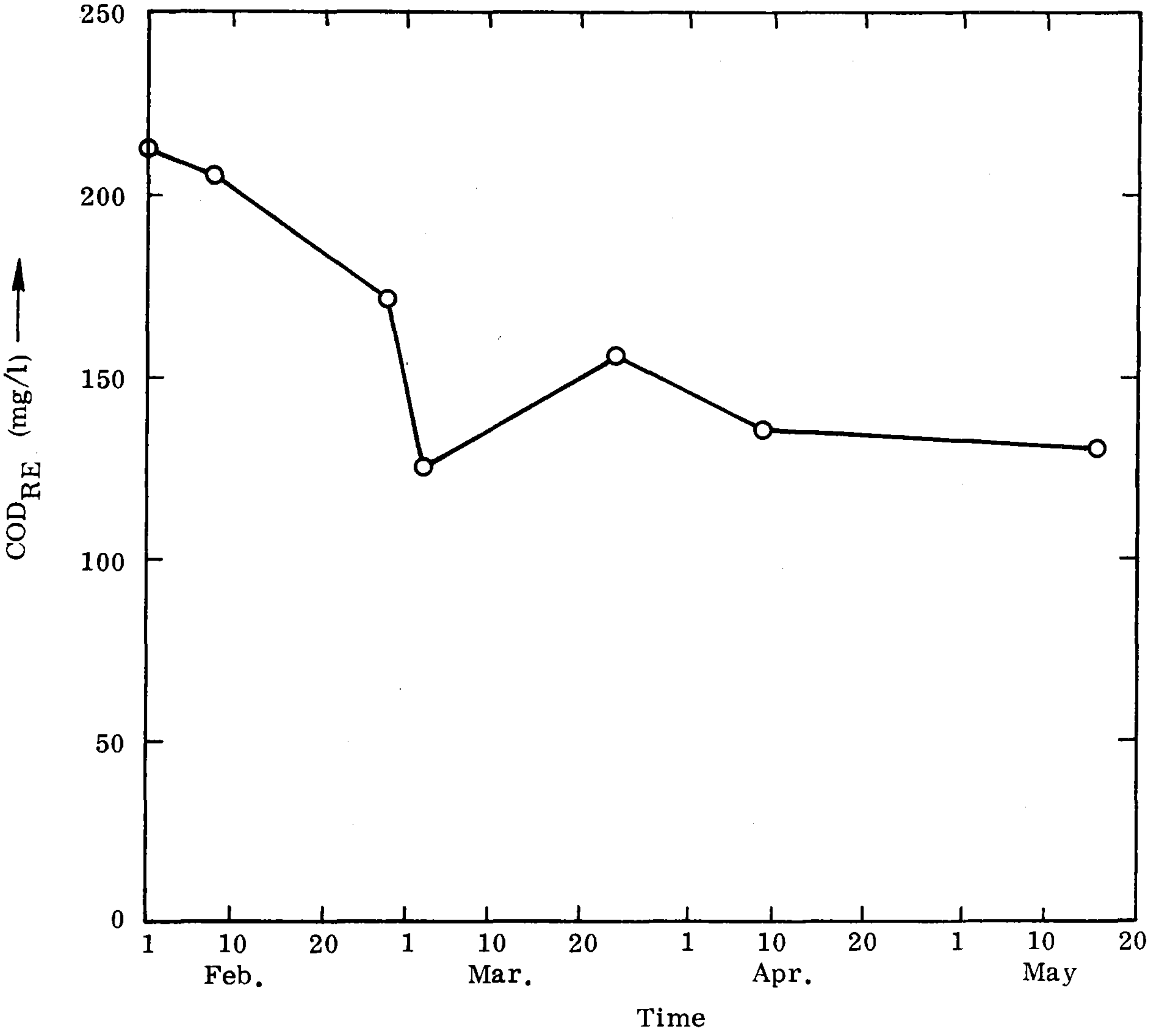

Figure A3. COD of recycled effluent at 90% recycle.

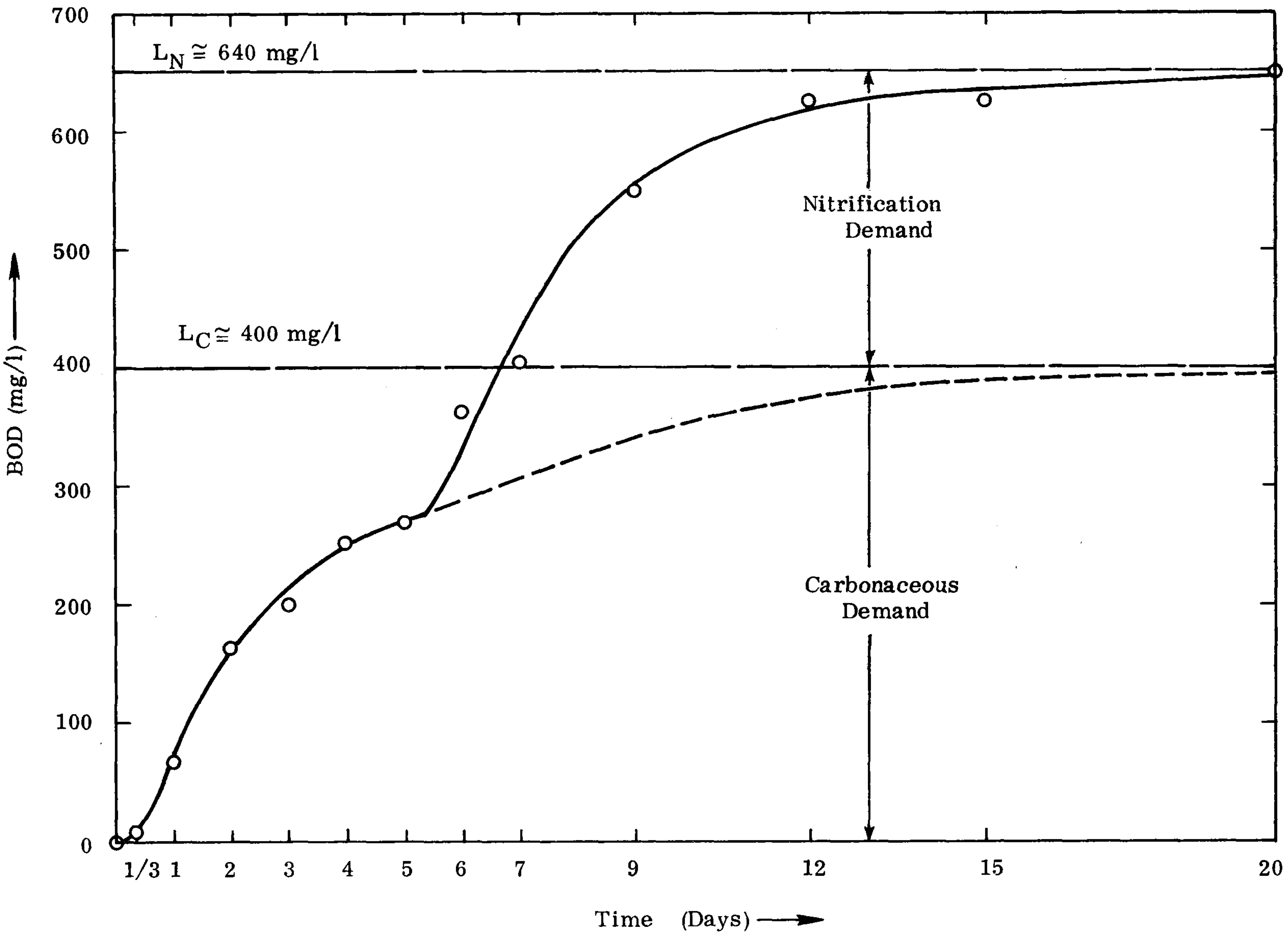

Figure A4. Ultimate BOD curve for synthetic feed.

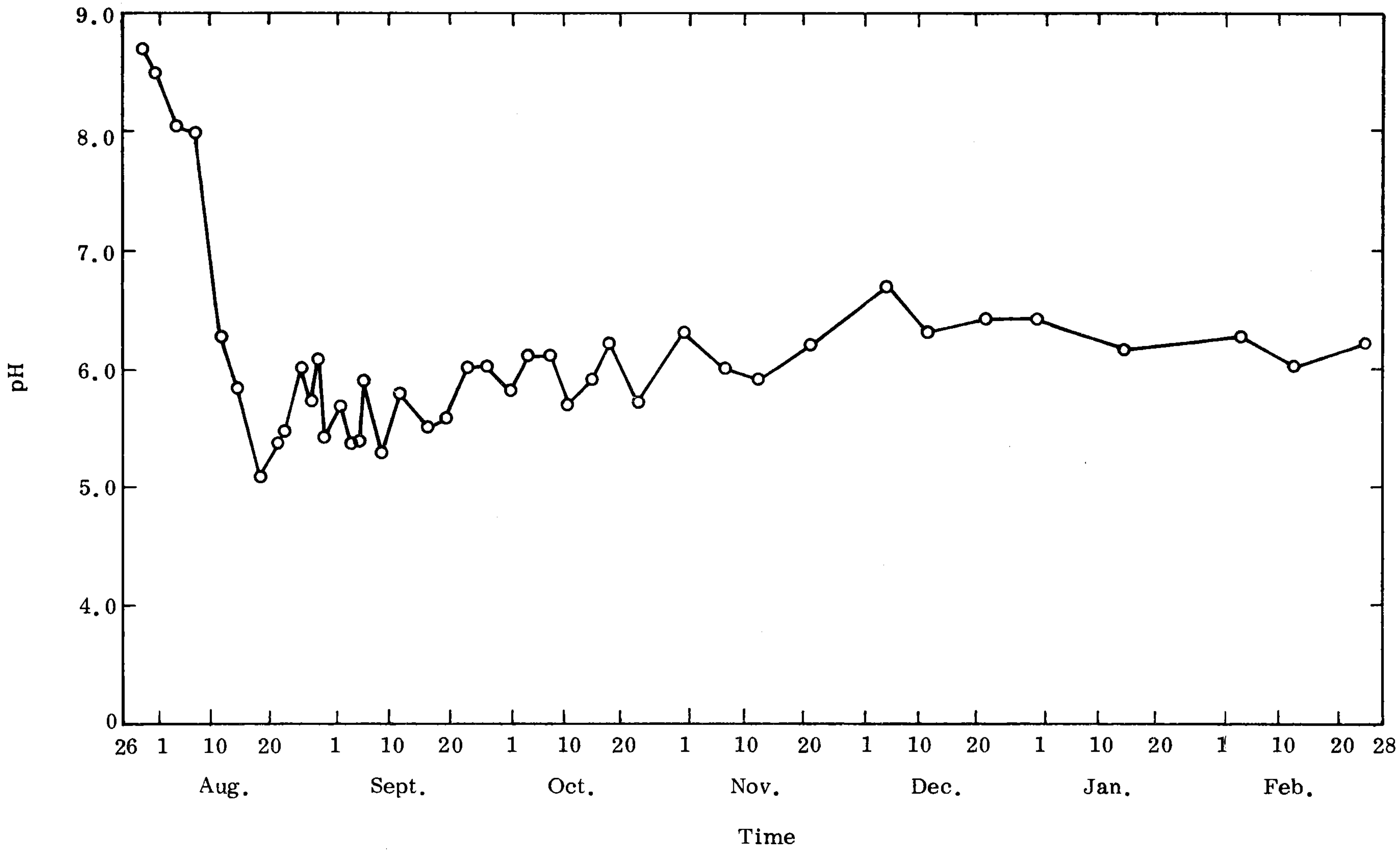

Figure A5. pH of mixed liquor at 95% recycle.

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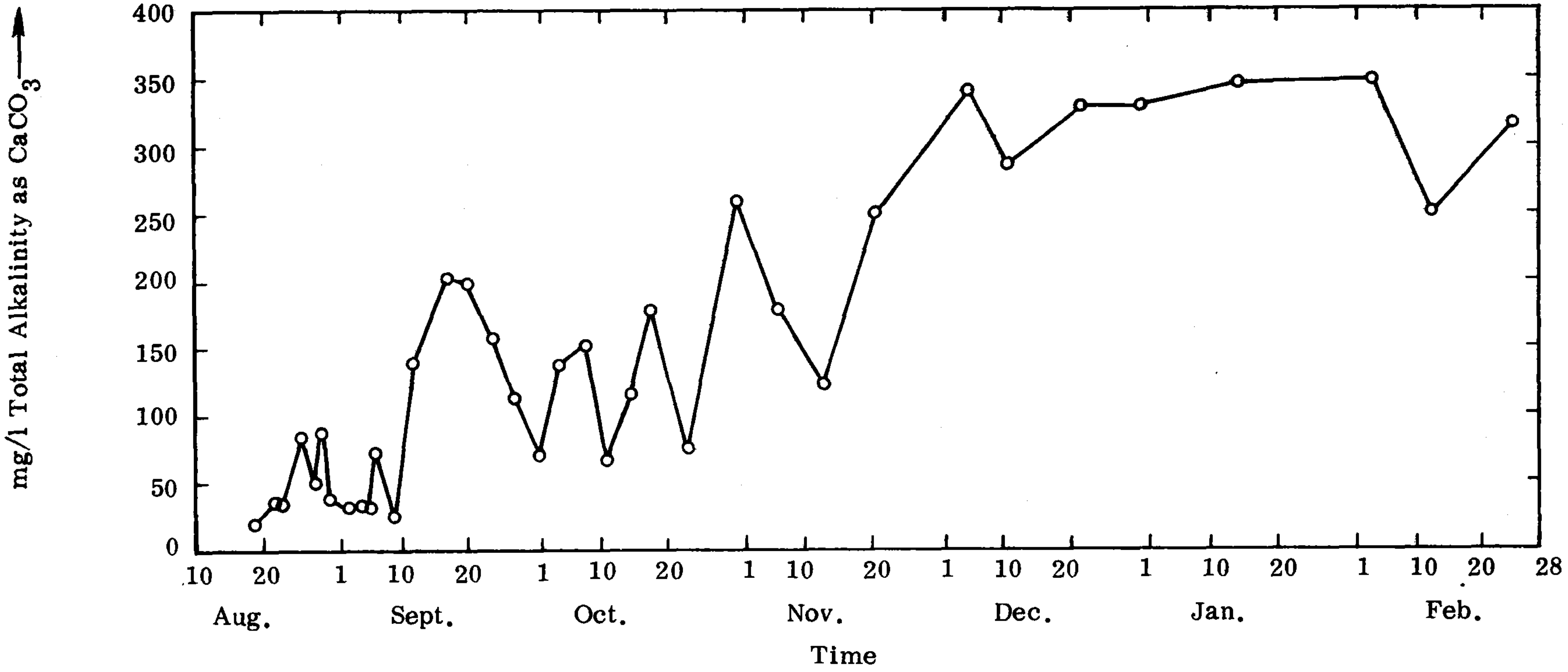
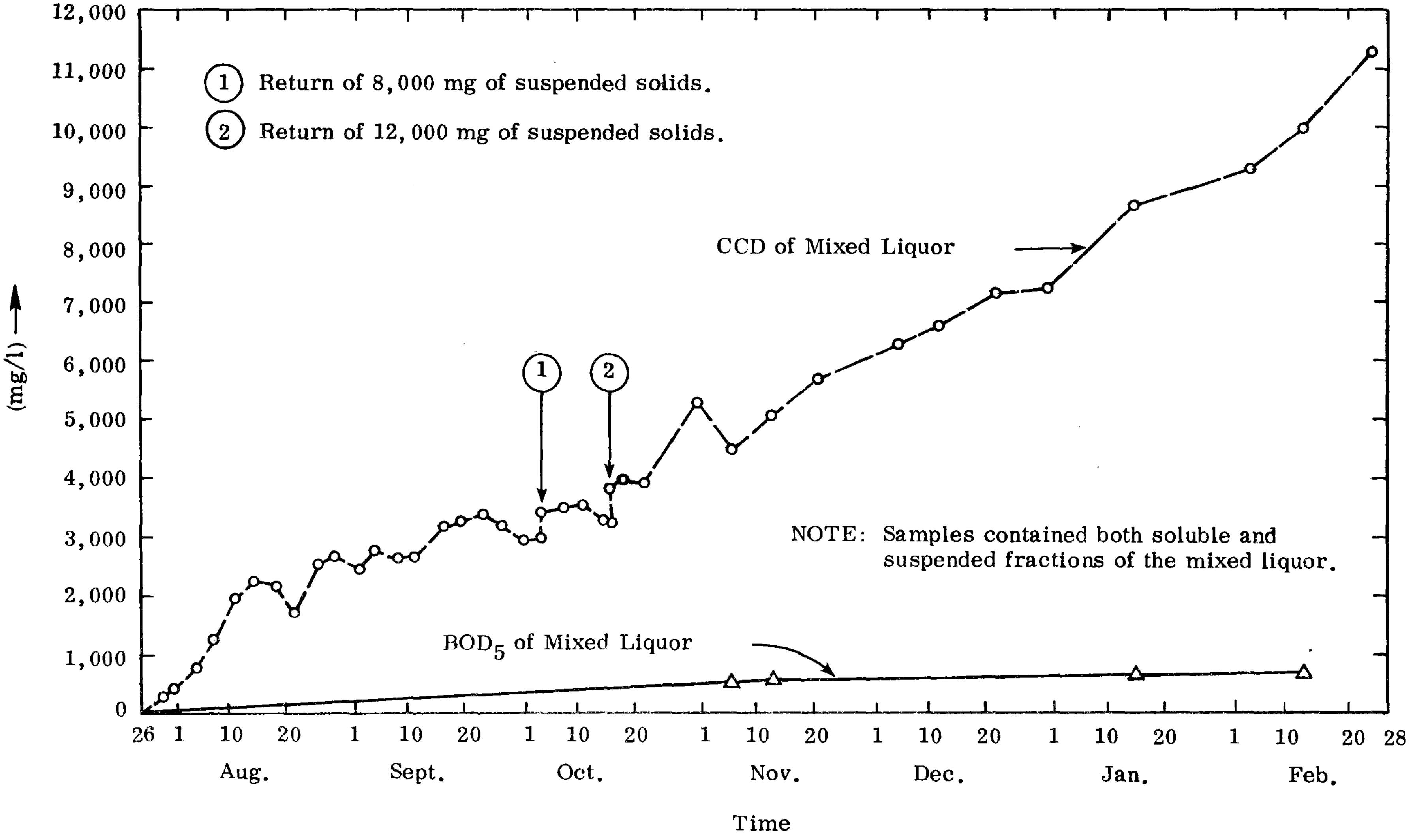


Figure A6. Total alkalinity as mg/l $CaCO_3$ of mixed liquor at 95% recycle.



① Return of 8,000 mg of suspended solids.

② Return of 12,000 mg of suspended solids.

NOTE: Samples contained both soluble and suspended fractions of the mixed liquor.

Figure A7. BOD_5 and COD of mixed liquor at 95% recycle.

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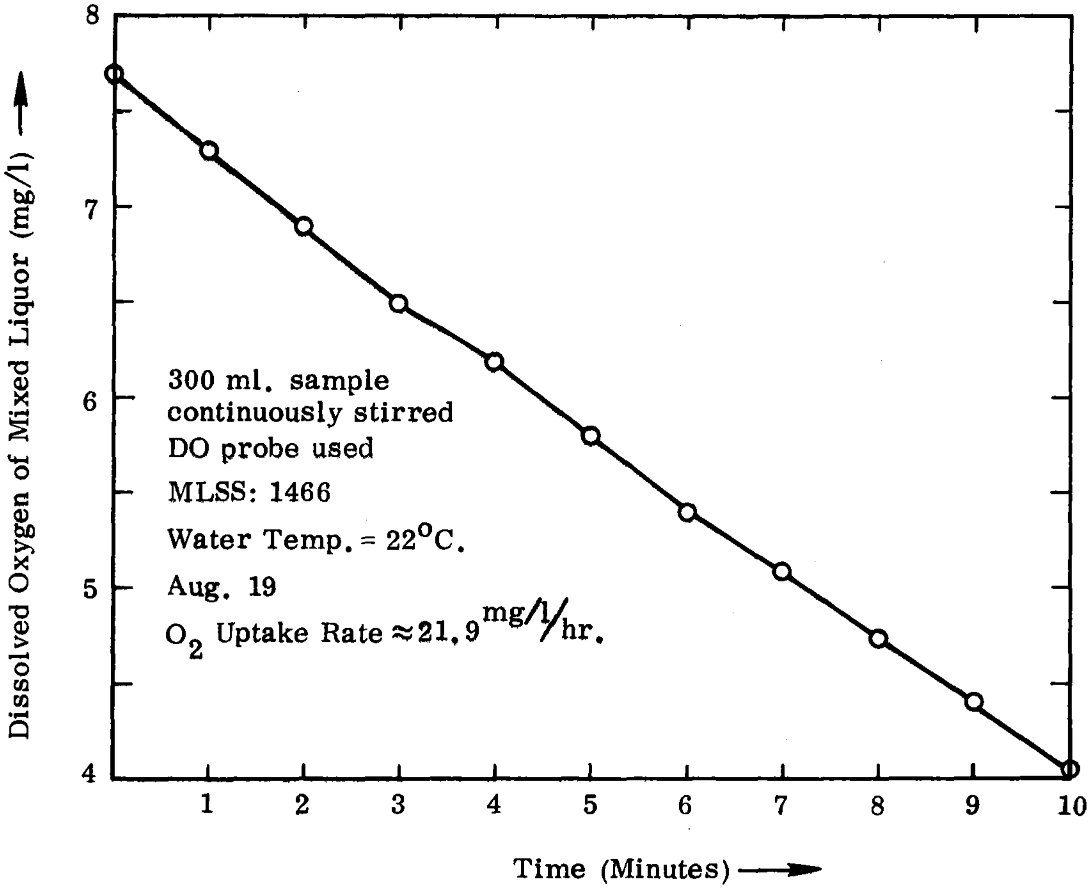
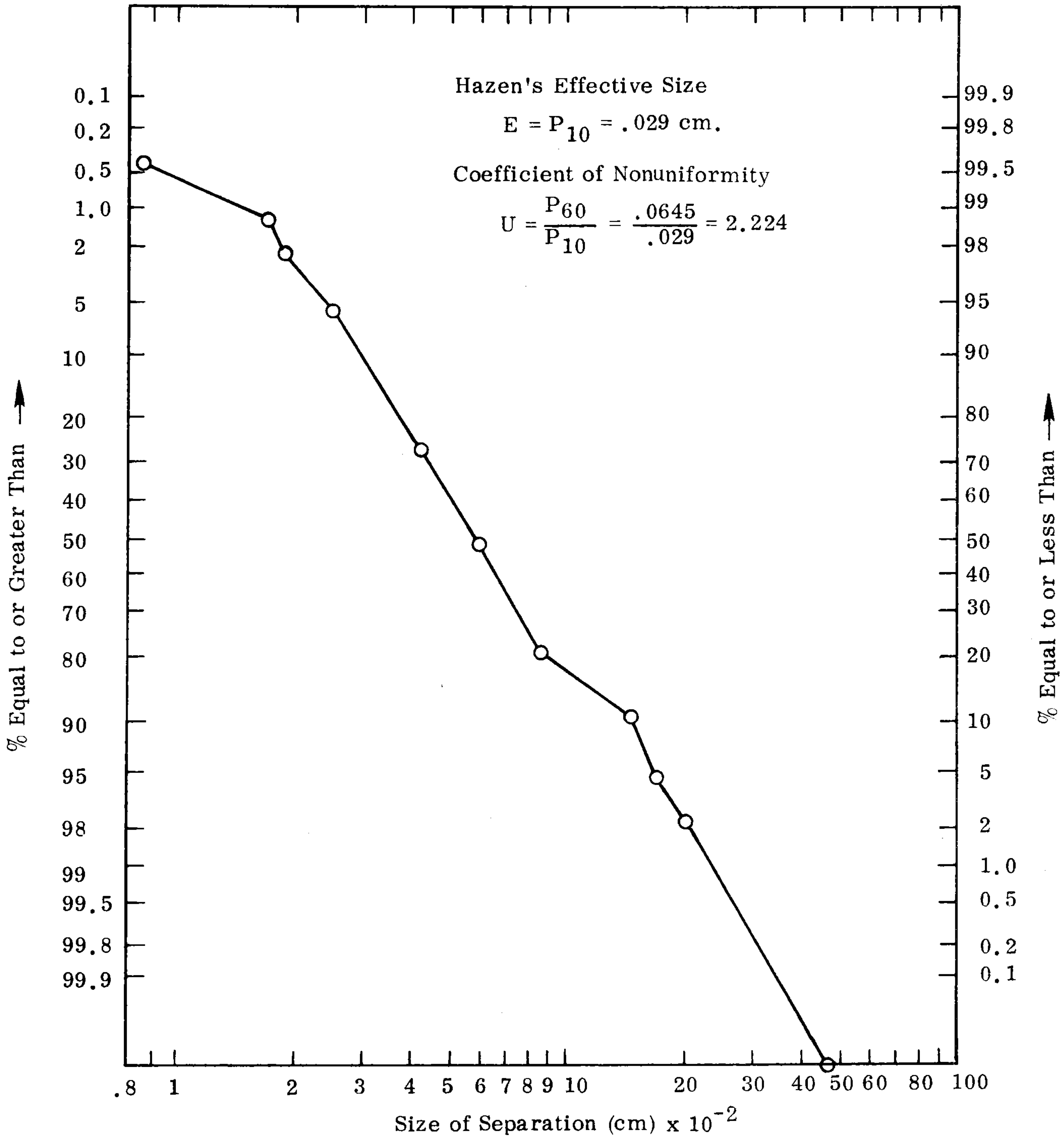


300 ml. sample
continuously stirred
DO probe used
MLSS: 1466
Water Temp. = 22°C.
Aug. 19
O_2 Uptake Rate ≈ 21.9 $^{mg/l}/_{hr.}$

Figure A8. Typical dissolved oxygen uptake curve by mixed liquor at 95% recycle.



Hazen's Effective Size

$$E = P_{10} = .029 \text{ cm.}$$

Coefficient of Nonuniformity

$$U = \frac{P_{60}}{P_{10}} = \frac{.0645}{.029} = 2.224$$

Figure A9. Grain size distribution of filter sand.

3886

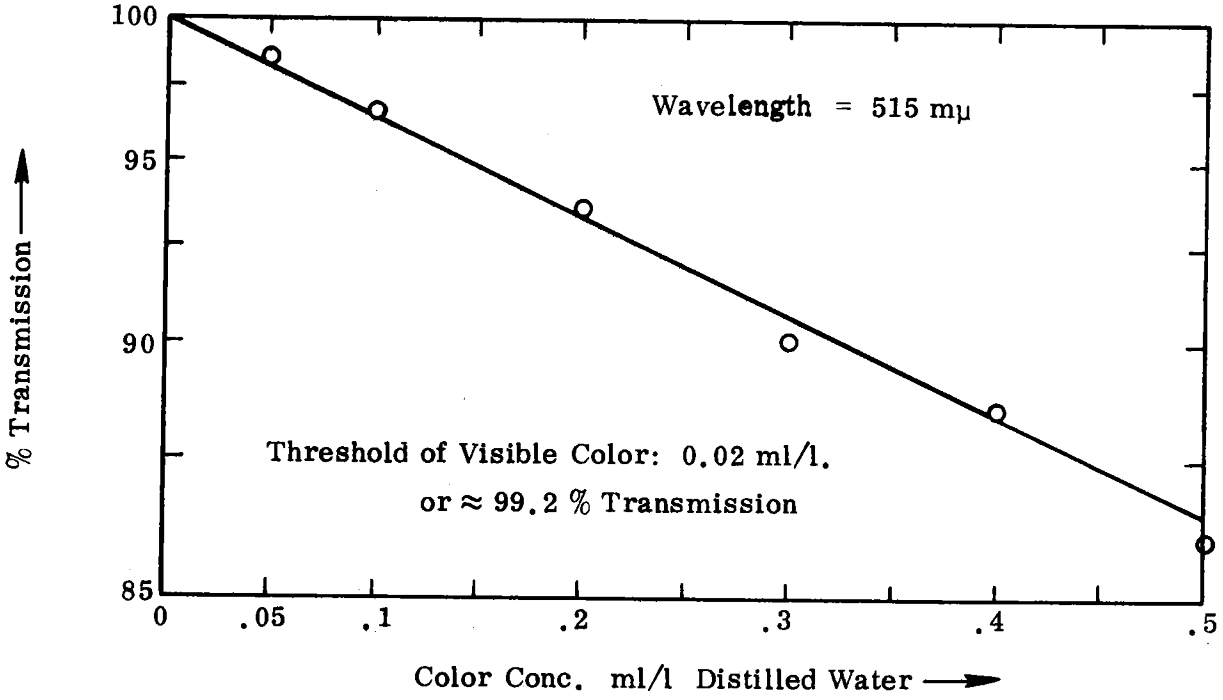


Figure A10. Color standard curve for Sauer's blue food color.

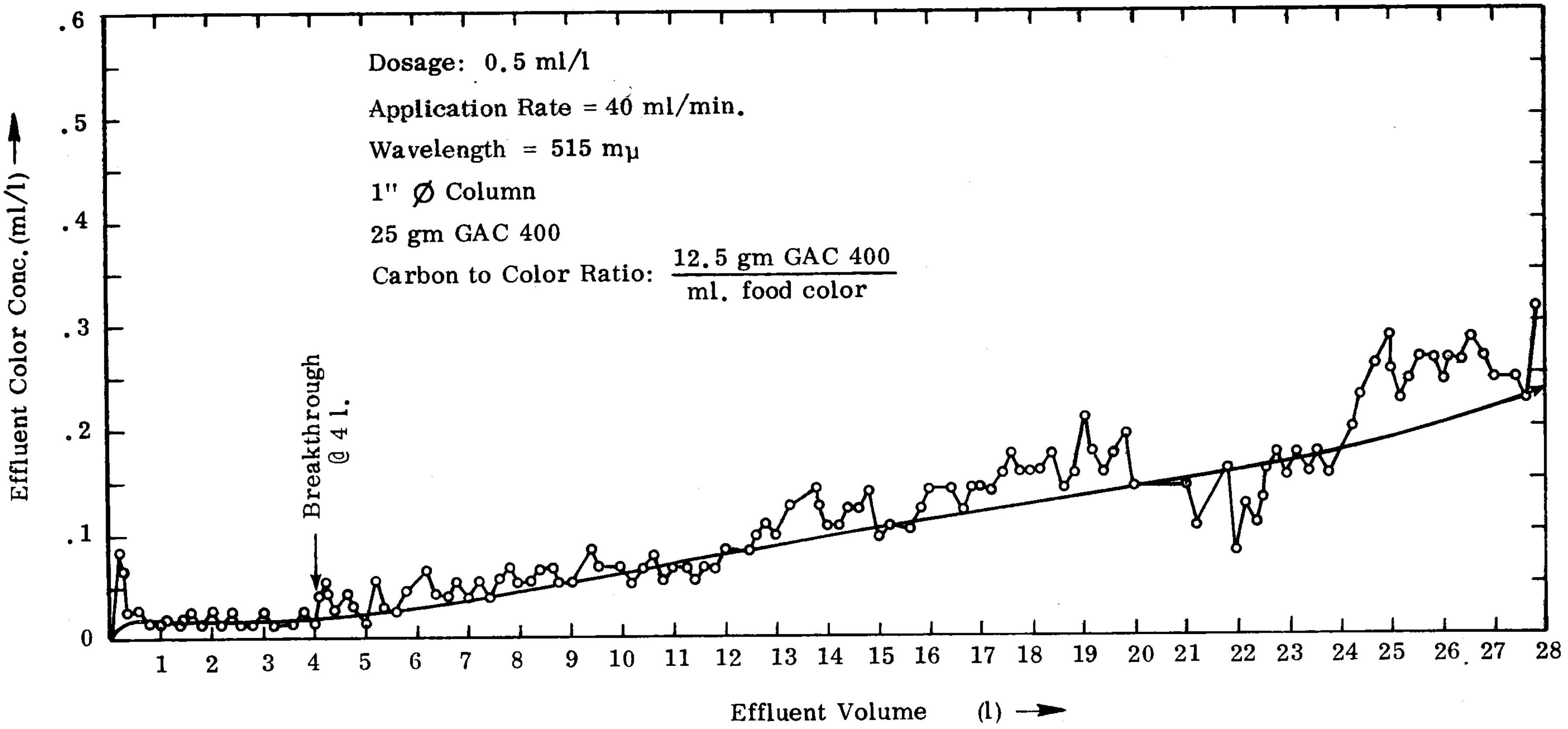


Figure A11. Food color breakthrough curve for tap water.

2883

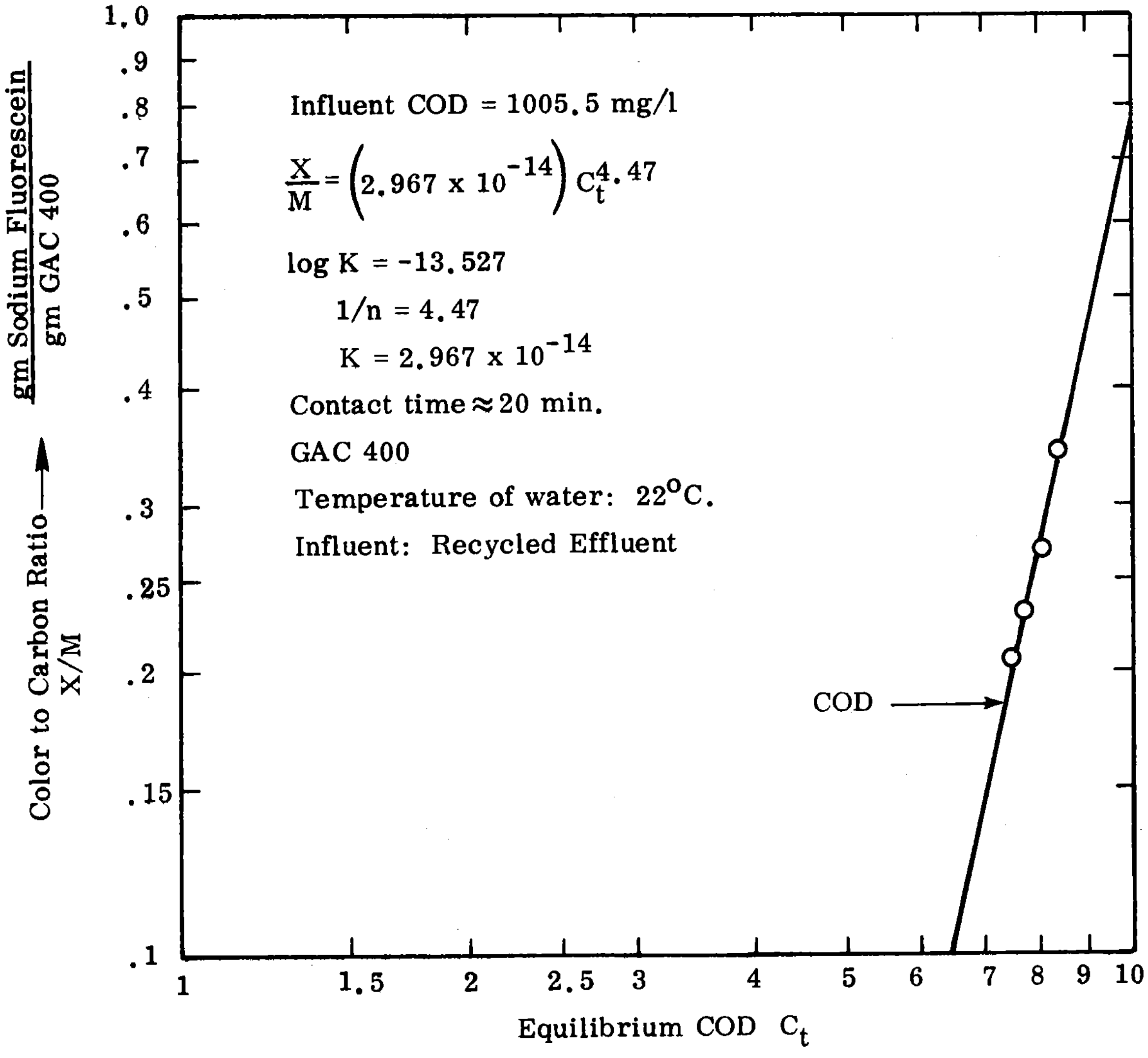


Figure A12. Freudlich isotherm for COD removal.

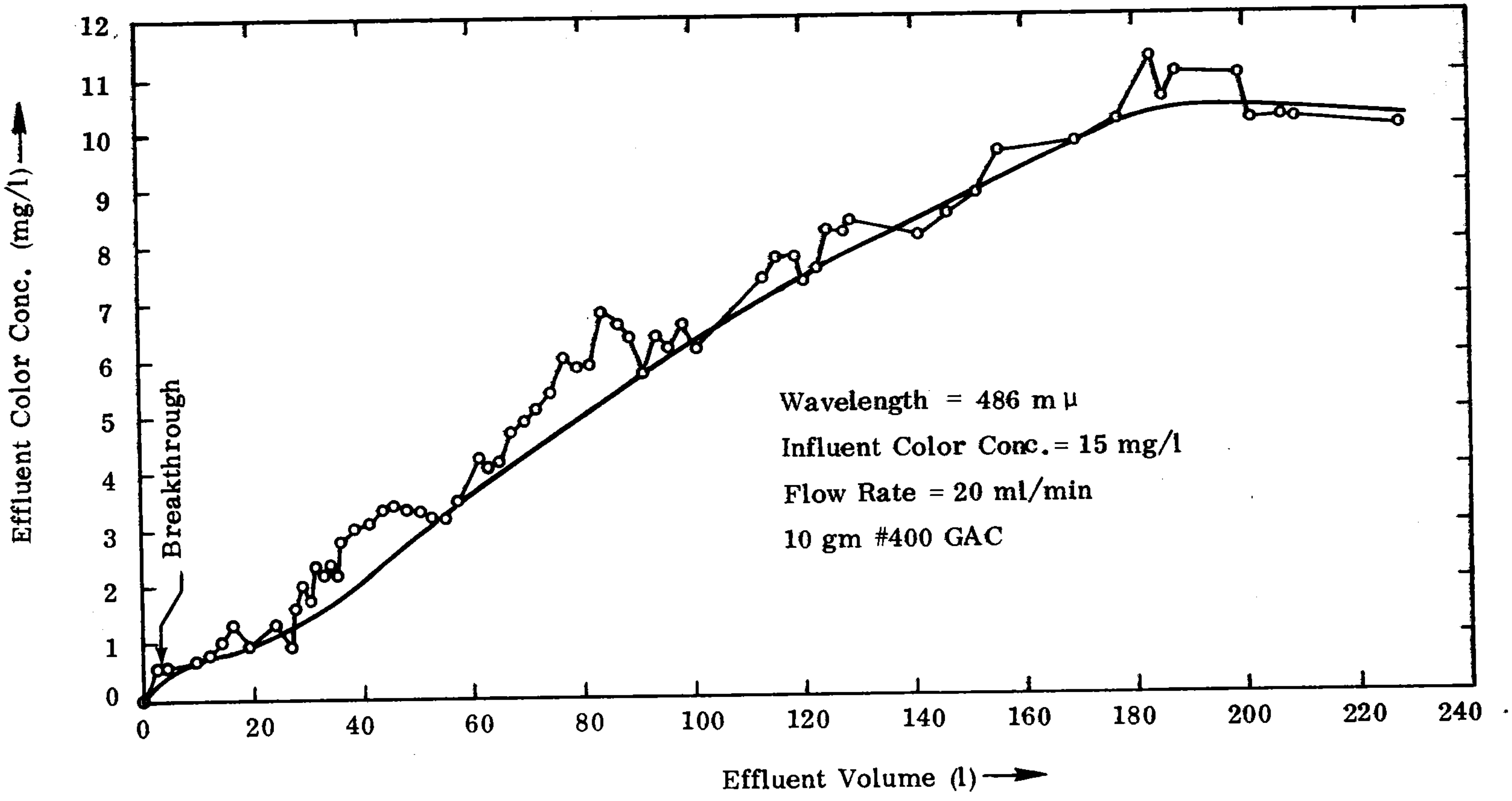


Figure A13. Sodium fluorescein breakthrough color curve for tap water.

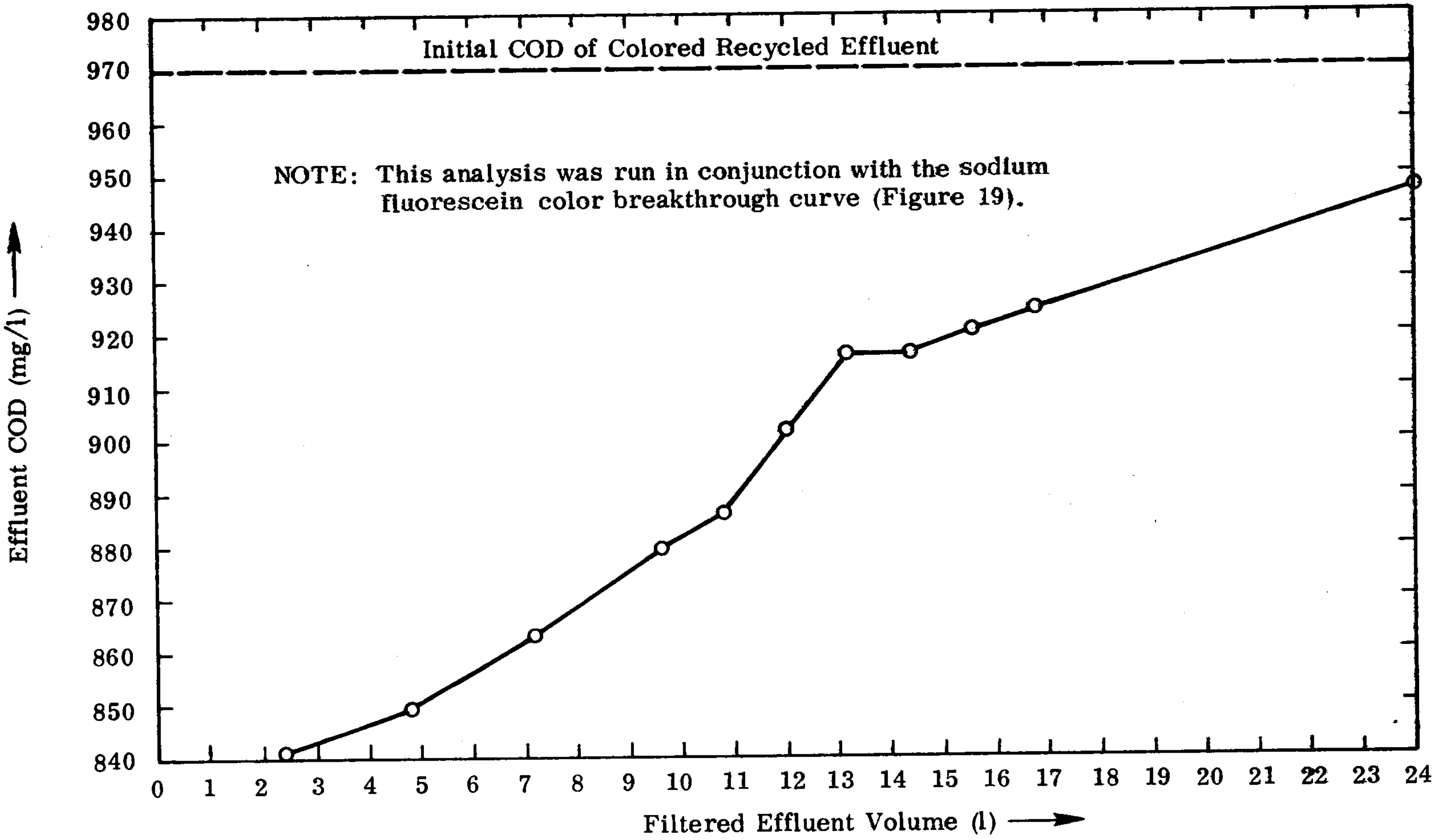
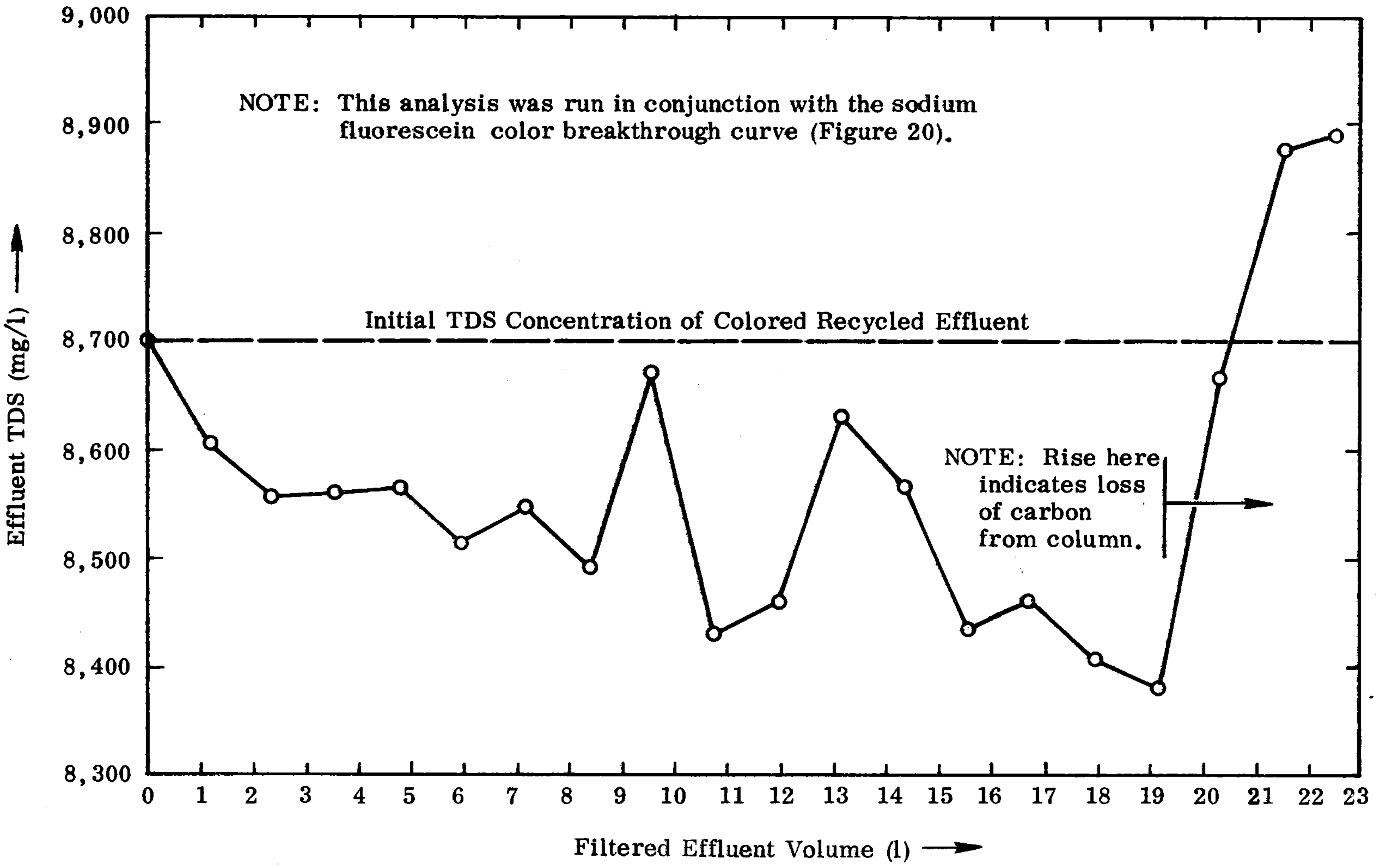


Figure A14. COD removal through carbon adsorption.



NOTE: This analysis was run in conjunction with the sodium fluorescein color breakthrough curve (Figure 20).

Initial TDS Concentration of Colored Recycled Effluent

NOTE: Rise here indicates loss of carbon from column.

Figure A15. TDS removal through carbon adsorption.

Table A1. Summary of Feed Constituent Analysis[(a)]

Ingredient	Daily Dosage	COD Added (mg per day)	BOD Added (mg per day)	TKN Added (mg per day)	NH_3-N Added (mg per day)
Sucrose	3.2 gm	3410	1984	0	0
Peptone	3.2 gm	3050	2240	346	24
MSG	0.3 gm	229	165	19	0
Yeast	0.65 gm	584	400	49	2
Urea	0.65 gm	0	0	237	1
$CaSO_4$	1.00 gm	0	0	0	0
$Ca(OH)_2$	2.0 gm[(b)]	0	0	0	0
Nutrients	3.475 gm[(c)]	27.5	8.0	575	405
Salts	4.00 gm[(d)]	130.34	3.0	0	0
TOTALS:	18.475 gm	7431 mg	4800 mg	1226 mg	432 mg
CONCENTRATIONS:	923.75 mg/l	371 mg/l	240 mg/l	61.3 mg/l	21.6 mg/l

(a) Based on analysis of individual components.

(b) $Ca(OH)_2$ daily dosage was 1.0 gm for 90% and 0% recycle; changes to 2.0 gm for 95%.

(c) The 3.475 gm of nutrients were added in 25 ml daily solutions.

(d) The 4.00 gm of salts were added in 25 ml daily solutions for 90% and 0% recycle. At 95% recycle, sodium sulfite was replaced by sodium carbonate and the salts were incorporated into the daily dry feed.

Table A2. Powdered Activated Carbon Adsorption of Food Color

Base food color dosage .5 ml/l

Base wavelength 515 mμ

Visual comparison batch tests

tap water : $\frac{\text{300 mg PAC}}{\text{ml food color}}$

recycled effluent: $\frac{\text{600 mg PAC}}{\text{ml food color}}$

Contact time determinations

carbon dosage : $\frac{\text{600 mg PAC}}{\text{ml food color}}$

Contact Time	Sample	Percent Transmission	Color Concentration	Residual COD (mg)
*	Raw Recycled Effluent	82.5	0.74 ml/l	344.1
*	Colored Rec. Effluent	71.0	1.14 ml/l	445.2
10	Colored Rec. Effluent	84.5	.59 ml/l	338.3
15	Colored Rec. Effluent	87.0	.47 ml/l	328.6
20	Colored Rec. Effluent	93.0	.21 ml/l	324.7

Table A3. Summary of Manufacturer Correspondence for Evaporation-Desalination Equipment for Highway Rest Areas

Process Equipment	Manufacturer	Capabilities	Requirements	Capital Costs
Badger Vapor(158) Compression Distiller	Mechanical Equipment Co. Inc., New Orleans, Louisiana	Produces 50 GPH of fresh distilled water when supplied with 1.66 GPM of discharge at 5 psig.	460 volts, 3 phase 60 cycle power at an average operating load of 8.1 KW.	$12,000
Two-State Flash(159) Type Distiller	Mechanical Equipment Co. Inc., New Orleans, Louisiana	Produces 50 GPH of fresh distilled water when supplied with 27 GPM of discharge	338,000 BTU/hr of heat which is available from 45 GPM of 180°F engine jacket water.	$9,870
Submerged Com-(160) bustion Unit	Ozark-Mahoning Company Tulsa, Oklahoma	Based on a 12-hour day, this unit can evaporate 1000 GPD using direct transfer of heat with little or no scaling on the heat transfer surface.	1 million BTU/hr requires about 16.7 SCF of gas per minute, and electricity for a 10 HP motor for the blower.	$12,500
Roga Reverse(161) Osmosis System	Universal Oil Products Co., ROGA Division San Diego, California	Majority of RO systems are large, ranging from 50,000 GPD to millions of GPD.	A 1000 GPD system treating a stream containing 5000-10,000 ppm would have a maximum recovery of about 20%.	Equipment will not meet needs
ENRO Spiral(162) Wrap System of Reverse Osmosis	Chemico Process Plants Company, Envirogenics Systems, El Monte, California	Operates at recovery of 76% to concentrate 1000 GPD @ 10,000 mg/l TDS to 240 GPD @40,000 mg/l TDS. Product water is 760 GPD @ 526 mg/l TDS with virtually no COD or BOD.	Power required to supply average operating load of 2 KW.	$10,000 plus additional investment for evaporator and conveyor to treat concentrated stream.

Table A4. Evaporation and Rainfall Data for Riverton, Virginia

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1959	1.85	2.04	1.00	1.58	.84	2.38	4.61	3.46	3.24	5.53	3.13	1.12	30.79
1960	5.45	1.27	2.50	1.83	4.37	2.06	2.18	7.39	6.00	2.55	3.56	2.35	41.51
1961	.93	1.26	.36	1.83	6.80	2.65	5.98	3.35	3.29	1.94	3.28	2.30	33.96
1962	2.27	1.81	5.28	2.29	2.72	4.02	3.08	3.16	3.26	2.36	.14	2.09	32.48
1963	2.13	6.02	4.94	1.34	2.40	3.82	.87	.98	5.78	1.33	1.60	2.56	33.77
1964	.00	6.78	2.15	2.57	3.22	2.38	4.55	1.91	2.38	3.47	2.03	4.57	36.01
1965	3.24	2.31	2.38	5.79	3.41	4.08	2.75	2.36	1.29	1.27	1.54	2.57	32.99
1966	1.86	.61	.17	3.86	2.09	1.85	4.18	2.59	1.24	1.71	1.35	9.53	31.04
1967	2.18	3.22	3.05	1.11	1.42	4.39	.47	4.53	.93	4.05	6.21	2.95	34.51
1968	2.55	.94	2.93	2.61	.03	3.06	2.59	5.14	1.87	3.69	4.06	4.43	33.90
Average	2.25	2.62	2.48	2.48	2.73	3.07	3.13	3.48	2.93	2.79	2.69	3.45	34.10
Average Evap.	2.79	2.31	1.42	1.02	1.54	3.22	4.23	5.30	6.03	6.01	5.55	4.17	43.59
Net difference between rainfall and evaporation	+.54	-.31	-1.06	-1.46	-1.19	+.15	+1.10	+1.82	+3.10	+3.22	+2.86	+.72	

+ Indicates net evaporation

- Indicates water surplus

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