

PURIFYING FOOD PROCESSING EFFLUENTS  
WITH GRANULAR ACTIVATED CARBON

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Arnold Wayne Hydamaka  
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## ABSTRACT

Physicochemical treatment of lye-peel potato waste water and dairy waste using chemical coagulants followed by activated carbon was shown to be possible.

COD reductions of about 90 per cent were achieved. Turbidity was also removed, however the fixed residue of the purified effluent increased as a result of the coagulation process.

Adsorption isotherms were developed for the chemically clarified wastes. The isotherm results indicated an adsorption capacity of 309 mg/l COD per g carbon for the potato waste and 316 mg/l COD for the dairy waste.

Column studies on the wastes indicated that a multiple series column system would be the preferential arrangement.

Adsorption isotherms were developed for a number of pure organic substances which could become possible components of food processing effluents.

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## I. INTRODUCTION

The one-time use of water has become a luxury that we can no longer afford. Successful "advanced waste water treatment technology" by renovating wastewaters for deliberate reuse, would alleviate simultaneously two of our major waste resource problems - water pollution and water supply.

It is now generally recognized that our relatively fixed natural water supply will be inadequate to meet the demands of a growing population and expanding industry. Renovation and reuse of water becomes an increasing necessity, with the degree of purification required varying according to the specific use(43).

Water pollution is the downgrading of water quality to the point where it significantly affects water use. There is a pressing need to provide better pollution control than is now practised. Effluents discharged from conventional treatment plants contain refractory organic matter that exerts an oxygen demand on the receiving stream. Some of the organics maybe toxic to fish and other forms of biological life. The effluent may contain undesirable amounts of minerals, or nutrients which promote excessive algal and other plant growth. Advanced waste treatment is needed to remove all types of pollutants.

The use of activated carbon has been demonstrated to be the most promising of the advanced treatment

methods(103). Activated carbon will remove most soluble organics not removed by conventional secondary processes. There is growing evidence that chemical treatment of primary effluents, followed by activated carbon treatment, will provide final effluents of better quality than conventional secondary treatment(105,114).

Such a process has been designed in the Department of Food Science at the University of Manitoba by Dr. Gallop and associates(42) to treat food industry effluents. The food industry creates tremendous wastes, with the polluted water containing organic material up to 40,000 mg/l COD. Industrial pollution accounts for 45 percent of water pollution, with 85 percent of that total attributed to the food industry(6). Conventional secondary treatment plants do not operate effectively under the wide fluctuations in raw wastewater characteristics from food plant wastes. Dairy effluents and lye-peel effluents from potato processing are two food industry wastes that are being purified by the Manitoba Food Science(M.F.S.) process for possible reuse purposes.

There are many advantages of this advanced physico-chemical system. A comparison of conventional biological and M.F.S. waste treatment methods is summarized by Gallop(42). The effluent from the M.F.S. plant has the potential for water reuse applications. The degree of purification required will be dictated by the specific reuse intended.

Morris and Weber (66) state that whatever the cost of advanced technology, it must be the very lowest science and engineering can achieve. It is obvious that where wastewater can be treated and recycled for reuse, by the value of the recovered water, and possible sludge by-product value, the treatment costs are largely offset. Reclamation involves purification so as to adequately protect the environment, and in doing so, one greatly reduces new water demand.

## SCOPE OF INVESTIGATION

This study was initiated to determine the feasibility of using granular activated carbon treatment of food industry effluents for possible reuse purposes. The activated carbon treatment followed clarification of the primary effluent using chemical coagulants. Activated carbon was also added to raw effluents to determine the feasibility of this procedure. The food processing effluents treated were lye-peel potato waste and dairy waste. The carbon treated water was analysed for microbiological and chemical (organic and inorganic) quality to determine its reuse potential. The adsorption affinity of activated carbon for a wide range of organic substances, possible contaminants in food processing effluents was also determined.

## II.LITERATURE REVIEW

### 2.1 Activated Carbon: History

Historically, evidence of the use of activated carbon (in the form of charred wood) for improving the potability of drinking water is given in writing predating the Christian era (104).

Scientific recognition of adsorption phenomenon as it is now understood, is attributed to Scheele, who, in 1773, observed the uptake of gases from air by charcoal.

The earliest report on adsorption from aqueous solution dates back to 1785. Lowitz observed that charcoal would decolorize many liquids. He attributed the phenomenon to the removal of organic matter by adsorption, defined as the adhesion of molecules on the surface of a solid.

The first activated carbons were produced from wood char, bone char(34), blood char, and cocoanut char. Industrial development of an activated carbon was retarded because of engineering difficulties, and the absence of an apparent need for an activated carbon with more adsorption capacity. An invention patented by Ostrejko(72) in 1911, using steam activation, led to the development of modern commercial activated carbons.

The first significant application of activated carbon was in sugar refining in 1911(50). The use of

noxious gases during World War I stimulated efforts to develop highly activated carbons for use in gas-mask filters. The period following, marked by intense competition for new markets, led to continual advances in the quality of activated carbons for liquid phase adsorption. The applications which have successfully utilized activated carbon for liquid purification are very numerous(50).

## 2.2 Activated Carbon: Adsorption

Adsorption is a phenomenon whereby molecules from solution are attracted to and held to the surface of a solid. By giving a solid a very porous structure, a very large surface per unit volume results. Certain porous solids are, therefore, excellent adsorbents.

### 2.2.1 Adsorption Properties of Activated Carbon

Weber(104) described in detail the characteristics of activated carbon particles. Activated carbon is a very porous material, which has proven to have a high adsorption capacity for organics. The adsorption characteristics of activated carbon are associated with a system of remarkably small and uniform pores. Two systems of pore sizes exist in activated carbon particles. The macropores are large, having diameters of 30-10,000 Angstrom units, permeate the carbon particles allowing for solute diffusion, but contribute little to the surface area. The micropores are

fissures of 10-30 Angstrom units in diameter. The boundary surfaces of the micropores are largely responsible for the adsorption action of the carbon. This system of pores contributes to a surface area of approximately 400-1000 sq m/g for an activated carbon particle.

Structural details of activated carbon have been derived from studies of adsorption and from X-ray patterns(7). The physical nature of the surface of activated carbon has been discussed by Snoeyink and Weber(93,94). Investigations by Wolff(110,111) led to the description of activated carbon particles as consisting of large "regions" composed of stacks of graphitic planes or groups of such stacks. Channels through the graphitic regions are the macropores. Fissures within and parallel to the planes are the micropores.

### 2.2.2 Mechanism of Adsorption by Activated Carbon

Activated carbon is described as a highly porous material with a surface comprised of active sites at the edges of the crystalline planes of the solid(104). These active sites compete with the solvent for the solute, breaking the solute-solvent association, establishing a solute-solid association. Three kinetic steps occur consecutively in the adsorption process - transport of solute to the exterior surface of the adsorbent, diffusion through the pore spaces(macropores), and the adsorption

occurs at an active site on the surfaces bordering the inner pore space of adsorbent.

Most adsorptions are not easy to classify as to whether it involves a physical force (the enormous surface area - 1000 sq m/g within each particle of activated carbon exerts attractive forces similar to Van der Waals forces), or whether a chemical change occurs. The review of the literature(104) indicates that adsorption with activated carbon has many diverse aspects and no simple explanation can fully describe it.

### 2.2.3 Adsorption Theory

A number of mathematical models have been proposed to describe adsorption. The porous nature of the activated carbon raises a question as to whether adsorption results in monolayer or multilayer formation of adsorbate on the adsorbent.

Langmuir(61,62) proposed a model which is valid for single layer adsorption, but the mathematics is impossible when allowing for interaction of molecules. The equation of Brunauer, Emmet, and Teller(18), the "BET equation" is applicable for multilayer adsorption. Since it requires that the identity and concentration of adsorbate be known, it is not generally applicable to waste water systems. The Freundlich equation(41), although empirical in nature, is widely used and is recommended by the American Society for

Testing and Materials(69) for evaluating adsorption data. A Freundlich adsorption isotherm is a plotted curve that gives the points of equilibrium between the adsorbate concentration in the treated liquor and on the adsorbent, at a fixed temperature.

#### 2.2.4 Factors Influencing Adsorption by Activated Carbon

Adsorption as a unit operation for treatment of wastewater requires consideration of two physical chemical aspects of the process; the kinetics, and the equilibria of adsorption. The rate of adsorption dictates the contact time between solution and adsorbent, while the capacity of the adsorbent determines its useful life.

Weber and Morris(106,107) studied in detail the kinetics of adsorption and the equilibria and capacity for adsorption on carbon from solution. Their studies included many results of the effects of solute, solvent, pH, and temperature on adsorption.

The relative reaction rates of adsorption were found to vary reciprocally as the square of the diameter of the carbon particle; adsorption capacity was found to vary as the inverse of the particle diameter; and both the rate and extent of adsorption varied approximately linearly with adsorbent dosage.

Both adsorption rate and capacity increased with increasing concentration of solute in solution. An inverse

relationship is anticipated between the extent of adsorption of solute, and the solute solubility in solution. This is known as Lundelius's rule(65). This rule is only a general one as data in the literature both affirm and negate the rule(22). Traube's rule(99) states that adsorption from aqueous solution increases as a homologous series is ascended. Again, this rule is only general(22).

Bean et al(13) showed that carbon surfaces carry net negative charges. Many organic pollutants in wastewaters are anionic therefore some interferences in particle diffusion may occur. Studies indicate that adsorption is at a maximum for neutral species.

The studies by Weber and Morris(107) also concluded that temperature variations(18-37 C) normally experienced in wastewater treatment operations will not lead to significant variations in adsorption by activated carbon. This was also concluded by Linner and Gortner(63), and by Snoeyink and Weber(94).

Weber and Morris(107) concluded that adsorption of typical organic pollutants from wastewater increased with decreasing pH.

Wastewaters usually contain heterogeneous mixtures of substances. Seldom will adsorption be limited to removal of a single solute from solution. Weber and Morris (107) presented data that indicated that the sum of adsorption rates and total capacity of solutes was greater from a

multicomponent solution than for a single solute solution of the individual component members. Poon and Sung(79) reported that the total adsorption capacity of activated carbon could be enhanced in a multicomponent solution.

Sigworth(89) has discussed factors influencing the efficiency of adsorption on activated carbon.

## 2.3 Activated Carbon and Pollution Control

### 2.3.1 Feasibility of Activated Carbon For Wastewater Treatment

Activated carbon has been widely used since the early 1900's in water purification for the removal of taste and odor causing organics present in water at a concentration usually less than 5 mg/l COD (12,100,53).

The occurrence in municipal waste water of organic contaminants resistant to biological degradation presented a major technical challenge in advanced waste treatment(103). These refractory organics contributed to a COD of 50-100 mg/l in the secondary effluent. Morris and Weber in 1964(67) conducted a study showing the feasibility of activated carbon adsorption of biochemically resistant materials from solution. They also concluded that adsorption capacities of at least 10 percent should be realized with full use of the carbon. Morris and Weber (103) reported on a literature survey indicating that the use of activated carbon for wastewater renovation was very promising. Cassidy(22)

compiled a summary of numerous classes of organic compounds subject to adsorption.

Joyce and Sukenik(58,59), and Bishop et al(16) conducted studies on activated carbon treatment of waste sewage effluent. Anderson(2) discussed the usefulness of activated carbon for waste treatment.

The economic and practical feasibility of granular activated carbon has been reviewed in the literature in comparison with other advanced treatment methods(3,4,5,29, 38,92). The Advanced Waste Treatment research program summary report of 1964-1967 concluded that the technical and economic feasibility of granular activated carbon treatment of secondary effluent was established(103).

Cooper and Hager(28) in 1966, after reviewing the feasibility of waste treatment systems utilizing regenerable granular activated carbon, suggested its immediate application to the treatment of many industrial waste problems for pollution abatement or reclamation for reuse in industry to help alleviate the growing shortage of water.

### 2.3.2 Granular Activated Carbon

Studies by Weber and Morris(106,107) in 1963, 1964, concluded that the most efficient use of activated carbon is obtained by a columnar countercurrent operation. Column operation of activated carbon requires use of granular activated carbon.

Fornwalt and Hutchins(39) and Cooper and Hager(28) described the various forms of column operation. Fixed bed adsorption was reviewed by Barry(11) in 1960. Fluidized bed adsorbers were discussed by Keinath and Weber(60), and by Weber and Morris(108). Allen et al(1) discussed process design calculations for adsorption from liquids in fixed beds of granular activated carbon. Development of optimization models for carbon bed design was presented by Dostal et al(36) and by Cookson(26,27).

Another factor favoring use of granular activated carbon is that it can be economically regenerated and reused after it becomes spent, with average losses of about 5 percent(64,71).

Cooper and Hager(28) summarized factors favouring a granular carbon waste treatment operation. Hager and Fulker(48), and Hager and Flentje(47) reported that granular activated carbon in column design was more efficient than powdered carbon in a batch operation. Literature from the Pittsburg Activated Carbon Company described the advantages of a granular carbon purification system(78). Hyndshaw(54) presented a guide to the selection of granular versus powdered activated carbon. The wide range of applicability of granular activated carbon was reported by Rizzo(85).

### 2.3.3 Powdered Activated Carbon

Powdered activated carbon, by its physical nature, is normally limited to use in a batch-type operation. At present it has decisive disadvantages when compared with granular activated carbon in that it creates handling and dust problems, is not readily adaptable to continuous process, and creates the problem of disposal. Regeneration of powdered activated carbon is still in an experimental stage. A recent development by Zimpro Inc. (113) indicates that regeneration of powdered activated carbon could become economically feasible for wastewater reclamation.

Davies and Kaplan(33) attempted to use powdered activated carbon in column operation without success, due to a rapid pressure drop in the column. Garland and Beebe(45) reported on the use of powdered activated carbon in advanced waste treatment. Beebe and Stevens(15) tested operating parameters of a powdered activated carbon system for wastewater renovation. Shuckrow et al(87) reported on a physical chemical process employing alum and powdered activated carbon to treat wastewater with recovery of the alum and carbon for reuse. Stander et al (97,98) and Peck(75) suggested that powdered carbon systems are feasible for applications where dissolved organics are very low. Studies at Windhoek, South Africa by Stander et al(97,98) confirm that application of granular activated carbon plus regeneration is more feasible than use of powdered activated

carbon for waste treatment.

#### 2.3.4 Water Purification

Early use of activated carbon for treatment of water was to remove undesirable tastes and odors. During the eighteenth century, sailing ships stored drinking water in charred barrels for this purpose. This practice led to the installation of activated carbon filters in municipal water plants in Europe later in the century(104).

In the late 1920's and early 1930's high quality activated carbons were employed in many water treatment facilities in Europe and North America. The meat packing industry of Chicago, in 1928, is credited as being the first industry in America to use activated carbon for water treatment (104). Today, activated carbon is used extensively in water treatment operations in America. Jenkins (57) reported that in 1962 about 50 per cent of the population in communities greater than 25,000 received water that had been subjected to treatment with activated carbon. Advanced Waste Treatment Research Reports (103) indicate that granular activated carbon treatment for water and wastes is the most promising of the systems studied.

#### 2.3.5 Municipal Water and Waste Treatment

Early use of activated carbon in water and waste treatment was primarily for taste and odor control.

Hager and Flentje(47) in 1965, conducted studies showing that granular activated carbon adsorption removed most organic impurities from potable water supplies including detergents, insecticides, viruses, specific chemical pollutants, and taste and odor pollutants.

Joyce et al(59) reported on the treatment of municipal wastewater by packed activated carbon beds. The column effluent was clear, colorless, odorless, applicable to use in many industrial applications. The organic content(COD) was reduced from 50-70 mg/l to 12-20 mg/l.

Dostal et al(35) reported on the granular carbon purification system introduced in 1963 at Nitro, West Virginia. The column effluent met drinking water standards. Also, column bed design criteria were developed.

Parkhurst et al(73) used a packed bed granular activated carbon column system at the Pomona water reclamation plant in California. Removal efficiency of organic matter(COD) of about 55 lb/100 lb carbon was reported. Part of the removal efficiency was reported to be due to an active biological flora which developed within the carbon beds.

Granular activated carbon is being used as a tertiary treatment step in water purification at South Tahoe, California to produce one of the clearest bodies of water in the world. Culp and Roderick(30), and Culp and Roderick(31) reported on the use of activated carbon in the

treatment process. More than 80 percent of the organic material(COD) was removed yielding a colorless, odorless, clear water.

At Windhoek and Pretoria, South Africa, granular activated carbon is used for the reclamation of potable water from wastewater as reported by Cillie et al(24) in 1966, and by Stander and Van Vuuren(97,98).

Municipal wastewater treatment by physical chemical methods was discussed by Villiers et al(101), and by Bishop et al(17). From the studies it was concluded that removal of soluble organics from raw wastewater by activated carbon produced good quality water and should be economically feasible.

#### 2.3.6 Industrial Waste Treatment

Wide fluctuations in raw wastewater characteristics are common to industrial wastes. These wastes also may contain refractory and toxic contaminants. Conventional biological treatment systems operate least effectively under these conditions(42).

Activated carbon is used in a number of industrial applications for reclaiming solutions which could create a waste problem. Economic savings have resulted through reuse and recovery of valuable products, and elimination of their discharge as wastes. Sigworth(88) in 1963, discussed the potential of activated carbon for the treatment of

industrial wastes. Myrick and Dawtang(68) reported on activated carbon adsorption as a unit process in liquid industrial waste treatment.

Cooper and Hager(28) in 1966, suggested widespread use of granular activated carbon in industrial waste practises. Burleson et al(19) in 1968, and Zanitsch and Morand(112) discussed the tertiary treatment of secondary industrial effluents by activated carbon. They reported that removal of 85 percent of the refractory organic matter could be accomplished. Eckenfelder(37) also discussed industrial waste treatment by the use of activated carbon.

Phipps(76) in 1969, reported on the use of activated carbon to reclaim textile industry wastewater. Reclamation and in-plant reuse of approximately 80 percent of the plant's waste effluent was being achieved.

Gould and Taylor(46) reported that granular activated carbon effectively treated phenolic wastewater from a resin plant. Granular activated carbon treatment of the high organic waste load in effluents from an insecticide plant was reported in the literature from the Calgon corporation(20).

Hager and Reilly(49) in 1969, illustrated the wide variety of industrial wastewaters presently being treated by activated carbon. Rizzo(85) reported on the wide range of applications of granular carbon with case histories of the use of carbon for treating a variety of industrial wastes.

### 2.3.7 Food Industry Waste Treatment

Water is a major constituent of the food industry; polluted water is the major waste from the industry. A recent report in "Food" indicated that 45 percent of water pollution is caused by industry, with 85 percent of that total attributed to various food processing effluents(6). As population and demands for water increase, industry will be faced with requirements for tertiary or advanced waste treatment with need for water reuse(102). Gallop(42) indicated that the growth of the food industry is becoming more dependent on the solution of water and waste problems, than on other factors. Food industry wastes are as diverse as its products and processes(102).

Conventional primary and secondary treatment processes are presently largely used to treat food industry waste effluents. As the waste effluents from the industry will not meet the more stringent standards of water quality proposed by governmental action, the U.S. food processing industry in 1970 began a national program of research and development of pollution control methods capable of higher degrees of treatment with the aim of inplant water reuse(102). Activated carbon is being considered as a possible method of advanced waste treatment.

The use of activated carbon constitutes an integral part of the processing of many food products. Activated carbon was first used in the sugar industry over a hundred

years ago for removal of color, and organic contaminants(50). Activated carbon is also used to remove off-flavors in the soft drink industry, to remove colour, odor in alcoholic beverages, in purification purposes of oils, fats, gelatin, pectin, alginates, maple syrup, honey, candy, and to remove turbidity in fruit juices(50).

Fox(40) reported on the purification of brines for reuse using activated carbon filters to adsorb phenolics. Ralls et al(82) and Popper et al(80) also reported on this subject. The feasibility of activated carbon renovation of marashino cherry brine effluent was discussed by Beavers et al(14). Schultz et al(86) reported on the use of activated carbon for adsorbing volatiles in commercial apple essence. Ralls et al(81) reported on the use of granular activated carbon for treatment of various cannery wastes.

Gallop et al(44) demonstrated the potential of purifying several food industry wastes by the Manitoba Food Science Department process utilizing activated carbon, preferably made from selected solid organic wastes. The degree of purification of the water will be dictated by its specific reuse application. In the food processing industry, water of drinking water standard is required only for the final stages of production.

### 2.3.8 Physical Chemical Treatment

Interest has focused in the last few years on development of physical chemical processes to accomplish the degree of purity required by more stringent waste effluent standards(103). Conventional methods of waste treatment which include primary screening and secondary biological operations often do not provide the required degree of purity. Granular activated carbon was subsequently employed as a tertiary step following biological treatment.

The need for biological treatment before the granular activated carbon process was then questioned. The concept of applying activated carbon to a primary waste rather than secondary treated effluent is derived from the relative economics of a two stage versus a three stage system. Also, the leakage of certain organic fractions through activated carbon columns in the three stage system has been noted by investigators such as Joyce(59) and Parkhurst(73). The organic fraction is thought to be non adsorbable fragments produced during the biological process.

Zuckerman and Molof(114) produced high quality reuse water by physical chemical treatment. The treatment was considered superior to the conventional tertiary treatment sequence. Hopkins et al(51) reported on a physicochemical process for treatment of raw wastewater. Better organic removal was obtained than for conventional treatment, a high degree of removal of phosphate, nitrate, normally not

removed by conventional was achieved, and treatment was not affected by variations in waste composition and strength, nor by toxic substances, all which adversely affect biological treatment.

Rizzo and Schade(84) demonstrated that granular activated carbon treatment preceded by chemical clarification, purified raw sewage beyond levels normally obtained by conventional methods. They also suggested that bacterial action within the carbon columns produced beneficial results. Weber et al(105) also reported similar results.

Ayres et al(10) discussed the operation and performance of a physical chemical pilot plant treating domestic wastewater at Owasso, Michigan.

Development of a physical chemical system at Windhoek, South Africa to reclaim potable water from raw sewage was reported by Stander et al(98).

Physical chemical treatment for pulp and paper wastes was reported by Smith and Berger(91) and by Rimer(83); for refinery wastes by Huang and Hardie(52); for waste treatment by Calgon Corporation(21).

Hager and Reilly(49) illustrated the use of physical chemical treatment for municipal and industrial wastes. Cohen(25) in 1972, reviewed the literature on physical-chemical methods. Peacock(74) concluded that physical-chemical processes would replace conventional

biological processes.

The Manitoba Food Science Department has developed several processes of physical-chemical treatment for food processing wastes(42).

### III. Methods and Materials

#### 3.1 Adsorption Isotherm Study

The removal of impurities from solution by activated carbon is by adsorption. As a means of representing adsorption as a mathematical expression, the empirical Freundlich equation is most widely applicable. The method of testing and evaluation of the adsorption isotherms was as recommended by the ASTM(1965)(69). Literature available from the manufacturers of activated carbon describe test procedures and use of the Freundlich equation in evaluating adsorption isotherm data(8,9,32,55,69,77).

##### 3.1.1 Adsorbent

The adsorbent chosen for use in this study was Nuchar granular activated carbon, grade WV-L, particle size 8/30 (U.S. Sieve Series). The literature on this specific carbon indicates that it is intended for packed bed adsorption applications. The wide range of pore sizes enables it to efficiently adsorb from solutions a wide variety of both high and low molecular weight substances. The carbon is applicable to wastewater treatment, and can be fully regenerated(70).

Specifications and properties of WV-L granular activated carbon are shown in Appendix 1.

WV-L activated carbon was chosen for use in this study after comparison of four activated carbons for treatment of the potato and dairy effluents. WV-L carbon exhibited the largest adsorption capacity for these wastes as indicated in sections 4.3 and 4.4.

### 3.1.2 Equipment

#### (1) Conventional Laboratory Shaker

The batch study experiments with activated carbon were conducted using a New Brunswick Scientific (model C-33) laboratory rotary shaker. The Erlenmeyer flasks containing the activated carbon and the test liquid were shaken at 300 rpm for 1 hour.

#### (2) Pulverizing(77)

The granular activated carbon used in batch study experiments was pulverized so that it would pass through a 300 mesh screen. Pulverizing the carbon shortens the required contact time to reach equilibrium but does not change the adsorption capacity. Since the rate of adsorption does vary with the diameter of the carbon particles, pulverizing will eliminate this variable. The granular carbon was ground to the powdered form using a micro beating grinding mill.

### (3) Incubator Cabinet

For temperature control, the laboratory shaker was located in an incubator cabinet (Puffer Hubbard) model. The temperature was set at 22 C.

#### 3.1.3 Rate of Adsorption

Duplicate 1 gram samples of activated carbon were weighed and transferred to 250 ml Erlenmeyer flasks on a laboratory shaker. The test liquid (100ml) was added and the flasks were shaken at 300 rpm for predetermined time intervals. Control samples containing 100 ml of the test liquid alone were also shaken for the same time intervals. The samples were filtered free from the activated carbon by passing through Whatman filter paper No. 5. The clear filtrate was then analysed for impurities by the COD test.

Rate curves were plotted with per cent impurity removed as the ordinate and time as the abscissa. Rate of adsorption curves indicate the required contact time between the adsorbent and the test liquid to achieve the required degree of organic removal.

#### 3.1.4 Adsorption Isotherm Procedure

Different weights of pulverized activated carbon were transferred to 250 ml Erlenmeyer flasks. The dosages of carbon were chosen to give a wide range of organic removal in order to obtain a satisfactory adsorption isotherm.

The test liquid(100 ml) was added to flasks containing the activated carbon, and to one flask without carbon. This sample served as the control. The carbon treated samples and the control were shaken on the laboratory shaker at 300 rpm for 1 hour. This time was determined from the rate of adsorption study. The test liquid was then separated from the carbon by filtration through Whatman filter paper No. 5. The samples were collected after the filtrate became clear. This was necessary as carbon fines would interfere with the COD test. The control sample was filtered in the same manner.

The residual concentration of impurity remaining in solution was determined by the COD test. The experimental data was then calculated using the Freundlich equation to obtain adsorption isotherms. The adsorption capacity of the activated carbon for the test liquid was calculated from the adsorption isotherm plot(logarithmic).

### 3.1.5 Adsorption Isotherm Evaluation

The Freundlich equation for adsorption isotherms was used to calculate the experimental data measuring the adsorption capacity of the activated carbon. This method of measuring adsorption capacity is widely used and is recommended by the American Society for Testing and Materials (ASTM) (69). The Freundlich equation states that for data on adsorption obtained at a uniform temperature, there

is a mathematical correlation between the quantity of substance adsorbed and the unadsorbed quantity that is left in solution. The equation which relates the amount of impurity in solution to that in the adsorbed phase is written:

$$x/m = kc^{1/n}$$

$x$  = units of impurity adsorbed ( $C_0 - c$ )

$c$  = equilibrium concentration of impurity remaining in solution after adsorption

$m$  = carbon dosage

$x/m$  = concentration of impurity in adsorbed state

$k, n$  = constants

The isotherm equation is most often written in graphical form plotting  $\log x/m$  vs  $\log c$ , which theoretically yields a straight line.

$$\log x/m = \log k + 1/n \log c$$

$1/n$  = slope of the straight line plot

$k$  = intercept of the line at  $c = 1$

The adsorption isotherm plot indicates the degree of purity that can be obtained with activated carbon treatment. By extrapolation of the isotherm plot to intersect the horizontal straight line drawn from the influent concentration ( $C_0$ ), the adsorption capacity of the activated carbon can be determined.

This value,  $(x/m)C_0$ , represents the amount of impurity adsorbed per unit weight of carbon when the carbon

is in equilibrium with the influent concentration, and represents the ultimate adsorption capacity of the carbon. This equilibrium should eventually be reached in column treatment, when the carbon column becomes exhausted ( $C_f = C_o$ ).

The slope  $(1/n)$  is significant in evaluation of the isotherms, and in calculating the dosage of carbon required in countercurrent systems(8).

### 3.2 Laboratory Column Studies(9,32,39,56,77,109)

#### 3.2.1 Column Construction

The granular carbon columns used in this study were constructed from cylindrical glass tubing. Small stainless steel spigots were attached by tygon tubing to drawnout stems of the glass columns. The carbon column was 1 inch in diameter and 25 inches in length. For bed support, a piece of fine wire mesh screen was fitted to the bottom of the column.

#### 3.2.2 Activated Carbon Preparation

The granular activated carbon(Nuchar WV-L) used in this study was of mesh size 8 x 30. The granular carbon was slurried with hot water and boiled before loading into the column. This procedure was used to expel entrapped air from the pore structure of the granular activated carbon and also

aided in removing carbon fines from the system.

### 3.2.3 Carbon Loading

Carbon loading of the bed was accomplished by displacing a heel of water previously placed in the column. The carbon was added in a slurry to avoid entrapping air in the carbon bed, which could cause channeling during column operation. Gentle tapping of the column as the activated carbon was added allowed the bed to pack and settle more efficiently.

### 3.2.4 Column Preparation

The activated carbon columns were washed free of carbon fines by passing distilled water upwards through the column at high flow rates. By this backwash procedure the carbon fines were washed out to prevent clogging of the small diameter spigots used in flow rate control; also the leakage of the carbon fines into the column effluent would interfere with the COD analysis. This washing procedure also helped in settling the carbon bed.

### 3.2.5 Feed Delivery

The column influent was pumped from a storage container to a constant head overflow container. The flow rate of the liquid to the overflow container was regulated slightly greater than that of the column flow rate. The feed

from the overflow vessel was siphoned to the carbon columns. This procedure also accomplished a constant head on the carbon columns.

### 3.2.6 Flow Rate Control

Flow rate of the test liquid through the columns was regulated by adjusting the opening of the stainless steel spigots. The flow rates were measured as bed volumes per hour (BV/Hr). Residence time in the column was calculated by dividing the fractional void volume by the number of bed volumes of liquid pumped through per hour.

$$Tr = 0.4 / (BV/HR)$$

Tr = column residence time

0.4 = fractional void volume for WV-L carbon

BV = cross sectional area times the column height  
and includes both carbon and void bed volume

The manufacturers' recommended range of flow rates was 0.5 - 6.0 BV/Hr depending on the degree of purification required, and the type and concentration of impurity in the waste to be treated.

### 3.2.7 Column Evaluation

The concentrations of organics in the column influent and the effluent from the column were measured at regular intervals by the COD test. A plot of impurity remaining in the effluent versus throughput volume resulted

in a graphical picture of a wave front. The point on the curve at which impurity first appears in the effluent is termed the breakpoint, while the wave front is termed the breakthrough or column exhaustion curve. The shape of the column exhaustion curve is significant in predicting the proper column system for treatment of a particular waste. Single column tests yield enough parameters for the design of multiple column systems(39).

The number of carbon columns required in a multiple column system can be determined by a graphical technique. This technique is based on the assumption that all columns will have similar breakthrough curves(39).

The activated carbon capacity for organics (the organic loading on the column) was determined by use of a computer programme for determining "area under the curve". The capacity was measured as mg COD/g carbon.

### 3.3 Chemical Analysis

#### 3.3.1 Chemical Oxygen Demand (COD) (96)

##### Reagents

1. Potassium dichromate solution (0.25N) : potassium dichromate was dried in an oven for two hours, then cooled in a dessicator. Potassium dichromate (12.259g) was dissolved in distilled water, diluted to 1000 ml in a volumetric flask.

2. Sulphuric acid - Silver Sulphate Solution : Silver sulphate (22.0g) was added to concentrated sulphuric acid (4.08kg) and allowed to stand for two days for dissolution.

3. Ferroin Indicator Solution : Hydrated ferrous sulphate (0.695g) and 1,10-phenanthraline monohydrate (1.485g) were dissolved in distilled water and diluted to 100 ml.

4. Mercuric Sulphate : Analytical grade crystals were used.

5. Ferrous Ammonium Sulphate Titrant (0.1N) : ferrous ammonium sulphate (39g) was dissolved in distilled water. Concentrated sulphuric acid (20ml) was added and the contents were allowed to cool. The solution was diluted to 1000 ml in a volumetric flask.

## Method

Mercuric sulphate (0.4g) was weighed and transferred to a 250 ml flat bottom boiling flask. The sample (20ml) was added to the flask, followed by 10 ml of standard potassium dichromate solution. The sulphuric acid - silver sulphate solution was then carefully added to the mixture. The flasks were swirled to ensure uniform mixing. Anti-bumping granules (BDH) were then added to each flask. The samples were refluxed for 2 hours using "Corning" hot plates and Liebig and coil condensers. Blank determinations were carried out by substituting distilled water for sample substrate. After the samples were allowed to cool, the condensers were washed down with distilled water to make a final volume of approximately 140 ml. Ferroin indicator (3 drops) was added to each flask which were then titrated to a reddish brown end-point with the 0.1N ferrous ammonium sulphate solution.

## Addition of Mercuric Sulphate

Mercuric sulphate was added to the samples before refluxing to form a soluble mercuric chloride complex with the chlorides present to eliminate the chlorides from taking part in the reaction. A mercuric sulphate:chloride ratio of 10:1 is necessary.

### Standardization of Ferrous Ammonium Sulphate Solution

A 10 ml aliquot of standard potassium dichromate(0.25) was added to a 250 ml Erlenmeyer flask. The potassium dichromate solution was diluted to 1000 ml with distilled water. Concentrated sulphuric acid (30ml) was added, the solution was swirled and allowed to cool. Ferroin indicator (3 drops) was added and the solution was titrated to a reddish-brown end point with the ferrous ammonium sulphate solution.

### Calculation of COD

The COD of the samples was calculated using the equation :  $(V_a - V_b) (N) (8000 / V_s)$ .

$V_a$  = ml of ferrous ammonium sulphate used for blank titration

$V_b$  = ml of ferrous ammonium sulphate used for sample titration

$N$  = normality of ferrous ammonium sulphate used in titration

$V_s$  = sample size (ml)

The constant 8000 converts millequivalents of oxidant consumed to milligrams of oxygen required to oxidize one liter of the solution. COD was expressed in mg/l.

### 3.3.2 Determination of Total Soluble Iron

#### Reagents

1. Iso-amyl alcohol
2. Nitric acid : concentrated
3. Potassium thiocyanate : 20% (w/v)
4. Ferrous ammonium sulphate
5. Sulphuric acid : 5% (v/v)

#### Method

A 20 ml sample was measured into a large test tube. Nitric acid was added (4 drops) and the tube was heated in a boiling water bath for forty minutes. The sample was cooled and transferred to a 125 ml separatory funnel. Isoamyl alcohol (10ml) and potassium thiocyanate (5ml) was added. The funnel was capped, shaken 60 times, then allowed to stand for five minutes. The colorless bottom aqueous layer was then discarded. The alcohol layer was filtered through dry filter paper, and the optical density was determined at 490 nm on a Bausch and Lomb "Spectronic 20" using clear isoamyl alcohol as a blank.

#### Calculation of Total Soluble Iron

The concentration of total soluble iron, expressed as mg/l iron was determined from a calibration graph.

### Calibration Graph

Ferrous ammonium sulphate(3.514g) was dissolved in distilled water. Sulphuric acid (100ml) was added and mixed, then nitric acid (17ml) was added. The solution was allowed to stand overnight, then the volume was made up to 1 liter in a volumetric flask using distilled water; 10 ml of this solution was diluted to 1 liter with distilled water (1ml = 0.005mg Fe). A calibration graph was prepared using aliquots of the above solution (2ml to 10ml) and diluting to 20 ml before using the above procedure.

### 3.3.3 Determination of Chloride (96)

#### Reagents :

1. Potassium Chromate Indicator Solution : Potassium chromate (20g) was dissolved in distilled water, then diluted to 1 l with distilled water in a volumetric flask.

2. Standard Silver Nitrate Titrant : Silver nitrate of approximately 0.1 N was prepared by dissolving 8.5 g silver nitrate in distilled water and diluting to 500 ml in a volumetric flask.

3. Sodium Chloride : Sodium chloride was of analytical grade.

### Method

A 10 ml sample was diluted to 50 ml with distilled water in a 250 ml Erlenmyer flask. Potassium chromate indicator (2ml) was added. The sample was then titrated with silver nitrate solution to a pinkish-yellow end point which is a silver chromate precipitate. Blanks were determined using 50 ml distilled water.

### Standardization of Silver Nitrate

The standardization was conducted in triplicate. Sodium chloride was dried for one hour, then cooled in a dessicator. Weighed portions of approximately 0.2g sodium chloride were then placed in separate 250 ml Erlenmyer flasks. The sample was dissolved in 50 ml water. Potassium chromate (2ml) was added and the sample was titrated with silver nitrate solution to a pinkish-yellow end point.

### Calculation of Chloride

Chloride was calculated from the formula :  $(\text{vol A} - \text{Vol B}) (N) (35,450/\text{vol S})$ , where vol A is the ml titration for sample, vol B is the ml titration for blank, vol S is the ml sample used, N is the normality of silver nitrate, 35,450 is an equivalent weight factor. The results are expressed as mg/l chloride.

#### 3.3.4.Measurement of Turbidity (96)

Turbidity was measured with a Nephelometer (EEL, UNIGALVO TYPE 20, U.K.) The standard was set at 100 on the linear scale using the sensitivity control. Distilled water at 1.33 was used as the reference.

#### 3.3.5Measurement of Total Residue (96)

##### Apparatus :

1. Evaporating dish
2. Steam bath
3. Drying oven
4. Dessicator
5. Analytical balance

##### Procedure

Evaporating dishes were dried in the oven to constant weight. A 20 ml sample was then added to the weighed dishes. The samples were evaporated on a steam bath, the dishes were transferred to the drying oven maintained at 103 C. The dishes were again dried to constant weight. The dishes were allowed to cool in an a dessicator before weighing.

### Calculation of Total Residue

Results were reported as mg/l total residue using the formula : (mg total residue)(1000)/ ml sample

### 3.3.6. Bacteriological Analysis (95)

Continuous column operation of the simulated wastes resulted in biological activity in the column bed. The number of viable bacteria cells in the column influent, column effluent, and activated carbon from the column were determined by the method recommended by the A.P.H.A. (1965). Using a serial dilution technique, the samples were plated at time intervals on standard plate count agar. The plates were incubated at 32 C for 48 hours. The average of colony counts of a suitable dilution containing 30-300 colonies was selected to enumerate the viable bacteria cells per ml.

### 3.4 Activated Carbon Adsorption of Organic Compounds

Phase 1 of this study dealt with adsorption studies of a series of organic compounds which are major constituents of food. These organics are possible components of the waste effluent from food processing plants. Substrates studied included organic acids, proteins, amino acids, and carbohydrates.

Batch testing was conducted with activated carbon to develop adsorption isotherms for each constituent. The

adsorption isotherms indicated the affinity of the activated carbon for these organics. Rate of adsorption studies were included for a number of selected organics to determine the carbon contact time required for equilibrium conditions.

#### 3.4.1 Rate of Adsorption

Rate of adsorption graphs were obtained for selected pure compounds representative of the groups of compounds likely to occur in food processing effluents. The compounds included were egg albumin, sucrose, glucose, and lactose. The method for obtaining the plots and evaluation of the results were as described in section 3.1.5.

#### 3.4.2 Adsorption Isotherm Study

The method for obtaining the adsorption isotherms was as described in section 3.1.4. The adsorbates used in this study were of analytical grade. The initial substrate concentration was 1 g/l. Most solutions of the organics were prepared by dissolving the organics in distilled water and diluting to 1 liter in a volumetric flask. For some organic substrates heat, and/or dilute sodium hydroxide solution (0.5g/l) were required for dissolution. The method of evaluation of the adsorption isotherms was as described in section 3.1.5.

### 3.5 Physical Chemical Treatment of Simulated Lye-Peel Potato Waste

Phase 2 of this study dealt with the evaluation of physical chemical treatment of simulated lye-peel potato wastewater. The simulated waste was chemically clarified then treated with activated carbon.

Preliminary studies at the Food Science Department indicated the feasibility of chemically clarifying this waste. Activated carbon treatment evaluation included adsorption isotherm studies to determine the feasibility of this treatment step, followed by granular carbon column testing after the adsorption isotherms showed favourable results.

#### 3.5.1 Preparation of Simulated Lye-Peel Potato Wastewater

The potatoes, Netted Gem variety, were obtained from the Department of Plant Science, University of Manitoba. The potatoes were peeled; the peels were packed in polyethylene bags and stored in a freezer. Simulated lye-peel waste was prepared as follows: 2000 g of potato peels were blended for 5 minutes with cold water in a Waring blender. The mix was added to 80 l of water in a steam kettle. Sodium hydroxide flakes (320g) were added as the mix was being agitated. The temperature was raised to 78 C, then allowed to cool to 20 C. The waste was stored overnight in a cooler at 1.7 C before treating with chemical coagulants.

### 3.5.2 Treatment of Waste

The simulated potato waste was chemically clarified using a solution of ferric chloride - aluminum chloride (1M, 1M). The dose of coagulant varied from 16 - 30 ml per 950 ml batch size. The clarified waste was filtered through Whatman filter paper No. 4 to remove any particulate matter, then treated with activated carbon.

### 3.5.3 Adsorption Isotherm Study

#### 3.5.3.1 Selection of Activated Carbon

Four commercial granular activated carbons were evaluated as possible adsorbents in this study. The method of evaluation was by the adsorption isotherm test. The carbon whose isotherm exhibited the largest  $(x/m)C_0$  value (maximum adsorption capacity) was chosen as the most efficient carbon.

#### 3.5.3.2 Rate of Adsorption

The rate of adsorption plot was obtained for simulated potato waste by the method described in section 3.1.3.

#### 3.5.3.3 Adsorption Isotherm Study

Adsorption isotherms were obtained for the lye-peel potato waste treated with varying coagulant dose (16 - 30 ml

coagulant per 950 ml batch size). The adsorption isotherms were evaluated by the method described in section 3.1.5. The method for obtaining the adsorption isotherms was as described in section 3.1.4.

### 3.5.4 Granular Activated Carbon Column Treatment

#### 3.5.4.1 Flow Rate Determination

Preliminary column studies dealt with determining the optimum flow rate and column residence time for continuous column operation. The chemically clarified waste was passed through the carbon columns at flow rates 0.5 - 8.0 BV/Hr to determine the COD reduction at each residence time. Column construction, dimensions, and operation were described in section 3.2.

#### 3.5.4.2 Continuous Column Testing

Chemically clarified simulated lye-peel potato wastewater (22 ml coagulant per 950 ml batch size) was passed through activated carbon columns 1 inch in diameter, packed to a bed depth of 20 inches with WV-L granular activated carbon. The potato waste (1001) was passed through the columns operated at flow rates 1 BV/Hr, 2 BV/Hr. Breakthrough curve were developed for each column operation by analysing the column influent and effluent for organic concentration (COD), and plotting these results versus

throughput volume. Evaluation of the column treatment was by the method described in section 3.2.7.

The column influent and effluent were also analysed for turbidity, total solids, chloride, and iron content. The methods of analysis were described in section 3.3.

### 3.6 Physical Chemical Treatment of Simulated Dairy Waste

Phase 3 of this study dealt with the evaluation of physical chemical treatment of simulated dairy(milk) waste. A number of chemicals were used as coagulants to clarify the waste. The clarified waste was then batch treated with activated carbon to determine the feasibility of the adsorption process. The adsorption isotherm results warranted carbon column studies.

#### 3.6.1 Preparation of Simulated Dairy Waste

The simulated dairy waste was prepared as follows: To 12,500 g of water, 200 ml milk was added. "Triple"(4g) a caustic soda wash, "GLX"(2g) a washing compound, "Keego"(2g) a washing and corrosion prevention compound, "Dilac"(2ml) an acid wash, and active chlorine(1ml) were then added. The simulated dairy waste was formulated by the Dairy division of the Food Science Department.

#### 3.6.2 Treatment of Waste

The simulated dairy waste was chemically clarified

using different coagulants - ferric chloride/aluminum chloride(1M,1M), ferric chloride(2M), alum, and lime.

The waste was allowed to settle, the supernatant was filtered through Whatman filter paper No.4. The waste was then treated with activated carbon in batch and column tests.

### 3.6.3 Adsorption Isotherm Study

#### 3.6.3.1 Selection of Activated Carbon

Four commercial granular activated carbons were evaluated as possible adsorbents in this study. The method of selecting an activated carbon was by evaluation of the adsorption isotherms of the test carbons. The method used to develop the adsorption isotherms was as described in section 3.1.4. The method of evaluation was as described in section 3.1.5.

#### 3.6.3.2 Rate of Adsorption

A rate of adsorption graph was obtained for the dairy waste. The method was described in section 3.1.3.

#### 3.6.3.3 Adsorption Isotherm

Adsorption isotherms were obtained for the chemically clarified dairy waste and for raw dairy waste. The method for obtaining the isotherms was described in

section 3.1.4. The evaluation procedure was described in section 3.1.5.

#### 3.6.4 Granular Activated Carbon Column Study

The granular activated carbon column treatment of the simulated dairy waste was the same as described in section 3.5.4 for the treatment of lye-peel potato wastewater.

## IV. Results and Discussion

### 4.1 Data Compilation

The data analysis was carried out on the University of Manitoba's IBM 360/65 system. The calculations were done in single precision arithmetic using specially written programs in Fortran.

The programs in Fortran were set up as to calculate adsorption isotherm data and compile this data in tabular form; plot the adsorption isotherm data in logarithmic form  $x/m$  (impurity removed per unit weight of activated carbon) versus final COD; and from the linear plot compute the values  $(x/m)C_0$  - optimum theoretical adsorption capacity per unit weight of carbon,  $1/n$ , slope of adsorption isotherm, and  $k$  a constant; to compute "area under a curve"; and to determine the correlation coefficient of the linear adsorption isotherm.

### 4.2 Adsorption of Organic Solutions from Aqueous Solution

An important parameter of activated carbon studies in wastewater purification is the affinity of the adsorbent for carbohydrates, amino acids, and organic acids, components which comprise a large fraction of the soluble organic matter. These organics are food constituents, therefore could become components of waste effluent from food processing operations.

Solutions of the organic components were studied at an initial concentration of 1 g/l. The COD values for the majority of substances at this level, were within the range of the COD values for food processing effluents (400-2000 mg/l), treated with granular activated carbon later in this study. Adsorption isotherms were obtained for each adsorbate using the Freundlich adsorption isotherm equation. The results are listed in tables 1-3. Graphical representation of the adsorption isotherms is illustrated in figures 2-8. Experimental data used to derive the adsorption isotherms are listed in Appendix 2,3,4.

#### 4.2.1 Rate of Adsorption Study

Rate of adsorption curves were obtained for a number of pure substances, and also for simulated lye-peel potato waste, and dairy waste.

From these rate curves (Fig. 1,9) the time required for the adsorption system to reach equilibrium conditions could be determined. Equilibrium conditions are required for adsorption isotherm studies.

The rate curves were characterized by a relatively rapid initial rate of adsorption which decreased markedly after approximately 20 minutes to give a gradual approach to an equilibrium condition. Adsorption is indicated by the decreasing concentration of impurity in the liquor as measured by the COD test.

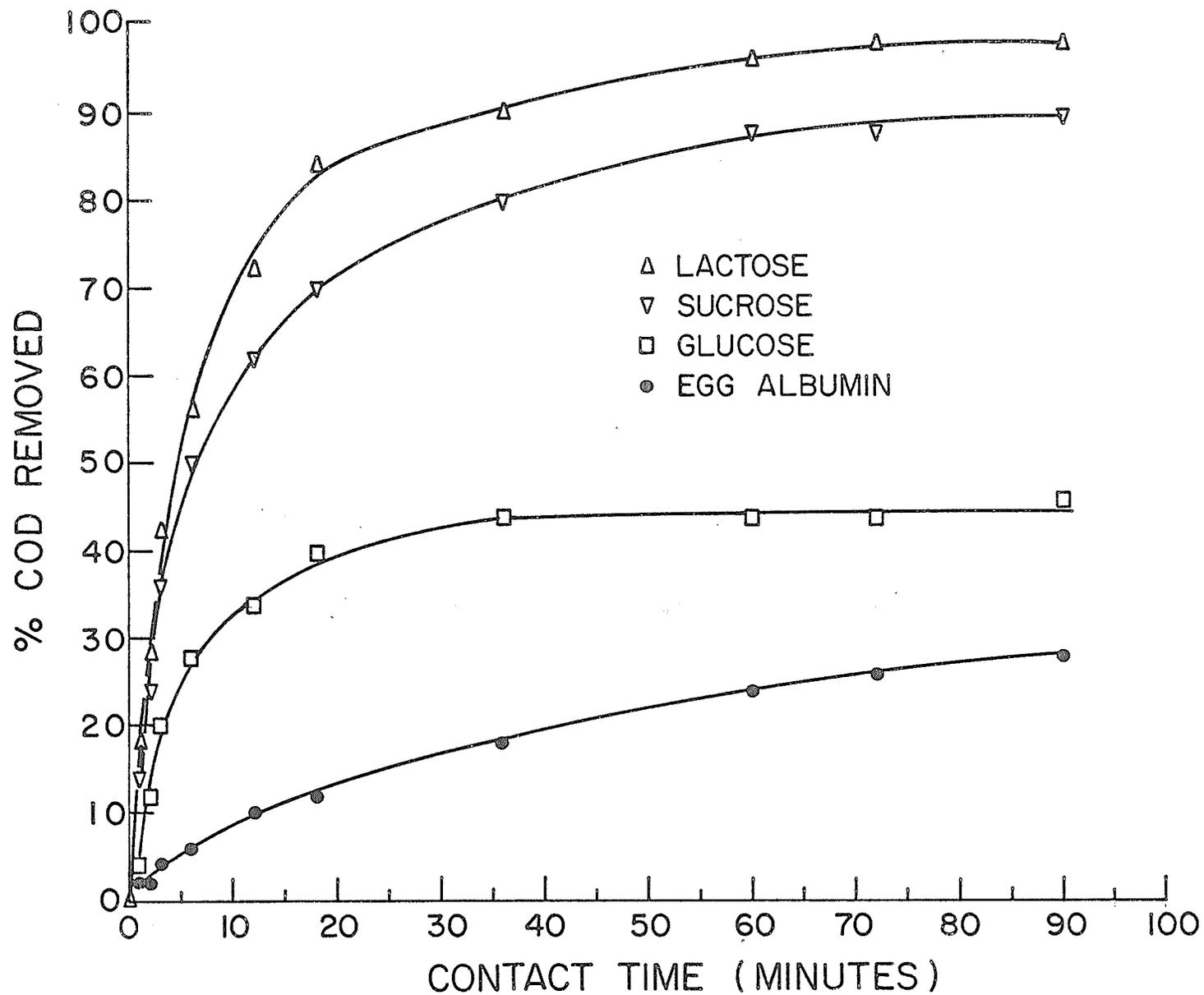


Fig. I Rate of Adsorption for Pure Substances.

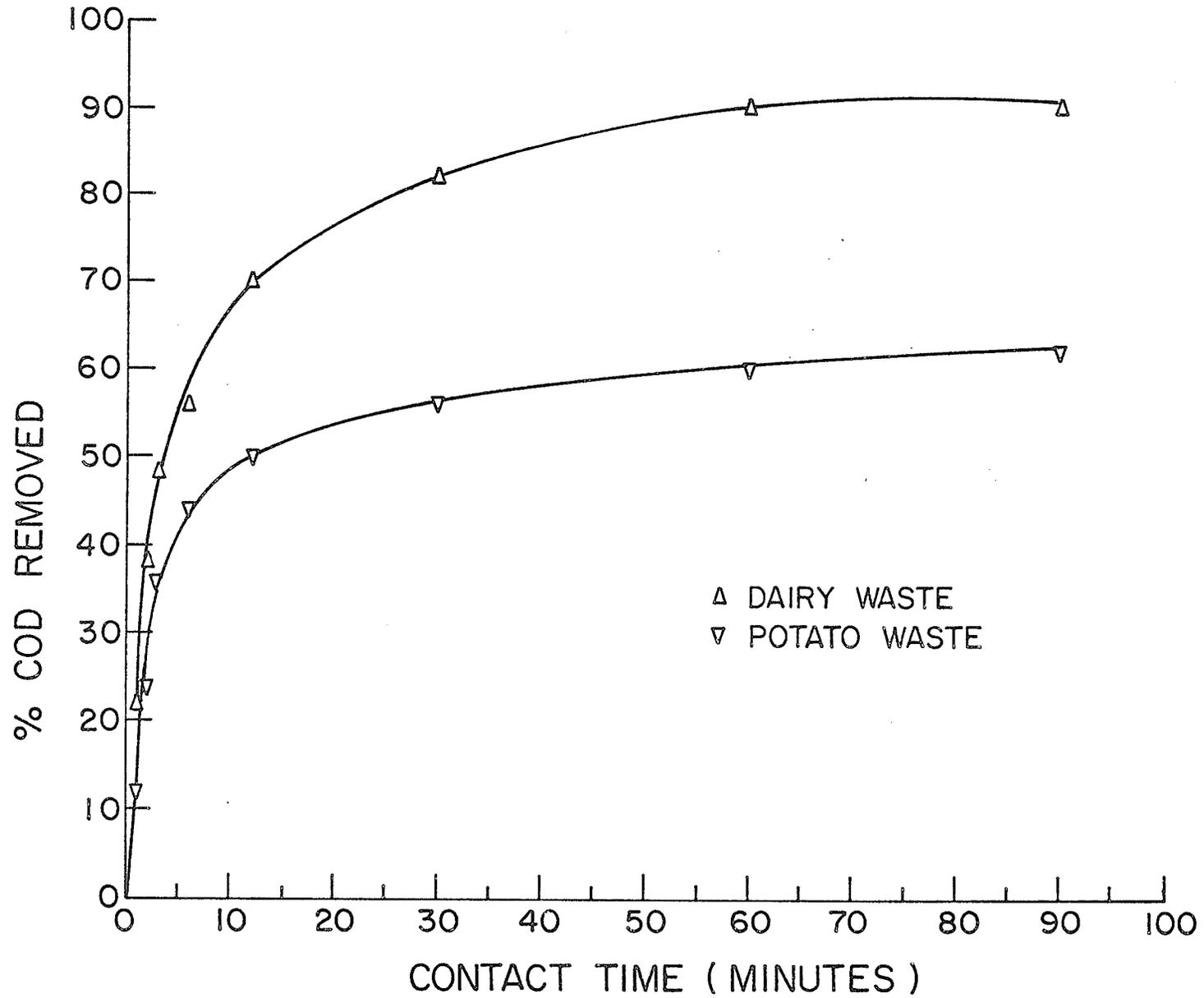


Fig. 9 Rate of Adsorption for Dairy and Potato Waste.

#### 4.2.2 Carbohydrate Adsorption

Adsorption isotherms were obtained for a number of carbohydrates including a series of sugar solutions, and high molecular weight carbohydrates.

The results are listed in table 1. Graphical representation of the adsorption isotherms is illustrated in figures 2,3. The experimental data used to develop the adsorption isotherms is listed in Appendix 2.

The order of adsorption of the sugars was trisaccharide greater than disaccharide greater than monosaccharide. The disaccharides maltose and lactose showed nearly equal adsorption and showed better adsorption than sucrose. The pentose monosaccharide sugar ribose showed better adsorption than the hexose monosaccharides. The order of adsorption of the monosaccharides was ribose greater than galactose greater than glucose greater than fructose.

The trisaccharides and disaccharides showed remarkably high adsorption capacities of 200-300 mg COD/g carbon. The monosaccharides were considerably less adsorbed exhibiting adsorption capacities on activated carbon of 44-85 mg COD/g carbon.

The sugar acid galacturonic acid showed good adsorption on activated carbon. The adsorption capacity of the activated carbon was 119 mg COD/g carbon. Polygalacturonic acid was poorly adsorbed on the activated carbon illustrated by the high slope (11.44) of the isotherm

TABLE I  
 ADSORPTION ISOTHERMS  
 CARBOHYDRATES

TREATMENT	CO <sub>2</sub> INITIAL	1/N	K	(X/M)CO
RAFFINOSE	920	0.149	1068.851	295
MALTOSE	1036	0.307	309.428	261
LACTOSE	998	0.303	315.819	256
SUCROSE	1051	0.268	307.962	199
GLUCOSE	1080	0.713	4.101	60
FRUCTOSE	1013	0.775	2.039	44
GALACTOSE	1067	0.718	4.655	70
RIPOSE	1315	0.687	6.089	85
POTATO STARCH	1041	1.599	0.017	116
POLYGALACTURONIC ACID	840	11.435	0.000	24
GALACTURONIC ACID	678	0.619	20.982	119
GLYCEROL	1172	6.333	0.000	41

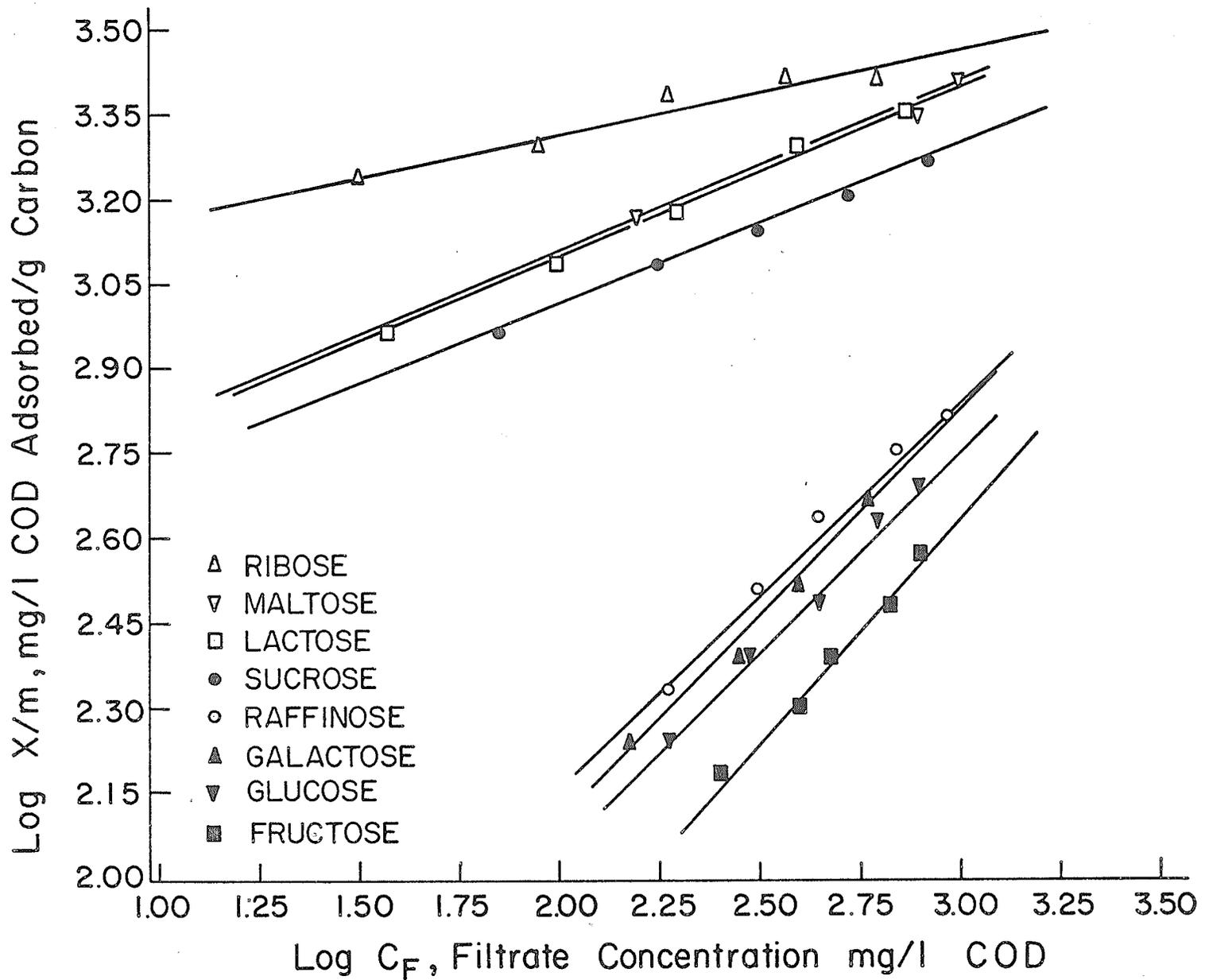


Fig. 2 Adsorption Isotherms for Carbohydrate Sugars.

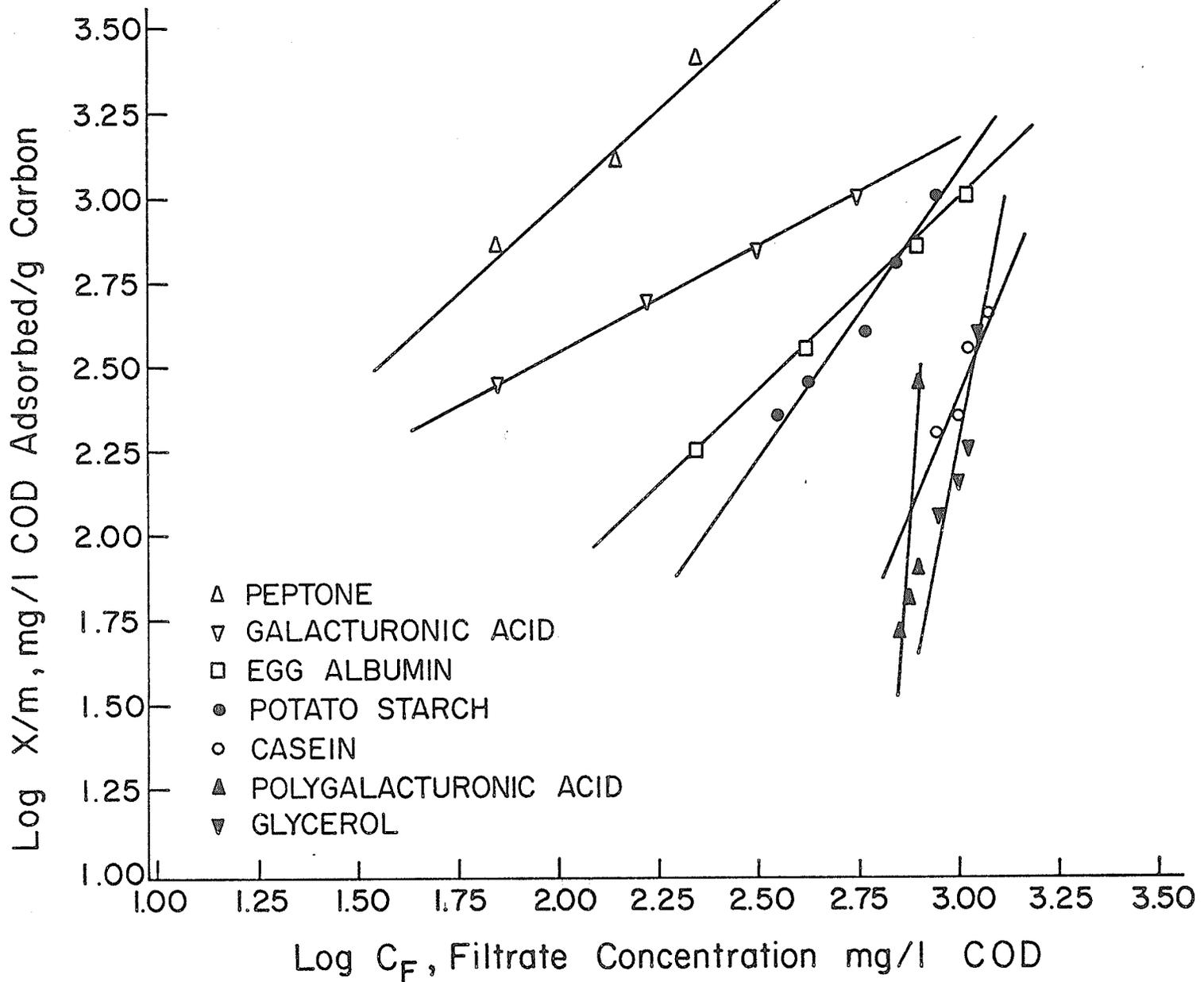


Fig. 3 Adsorption Isotherms for High Molecular Weight Carbohydrates and Protein.

and low  $(x/m)C_0$  value (24 mg COD/g carbon). Potato starch exhibited a large optimum adsorption value of 116 mg COD/ g carbon, however the slope (1.59) of the isotherm indicated that the adsorption was large at the high initial concentration but was considerably less at lower levels of starch concentration. Large doses of carbon would be required for maximum removal of starch from solution.

#### 4.2.3 Protein and Amino Acid Adsorption

The adsorption isotherm results for protein and amino acids are shown in table 2. Graphical representation of the isotherms is illustrated in figures 3,4. Experimental data is tabulated in Appendix 3.

The proteins casein and egg albumin were adsorbed to a lesser degree than peptone, a hydrolysed derivative of protein. The molecular weight of peptone is much less than for the proteins. From a molecular weight basis it could be predicted that the amino acids should be better adsorbed than peptone. In general, this was not the case. Chemical structure was probably a major factor influencing adsorption.

The aliphatic monoamino monocarboxylic acids - glycine, alanine, serine were poorly adsorbed on activated carbon, showing almost negligible adsorption. The aliphatic monoamino dicarboxylic amino acids asparagine, glutamine, are better adsorbed indicating that the addition of the

TABLE 2  
 ADSORPTION ISOTHERMS  
 PROTEIN AND AMINO ACIDS

TREATMENT	CCD INITIAL	1/N	K	(X/M)CO
GLYCINE	8380	4.178	0.000	13
ALANINE	1053	1.106	0.053	11
SERINE	759	7.500	0.000	18
CYSTINE	1116	0.494	14.865	48
METHIONINE	1108	0.355	103.139	125
ASPARAGINE	739	3.833	0.000	103
GLUTAMINE	972	0.466	20.346	50
LYSINE	1171	2.578	0.000	83
PHENYLALANINE	1796	0.226	793.731	430
TYROSINE	1606	0.568	47.147	312
TRYPTOPHAN	1804	0.208	945.875	450
PEPTONE	1528	1.083	6.864	1928
CASEIN	1300	2.721	0.000	52
EGG ALBUMIN	1188	1.094	0.496	115

second carboxyl group to the amino acid increases the adsorption capacity of adsorbate. The sulphur containing amino acids - cysteine and methionine also showed better adsorption capacities than the aliphatic monoamino monocarboxylic amino acids. The basic aliphatic amino acid lysine also showed good adsorption. In general, it was found that adsorption increased with increasing chain length of the amino acids.

The importance of the benzene nucleus on adsorption was indicated by the marked difference in adsorption between the aromatic and aliphatic amino acids. Phenylalanine and tyrosine were adsorbed to a much greater extent than the aliphatic amino acids. Tyrosine was adsorbed to a lesser extent than phenylalanine.

The presence of the hydroxyl group to the ring structure of tyrosine probably reduced adsorption by its interaction with water, lessening the tendency toward escape from solution to the adsorbent. The heterocyclic amino acid tryptophan showed better adsorption than the aromatic amino acids. The order of adsorption of amino acids on activated carbon was heterocyclic greater than aromatic greater than aliphatic amino acids.

From these studies, the adsorption of protien and amino acids was shown to be favourable.

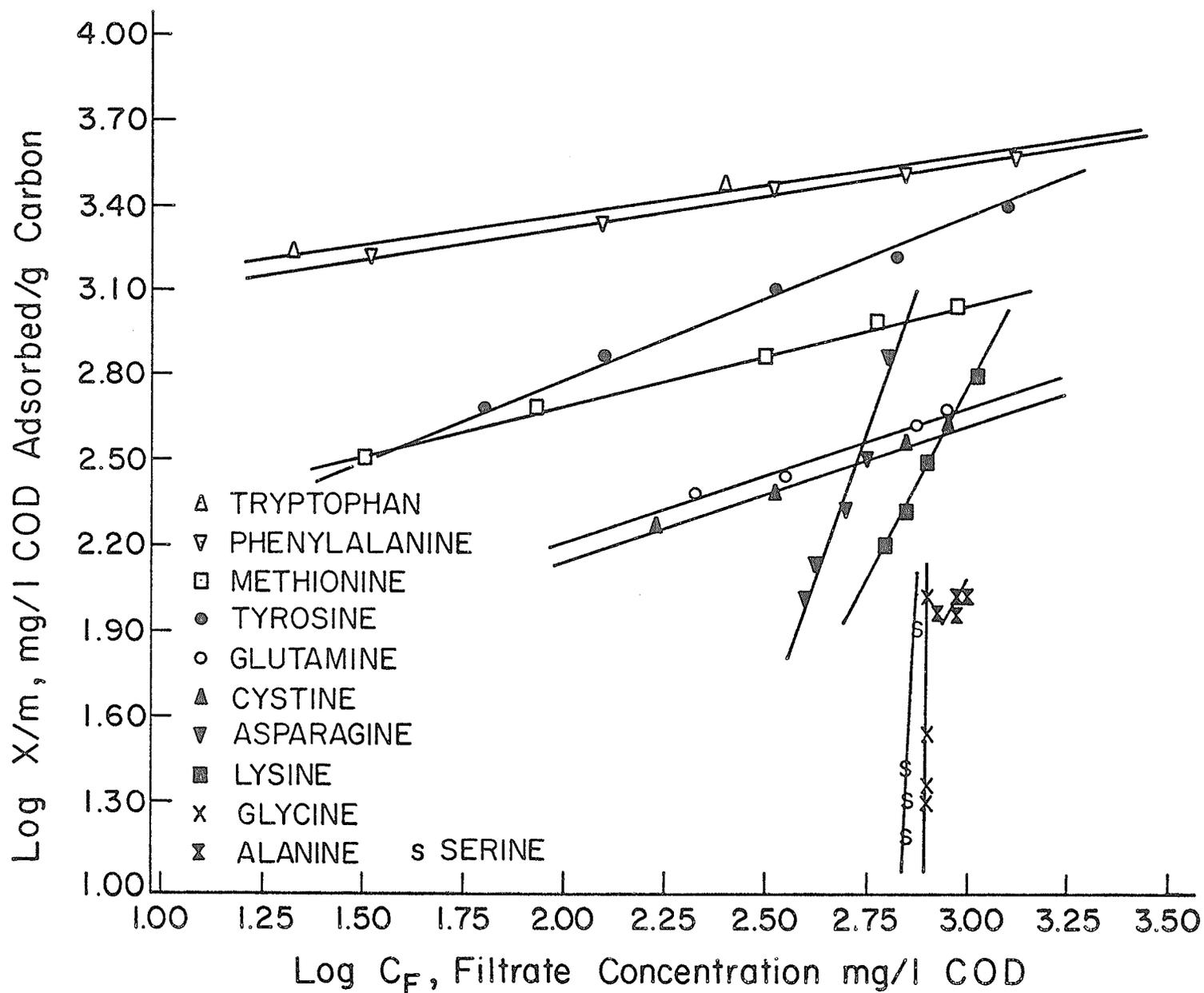


Fig. 4 Adsorptions Isotherms for Amino Acids.

#### 4.2.4 Organic Acid Adsorption

Structure also influenced the adsorption of organic acids on active carbon. The results of the adsorption isotherm studies are shown in table 3. The graphical representation of the isotherms are shown in figures 5-8. Experimental data used in developing the isotherms is listed in Appendix 4.

Results indicated that the adsorption of organic acids increased with increasing number of carboxylic groups. The order of adsorption of organic acids was aromatic greater than tricarboxylic greater than dicarboxylic greater than monocarboxylic acid (fig.5). An increase in chain length of the organic acids also increased adsorption (fig.5). A general rule of adsorption is that in an homologous series, adsorption will increase with increasing members of a series. The adsorption of the series of fatty acids formic, acetic, butyric, on activated carbon carbon illustrates this rule (fig.8). For the series of dicarboxylic acids, the introduction of the double bond increased adsorption; fumaric greater than succinic (fig.7). The introduction of an NH<sub>2</sub> group decreased adsorption, the order of adsorption was succinic greater than aspartic and glutaric greater than glutamic (fig.6). Also for the adsorption on WV-L carbon of dicarboxylic acids at an initial concentration of 1g/l the order of adsorption was malic greater than tartaric greater than succinic (fig.7).

TABLE 3  
 ADSORPTION ISOTHERMS  
 ORGANIC ACIDS

TREATMENT	COD INITIAL	1/N	K	(X/M)CO
FORMIC ACID	325	0.477	8.402	11
ACETIC ACID	1085	0.433	32.209	66
BUTYRIC ACID	171	0.465	85.209	271
OXALIC ACID	171	1.143	0.666	24
SUCCINIC ACID	807	0.294	132.212	95
FUMARIC ACID	714	0.522	34.778	107
MALIC ACID	752	0.670	14.289	121
TARTARIC ACID	608	0.744	8.402	100
GLUTARIC ACID	786	0.231	343.977	160
CITRIC ACID	776	0.691	17.930	178
BENZOIC ACID	1504	0.220	652.978	328
ASCORBIC ACID	896	0.680	14.033	143
LACTIC ACID	863	0.806	6.736	156
ASPARTIC ACID	621	1.770	0.005	41
GLUTAMIC ACID	864	0.370	58.273	71

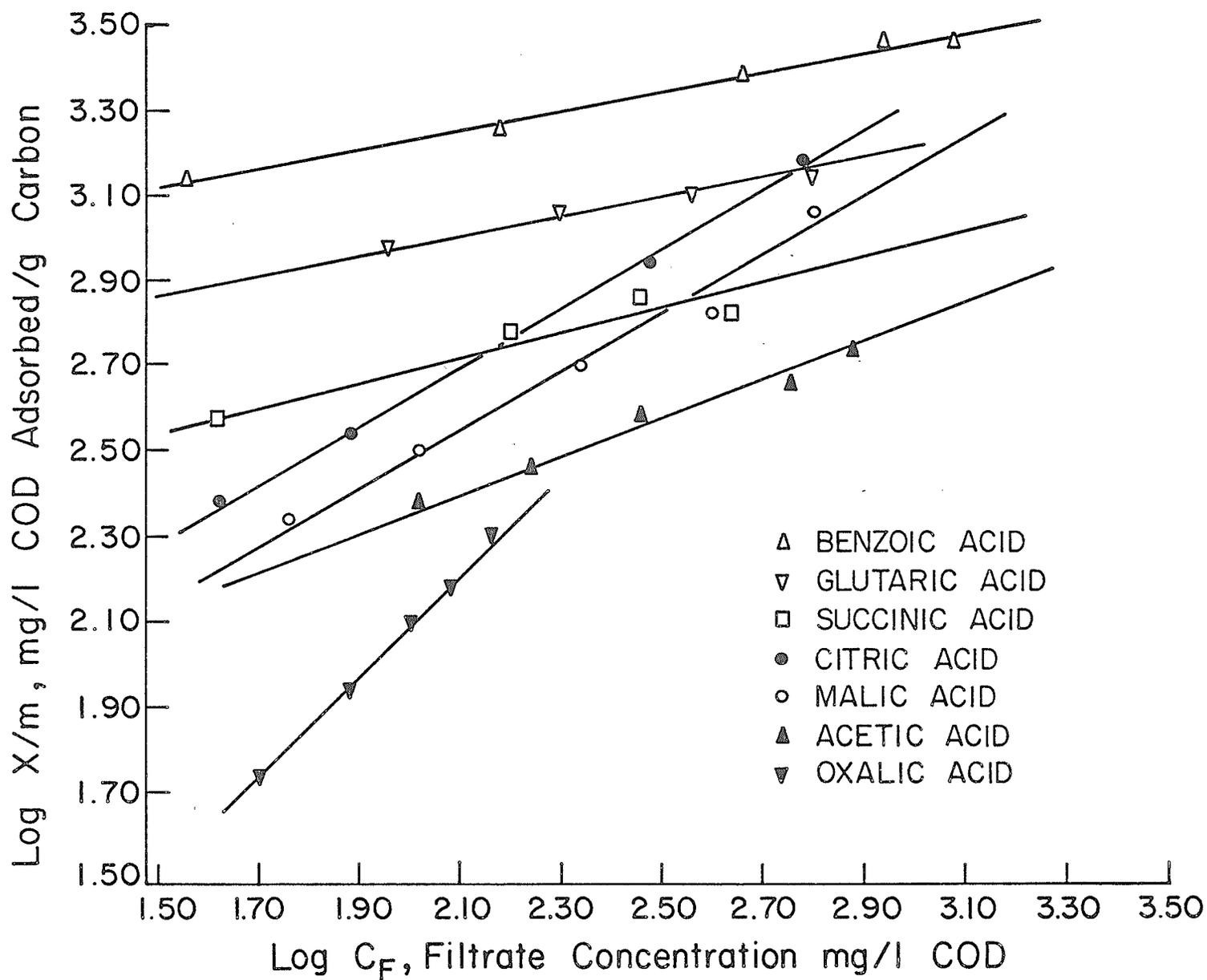


Fig. 5 Adsorption Isotherms for Organic Acids.

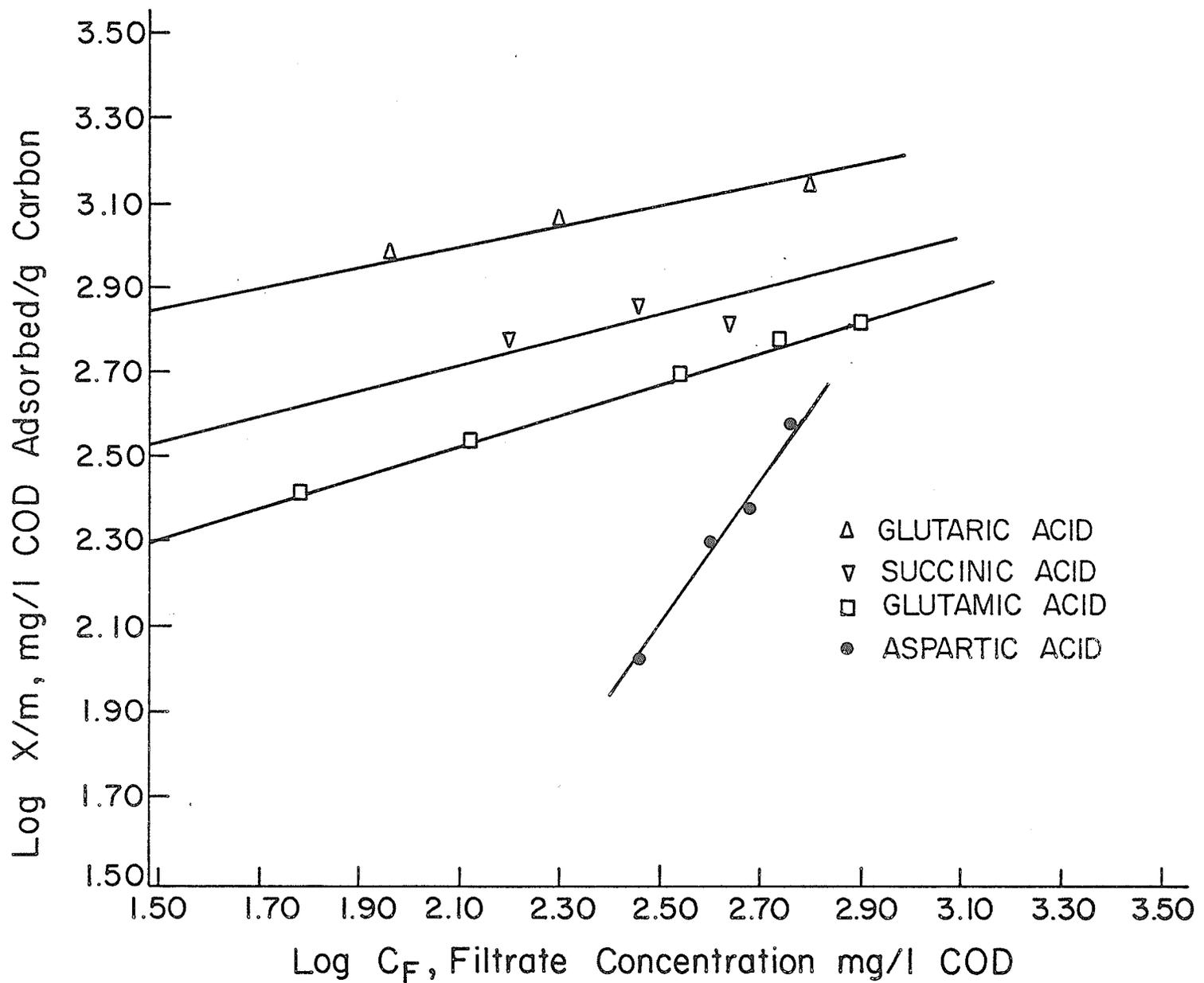


Fig. 6 Adsorption Isotherms for Organic Acids.

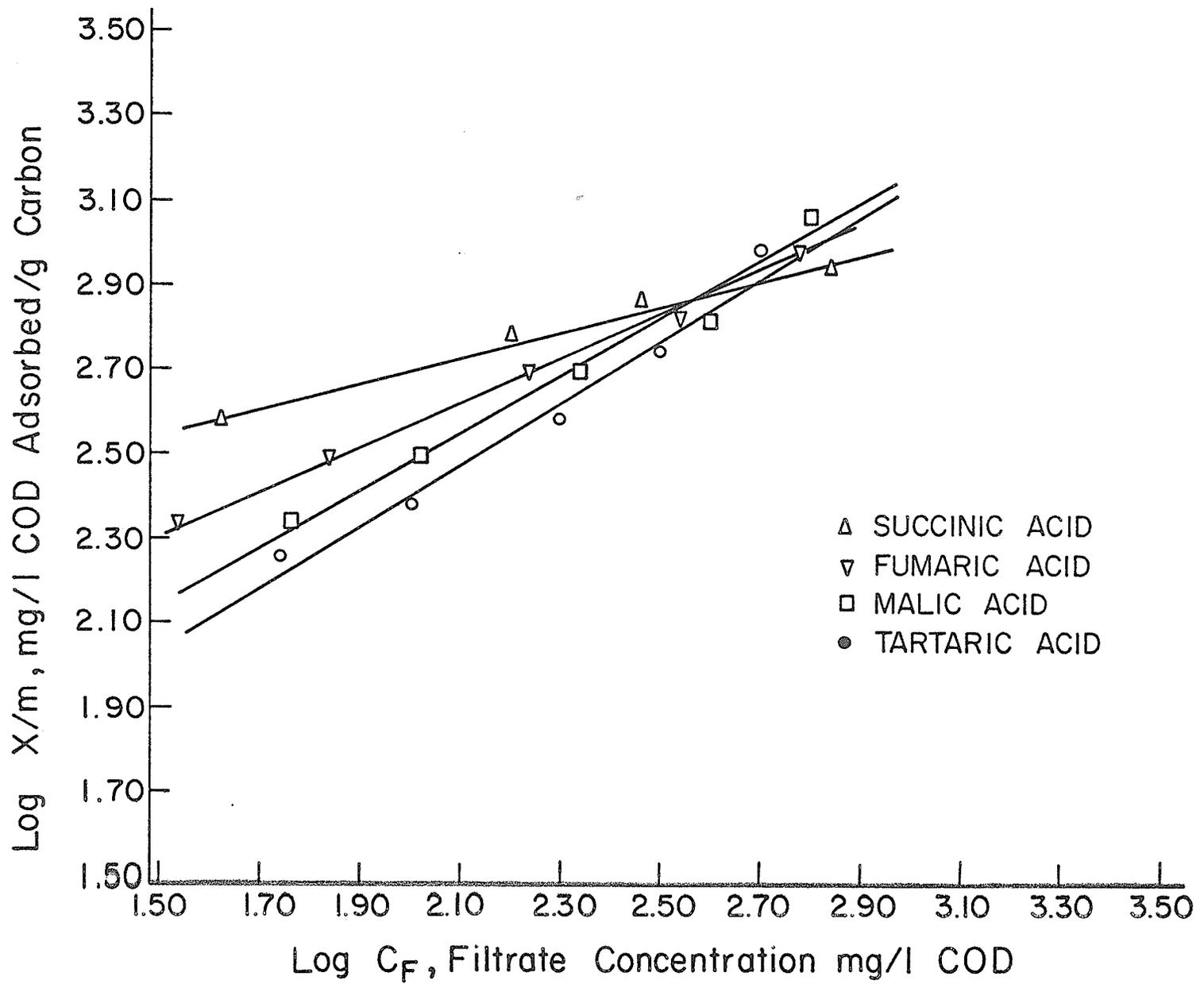


Fig. 7 Adsorption Isotherms for Organic Acids.

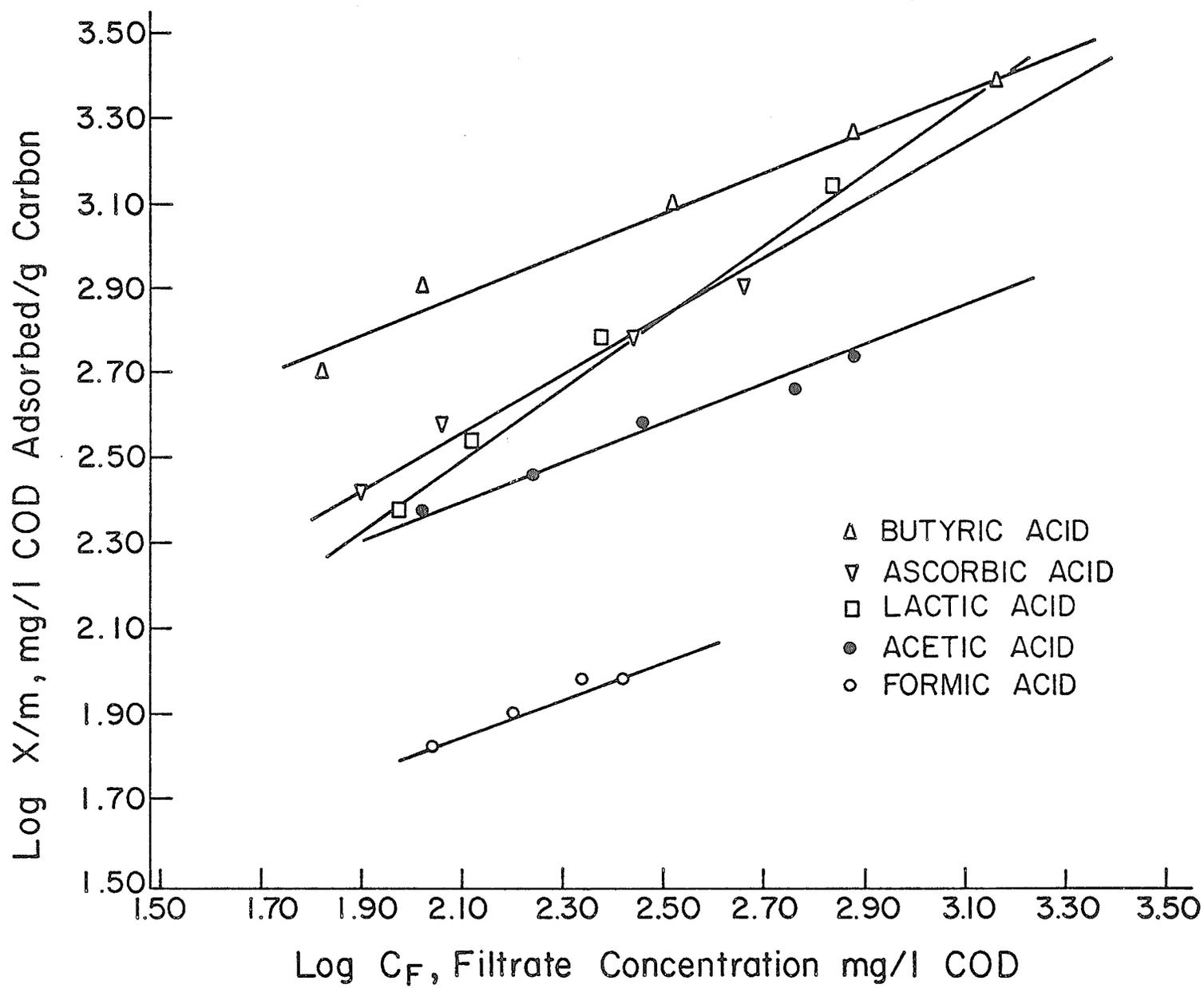


Fig. 8 Adsorption Isotherms for Organic Acids.

The aromatic organic acid, benzoic acid, exhibited a much greater adsorption capacity on activated carbon than the aliphatic acids. Aromatic substances were shown in this study of organic constituents to be well adsorbed on activated carbon.

The adsorption of pure substances has been discussed in the literature(22,23,63). Adsorption of the pure substances can usually be related to chemical structure of the substance(22). The results obtained in this study in general were in agreement with the results reported in the literature. However, it is necessary to determine the adsorption capacity of each particular activated carbon. Activated carbons made from different source materials and activation conditions will be dissimilar in adsorptive properties. Adsorption isotherms were developed for forty-one pure substances using WV-L nuchar activated carbon. These isotherms indicated the adsorptive capacity of the carbon for these individual pure substances. Certain compounds such as high molecular weight carbohydrate sugars, aromatic amino and organic acids, and several carboxylic acids exhibited high adsorptive capacity on the carbon.

#### 4.3 Physical Chemical Treatment of Lye-Peel Potato Wastewater

The object of this phase of the study was to determine the feasibility of physical chemical treatment - chemical clarification followed by activated carbon

adsorption - for simulated lye-peel potato wastewater.

#### 4.3.1 Adsorption Isotherm Study

##### 4.3.1.1 Activated Carbon Selection

Four commercial granular activated carbons were evaluated to determine the feasibility of treating lye-peel potato wastewater with activated carbon and to determine the most efficient carbon based on results from the Freundlich adsorption isotherm equation.

The results of this experiment are shown in table 4. Graphical representation of the Freundlich adsorption isotherms (logarithmic plots) is shown in Fig. 10. Experimental data for the adsorption isotherms of the four test carbons is shown in Appendix 5.

The results indicate that WV-L granular activated carbon was the preferred carbon based on the optimum  $x/m$  value and the degree of purification achieved. The  $(x/m)C_0$  value indicates a capacity of 308 mg COD/g carbon or approximately 31 percent by weight for WV-L activated carbon. These values are only approximations of the amount of organic adsorbed, since the COD values do not indicate the actual weight of organics, but the weight of oxygen consumed in the standard COD test.

TABLE 4  
ADSORPTION ISOTHERMS  
TEST CARBONS FOR POTATO WASTE

TREATMENT	COD INITIAL	1/N	K	(X/M)CO
CARBON WV-L	577	2.630	0.000	308
CARBON A	577	2.350	0.000	141
CARBON B	577	2.968	0.000	185
CARBON C	577	2.475	0.000	222

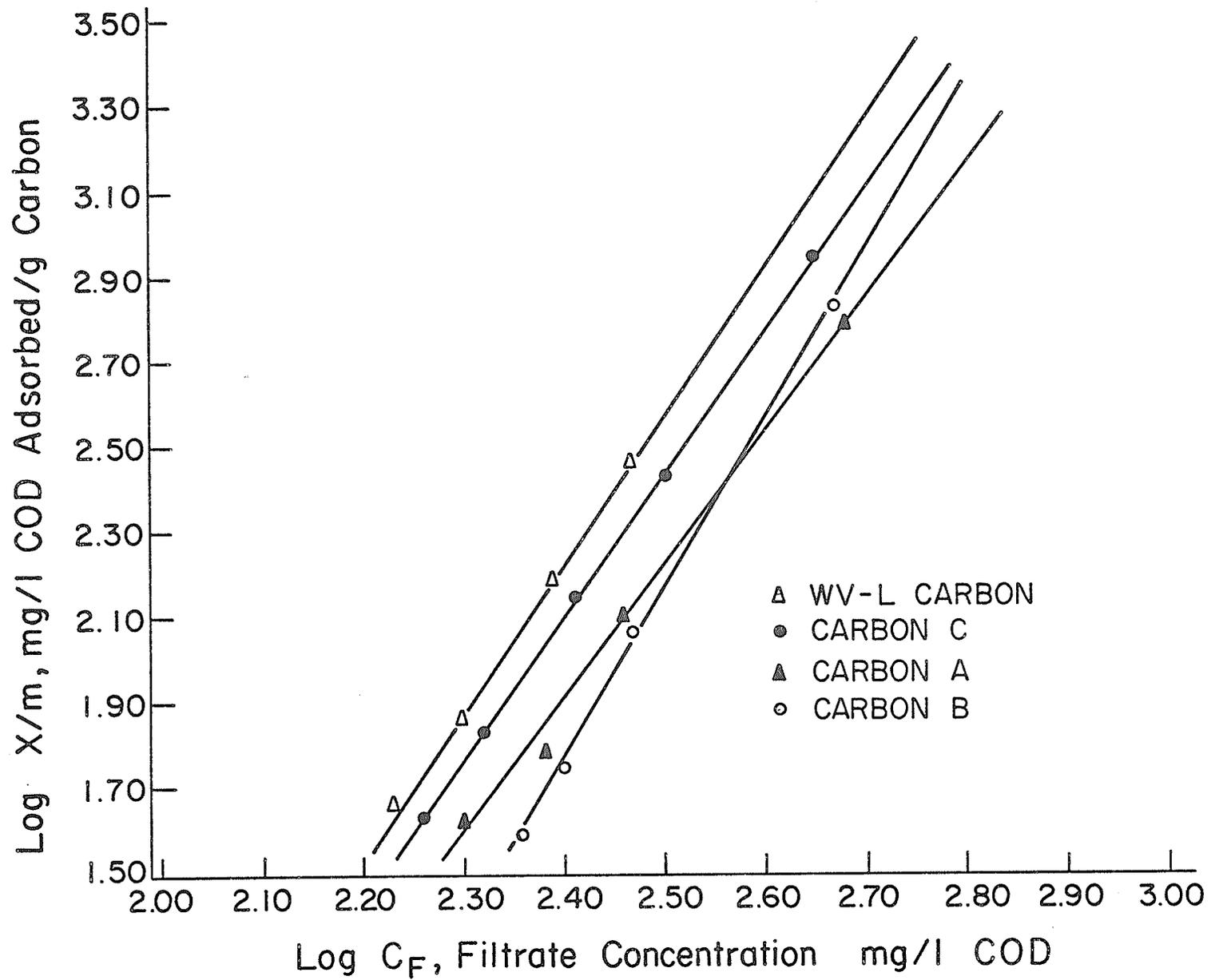


Fig. 10 Adsorption Isotherms of Test Carbons for Potato Waste.

#### 4.3.1.2 Adsorption Isotherm Evaluation

Adsorption isotherms were obtained for the simulated lye-peel potato wastewater chemically clarified with ferric chloride/aluminum chloride coagulant at dosages ranging from 16- 30 ml per batch size of 950 ml. The object of this experiment was to evaluate the effect of the clarification-adsorption treatment of the simulated wastewater. Adsorption isotherms were also obtained for untreated lye-peel potato wastewater.

The experimental data was evaluated using the Freundlich adsorption isotherm equation (3.1.5). The results of the experiment are shown in table 5. Graphical representation of the adsorption isotherms are shown in Fig. 11. The experimental data used to develop the isotherms is listed in Appendix 6.

The adsorption isotherms are characterized by high slopes (greater than 2) indicating that adsorption is great at the large initial concentration of waste, but is much less at dilute concentrations indicating the difficulty in removing the final traces of COD. The results indicated that a maximum of approximately 88 percent removal of COD was effected by the adsorption treatment stage.

The optimum adsorption capacity  $(x/m)C_0$  found by extrapolation of the adsorption isotherms was large, ranging from 24-35 percent COD removed per unit carbon. An  $(x/m)C_0$  value greater than 10 percent indicates that a carbon

TABLE 5

## ADSORPTION ISOTHERMS

## CLARIFIED POTATO WASTE

TREATMENT	COD INITIAL	1/N	K	(X/M)CO
FeCl <sub>3</sub> / AlCl <sub>3</sub> 160 ML	888	2.876	0.000	257
180 ML	768	2.477	0.000	239
200 ML	680	2.502	0.000	262
220 ML	668	2.166	0.000	240
260 ML	625	2.360	0.000	353
300 ML	590	2.399	0.000	263
FILTERED 0 ML	2137	1.967	0.000	1754

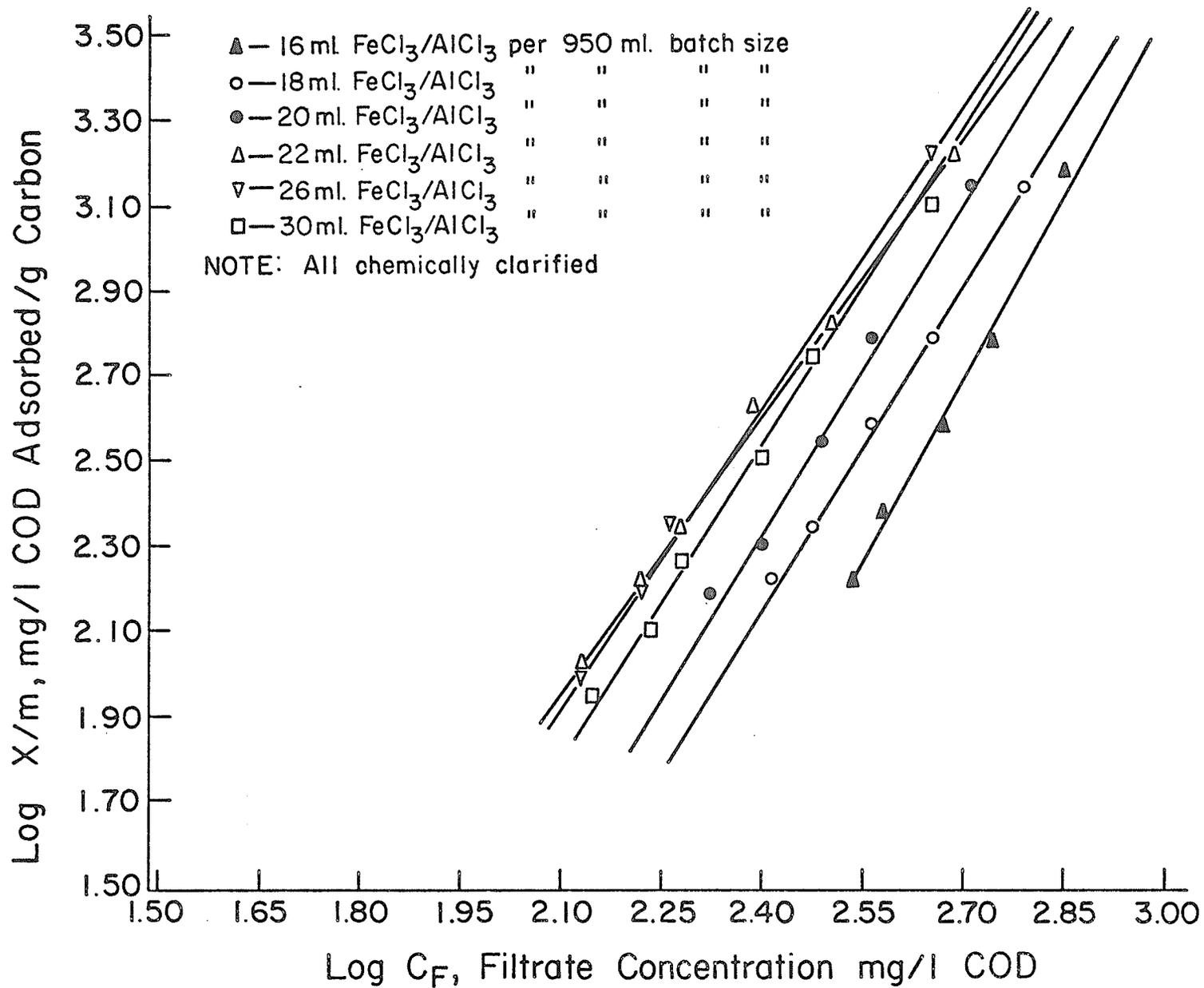


Fig. II Adsorption Isotherms for Chemically Treated Potato Waste.

adsorption system is likely to be feasible(55).

The simulated potato wastewater treated with coagulant dose 26 ml ferric chloride/aluminum chloride exhibited the largest (x/m)Co value - 353 mg COD/g carbon. The (x/m)Co value showed a general increase with added increments of coagulant dose in the range 16-26 ml coagulant per batch size of 950 ml potato wastewater. The (x/m)Co value for 16 ml dosage of coagulant was 257 mg COD/g carbon.

Coagulant doses below 22 ml were not always effective in clarifying the simulated wastewater. Activated carbon, however, was effective in removing the color remaining in solution due to the incomplete flocculation of coagulant.

The adsorption isotherms indicated that a greater degree of purity could be reached with added increments of coagulant to the simulated wastewater, indicating that the coagulant flocculates out impurities which are not adsorbed by the activated carbon. However, from an economic viewpoint, the lowest dosage of coagulant required to produce good clarity would probably be the most feasible. Therefore, a coagulant dose of 22 ml exhibiting an (x/m)Co value of 309 mg COD/g carbon and 88 percent removal of impurity from the wastewater, or lower dosages, would be the most feasible treatment.

The adsorption isotherm for the untreated potato wastewater showed an (x/m)Co value of 175 mg COD/g carbon.

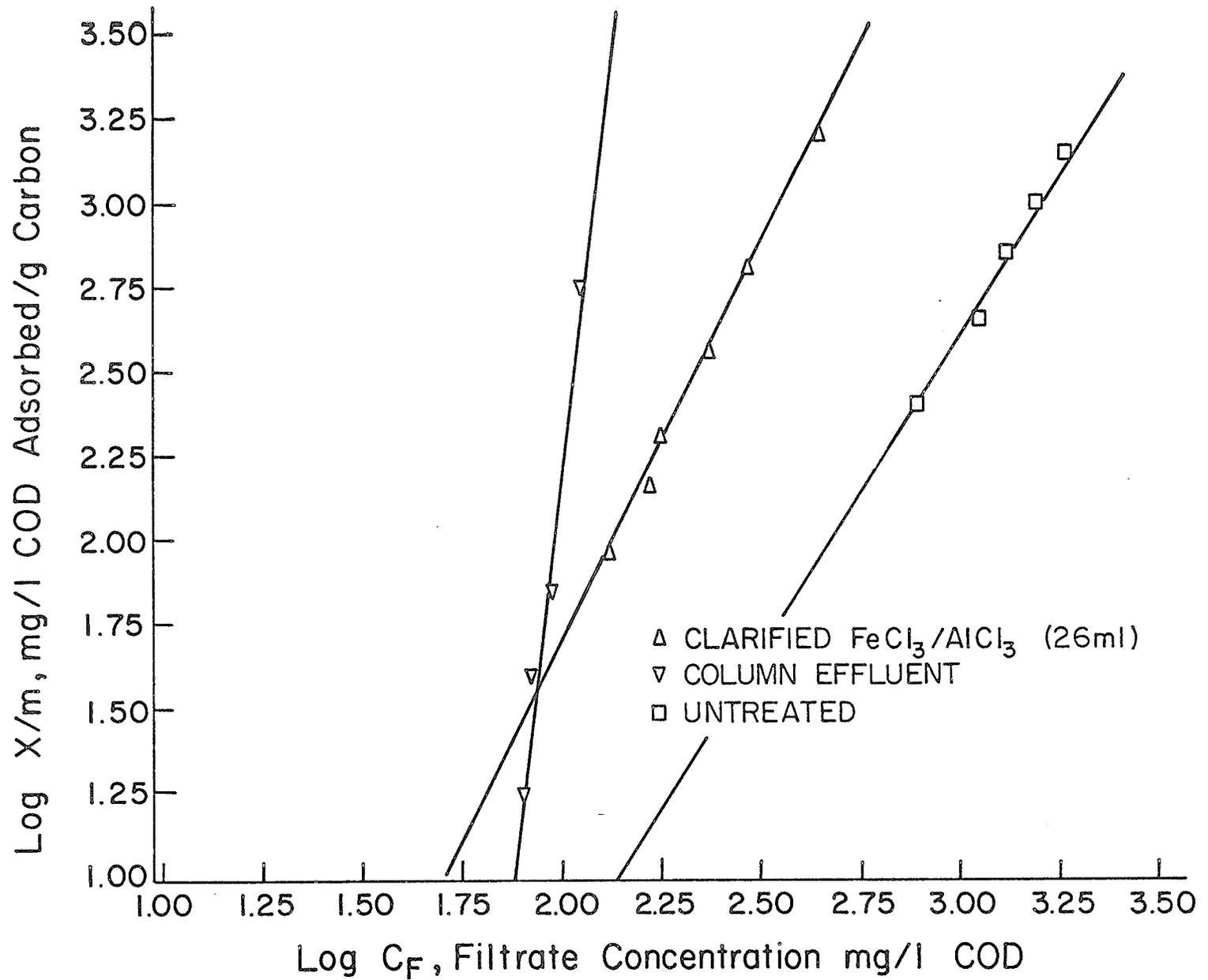


Fig. 12 Adsorption Isotherms for Potato Waste.

The adsorption isotherm is illustrated in Fig. 12. The waste was filtered before treatment with activated carbon. The adsorption isotherm predicts that theoretically the waste could be purified to about 160 mg/l COD. However a prohibitively high dosage of activated carbon would be required. A pre-treatment of the waste before activated carbon adsorption would be the preferential treatment.

The clarification-adsorption treatment of the lye-peel potato waste reduced the organic pollution by approximately 98- 99 percent.

#### 4.3.2 Granular Carbon Column Studies

Granular activated carbon column testing of the chemically clarified simulated lye-peel wastewater was undertaken after initial adsorption isotherm studies indicated that use of activated carbon for removal of pollutants was feasible. The optimum adsorption capacity  $(x/m)_{Co}$  of the activated carbon was greater than 10 percent, the required loading considered feasible for a carbon system.

##### 4.3.2.1 Flow Rate Determination

Initial column testing was conducted to determine the effect of column residence time, column bed depth on COD reduction of the chemically treated lye-peel waste (16-30 ml ferric chloride/aluminum chloride per 950 ml batch size).

TABLE 6

## EFFECT OF COLUMN RESIDENCE TIME ON COD REMOVAL

COAGULANT	DOSE	COD INFLUENT (mg/l)			COD EFFLUENT (mg/l)				
		0min	3min	6min	12min	24min	48min		
FeCl <sub>3</sub> /AlCl <sub>3</sub>	ml								
	16	888	274	193	168	119	96		
	18	768	264	179	147	115	94		
	20	680	272	149	119	109	90		
	22	656	229	149	104	94	82		
	26	616	198	140	100	90	78		
30	590	195	140	100	90	78			

TABLE 7  
EFFECT OF BED DEPTH ON COD REDUCTION

BED DEPTH inches	RESIDENCE TIME min	COD INFLUENT mg/l	COD EFFLUENT mg/l
20	48	644	86
40			84
80			84
20	24	644	97
40			92
80			92
20	12	644	115
40			112
80			109
20	6	644	147
40			147
80			142
20	3	644	237
40			233
80			233

The activated carbon column was as described in sec. 3.2.

The effect of column residence time on COD reduction was determined by passing the waste through the carbon column at flow rates 8,4,2,1,0.5 BV/Hr corresponding to a column residence time of 3,6,12,24,48 minutes respectively. Three liters of waste were passed through each column to determine the effect of bed depth on COD removal. Results are shown in table 6.

The results of the column studies were in agreement with the adsorption isotherm studies. There was fast initial rate of adsorption which progressively decreased. Adsorption was strong at high initial COD concentrations but much less at low levels of COD. There was a fast initial rate of adsorption which progressively decreased. A 6 minute column contact time reduced the COD about 65 percent. A 24 minute column contact time reduced the COD approximately 85 percent. This is predicted by the steep slopes (greater than 2) of the adsorption isotherms.

The adsorption isotherms and column studies indicated that the lye-peel waste contained approximately 13 percent unadsorbable organics. The best results indicated that the COD could be reduced to 78 mg/l COD. Fig. 12 shows an adsorption isotherm of column effluent, indicating the unadsorbable nature of the organics left in solution. Chemical analysis of the purified potato waste indicated that dissolved starch or other high molecular weight

carbohydrates were the major contributing factor of the residual COD. Adsorption isotherms for these compounds were steep, indicating the difficulty in removing final traces of these compounds.

The COD reductions for the chemically treated wastewaters were comparable at each column residence time. Data from table 6 indicated that column residence time was the important factor in the column studies. Increase in bed depth at constant column residence time did not seem to significantly affect the COD removal (table 7).

The column contact time will be determined by the degree of purity of wastewater required and economics of the process. The activated carbon will perform more efficiently at longer column contact times, but at the expense of the amount of liquid that can be treated in a given time.

For maximum COD removal, table 6 indicates that a contact time of at least 24 minutes is required.

#### 4.3.2.2 Column Studies : Breakthrough Curve

Chemically clarified (22ml ferric chloride/aluminum chloride per 950 ml batch size) lye-peel wastewater was passed through granular active carbon columns to determine the shape of the breakthrough curve, and to find the adsorption capacity of the granular active carbon. The waste passed through the carbon columns at flow rates 2 BV/Hr, 1BV/Hr resulting in column residence times of 12 minutes, 24

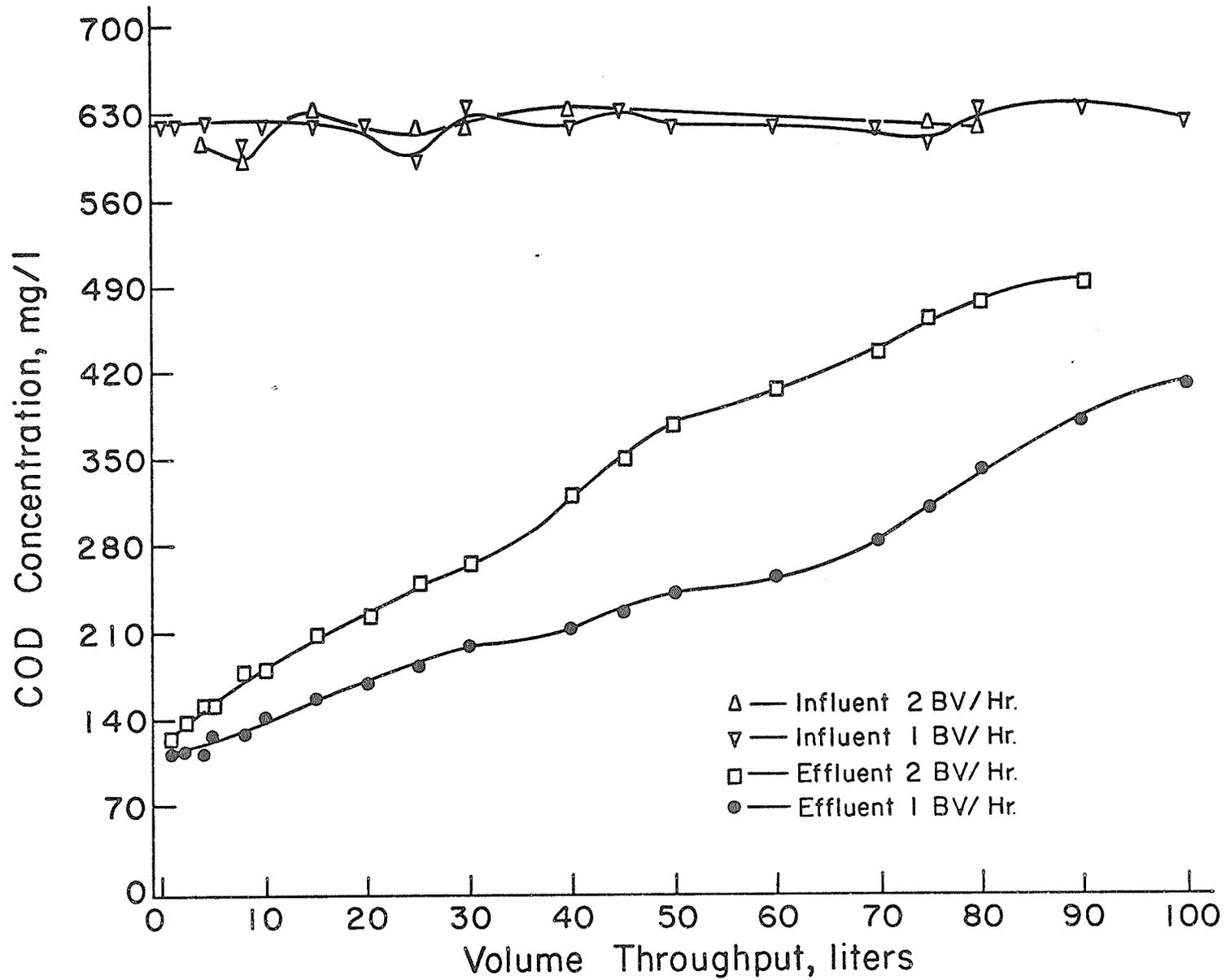


Fig. 13 Column Breakthrough Curve for Potato Waste.

minutes respectively (3.2.6). The resulting wave profile could be used in predicting the number of columns and residence time required for the proposed carbon column operation(39). Also, from the column exhaustion curve the volume of waste effluent that can be treated before the breakthrough point and the point of total column exhaustion can be determined. The wave profiles obtained for the column breakthrough curves are shown in Fig. 13.

The method for evaluating the carbon column system was as outlined in "Methods and Materials" section 3.2.7.

The relatively flat breakthrough curves indicated that there were many impurities of different composition being removed by adsorption. The breakthrough curve was gradual indicating that the adsorption zone was deep. However, the allowable effluent concentration was reached considerably before the column was exhausted, indicating that a multiple column system was desirable. A series column system would give most beneficial use of the carbon. This was also predicted by the adsorption isotherms for the lye-peel potato wastewater. The steep slope of the isotherms indicated much "reserve capacity" for the active carbon.

The number of columns required for the system is based on the column exhaustion curve. Single column laboratory testing will yield enough parameters for design of the series column system(39). An assumption is made that all columns will have similar shaped column exhaustion

curves. Actual curves will be more favourable as influent to any column is partly purified.

The column breakthrough curves for the lye-peel waste indicated that after 100 liters of waste had passed through the columns operated at a flow rate 1 BV/Hr, 2 BV/Hr the organic loading on the activated carbon was 37 percent, 26 percent by weight.

#### 4.3.2.3 Miscellaneous Analytical Results on Chemically Treated

##### Lye-Peel Potato Waste Before and After Column Treatment

Analytical results were obtained for various parameters of water quality criteria requirements for water used in the food processing industry. Analytical determinations for levels of turbidity, total solids, chloride ion, total iron were performed on the chemically treated waste before and after activated carbon column treatment. The data was obtained for waste treated with coagulant doses of 16-30 ml ferric chloride/ aluminum chloride per 950 ml batch size, and passed through an activated carbon bed at 1 BV/Hr. Three liters of waste were passed through the column before the water was analysed. The results are presented in table 8.

The results indicate that total solids, chloride, iron, are not appreciably affected by granular carbon treatment(90). The carbon column was effective in removing turbidity.

Determination of iron and chloride was performed as they would be possible contaminants from the coagulation treatment stage. Levels of either component exceeding limits recommended for the food processing industry would deter the possibility of water reuse before an added treatment stage. Salt formed from the addition of the coagulant to the alkaline waste would account for the high total residue in the purified water. Chloride ion is available in solution from the coagulant, while sodium ion results from the sodium hydroxide flakes used in lye peeling of potatoes.

The recommended limits for water used in the food industry is 10 units turbidity, 600 mg/l chloride, 850 mg/l residue on evaporation, and 1.0 mg/l iron. Turbidity and iron are within these recommended limits. Residue on evaporation and chloride are high and increased with increasing dosage of coagulant.

The lowest possible coagulant dose should be used to keep the above parameters at a minimum. However coagulant doses less than 22 ml per 950 ml batch size often showed incomplete coagulation resulting in high turbidity which was not always effectively removed by the activated carbon column.

TABLE 8

MISCELLANEOUS CHEMICAL ANALYSIS ON LYE - PEEL  
POTATO WASTE BEFORE AND AFTER COLUMN TREATMENT

COAGULANT	DOSE ml	TURBIDITY		TOTAL SOLIDS mg/l		CHLORIDE mg/l		IRON mg/l	
		before	after	before	after	before	after	before	after
FeCl <sub>3</sub> /AlCl <sub>3</sub>	16	38	27	5600	5426	3957	3780	1.52	1.03
(1M, 1M)	18	23	10	6008	5767	4418	4234	.48	.31
	20	9	1	6818	6477	4611	4449	.23	.15
	22	2	1	7556	7215	5913	5800	.20	.17
	26	1	1	8621	8333	6640	6429	.27	.23
	30	1	1	10120	9715	7000	6811	.28	.22

#### 4.4 Physical Chemical Treatment of Simulated Dairy Waste

The feasibility of treating simulated dairy waste by physical chemical treatment was investigated. The physical chemical treatment of the primary waste consisted of chemical clarification followed by activated carbon adsorption.

##### 4.4.1 Adsorption Isotherm Study

###### 4.4.1.1 Activated Carbon Selection

Four available granular activated carbons were used in the initial adsorption testing to determine the feasibility of treating simulated dairy waste with activated carbon, and to determine the most efficient carbon for the adsorption stage. Evaluation was based on results using the Freundlich adsorption isotherm equation. The activated carbon whose adsorption isotherm exhibited the highest  $(x/m)C_0$  value (maximum theoretical amount of impurities adsorbed by a unit weight of carbon) was considered the most efficient carbon. Results are shown in table 9. Graphical representation of the Freundlich adsorption isotherms for the test carbons is illustrated in Fig. 14.

The results indicated that WV-L activated carbon was the preferred carbon based on the  $(x/m)C_0$  value. The  $(x/m)C_0$  value for WV-L carbon was 316 mg COD/g carbon. The dairy waste was chemically clarified (ferric chloride, alum,

TABLE 9

## ADSORPTION ISOTHERMS

## TEST CARBONS FOR DAIRY WASTE

TREATMENT	COD INITIAL	1/N	K	(X/M)CO
CARBON WV-L	864	0.495	111.030	315
CARBON A	864	0.395	168.866	244
CARBON B	864	0.386	147.403	201
CARBON C	864	0.413	173.301	283

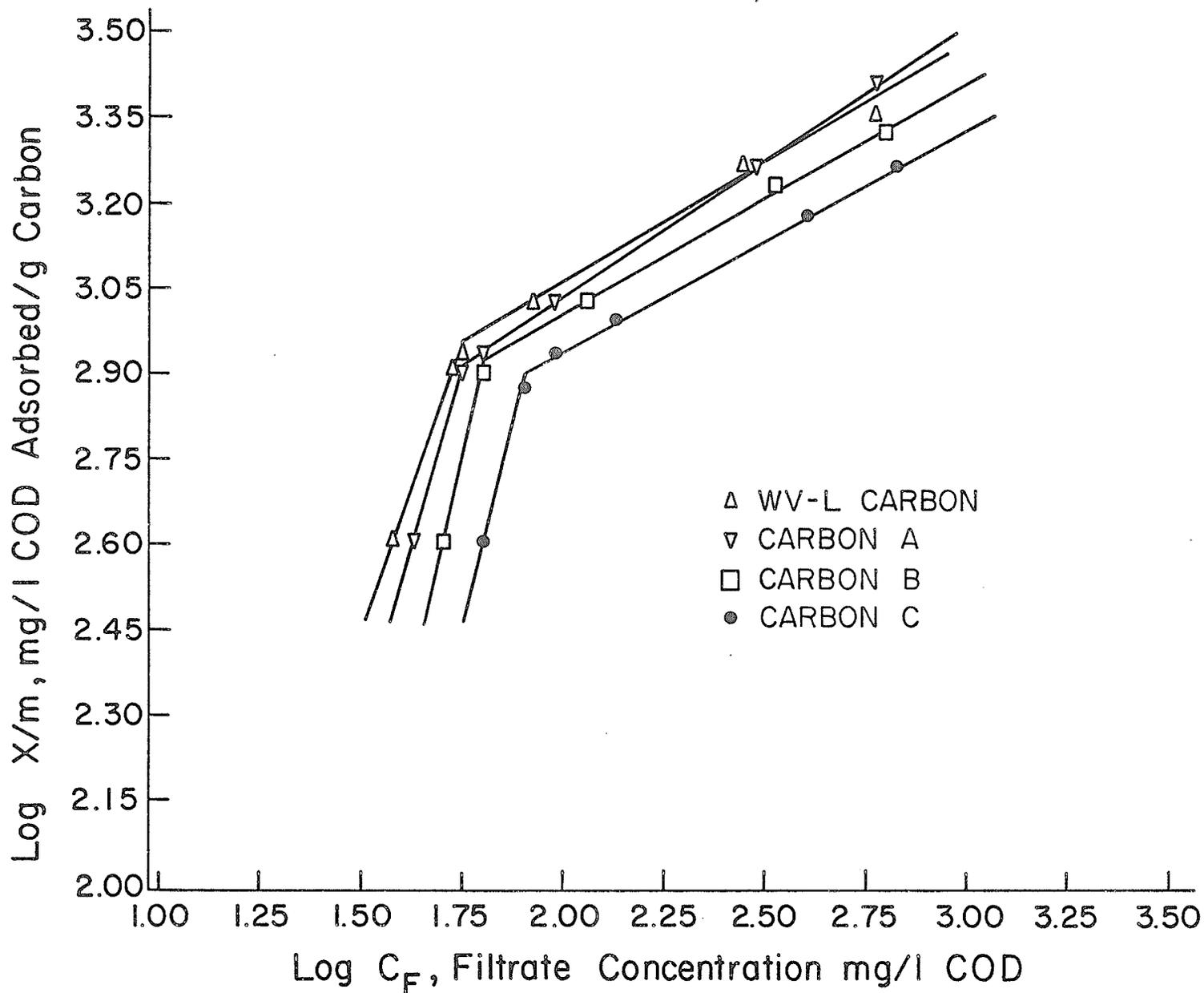


Fig. 14 Adsorption Isotherms for Test Carbons for Dairy Waste.

sulphuric acid, 1ml, 1ml, 0.5ml) prior to the adsorption stage. The experimental data used in evaluating the adsorption isotherm equation is listed in Appendix 7. The initial testing also indicated the feasibility of the adsorption stage in treating the simulated dairy waste, as determined from the  $(x/m)_{Co}$  value.

#### 4.4.1.2 Adsorption Isotherm Evaluation

Adsorption isotherms were obtained for a series of chemically clarified wastes. The chemical coagulants used in this study to clarify the waste included ferric chloride, ferric chloride/aluminum chloride, alum, lime. Acid was also included as an aid in removal of turbidity. The results are shown in table 10. Graphical representation of the isotherms is presented in Fig. 15. Experimental data used in evaluating the Freundlich adsorption equation is shown in Appendix 8.

The results indicated that physical chemical treatment of simulated dairy waste is feasible. The chemical coagulants used were effective in clarifying the waste. Comparatively low levels of coagulant dose were required for clarification of the dairy waste as compared to the dosage level for potato waste. Two ml ferric chloride/aluminum chloride coagulant were required for clarification of dairy waste, while 22 ml of coagulant were required for potato waste clarification (950 ml batch size). The coagulation

stage reduced the COD of the waste by 65-70 percent. In general, as increments of coagulant dose increased within a series, the greater the COD reduction until a maximum was reached. However, the optimum adsorption capacity  $(x/m)C_0$  of the activated carbon decreased, as illustrated in table 10. This result indicated that the preferential treatment for utilization of optimum adsorption capacity of the carbon is the lowest possible dose of coagulant which would clarify the waste effectively. The waste which had been treated with low dosages of coagulant which would not clarify the waste completely, often exhibited high optimum adsorption capacities for the activated carbon. These figures may be unrealistic and may be attributed to the presence of very fine suspended organic solids which pass through the filter paper used to filter the blank samples therefore contributing to the COD value, but are mechanically trapped in the activated carbon filter cake when these samples are filtered.

The adsorption isotherms of the chemically clarified dairy waste are non-linear as illustrated in Fig. 15. The sudden change in slope of the curve indicates that two or more major organic contaminants are present, which are not equally adsorbed. The steep slope of the isotherm is associated with organic content that is not appreciably adsorbed by activated carbon. Larger dosages of carbon are required for nearly complete removal of COD. The flatter

TABLE 10  
 ADSORPTION ISOTHERMS  
 CLARIFIED DAIRY WASTE

TREATMENT	ml	CCD INITIAL	1/N	K	(X/M)CO
FeCl <sub>3</sub>	1.0	1033	0.356	237.454	278
	1.5	944	0.371	227.470	289
	1.75	852	0.288	310.700	217
	2.0	833	0.271	331.616	206
	3.0	763	0.290	280.686	193
	3.5	756	0.279	297.512	189
FeCl <sub>3</sub> / AlCl <sub>3</sub>	1.5	960	0.398	201.182	309
	1.75	867	0.293	321.077	234
	2.0	833	0.288	300.390	209
	2.5	759	0.330	222.532	208
	3.0	763	0.300	272.093	199
	3.5	763	0.302	268.162	198
ALUM	2.0	973	0.383	230.552	321
	3.0	956	0.320	278.958	251
	4.0	924	0.330	279.292	265
	5.0	876	0.316	286.107	244
	6.0	876	0.351	236.196	254
	FeCl <sub>3</sub> / ALUM	0.5 3.0	830	0.227	381.257
1.0 2.0		853	0.208	452.994	175
1.5 1.5		838	0.185	472.968	165
2.0 1.2		841	0.217	393.443	171
3.0 1.0		824	0.120	666.090	149
FeCl <sub>3</sub> / ALUM / H <sub>2</sub> SO <sub>4</sub>	0.5 2.0 1.0	853	0.326	219.808	198
	1.0 1.0 0.5	889	0.364	235.559	279
	1.0 0.5 0.5	888	0.320	302.229	265
	1.5 0.5 0.5	862	0.230	296.770	219
ALUM / LIME / HCl	2.0 1.5 1.0	924	0.356	240.823	273
	2.0 1.5 1.5	895	0.372	212.981	267
	2.0 2.5 1.5	932	0.342	229.811	238
NC TREATMENT		3009	1.238	1.084	2192

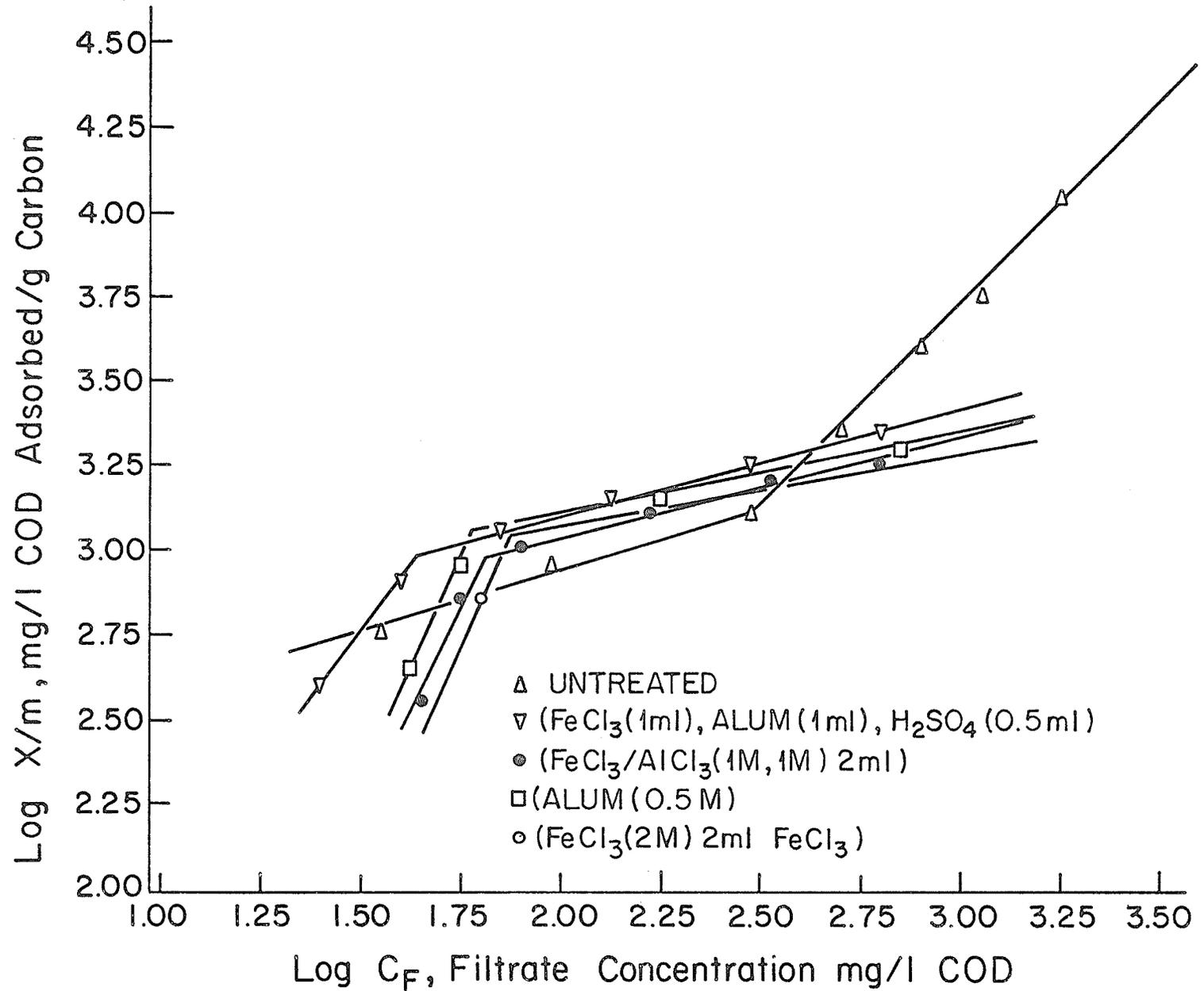


Fig. 15 Adsorption Isotherms for Dairy Waste.

portion of the isotherm graph (slope = 0.30) indicates good adsorption throughout that range. The bulk of the organic matter adsorbed probably consisted of the milk sugar lactose which earlier in this study had been shown to be appreciably adsorbed by activated carbon. About 95 percent removal of COD was effected before the departure from linearity.

The coagulant combination ferric chloride, alum, sulphuric acid (1ml, 1ml, 0.5ml) was selected as the preferred treatment based on clarification properties, COD reduction, sludge settling, turbidity removal, activated carbon adsorption capacity.

The adsorption isotherm of the untreated dairy waste is shown in Fig. 15. The isotherm graph is also non-linear. The  $(x/m)_{Co}$  value is extremely high - 2192 mg COD/g carbon. This value is only an approximation of the amount of organics adsorbed since the COD value does not indicate the actual concentration, but the weight of oxygen consumed in the standard COD test. Also, this figure was calculated from the extrapolation of the upper portion of the isotherm before the departure from linearity. The adsorption isotherm indicates that over 99 percent of the COD influent was removed by adsorption. The activated carbon removed the turbidity from the dairy waste yielding a clear effluent. The treatment of dairy waste with activated carbon has good potential and the effluent relatively free from pollution,

has a definite reuse potential.

#### 4.4.2 Granular Column Treatment

The adsorption isotherms for chemically treated simulated dairy waste indicated the feasibility of treating this waste with activated carbon. An optimum loading on the carbon of 10 percent by weight is considered feasible. The adsorption isotherm values for optimum carbon capacity exceeded this limit.

##### 4.4.2.1 Flow Rate Determination

Initial carbon column testing was directed at determining the effect of column residence time, column bed depth on COD reduction of the simulated dairy waste. The dairy waste was chemically clarified and passed through Whatman filter paper No.4 before column treatment. The flow rates were regulated at 8, 4, 2, 1 BV/Hr corresponding to a column residence time of 3, 6, 12, 24 minutes respectively. Three liters of water were passed through each column. The results are shown in table 11. A series column arrangement was used to determine the effect of bed depth on COD removal. Results are presented in table 12.

The results indicate that a short column contact time (3 minutes) would reduce the COD over 90 percent. Approximately 99 percent COD reduction could be achieved at higher column contact times of 12-24 minutes. Data from

TABLE 11

## EFFECT OF COLUMN RESIDENCE TIME ON COD REMOVAL

COAGULANT	DOSE ml	COD INFLUENT (mg/l)		COD EFFLUENT (mg/l)				
		0min	3min	6min	12min	24min	48min	
FeCl <sub>3</sub>	1.5	940	97	61	49	39	15	
	1.75	855	69	24	13	13	13	
	2.0	835	62	24	13	13	13	
FeCl <sub>3</sub> /AlCl <sub>3</sub>	1.5	965	102	66	44	36	14	
	1.75	867	67	24	13	13	13	
	2.0	833	67	24	13	13	13	
Alum	3.0	956	79	30	15	13	13	
	4.0	925	73	30	15	13	13	
	5.0	876	69	24	13	13	13	
FeCl <sub>3</sub> , Alum H <sub>2</sub> SO <sub>4</sub>	1,1 0.5	888	73	24	13	13	13	

TABLE 12  
EFFECT OF BED DEPTH ON COD REDUCTION

BED DEPTH inches	RESIDENCE TIME min	COD INFLUENT mg/l	COD EFFLUENT mg/l
20	24	888	15
40			15
80			15
20	12	888	18
40			15
80			15
20	6	888	33
40			29
80			29
20	3	888	79
40			79
80			73

COAGULANT:  $\text{FeCl}_3$ , Alum,  $\text{H}_2\text{SO}_4$  (1,1,0.5ml per 950ml batch)

table 12 indicated that column residence time was an important factor in column studies. Increase in bed depth at constant column residence time did not affect the COD removal. Column residence time is the important factor in "scaling up" the system.

The waste treated with lower limits of coagulant dose - 1.5 ml ferric chloride or 1.5 ml ferric chloride/aluminum chloride per 950 ml batch size, was less effectively treated by the carbon column. Slightly higher COD values were recorded at the various residence times. The turbidity of the waste was not completely removed by the column treatment. Incomplete coagulation at this lower limits of coagulant dose resulted in the breakthrough in turbidity and higher COD values than for clarified waste.

The column studies indicated that nearly complete removal of COD was effected by the granular activated carbon.

#### 4.4.2.2 Column Studies : Breakthrough Curve

Chemically clarified (ferric chloride, alum, sulphuric acid, 1ml, 1ml, 0.5ml) simulated dairy waste was passed through an activated carbon column to determine the capacity of the activated carbon for organics removal, and to determine the shape of the resulting breakthrough curve, an important parameter in designing a carbon column operation for a particular waste. The dairy waste was

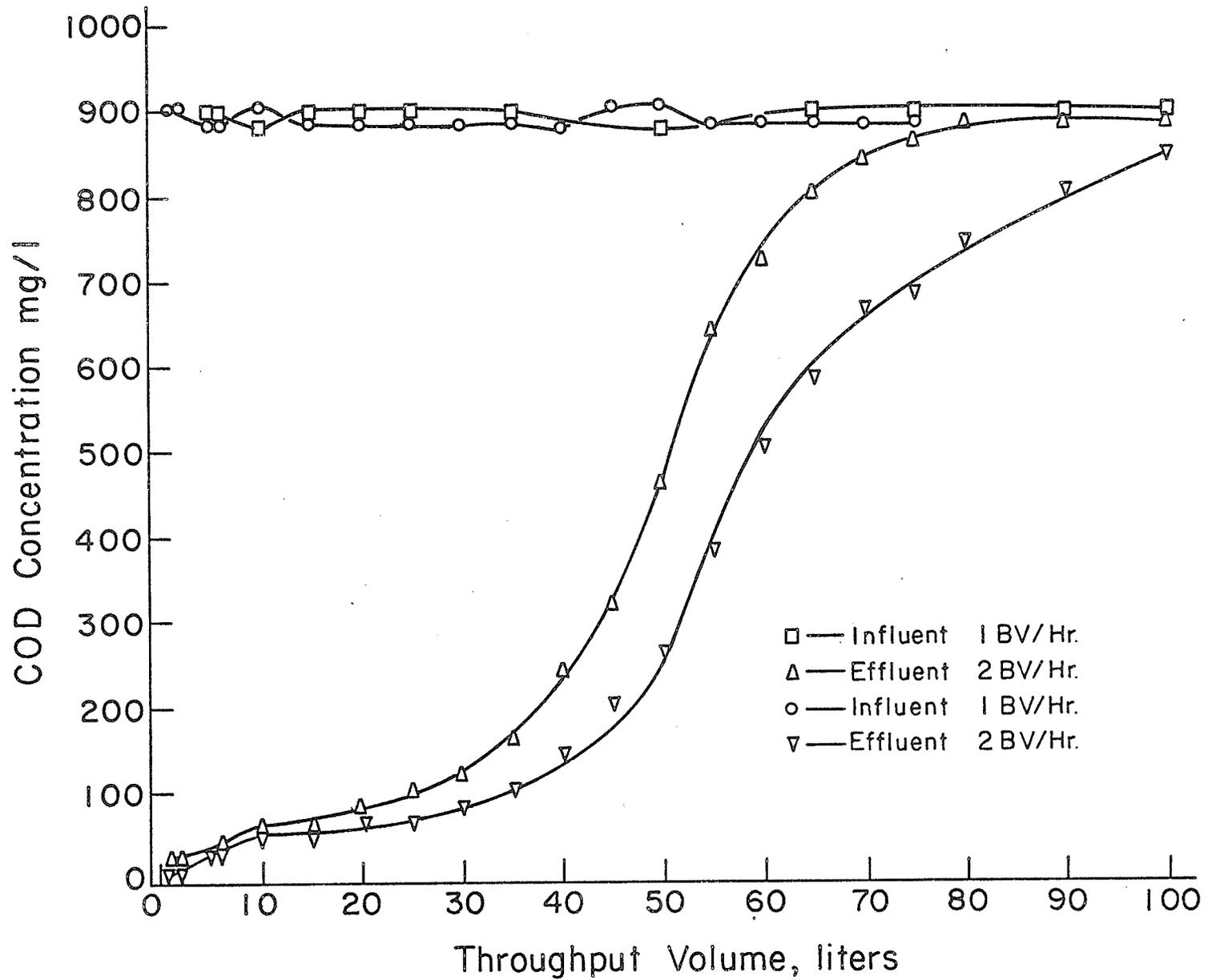


Fig. 16 Column Breakthrough Curve for Dairy Waste.

clarified, filtered, then passed through the activated carbon columns at flow rates 2 BV/HR, 1 BV/HR.

The column breakthrough curves for the dairy waste are shown in fig. 16. The relatively steep breakthrough curve indicated the possibility of a single impurity being removed by the carbon. A steep breakthrough curve is characterized by a short adsorption zone.

The allowable concentration of impurity in the effluent was reached considerably before the column was fully exhausted, therefore indicating the probability of using a multiple column installation. The number of columns required for the system is calculated graphically from the shape of the column breakthrough curves and is related to the allowable concentration of impurity in the effluent.

After 100 liters of clarified dairy waste had passed through the activated carbon columns at 2 BV/Hr, 1 BV/Hr the organic loading on the activated carbon was 41.4 percent, 51.1 percent respectively.

#### 4.4.2.3 Miscellaneous Chemical Analysis on Clarified Simulated Dairy Waste Before and After Column Treatment

Analytical results were obtained for various parameters of water quality criteria requirements for water used in the food processing industry. Analytical determination for levels of turbidity, residue on evaporation, chloride, were performed on the chemically

TABLE 13

MISCELLANEOUS CHEMICAL ANALYSIS ON DAIRY WASTE  
BEFORE AND AFTER COLUMN TREATMENT (1BV/HR)

COAGULANT	DOSE ml	TURBIDITY		TOTAL SOLIDS mg/l		CHLORIDE mg/l	
		before	after	before	after	before	after
FeCl <sub>3</sub>	1.5	69	28	1784	1683	270	244
	1.75	23	3.2	1690	1626	360	337
	2.0	3.5	1	1728	1669	402	382
FeCl <sub>3</sub> /AlCl <sub>3</sub>	1.5	73	29	1768	1672	249	222
	1.75	27	3.5	1712	1658	387	370
	2.0	5.0	1	1744	1683	344	331
Alum	3	49	3.7	1824	1731	13	9
	4	4.5	1.2	1796	1723	11	9
	5	2.0	1	1912	1858	13	9
FeCl <sub>3</sub> , Alum H <sub>2</sub> SO <sub>4</sub>	1,1 0.5	2.0	1	1776	1698	158	133

treated waste before and after activated carbon column treatment at 1 BV/Hr. Three liters of waste were passed through the column before the analysis. The results are presented in table 13.

The results indicate that total residue, and chloride are not appreciably reduced by the activated carbon column treatment. The column was effective in removing turbidity.

Recommended maximum concentration limits for water used in the milk processing industry are chloride 30 mg/l, total solids 500 mg/l. Turbidity was within the recommended limit, also chloride if alum or lime are used as coagulants. Total solids, an appreciable portion due to salts in aqueous solution formed by the coagulant ions, were higher than the recommended limit.

#### 4.5 Biological Activity in the Carbon Column

Continuous column operation of the simulated lye-peel potato wastewater, and dairy waste resulted in biological activity in the carbon bed. The build up of soluble organic material on the activated carbon rapidly promoted biological activity within the adsorption system. It has been suggested in the literature(51) that activated carbon provides an excellent surface for concentration of organic biological substrate material. The high organic load of the column influent provided ample substrate material for

rapid microbiological growth.

Standard plate counts were performed at time intervals on samples of the waste influent, effluent from the carbon bed, and on samples of activated carbon from the column. These results are reported in table 14.

The results indicate the rapid build up of organics on the activated carbon, and the gradual increase in microbial counts in the column effluent.

The biological growth first occurred at the influent end of the carbon column (where concentration of organics is highest) and gradually spread downwards throughout the column. The biological activity produced anaerobic conditions in the columns as evidenced by the evolution of gas bubbles. The columns were converted into submerged anaerobic trickling filters.

The desirability of biological growth in the carbon column has not been fully determined(17). Weber et al(105) reported that the biological activity did not appear to hinder the adsorption process. The biological activity on the carbon may remove poorly adsorbable organics, and, as has been reported may increase the carbon loading in the column up to 100 percent as that predicted from laboratory adsorption isotherm studies.

However the occurrence of the microbial growth suggested several operational difficulties. Frequent backwashing of the column would be necessary to remove the

TABLE 14

COLUMN MICROBIOLOGY  
Standard Plate Count

## Lye-Peel Potato Waste

Time	Column Influent	Column Effluent	Activated Carbon
0	19x10		18x10
24	29x10	19x10	63x10
48	48x10	39x10	15x10
72	63x10	16x10	39x10

## Dairy Waste

0	97x10		67x10
24	83x10	28x10	88x10
48	27x10	84x10	19x10
72	45x10	25x10	47x10

microbial slimes. Chlorination or other sterilization means would be required to ensure desirable effluent quality. Prechlorination of the column influent is a possible means of controlling the microbial growth, however, activated carbon adsorbs chlorine, thereby reducing its adsorption capacity for organics.

Oxygen has been added to the carbon columns to eliminate the anaerobic conditions but this is a cost factor, and the oxygen has been reported to stimulate aerobic growth resulting in increased pressure losses across packed-bed columns. Expanded upflow beds of carbon should minimize the pressure losses and back wash requirements. Determination of the effect of the biological activity on product quality and operation maintenance requires additional study as indicated by the literature(17).

## V. Conclusions

This study indicated the technical feasibility of physical chemical treatment for the purification of simulated lye-peel potato and dairy waste effluent. The clarification, adsorption process can be used to reduce the organic load of the waste effluent up to approximately 99 percent.

The clarification process reduced the COD of the primary effluent by approximately 75 percent. The adsorption capacity of the activated carbon for the clarified potato effluent was 309 mg/l COD per gram carbon, and 316 mg/l COD per gram carbon for the clarified dairy waste. An adsorption capacity of 10 percent is considered desirable for activated carbon treatment. Adsorption isotherm studies for several commercial carbons indicated that WV-L Nuchar activated carbon was the preferred adsorbent.

A coagulation dose of 22 ml ferric chloride/aluminum chloride (1M,1M) per batch size 950 ml, was required to clarify the potato waste. The choice of coagulant was based on previous studies at the Food Science Department. Lower limits of coagulant dose (16-20ml) were not always effective in clarification; however the adsorption process showed favourable results. Further studies should deal with the clarification-adsorption process at these lower limits of coagulant dose.

A coagulation dose of 2 ml ferric chloride/aluminum

chloride (1M,1M) per 950 ml batch size was effective in clarifying the simulated dairy waste. Various other inorganic coagulants, singularly and in combination were also investigated for clarification of the dairy waste. The coagulant combination ferric chloride, alum, sulphuric acid (1ml, 1ml, 0.5ml) was selected as the most promising based on clarification properties, COD reduction, sludge settling, turbidity removal, economics, and activated carbon adsorption capacity.

The chemical clarification process for the waste effluents supplied inorganic ions from the coagulant in excess of the maximum limit allowed for water used the food processing industry. The inorganic salts also increased the fixed residue of the purified effluent. The potential for water reuse for most applications would be deterred without dilution, or further advanced treatment such as reverse osmosis. Chemical coagulation dose should be kept at a minimum for technical and economic reasons. Further studies should examine the effectiveness of organic polyelectrolyte flocculants in the clarification process.

The residual COD in the treated potato effluent was 70-80 mg/l COD. The major contributing factor to this COD was dissolved starch or other high molecular weight carbohydrates. The dairy waste had a low residual COD of 10-20 mg/l.

The treatment process of adding activated carbon to

primary dairy waste showed potential as a purification method. Approximately 99 percent of the COD could be removed, with a clear effluent resulting.

Granular carbon column testing of the lye-peel potato waste and dairy waste indicated that a multiple column series system was the preferred system. For potato waste, a column residence time of at least 24 minutes was required for optimum adsorption, while 12 minutes was required for the simulated dairy waste.

The high organic loading on the carbon columns initiated rapid microbial growth within the activated carbon columns. The literature indicates that the desirability of biological growth in the adsorption system has not been concluded. The growth does not appear to hinder the adsorption process; however several operational difficulties would probably occur and post chlorination of the column effluent would probably be required to ensure sterility of the effluent.

Adsorption isotherms were developed for a number of organic substances which could become possible components of food processing effluents. The substances included carbohydrates, proteins, amino acids, and organic acids. The adsorption capacity of the individual compounds indicates the feasibility of removal in the adsorption treatment stage.

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APPENDIX I.

## Product Data Bulletin

# ***NUCHAR***

## Granular Active Carbon

Grade: Nuchar WV-L 8x30

### Description and Typical Applications

Nuchar WV-L 8 x 30 is a dense, hard and regenerable granular active carbon, intended for packed bed adsorption applications. Its pore structure has been designed to include a broad spectrum of pore sizes. Nuchar WV-L 8 x 30 is highly uniform and dependable in quality, being manufactured at Westvaco's new and modern plant in Covington, Virginia.

### Recommended Uses

The wide range of pore size in Nuchar WV-L 8 x 30 enables it to efficiently adsorb from solutions a great variety of both high and low molecular weight substances. Its hardness means minimum losses during mechanical handling or during thermal regeneration. It can be used in either fixed bed or moving bed processes. Applications where Nuchar WV-L 8 x 30 is particularly well suited include corn sugar and syrup processing, purification of chemicals and pharmaceuticals, and waste water treatment.

Nuchar WV-L 8 x 30 can be fully regenerated by thermal reactivation in most cases. In applications where the usage is large regeneration may be most economical. Under some circumstances partial regeneration can be accomplished by chemical means.

### Specifications

Molasses Decolorizing Index, Minimum	6.3
Iodine Number, Minimum	950
Abrasion Number, Minimum	70
Moisture When Packed (%), Maximum	2
Ash (%), Maximum	7.5
Particle Size (U.S. Sieve Series)	8 x 30
Oversize (%), Maximum	8
Undersize (%), Maximum	5

### Typical Properties

Apparent Density (lb./ft <sup>3</sup> )	30
Bed Density, Backwashed and Drained (lb./ft <sup>3</sup> )	26
Surface Area (Nitrogen BET Method) (m <sup>2</sup> /g)	1000
Particle Density, Wetted in Water (g/cc)	1.4
Effective Size (mm)	0.90
Uniformity Coefficient	1.80
Void in Packed Bed (%)	40

Note: Precise pore size distribution is available on request.

See reverse side for Pressure Drop characteristics.

APPENDIX II.  
ADSORPTION ISOTHERM DATA  
FOR CARBOHYDRATES

RIBOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1315.			3.119	
0.50	982.	333.	666.0	2.992	2.823
1.00	736.	579.	579.0	2.867	2.763
2.00	460.	855.	427.5	2.663	2.631
3.00	329.	986.	328.7	2.517	2.517
5.00	197.	1118.	223.6	2.294	2.349

1/N= 0.687                    K= 6.089  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 84.6  
 % REDUCTION= 99.%

GLUCOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1080.			3.033	
0.50	832.	248.	496.0	2.920	2.695
1.00	652.	428.	428.0	2.814	2.631
2.00	464.	616.	308.0	2.667	2.489
3.00	316.	764.	254.7	2.500	2.406
5.00	196.	884.	176.8	2.292	2.247

1/N= 0.713                    K= 4.101  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 59.6  
 % REDUCTION= 99.%

FRUCTOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1013.			3.006	
0.50	825.	188.	376.0	2.916	2.575
1.00	691.	322.	322.0	2.839	2.508
2.00	496.	517.	258.5	2.695	2.412
3.00	405.	608.	202.7	2.607	2.307
5.00	253.	760.	152.0	2.403	2.182

1/N= 0.775                    K= 2.039  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 43.6  
 % REDUCTION= 99.%

GALACTOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1067.			3.028	
0.50	781.	286.	572.0	2.893	2.757
1.00	599.	468.	468.0	2.777	2.670
2.00	402.	665.	332.5	2.604	2.522
3.00	286.	781.	260.3	2.456	2.416
5.00	156.	911.	182.2	2.193	2.261

1/N= 0.718                      K= 4.655                      OPTIMUM X/M= 69.8  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION= 99.%

SUCROSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1051.			3.022	
0.10	862.	189.	1890.0	2.936	3.276
0.30	547.	504.	1680.0	2.738	3.225
0.50	334.	717.	1434.0	2.524	3.157
0.70	179.	872.	1245.7	2.253	3.095
1.00	74.	977.	977.0	1.869	2.990

1/N= 0.268                      K= 307.962                      OPTIMUM X/M= 198.7  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

LACTOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	998.			2.999	
0.10	763.	235.	2350.0	2.883	3.371
0.30	404.	594.	1980.0	2.606	3.297
0.50	211.	787.	1574.0	2.324	3.197
0.70	105.	893.	1275.7	2.021	3.106
1.00	38.	960.	960.0	1.580	2.982

1/N= 0.303                      K= 315.819                      OPTIMUM X/M= 255.5  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

MALTOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1036.			3.015	
0.10	797.	239.	2390.0	2.901	3.378
0.30	435.	601.	2003.3	2.638	3.302
0.50	223.	813.	1626.0	2.348	3.211
0.70	108.	928.	1325.7	2.033	3.122
1.00	46.	990.	990.0	1.663	2.996

1/N= 0.307                      K= 309.428  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 260.8  
 % REDUCTION=100.0%

RAFFINOSE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	920.			2.964	
0.10	648.	272.	2720.0	2.812	3.435
0.20	392.	528.	2640.0	2.593	3.422
0.30	197.	723.	2410.0	2.294	3.382
0.40	92.	828.	2070.0	1.964	3.316
0.50	32.	888.	1776.0	1.505	3.249

1/N= 0.149                      K= 1068.851  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 294.6  
 % REDUCTION= 98.0%

POTATO STARCH

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1041.			3.017	
0.10	937.	104.	1040.0	2.972	3.017
0.50	724.	317.	634.0	2.860	2.802
1.00	596.	445.	445.0	2.775	2.648
2.00	444.	597.	298.5	2.647	2.475
3.00	364.	677.	225.7	2.561	2.353

1/N= 1.599                      K= 0.017  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 116.4  
 % REDUCTION= 99.0%

GALACTURONIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	678.			2.831	
0.10	568.	110.	1100.0	2.754	3.041
0.50	321.	357.	714.0	2.507	2.854
1.00	171.	507.	507.0	2.233	2.705
2.00	73.	605.	302.5	1.863	2.481

1/N= 0.619                      K= 20.982                      OPTIMUM X/M= 118.8  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

POLYGALACTURONIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	840.			2.924	
0.10	810.	30.	300.0	2.908	2.477
0.50	800.	40.	80.0	2.903	1.903
1.00	774.	66.	66.0	2.889	1.820
2.00	728.	112.	56.0	2.862	1.748

1/N=11.435                      K= 0.000                      OPTIMUM X/M= 23.5  
 CORRELATION COEFFICIENT=0.72                      % REDUCTION= 52.%

GLYCEROL

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1172.			3.069	
0.10	1132.	40.	400.0	3.054	2.602
0.50	1078.	94.	188.0	3.033	2.274
1.00	1015.	157.	157.0	3.006	2.196
2.00	944.	228.	114.0	2.975	2.057

1/N= 6.333                      K= 0.000                      OPTIMUM X/M= 40.9  
 CORRELATION COEFFICIENT=0.93                      % REDUCTION= 87.%

APPENDIX III.  
ADSORPTION ISOTHERM  
DATA FOR PROTEINS  
AND AMINO ACIDS

ALANINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1053.			3.022	
0.10	1041.	12.	120.0	3.017	2.079
0.50	999.	54.	108.0	3.000	2.033
1.00	956.	97.	97.0	2.980	1.987
2.00	861.	192.	96.0	2.935	1.982

1/N= 1.106                      K= 0.053  
 CORRELATION COEFFICIENT=0.86

OPTIMUM X/M= 11.6  
 % REDUCTION= 74.%

GLYCINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	838.			2.923	
0.10	827.	11.	110.0	2.918	2.041
0.50	820.	18.	36.0	2.914	1.556
1.00	812.	26.	26.0	2.910	1.415
2.00	797.	41.	20.5	2.901	1.312

1/N=41.778                      K= 0.000  
 CORRELATION COEFFICIENT=0.93

OPTIMUM X/M= 12.9  
 % REDUCTION= 86.%

SERINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	759.			2.880	
0.10	750.	9.	90.0	2.875	1.954
0.50	744.	15.	30.0	2.872	1.477
1.00	737.	22.	22.0	2.867	1.342
2.00	728.	31.	15.5	2.862	1.190

1/N=75.000                      K= 0.000  
 CORRELATION COEFFICIENT=0.91

OPTIMUM X/M= 18.1  
 % REDUCTION= 83.%

CASEIN

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1300.			3.114	
0.10	1250.	50.	500.0	3.097	2.699
0.50	1122.	178.	356.0	3.050	2.551
1.00	1057.	243.	243.0	3.024	2.386
2.00	894.	406.	203.0	2.951	2.307

1/N= 2.721                      K= 0.000  
 CORRELATION COEFFICIENT=0.95

OPTIMUM X/M= 51.6  
 % REDUCTION= 90.%

CYSTINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1116.			3.048	
0.50	900.	216.	432.0	2.954	2.635
1.00	739.	377.	377.0	2.869	2.576
2.00	466.	650.	325.0	2.668	2.512
3.00	335.	781.	260.3	2.525	2.416
5.00	173.	943.	188.6	2.238	2.276

1/N= 0.494                      K= 14.865  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 47.8  
 % REDUCTION= 99.%

METHIONINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1108.			3.045	
0.10	986.	122.	1220.0	2.994	3.086
0.50	610.	498.	996.0	2.785	2.998
1.00	321.	787.	787.0	2.507	2.896
2.00	88.	1020.	510.0	1.944	2.708
3.00	33.	1075.	358.3	1.519	2.554

1/N= 0.355                      K= 103.139  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 124.6  
 % REDUCTION=100.%

ASPARAGINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	739.			2.869	
0.10	665.	74.	740.0	2.823	2.869
0.50	563.	176.	352.0	2.751	2.547
1.00	514.	225.	225.0	2.711	2.352
2.00	443.	296.	148.0	2.646	2.170
3.00	407.	332.	110.7	2.610	2.044

1/N= 3.833                      K=      0.000  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M=      102.8  
 % REDUCTION= 99.%

GLUTAMINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	972.			2.988	
0.10	920.	52.	520.0	2.964	2.716
0.50	763.	209.	418.0	2.883	2.621
1.00	578.	394.	394.0	2.762	2.595
2.00	357.	615.	307.5	2.553	2.488
3.00	214.	758.	252.7	2.330	2.403

1/N= 0.466                      K=      20.346  
 CORRELATION COEFFICIENT=0.98

OPTIMUM X/M=      50.0  
 % REDUCTION= 97.%

LYSINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1171.			3.069	
0.10	1100.	71.	710.0	3.041	2.851
0.50	942.	229.	458.0	2.974	2.661
1.00	829.	342.	342.0	2.919	2.534
2.00	711.	460.	230.0	2.852	2.362
3.00	644.	527.	175.7	2.809	2.245

1/N= 2.578                      K=      0.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M=      82.4  
 % REDUCTION=100.%

PHENYLALANINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1796.			3.254	
0.10	1396.	400.	4000.0	3.145	3.602
0.30	717.	1079.	3596.7	2.856	3.556
0.50	341.	1455.	2910.0	2.533	3.464
0.70	126.	1670.	2385.7	2.100	3.378
1.00	35.	1761.	1761.0	1.544	3.246

1/N= 0.226                      K= 793.731  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 430.3  
 % REDUCTION=100.%

TYROSINE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1606.			3.206	
0.10	1320.	286.	2860.0	3.121	3.456
0.50	671.	935.	1870.0	2.827	3.272
1.00	338.	1268.	1268.0	2.529	3.103
2.00	132.	1474.	737.0	2.121	2.867
3.00	64.	1542.	514.0	1.806	2.711

1/N= 0.568                      K= 47.147  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 311.7  
 % REDUCTION=100.%

TRYPTOPHAN

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1804.			3.256	
0.10	1377.	427.	4270.0	3.139	3.630
0.30	722.	1082.	3606.7	2.859	3.557
0.50	253.	1551.	3102.0	2.403	3.492
0.70	96.	1708.	2440.0	1.982	3.387
1.00	22.	1782.	1782.0	1.342	3.251

1/N= 0.208                      K= 945.875  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 449.8  
 % REDUCTION= 99.%

PEPTONE

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1528.			3.184	
0.10	700.	828.	8280.0	2.845	3.918
0.30	351.	1177.	3923.3	2.545	3.594
0.50	232.	1296.	2592.0	2.365	3.414
1.00	144.	1384.	1384.0	2.158	3.141
2.00	72.	1456.	728.0	1.857	2.862

1/N= 1.083                      K=        6.864  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 1923.9  
 % REDUCTION=100.%

EGG ALBUMIN

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1188.			3.075	
0.10	1080.	108.	1080.0	3.033	3.033
0.50	800.	388.	776.0	2.903	2.890
1.00	654.	534.	534.0	2.816	2.728
2.00	432.	756.	378.0	2.635	2.577
5.00	226.	962.	192.4	2.354	2.284

1/N= 1.094                      K=        0.496  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 114.7  
 % REDUCTION= 99.%

APPENDIX IV.  
ADSORPTION ISOTHERM  
DATA FOR ORGANIC ACIDS

GLUTAMIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	864.			2.937	
0.10	795.	69.	690.0	2.900	2.839
0.50	562.	302.	604.0	2.750	2.781
1.00	350.	514.	514.0	2.544	2.711
2.00	138.	726.	363.0	2.140	2.560

1/N= 3.000                      K= 62.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 0.0  
 % REDUCTION=\*\*\*\*%

FORMIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	325.			2.512	
0.50	273.	52.	104.0	2.436	2.017
1.00	229.	96.	96.0	2.360	1.982
2.00	165.	160.	80.0	2.217	1.903
3.00	113.	212.	70.7	2.053	1.849

1/N= 0.447                      K= 8.402  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 11.2  
 % REDUCTION= 99.%

ACETIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1085.			3.035	
0.50	790.	295.	590.0	2.898	2.771
1.00	593.	492.	492.0	2.773	2.692
2.00	301.	784.	392.0	2.479	2.593
3.00	180.	905.	301.7	2.255	2.480
4.00	108.	977.	244.3	2.033	2.388

1/N= 0.433                      K= 32.209  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 66.3  
 % REDUCTION= 99.%

BUTYRIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1710.			3.233	
0.10	1467.	243.	2430.0	3.166	3.386
0.50	776.	934.	1868.0	2.890	3.271
1.00	345.	1365.	1365.0	2.538	3.135
2.00	105.	1605.	802.5	2.021	2.904
3.00	67.	1643.	547.7	1.826	2.739

1/N= 0.465                      K= 85.246                      OPTIMUM X/M= 271.1  
 CORRELATION COEFFICIENT=0.99                      % REDUCTION= 99.%

OXALIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	171.			2.233	
0.10	150.	21.	210.0	2.176	2.322
0.30	124.	47.	156.7	2.093	2.195
0.50	103.	68.	136.0	2.013	2.134
1.00	77.	94.	94.0	1.886	1.973
2.00	51.	120.	60.0	1.708	1.778

1/N= 1.143                      K= 0.666                      OPTIMUM X/M= 23.7  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

SUCCINIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	807.			2.907	
0.10	714.	93.	930.0	2.854	2.968
0.50	446.	361.	722.0	2.649	2.859
0.70	299.	508.	725.7	2.476	2.861
1.00	164.	643.	643.0	2.215	2.808
2.00	42.	765.	382.5	1.623	2.583

1/N= 0.294                      K= 132.212                      OPTIMUM X/M= 94.5  
 CORRELATION COEFFICIENT=0.98                      % REDUCTION= 96.%

FUMARIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	714.			2.854	
0.10	614.	100.	1000.0	2.788	3.000
0.50	352.	362.	724.0	2.547	2.860
1.00	179.	535.	535.0	2.253	2.728
2.00	72.	642.	321.0	1.857	2.507
3.00	36.	678.	226.0	1.556	2.354

1/N= 0.522                      K= 34.778  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 107.3  
 % REDUCTION=100.0%

MALIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	752.			2.876	
0.10	632.	120.	1200.0	2.801	3.079
0.50	404.	348.	696.0	2.606	2.843
1.00	220.	532.	532.0	2.342	2.726
2.00	108.	644.	322.0	2.033	2.508
3.00	60.	692.	230.7	1.778	2.363

1/N= 0.670                      K= 14.289  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 120.6  
 % REDUCTION= 98.0%

TARTARIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	608.			2.784	
0.10	510.	98.	980.0	2.708	2.991
0.50	320.	288.	576.0	2.505	2.760
1.00	204.	404.	404.0	2.310	2.606
2.00	104.	504.	252.0	2.017	2.401
3.00	56.	552.	184.0	1.748	2.265

1/N= 0.744                      K= 8.402  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 99.2  
 % REDUCTION= 98.0%

GLUTARIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	786.			2.895	
0.10	635.	151.	1510.0	2.803	3.179
0.30	377.	409.	1363.3	2.576	3.135
0.50	202.	584.	1168.0	2.305	3.067
0.70	94.	692.	988.6	1.973	2.995
1.00	31.	755.	755.0	1.491	2.878

1/N= 0.231                      K= 343.977  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 160.1  
 % REDUCTION=100.%

CITRIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	776.			2.890	
0.10	622.	154.	1540.0	2.794	3.188
0.50	310.	466.	932.0	2.491	2.969
1.00	162.	614.	614.0	2.210	2.788
2.00	76.	700.	350.0	1.881	2.544
3.00	43.	733.	244.3	1.633	2.388

1/N= 0.691                      K= 17.930  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 178.2  
 % REDUCTION=100.%

BENZOIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1504.			3.177	
0.10	1203.	301.	3010.0	3.080	3.479
0.20	902.	602.	3010.0	2.955	3.479
0.40	465.	1039.	2597.5	2.667	3.415
0.70	155.	1349.	1927.1	2.190	3.285
1.00	38.	1466.	1466.0	1.580	3.166

1/N= 0.220                      K= 652.978  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 327.3  
 % REDUCTION= 99.%

ASCORBIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	896.			2.952	
0.10	762.	134.	1340.0	2.882	3.127
0.50	462.	434.	868.0	2.665	2.939
1.00	278.	618.	618.0	2.444	2.791
2.00	120.	776.	388.0	2.079	2.589
3.00	81.	815.	271.7	1.908	2.434

1/N= 0.680                      K= 14.033  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 142.7  
 % REDUCTION= 99.%

LACTIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	863.			2.936	
0.10	719.	144.	1440.0	2.857	3.158
0.50	460.	403.	806.0	2.663	2.906
1.00	240.	623.	623.0	2.380	2.794
2.00	138.	725.	362.5	2.140	2.559
3.00	96.	767.	255.7	1.982	2.408

1/N= 0.806                      K= 6.736  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 156.1  
 % REDUCTION= 98.%

ASPARTIC ACID

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	621.			2.793	
0.10	581.	40.	400.0	2.764	2.602
0.50	501.	120.	240.0	2.700	2.380
1.00	414.	207.	207.0	2.617	2.316
2.00	342.	279.	139.5	2.534	2.145
3.00	292.	329.	109.7	2.465	2.040

1/N= 1.770                      K= 0.005  
 CORRELATION COEFFICIENT=0.98

OPTIMUM X/M= 40.7  
 % REDUCTION= 97.%

APPENDIX V.  
ADSORPTION ISOTHERM  
DATA FOR TEST CARBONS  
FOR POTATO WASTE

CARBON WV-L

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	577.			2.761	
0.10	432.	145.	1450.0	2.635	3.161
0.50	300.	277.	554.0	2.477	2.744
1.00	248.	329.	329.0	2.394	2.517
2.00	202.	375.	187.5	2.305	2.273
3.00	173.	404.	134.7	2.238	2.129

1/N= 2.630                      K= 0.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 307.7  
 % REDUCTION=100.%

CARBON A

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	577.			2.761	
0.10	484.	93.	930.0	2.685	2.968
0.50	352.	225.	450.0	2.547	2.653
1.00	290.	287.	287.0	2.462	2.458
2.00	241.	336.	168.0	2.382	2.225
3.00	202.	375.	125.0	2.305	2.097

1/N= 2.350                      K= 0.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 141.3  
 % REDUCTION=100.%

CARBON B

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	577.			2.761	
0.10	477.	100.	1000.0	2.679	3.000
0.50	352.	225.	450.0	2.547	2.653
1.00	298.	279.	279.0	2.474	2.446
2.00	254.	323.	161.5	2.405	2.208
3.00	231.	346.	115.3	2.364	2.062

1/N= 2.968                      K= 0.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 185.4  
 % REDUCTION=100.%

CARBON C

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	577.			2.761	
0.10	456.	121.	1210.0	2.659	3.083
0.50	317.	260.	520.0	2.501	2.716
1.00	260.	317.	317.0	2.415	2.501
2.00	213.	364.	182.0	2.328	2.260
3.00	184.	393.	131.0	2.265	2.117

1/N= 2.475                      K= 0.000  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 221.9  
 % REDUCTION=100.0%

APPENDIX VI.  
ADSORPTION ISOTHERM  
DATA FOR CLARIFIED  
POTATO WASTE

NO TREATMENT

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	2137.			3.330	
0.10	1985.	152.	1520.0	3.298	3.182
0.50	1624.	513.	1026.0	3.211	3.011
1.00	1383.	754.	754.0	3.141	2.877
2.00	1143.	994.	497.0	3.058	2.696
5.00	812.	1325.	265.0	2.910	2.423

1/N= 1.967                      K= 0.000                      OPTIMUM X/M= 175.4  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 160 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	888.			2.948	
0.10	728.	160.	1600.0	2.862	3.204
0.50	568.	320.	640.0	2.754	2.806
1.00	480.	408.	408.0	2.681	2.611
2.00	391.	497.	248.5	2.592	2.395
3.00	346.	542.	180.7	2.539	2.257

1/N= 2.876                      K= 0.000                      OPTIMUM X/M= 257.0  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION= 99.%

FECL3/ALCL3 (1M/1M) 180 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	768.			2.885	
0.10	622.	146.	1460.0	2.794	3.164
0.50	453.	315.	630.0	2.656	2.799
1.00	376.	392.	392.0	2.575	2.593
2.00	300.	468.	234.0	2.477	2.369
3.00	261.	507.	169.0	2.417	2.228

1/N= 2.477                      K= 0.000                      OPTIMUM X/M= 238.8  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 200 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	680.			2.833	
0.10	537.	143.	1430.0	2.730	3.155
0.50	374.	306.	612.0	2.573	2.787
1.00	313.	367.	367.0	2.496	2.565
2.00	252.	428.	214.0	2.401	2.330
3.00	218.	462.	154.0	2.338	2.188

1/N= 2.502                      K= 0.000                      OPTIMUM X/M= 261.6  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.0%

FECL3/ALCL3 (1M/1M) 220 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	668.			2.825	
0.10	496.	172.	1720.0	2.695	3.236
0.50	320.	348.	696.0	2.505	2.843
1.00	249.	419.	419.0	2.396	2.622
2.00	193.	475.	237.5	2.286	2.376
3.00	168.	500.	166.7	2.225	2.222
5.00	137.	531.	106.2	2.137	2.026

1/N= 2.166                      K= 0.003                      OPTIMUM X/M= 338.9  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.0%

FECL3/ALCL3 (1M/1M) 260 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	625.			2.796	
0.10	456.	169.	1690.0	2.659	3.228
0.50	306.	319.	638.0	2.486	2.805
1.00	244.	381.	381.0	2.387	2.581
2.00	187.	438.	219.0	2.272	2.340
3.00	168.	457.	152.3	2.225	2.183
5.00	137.	488.	97.6	2.137	1.989

1/N= 2.360                      K= 0.001                      OPTIMUM X/M= 352.7  
 CORRELATION COEFFICIENT=1.00                      % REDUCTION=100.0%

APPENDIX VII.  
ADSORPTION ISOTHERM  
DATA FOR TEST CARBONS  
FOR DAIRY WASTE

CARBON WV-L

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	864.			2.937	
0.10	599.	265.	2650.0	2.777	3.423
0.30	308.	556.	1853.3	2.489	3.268
0.70	95.	769.	1098.6	1.978	3.041
0.90	66.	798.	886.7	1.820	2.948
1.00	58.	806.	806.0	1.763	2.906
2.00	43.	821.	410.5	1.633	2.613

1/N= 0.495                      K= 111.030  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 315.4  
 % REDUCTION=100.0%

CARBON A

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	864.			2.937	
0.10	648.	216.	2160.0	2.812	3.334
0.30	351.	513.	1710.0	2.545	3.233
0.70	104.	760.	1085.7	2.017	3.036
0.90	70.	794.	882.2	1.845	2.946
1.00	66.	798.	798.0	1.820	2.902
2.00	52.	812.	406.0	1.716	2.609

1/N= 0.395                      K= 168.866  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 243.5  
 % REDUCTION=100.0%

CARBON B

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	864.			2.937	
0.10	682.	182.	1820.0	2.834	3.260
0.30	415.	449.	1496.7	2.618	3.175
0.70	135.	729.	1041.4	2.130	3.018
0.90	96.	768.	853.3	1.982	2.931
1.00	83.	781.	781.0	1.919	2.893
2.00	66.	798.	399.0	1.820	2.601

1/N= 0.386                      K= 147.403  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 200.6  
 % REDUCTION= 99.0%

CARBON C

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	864.			2.937	
0.10	625.	239.	2390.0	2.796	3.378
0.30	294.	570.	1900.0	2.468	3.279
0.70	85.	779.	1112.9	1.929	3.046
0.90	58.	806.	895.6	1.763	2.952
1.00	54.	810.	810.0	1.732	2.908
2.00	39.	825.	412.5	1.591	2.615

1/N= 0.434                      K= 153.025  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 288.1  
 % REDUCTION= 99.%

APPENDIX VIII.  
ADSORPTION ISOTHERM  
DATA FOR CLARIFIED  
DAIRY WASTE

FECL3 (1M) 1.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	1003.			3.001	
0.10	743.	260.	2600.0	2.871	3.415
0.30	413.	590.	1966.7	2.616	3.294
0.50	227.	776.	1552.0	2.356	3.191
0.70	103.	900.	1285.7	2.013	3.109
1.00	79.	924.	924.0	1.898	2.966
2.00	53.	950.	475.0	1.724	2.677

1/N= 0.356                      K= 237.454  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 277.6  
 % REDUCTION= 98.%

FECL3 (1M) 1.5 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	944.			2.975	
0.10	689.	255.	2550.0	2.838	3.407
0.30	344.	600.	2000.0	2.537	3.301
0.50	170.	774.	1548.0	2.230	3.190
0.70	94.	850.	1214.3	1.973	3.084
1.00	78.	866.	866.0	1.892	2.938
2.00	46.	898.	449.0	1.663	2.652

1/N= 0.371                      K= 227.470  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 288.9  
 % REDUCTION=100.%

FECL3 (1M) 1.75 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	852.			2.930	
0.10	654.	198.	1980.0	2.816	3.297
0.30	345.	507.	1690.0	2.538	3.228
0.50	163.	689.	1378.0	2.212	3.139
0.70	85.	767.	1095.7	1.929	3.040
1.00	62.	790.	790.0	1.792	2.898
2.00	42.	810.	405.0	1.623	2.607

1/N= 0.288                      K= 310.700  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 216.9  
 % REDUCTION= 99.%

FECL3 (1M) 2.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	833.			2.921	
0.10	646.	187.	1870.0	2.810	3.272
0.30	337.	496.	1653.3	2.528	3.218
0.50	159.	674.	1348.0	2.201	3.130
0.70	83.	750.	1071.4	1.919	3.030
1.00	66.	767.	767.0	1.820	2.885
2.00	46.	787.	393.5	1.663	2.595

1/N= 0.271                      K= 331.616  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 205.8  
 % REDUCTION= 98.%

FECL3 (1M) 3.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	763.			2.883	
0.10	585.	178.	1780.0	2.767	3.250
0.50	153.	610.	1220.0	2.185	3.086
0.70	76.	687.	981.4	1.881	2.992
1.00	55.	708.	708.0	1.740	2.850
2.00	35.	728.	364.0	1.544	2.561
3.00	29.	734.	244.7	1.462	2.389

1/N= 0.290                      K= 280.686  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 192.8  
 % REDUCTION=100.%

FECL3 (1M) 3.5 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	756.			2.879	
0.10	585.	171.	1710.0	2.767	3.233
0.30	302.	454.	1513.3	2.480	3.180
0.50	149.	607.	1214.0	2.173	3.084
0.70	75.	681.	972.9	1.875	2.988
1.00	62.	694.	694.0	1.792	2.841
2.00	40.	716.	358.0	1.602	2.554

1/N= 0.279                      K= 297.512  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 188.8  
 % REDUCTION= 99.%

FECL3/ALCL3 (1M/1M) 1.5 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	960.			2.982	
0.10	689.	271.	2710.0	2.838	3.433
0.30	345.	615.	2050.0	2.538	3.312
0.50	174.	786.	1572.0	2.241	3.196
0.70	96.	864.	1234.3	1.982	3.091
1.00	62.	898.	898.0	1.792	2.953
2.00	42.	918.	459.0	1.623	2.662

1/N= 0.398                      K= 201.182  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 308.9  
 % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 1.75 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	867.			2.938	
0.10	658.	209.	2090.0	2.818	3.320
0.30	325.	542.	1806.7	2.512	3.257
0.50	155.	712.	1424.0	2.190	3.154
0.70	78.	789.	1127.1	1.892	3.052
1.00	50.	817.	817.0	1.699	2.912
2.00	38.	829.	414.5	1.580	2.618

1/N= 0.293                      K= 321.077  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 232.8  
 % REDUCTION= 99.%

FECL3/ALCL3 (1M/1M) 2.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	833.			2.921	
0.10	641.	192.	1920.0	2.807	3.283
0.30	345.	488.	1626.7	2.538	3.211
0.50	174.	659.	1318.0	2.241	3.120
0.70	83.	750.	1071.4	1.919	3.030
1.00	58.	775.	775.0	1.763	2.889
2.00	46.	787.	393.5	1.663	2.595

1/N= 0.288                      K= 300.390  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 207.8  
 % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 2.5 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	759.			2.880	
0.10	569.	190.	1900.0	2.755	3.279
0.30	304.	455.	1516.7	2.483	3.181
0.50	152.	607.	1214.0	2.182	3.084
0.70	76.	683.	975.7	1.881	2.989
1.00	54.	705.	705.0	1.732	2.848
2.00	36.	723.	361.5	1.556	2.558

1/N= 0.330                      K= 232.532  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 207.2  
 % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 3.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	763.			2.883	
0.10	581.	182.	1820.0	2.764	3.260
0.50	145.	618.	1236.0	2.161	3.092
0.70	76.	687.	981.4	1.881	2.992
1.00	50.	713.	713.0	1.699	2.853
2.00	36.	727.	363.5	1.556	2.561
3.00	29.	734.	244.7	1.462	2.389

1/N= 0.300                      K= 272.093  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 198.9  
 % REDUCTION=100.%

FECL3/ALCL3 (1M/1M) 3.5 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	763.			2.883	
0.10	581.	182.	1820.0	2.764	3.260
0.50	149.	614.	1228.0	2.173	3.089
0.70	76.	687.	981.4	1.881	2.992
1.00	50.	713.	713.0	1.699	2.853
2.00	36.	727.	363.5	1.556	2.561
3.00	28.	735.	245.0	1.447	2.389

1/N= 0.302                      K= 268.162  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 198.4  
 % REDUCTION=100.%

## ALUM (1M) 2.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	973.			2.988	
0.10	687.	286.	2860.0	2.837	3.456
0.30	348.	625.	2083.3	2.542	3.319
0.50	156.	817.	1634.0	2.193	3.213
0.70	87.	886.	1265.7	1.940	3.102
1.00	68.	905.	905.0	1.833	2.957
2.00	37.	936.	468.0	1.568	2.670

1/N= 0.383                      K= 230.552  
CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 320.8  
% REDUCTION= 99.%

## ALUM (1M) 3.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	956.			2.980	
0.10	736.	220.	2200.0	2.867	3.342
0.30	382.	574.	1913.3	2.582	3.282
0.50	183.	773.	1546.0	2.262	3.189
0.70	76.	880.	1257.1	1.881	3.099
1.00	59.	897.	897.0	1.771	2.953
2.00	44.	912.	456.0	1.643	2.659

1/N= 0.251                      K= 423.405  
CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 236.7  
% REDUCTION=100.%

## ALUM (1M) 4.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	924.			2.966	
0.10	685.	239.	2390.0	2.836	3.378
0.30	342.	582.	1940.0	2.534	3.288
0.50	171.	753.	1506.0	2.233	3.178
0.70	83.	841.	1201.4	1.919	3.080
1.00	52.	872.	872.0	1.716	2.941
2.00	40.	884.	442.0	1.602	2.645

1/N= 0.330                      K= 279.292  
CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 265.4  
% REDUCTION=100.%

## ALUM (1M) 5.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	876.			2.943	
0.10	653.	223.	2230.0	2.815	3.348
0.30	332.	544.	1813.3	2.521	3.258
0.50	171.	705.	1410.0	2.233	3.149
0.70	76.	800.	1142.9	1.881	3.058
1.00	52.	824.	824.0	1.716	2.916
2.00	40.	836.	418.0	1.602	2.621

1/N= 0.316                    K= 286.107  
CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 243.7  
% REDUCTION= 99.%

## ALUM (1M) 6.0 ML

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	876.			2.943	
0.10	650.	226.	2260.0	2.813	3.354
0.30	324.	552.	1840.0	2.511	3.265
0.50	168.	708.	1416.0	2.225	3.151
0.70	87.	789.	1127.1	1.940	3.052
1.00	55.	821.	821.0	1.740	2.914
2.00	40.	836.	418.0	1.602	2.621

1/N= 0.351                    K= 236.196  
CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 254.5  
% REDUCTION=100.%

FECL3/ALUM (0.5, 3.0 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	830.			2.919	
0.10	666.	164.	1640.0	2.823	3.215
0.30	381.	449.	1496.7	2.581	3.175
0.50	200.	630.	1260.0	2.301	3.100
0.70	91.	739.	1055.7	1.959	3.024
1.00	79.	751.	751.0	1.898	2.876
2.00	55.	775.	387.5	1.740	2.588

1/N= 0.227                      K= 381.257  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 174.7  
 % REDUCTION= 99.%

FECL3/ALUM (1.0, 2.0 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	853.			2.931	
0.10	679.	174.	1740.0	2.832	3.241
0.30	383.	470.	1566.7	2.583	3.195
0.50	181.	672.	1344.0	2.258	3.128
0.70	77.	776.	1108.6	1.886	3.045
1.00	72.	781.	781.0	1.857	2.893
2.00	68.	785.	392.5	1.833	2.594

1/N= 0.208                      K= 452.994  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 183.9  
 % REDUCTION=100.%

FECL3/ALUM (1.5, 1.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	838.			2.923	
0.10	679.	159.	1590.0	2.832	3.201
0.30	410.	428.	1426.7	2.613	3.154
0.50	198.	640.	1280.0	2.297	3.107
0.70	86.	752.	1074.3	1.934	3.031
1.00	75.	763.	763.0	1.875	2.883
2.00	55.	783.	391.5	1.740	2.593

1/N= 0.185                      K= 472.968  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 164.8  
 % REDUCTION=100.%

FECL3/ALUM (2.0, 1.2 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	841.			2.925	
0.10	679.	162.	1620.0	2.832	3.210
0.30	404.	437.	1456.7	2.606	3.163
0.50	211.	630.	1260.0	2.324	3.100
0.70	97.	744.	1062.9	1.987	3.026
1.00	81.	760.	760.0	1.908	2.881
2.00	75.	766.	383.0	1.875	2.583

1/N= 0.217                      K= 393.443  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 170.2  
 % REDUCTION=100.0%

FECL3/ALUM (3.0, 1.0 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	824.			2.916	
0.10	679.	145.	1450.0	2.832	3.161
0.30	412.	412.	1373.3	2.615	3.138
0.50	198.	626.	1252.0	2.297	3.098
0.70	156.	668.	954.3	2.193	2.980
1.00	81.	743.	743.0	1.908	2.871
2.00	60.	764.	382.0	1.778	2.582

1/N= 0.239                      K= 315.834  
 CORRELATION COEFFICIENT=0.87

OPTIMUM X/M= 157.6  
 % REDUCTION= 76.0%

FECL3/ALUM/H2SO4 (0.5 2.0 1.0 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	853.			2.931	
0.10	679.	174.	1740.0	2.832	3.241
0.30	383.	470.	1566.7	2.583	3.195
0.50	198.	655.	1310.0	2.297	3.117
0.70	94.	759.	1084.3	1.973	3.035
1.00	75.	778.	778.0	1.875	2.891
2.00	45.	808.	404.0	1.653	2.606

1/N= 0.326                      K= 219.808  
 CORRELATION COEFFICIENT=0.95

OPTIMUM X/M= 198.4  
 % REDUCTION= 90.%

FECL3/ALUM/H2SO4 (1.0 1.0 0.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	889.			2.949	
0.10	650.	239.	2390.0	2.813	3.378
0.30	311.	578.	1926.7	2.493	3.285
0.50	140.	749.	1498.0	2.146	3.176
0.70	71.	818.	1168.6	1.851	3.068
1.00	41.	848.	848.0	1.613	2.928
2.00	26.	863.	431.5	1.415	2.635

1/N= 0.364                      K= 235.559  
 CORRELATION COEFFICIENT=0.99

OPTIMUM X/M= 279.1  
 % REDUCTION= 98.%

FECL3/ALUM/H2SO4 (1.0 0.5 0.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	888.			2.948	
0.10	629.	259.	2590.0	2.799	3.413
0.30	353.	535.	1783.3	2.548	3.251
0.50	153.	735.	1470.0	2.185	3.167
0.70	62.	826.	1180.0	1.792	3.072
1.00	51.	837.	837.0	1.708	2.923
2.00	29.	859.	429.5	1.462	2.633

1/N= 0.378                      K= 214.253  
 CORRELATION COEFFICIENT=0.96

OPTIMUM X/M= 279.2  
 % REDUCTION= 93.%

FECL3/ALUM/H2SO4 (1.5 0.5 0.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	862.			2.936	
0.10	670.	192.	1920.0	2.826	3.283
0.30	349.	513.	1710.0	2.543	3.233
0.50	160.	702.	1404.0	2.204	3.147
0.70	66.	796.	1137.1	1.820	3.056
1.00	47.	815.	815.0	1.672	2.911
2.00	33.	829.	414.5	1.519	2.618

1/N= 0.295                      K= 296.770                      OPTIMUM X/M= 218.6  
 CORRELATION COEFFICIENT=0.96                      % REDUCTION= 93.%

ALUM/LIME/HCL (2.0 1.5 1.0 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	924.			2.966	
0.10	682.	242.	2420.0	2.834	3.384
0.30	341.	583.	1943.3	2.533	3.289
0.50	170.	754.	1508.0	2.230	3.178
0.70	92.	832.	1188.6	1.964	3.075
1.00	54.	870.	870.0	1.732	2.940
2.00	40.	884.	442.0	1.602	2.645

1/N= 0.395                      K= 190.783                      OPTIMUM X/M= 283.4  
 CORRELATION COEFFICIENT=0.99                      % REDUCTION= 99.%

ALUM/LIME/HCL (2.0 1.5 1.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	895.			2.952	
0.10	680.	215.	2150.0	2.833	3.332
0.30	358.	537.	1790.0	2.554	3.253
0.50	145.	750.	1500.0	2.161	3.176
0.70	54.	841.	1201.4	1.732	3.080
1.00	34.	861.	861.0	1.531	2.935
2.00	14.	881.	440.5	1.146	2.644

1/N= 0.277                      K= 359.917                      OPTIMUM X/M= 236.5  
 CORRELATION COEFFICIENT=0.98                      % REDUCTION= 95.%

ALUM/LIME/HCL (2.0 2.5 1.5 ML)

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	932.			2.969	
0.10	744.	188.	1880.0	2.872	3.274
0.30	400.	532.	1773.3	2.602	3.249
0.50	183.	749.	1498.0	2.262	3.176
0.70	74.	858.	1225.7	1.869	3.088
1.00	36.	896.	896.0	1.556	2.952
2.00	16.	916.	458.0	1.204	2.661

1/N= 0.240                      K= 408.887  
 CORRELATION COEFFICIENT=0.98

OPTIMUM X/M= 211.3  
 % REDUCTION= 95.%

NO TREATMENT

GRAMS CARBON	CODF	X	X/M	LOG CODF	LOG X/M
0.00	3009.			3.478	
0.10	1793.	1216.	12160.0	3.254	4.085
0.30	1147.	1862.	6206.7	3.060	3.793
0.50	828.	2181.	4362.0	2.918	3.640
1.00	509.	2500.	2500.0	2.707	3.398
2.00	315.	2694.	1347.0	2.498	3.129
3.00	99.	2910.	970.0	1.996	2.987
5.00	37.	2972.	594.4	1.568	2.774

1/N= 1.238                      K= 1.084  
 CORRELATION COEFFICIENT=1.00

OPTIMUM X/M= 2191.6  
 % REDUCTION=100.%