RESPONSES OF EXTENDED AERATION ACTIVATED SLUDGE TO QUANTITATIVE SHOCK LOADS

By

WISUT RAGTHAIDEE

Bachelor of Engineering

Chulalongkorn University

Bangkok, Thailand

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TO QUANTITATIVE SHOCK LOADS

Thesis Approved:

M. Ramanathan
Thesis Adviser

A. C. Gaudy Jr.

Don F Kincannon

D. D. Durham
Dean of the Graduate College

725048

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CHAPTER I

INTRODUCTION

The national water pollution problem in the United States is a complex one. It involves many facets. Water is withdrawn for use over and again for many purposes as it flows to the sea. In 1954, it was estimated that about one third of the average annual stream flow was withdrawn from stream for domestic and industrial use. One fifth of this amount was returned to stream as waste water. By the year 2000 A.D. it has been estimated that the demand for fresh water will increase to four fifths of the average stream flow. As a result, the waste flow is also expected to increase to an all-time high magnitude of two thirds the average stream flow (1). The need for preserving the quality of water is emphasized as demand rapidly approaches available resources. Several factors have contributed to this critical situation. In addition to pollution caused by the increase in population, the post-war technology and industrial growth have introduced many types of new chemicals and radioactive materials in such a way that, in many locations, they cause deleterious effects upon receiving waters. These are evident by foams, fish kills, foul taste, color, odor, and impairment to municipal and industrial water treatment facilities.

In the United States, during the past several years, a rapid concern of professional and public interest has occurred regarding the adequacy and quality of national water resources. The Senate Select

Committee on Water Resources, in its recently completed study of the nation's water requirements, gave special interest to the need for protecting water quality to permit repeated use (2). It can be readily seen that the increasing demands for water in the face of limited supplies require that wastes be engineered out of streams to the maximum extent possible.

Many attempts have already been made or are in progress to minimize the distribution of various pollutants into receiving streams. One of these processes is the well-known activated sludge process which has been employed in this country for over half a century. There is no doubt that it is the most widely accepted of the several processes that have gained national and world recognition in the past several years. This may be due to the fact that it has relatively high efficiency of organic removal, requires smaller area for treatment and provides a higher degree of operational flexibility than other processes.

Originally, the activated sludge process was developed to treat domestic wastes. Attempts to apply this process to various industrial wastes or the combination of domestic and industrial wastes has resulted in proposing numerous modifications to the conventional activated sludge process. These include tapered aeration, bio-sorption, step aeration, the Kraus process, complete mixing and extended aeration or total oxidation processes (3). All of these modifications, in common, attempted to provide better utilization of the process as well as to reduce the cost of treatment.

From an engineering standpoint the total oxidation or extended aeration activated sludge process is one of the most desirable of the several modifications proposed. The process has been claimed to possess

several advantages, of which the elimination of sludge treatment and disposal is the most important one. In certain locations where adequate land, within reasonable cost, is not available, the sludge disposal problem has become acute. It is believed that upon further development, the extended aeration activated sludge system could provide an ideal waste treatment process with high efficiency of organic removal, low cost, simple operation; one which requires no sludge disposal facilities. It is the purpose of this dissertation to study in detail the response of the extended aeration activated sludge process to quantitative shock loads.

Considerable attention has been focussed on the study of the effect of environmental changes on biological systems during recent years. These studies led to the belief that a rapid change in the ambient condition can adversely affect the activities of microorganisms in activated sludge (4, 5, 6). These rapid changes in environment are generally referred to as "shock loads." Even though the research works conducted on activated sludge throw some light on the behavior of biological systems to shock loads, they are not directly applicable to other biological systems. Since the ability of a biological system to absorb shock loads will depend upon several factors, such as sludge age, solids concentration, predominating species of microorganisms, etc., a separate study on the extended aeration process was found necessary. The experiments conducted during this investigation were developed with the above concept in mind and for the following purposes:

1. To investigate the performance of extended aeration activated sludge, operated over long periods without sludge wastage to various modes and degrees of quantitative shock loads. The

following modes of shock loads and operational conditions were studied using glucose as substrate:

a) Shock loads applied as slug dosage on batch-fed extended aeration activated sludge system.

b) Shock loads applied gradually (continuously) on continuous-flow extended aeration system.

2. To compare the shock load responses of extended aeration sludge operated both under batch and continuous flow conditions.

3. To determine the extent of quantitative shock load that can be successfully absorbed by extended aeration sludge.

CHAPTER II

LITERATURE REVIEW

A. Extended Aeration Activated Sludge Process

1. Description and Biochemistry

The extended aeration activated sludge system, a modification of the activated sludge process, differs from other aerobic systems in that the aeration periods are much longer (usually 18 to 24 hours) than other processes. The organisms in extended aeration systems have sufficient time to assimilate the exogenous food into cell materials and then to oxidize themselves. When proper ratio of food to microorganisms is maintained with sufficient aeration period, the rate of auto-oxidation and synthesis are approximately equal and the stabilization of organic wastes can be achieved without any net accumulation of organic sludge (7). Most extended aeration activated sludge systems consist of two basic components, namely, an aeration compartment and a settling compartment. In the aeration compartment, the waste is aerated and mixed with the mixed liquor to provide conditions suitable for growth of aerobic organisms. The ultimate BOD of the waste is exerted in this tank. In the settling compartment the suspended solids are allowed to settle and are then collected in some manner and returned to the aeration chamber. Since the aeration time is much longer than the conventional activated sludge process (usually 24 hours rather than 4-8 hours), it produces only a minimum of a highly stabilized biological sludge,

thus obviating the need for sludge handling and disposal facilities. This process has been claimed to possess many advantages, e.g., low initial cost and maintenance requirement, simple operation and ability to withstand shock loads.

The treatment of organic wastes in extended aeration activated sludge is similar to that which takes place in the conventional activated sludge process. The conversion can be thought to take place in two stages which occur simultaneously in the same tank. The first stage occurs when the suspended and dissolved organic matters are brought into contact with the microorganisms in the mixed liquor. During this stage, the organisms assimilate the organic substrate into protoplasm and storage products. In order for the organisms to synthesize new bacterial cells, energy must be supplied by other biochemical reactions. These energy releasing reactions, which are generally of the oxidation-reduction type, are collectively known as respiration. The fraction of total available substrate channelled into respiration has been shown to be approximately one third, with the remaining two thirds being used for synthesis (8). In the second stage, which occurs simultaneously with anabolic reaction, the synthesized cells undergo self-oxidation which is also referred to as "endogenous respiration." Endogenous respiration has been said to occur in the presence or absence of substrate apparently to provide energy for locomotion and other normal functions of the organisms (9).

The over-all stoichiometry of an aerobic biochemical process is generally expressed as follows:

Oxidation

(Substrate BOD) + $X(O_2)$ + Bacteria $\rightarrow$ CO_2 + H_2O + NH_3+ {Energy}

Synthesis

(Substrate BOD) + Bacteria + Energy → Y (Cell material)

Endogenous Respiration

(Cell material) + Z (O_2) → CO_2 + H_2O + NH_3

The coefficients X, Y, and Z are not true constants but depend on the process loading and the type of waste being treated. The values of X, Y and Z were estimated by a number of investigators and they have been shown to vary as follows: Y from 0.48 to 0.63 lbs VSS/lb BOD (10, 11, 12, 13, 14, 15, 16), X from 0.32 to 0.52 lb of oxygen/lb BOD and Z at approximately 1.4 lbs of oxygen/lb VSS (13, 17, 18, 19).

2. Process Loading

The degree of self-oxidation in the endogenous phase is dependent upon the availability of substrate and the extent of aeration time allowed. If the aeration time allowed is not sufficient to assimilate all of the exogenous substrate present in the system, then the endogenous respiration would probably occur at minimum rate. This could occur in two ways: (i) by having a short aeration time, and (ii) by having an unlimited source of food supply in the aerator. Conversely, if food is limited the organisms would undergo auto-oxidation, thereby reducing the net yield of sludge produced. Therefore, in order to obtain a system with minimal sludge, it must be operated in the endogenous phase. This is accomplished either by maintaining a low organic loading and a high biological solids concentration or by having a fairly long aeration period. McKinney (8) has shown that endogenous oxidation would occur when food (ultimate BOD): microorganisms (MLSS) ratio of 0.45 was maintained. The above design criteria was based on an arbitrary

detention time of 24 hours and applicable only to that detention time. Eckenfelder (20) indicated a maximum loading of 0.2 lbs applied BOD/day/lb volatile suspended solids. An extensive study of rated aeration plants led Ludwig et al. (21) to consider a loading of 0.02 - 0.04 lbs applied BOD/day/lb of volatile solids. In actual practice, the values of the above parameters are selected considering practical limitations and economy. A loading range from 10-15 lbs BOD/day/1000 cu-ft of aeration volume is usually employed in a plant with no sludge wasting in order to obtain 90-95 per cent removal efficiency (22).

3. Operational Efficiency and Control Variables

During recent years, extensive field studies have been made regarding the performance and the removal efficiency of the extended aeration activated sludge plants. In 1959 and 1960, the Ohio Department of Health (23) made extensive field studies of a number of extended aeration package plants in that state and found that a high degree of treatment is achieved in properly designed and operated plants. Joplin (24) reported on a field study of ten extended aeration package treatment plants in California and emphasized the relationship of routine operational and maintenance attention to the degree of treatment achieved. Kiker (25), from a field study of fourteen extended aeration package plants in Florida, also stressed the importance of operation and maintenance. Another study from fourteen package plants in Massachusetts (26) also revealed the same conclusion. Baker (27), following a study of package treatment plants in Florida in 1962, reported that such units were capable of achieving a better than 95 per cent BOD removal. From these studies it can be said that a high degree of treatment efficiency achieved from the extended aeration systems is a function of proper

design, operation and maintenance.

The concentration of mixed liquor suspended solids (MLSS) and the contact time of the organisms with the waste have considerable effect in the design of extended aeration systems. For a given mixed liquor solids concentration, an increase in the BOD loading will result in increasing the effluent solids and decreasing the BOD removal. Also the higher the mixed liquor solids concentration, the higher will be the BOD removal efficiency (28). The National Sanitation Foundation (13), from its studies on package treatment plants, recommended a solids concentration of 4000 mg/l as optimum level from an operational standpoint. The report also indicated that solids concentrations below 2500 mg/l are not desirable since it will rapidly change the food to microorganisms ratio. The maximum reduction in BOD and suspended solids was reported by Baker (29) at a solids concentration of 9500 mg/l. However, it is not desirable to maintain a mixed liquor solids concentration much in excess of 6000 mg/l since even minor fluctuations in flow rate may cause loss of solids in the effluent (13).

The quantities of oxygen necessary for any biological treatment process should be given prime consideration. The air requirement is related to the oxygen utilized for biological oxidation of the waste and to the oxygen transfer efficiency of the aeration device. Since extended aeration systems are operated on the basis of complete mixing, the aeration system must also ensure rapid and complete mixing of entering waste and biological solids. Simpson (19) suggested a normal air supply of not less than 1500 cu. ft/lb of applied BOD for extended aeration plants. Normally the oxygen required in terms of pounds of oxygen per pound of 5-day BOD removed is estimated to be between 1.2 to

1.3 (13, 28).

Nitrogen requirement has been one of the important aspects in the activated sludge process, and even more in plants operated as extended aeration type. In extended aeration plants, a major problem always associated with is nitrification or conversion of ammonia nitrogen to nitrite and nitrate. Part of this ammonia is liberated from the endogenous metabolism of cellular material. If ammonia is excessively present (or added in excess to nitrogen deficient wastes), the concentration of nitrate in the mixed liquor may be significant. This might hinder efficient separation of solids in the clarifier due to the release of nitrogen gas and rising sludge by denitrification. However, this situation can be avoided by maintaining sufficient D.O. in the clarifier at all times (30).

Conditions for proper operation of extended aeration plants also seem not to occur if nitrogen in the system is deficient. Symons and McKinney (31), in their study regarding the biochemistry of nitrogen in the synthesis of activated sludge, found that a decrease in nitrogen in the system was usually accompanied by a build-up of biologically non-degradable materials (polysaccharides) in the system. Thus, the biological solids concentration showed a steady increase in the system when solids wasting was not practiced. Since the extended aeration systems are designed to produce a minimum amount of biological solids, the nitrogen requirement should be sufficient enough to produce a minimum, if any, of inert or biologically non-degradable end products. Sawyer (32) suggested a BOD: N ratio of 17:1 for a conventional system where sludge with maximum nitrogen content is desired. For extended aeration systems, Simpson (19) recommended a BOD to N ratio of 90:1 which is one

fifth of the amount required for conventional activated sludge plants.

B. Factors Affecting the Activity of Sludge

Considerable research has been done in the study of the effect of various parameters that may influence the activity of mixed populations of microorganisms. Among these, dissolved oxygen, pH, temperature and sludge age have received much attention.

Hicks et al. (33) showed that the rate of BOD removal was not affected when the dissolved oxygen in the activated sludge mixed liquor was maintained between 1 to 6 mg/l. Smith (34) observed that the oxygen utilization rate was not affected when dissolved oxygen concentration was varied from 0.2 to 0.6 mg/l. In studying the effect of air flow rate on the response of activated sludge to quantitative shock loading, Gaudy et al. (35) concluded that the value of oxygen tension which affects metabolic rate lies below 0.5 mg/l dissolved oxygen. Their findings agree well with the study by Orford et al. (36), who concluded that at dissolved oxygen levels below 0.5 mg/l, the effluent BOD sharply increased with decreasing dissolved oxygen concentrations.

The effect of pH upon BOD removal efficiency in aerobic biological treatment process has been studied by several investigators. Ruchhoft et al. (37), after making an extensive study on the removal of glucose by activated sludge, concluded as follows: "lowering the pH of the sludge from neutral to 5.2 before the addition of glucose, definitely retarded glucose removal slightly, and lowering pH to 2.8 for the same time practically destroyed the glucose removing mechanism for several hours. Increasing the pH up to 11 for 30 minutes followed by neutralization had very little effect upon glucose removal. When activated sludge was aerated below pH 6.0 the rate of glucose removal was reduced

and at pH 3.9 it was practically stopped." Keefer and Meisel (38) found the optimum pH range for activated sludge treating sewage to be between 7.0 and 7.50 with an effective range between 6.0 and 9.0. They found that the process was only 43 per cent effective at pH 4.0 and at pH 10 only 54 per cent effective. Gehm (39) reported that Kraft pulping waste can be treated by the activated sludge process with a pH as high as 9.8. Another study by Heukelekian et al. (40) showed that there is a wide range of optimum pH value for the oxidation of industrial wastes, and that the pH need not be carefully controlled.

Another factor that has considerable importance in the treatment of waste waters is temperature. Arden and Lockett (41) were the first to report that lowering the temperature slowed down the process and that below 10^{o} C the process was greatly hampered. Trebler and Harding (42) indicated the importance of temperature in aerobic digestion of solids in an extended aeration plant treating whey wastes. They found that endogenous oxidation was maximum at 86^{o} F and at 68^{o} F the rate of endogenous oxidation of sludge was practically stopped. Ludzack et al. (43), after studying the performance of activated sludge subjected to changes in temperature, reported that BOD and COD removal was about 10 per cent higher at 30^{o} C than at 5^{o} C when the influent was treatable at both temperatures. However, the solids accumulation was substantially greater at 5^{o} C than at 30^{o} C. They also found that flocculation characteristics were poor at the lower operating temperature with an increase in tendency to foam. Ruchhoft et al. (37), employing glucose as substrate, showed that heating the sludge to 35^{o} C did not affect the removal rate of glucose but at 45^{o} C the rate was reduced for a considerable time and at 55^{o} C the glucose removing mechanism of the

sludge was practically destroyed. Sawyer and Rohlich (44) and Imhoff and Fair (45) indicated that 20 to 25^{o} C is the optimum range for economical and efficient operation of aerobic biological treatment systems.

Another factor which warrants consideration in the aerobic biological treatment process is sludge age. Torpey and Chasick (46) stated that deterioration of sludge will take place when the sludge age exceeds about six days. They defined sludge age as the average time a particle of suspended solids remains under aeration and expressed mathematically as pounds of dry weight of activated sludge in the aerator divided by the suspended solids load (pounds per day) in sewage entering the aeration system. Sludge age ranging from three to four days were recommended by them for most conventional plants.

C. Responses of Activated Sludge to Shock Loads

Shock loads may be defined in a broad sense as any rapid or abrupt change in the physical or chemical environment in a biological system (47). Since most waste treatment systems are subjected to frequent changes in their environment, research on the effects of shock load has received much attention during the last decade. It is therefore extremely important to determine the changes in environment which may cause deleterious effects upon the normal functioning of extended aeration activated sludge systems.

The major types of shock loads which may disrupt the treatment efficiency of the activated sludge plants can be described as follows:

1. Quantitative Shock Load. This involves generally a rapid change in the amount of organic constituents in the incoming waste, i.e., a rapid change in the organic loading to the system. This

type of shock load need not necessarily imply an increase in organic content of the waste, since a rapid decrease in the organic concentration may also cause operational problems and constitutes a shock load.

2. Toxic Shock Load. This involves an influx of wastes containing certain toxic components (e.g., heavy metals) that will disrupt the established metabolic pattern of the microbial population. Toxic shock load also includes a rapid change in pH of the incoming waste, although this is more easily controlled than those caused by salts of heavy metals such as copper, zinc, chromium, nickel or the cyanide compounds.

3. Qualitative Shock Load. The qualitative shock load refers to a change in the chemical nature of the incoming waste, i.e., a change in the structural configuration of the carbon source to which the sludge has been acclimated. The distinguishing characteristic of the qualitative shock load as described by Gaudy and Engelbrecht (47) is that the change involves only the structure of the molecule of the carbon source or a substantial portion thereof. This type of shock concerns neither the total organic concentration, which may remain the same as before the shock, nor does it imply that the change is toxic.

In general, the response of a system to shock loads is considered successful if it does not act in any way to the detriment of the normal functioning of the process. According to Gaudy and Engelbrecht (47), the most likely successful response to quantitative shock loads will be a rapid increase in sludge production. Where the increase in organic loading is accompanied also by a

proportional increase in other inorganic nutrients, the sludge production corresponds to an increase in cell replication. However, when the increase in organic loading is not accompanied by a corresponding increase in inorganic nutrients, the increase in solids concentration is not entirely due to cell replication. Gaudy and Engelbrecht (47) believed that this type of shock loading has been cited as a cause of sludge bulking by Kraus (48).

The response to any shock load will depend generally upon the degree of change introduced to the system as a result of shock load. If the change is adverse, the biochemical efficiency may be affected and the flocculation and settling characteristics of the sludge may be impaired. According to George (6) a successful response will depend upon many factors which included:

a. The severity and/or the rapidity of the shock load,
b. The detention time in the aerator,
c. The physiological characteristics of the sludge, e.g., sludge age,
d. The sludge concentration in aerator,
e. The oxygen tension, and
f. The predominating microbial populations in the sludge and the number of different species present, i.e., the degree of heterogeneity.

During recent years much work has been done to determine the effect and modes of response of the activated sludge to various types of shock loads. Gaudy (49), in his study of qualitative shock loads on activated sludge, reported that the successful response depended on the availability of a readily available nitrogen source and on culture age. Komolrit

(4) investigated the effect of qualitative shock loads in a continuous flow completely mixed unit and concluded that the successful response of such a system was dependent upon dilution rate, biological solids concentration, sludge activity and availability of nitrogen in the waste. Similar results were also reported by Krishnan (5) in his study on the effects of quantitative shock loads using a continuous flow reactor. George (6), from his study on hydraulic, pH and temperature shock loads, indicated that these variations can cause a severe effect upon biochemical efficiency as well as physical characteristics of the sludge. There are many other studies conducted to determine the effect changes in the loading factor on the behavior of biological treatment processes. These studies indicate that overloading and sometimes underloading was the major factor causing sludge bulking and loss of solids in the effluent (18, 50, 51, 52).

D. Accumulation of Inert Metabolic Products

As is the case with most new processes, the extended aeration activated sludge process has been the subject of much controversy. The accumulation of inert metabolic products and inactive biological solids are the major subjects for discussion.

Theoretically, extended aeration sludge would continue to oxidize itself to carbon dioxide and water so that no net accumulation of sludge would occur in the system. In practice, however, it is doubtful whether this ideal situation could be approached. Porges et al. (53), in a study using skim milk as substrate, reported that "true" endogenous phase oxidation occurs with one per cent loss in sludge weight per hour. The "true" endogenous phase refers to oxidation which occurs after the assimilation of exogenous substrate and the oxidation of storage

products within the cell. They also concluded that with extended periods of aeration the accumulation of sludge could approach zero. Thus the system could be operated at solids equilibrium, thereby, negating the need for sludge wastage and disposal. Kountz (54) supported this concept, however, he reported that the suspended solids concentration should not exceed 3000 mg/l in order to facilitate clarification. In a later study, Forney and Kountz (55) confirmed the attainment of equilibrium with skim milk waste in a continuous flow reactor. They found that for equilibrium conditions, the biological solids concentration was twelve times the influent substrate concentration.

While the preceding work had indicated that extended aeration systems could be operated without sludge wasting, Symons and McKinney (31) reported that operation without sludge wasting was not possible. Their conclusions were based upon studies with sodium acetate as substrate in batch fed unit. They also reported that microscopic examination of the sludge with Alcian blue stain revealed a build-up of extracellular polysaccharides which they felt were resistant to biodegradation. The above study and later studies seem to contradict the general belief that the activated sludge system could be operated as a total oxidation unit without sludge wasting.

In a later study of the total oxidation activated sludge process using dry skim milk as a source of organic matter, Kountz and Forney (56) reversed their previous conclusion and reported an accumulation of sludge at the rate of 0.122 lb/day. They were able to operate the system at equilibrium by wasting sludge at the same rate as it was accumulating. The equilibrium weight of sludge was fourteen times the weight of substrate fed per day. Results obtained, from a laboratory

scale using continuously fed activated sludge system and a synthetic waste as substrate, by McCarty and Broderson (28) indicated that total oxidation of sludge was not feasible. Stack and Convay, through Eckenfelder (20), also reported that ten per cent of the biological sludge remained unoxidized in the treatment of an organic chemical waste. Eckenfelder (20), from a study on activated sludge developed on settled sewage, reported that 35 to 45 per cent remained as non-oxidizable residue. He also found that the non-oxidizable fraction increased when unsettled sewage was used as substrate. Washington and Symons (57), employing radio isotopic techniques, found that volatile solids accumulated at the rate of 10 to 15 per cent of the ultimate BOD of the waste when the carbon source was fatty acid or carbohydrate in nature. However, the accumulation of sludge was less when amino acids were used as substrate. They also concluded that the accumulated biologically inert mass was mainly polysaccharide in nature. This observation was based on endogenous respiration studies of the sludge in which protein and fat contents of sludge undergo decomposition while carbohydrates do not. Busch and Myrick (58) studied both batch and continuous flow total oxidation systems in the laboratory and concluded that establishment of an equilibrium solids level was unattainable even after 103 days of operation. Their results are in support of the concept that sludge wasting is required to operate total oxidation systems at equilibrium. However, they pointed out that for certain types of industrial wastes for which the ratio of respiration to synthesis is high, total oxidation systems might be plausible.

In a batch study using glucose as substrate, McWhorter and Heukelekian (59) observed the typical rise in sludge concentration

wherein the peak concentration coincides with the time of substrate removal. However, upon continued aeration a decrease in biological solids concentration was observed. Eventually, the rate of decrease approached zero, and the terminal amount of sludge produced was 12 per cent of the amount of substrate added. This figure agrees well with the value of 10 to 15 per cent reported by Washington and Symons (57). McWhorter and Heukelekian noted this agreement and referred to the portion of sludge not subject to auto-oxidation as an inactive cell mass.

Based upon the works cited above, there has been general agreement that a gradual build-up of suspended solids concentration can be expected in systems operated without sludge wasting. Also, it has been generally concluded that an activated sludge cannot totally oxidize itself. Some 10 to 15 per cent of the organic feed is channelled into "permanent synthesis" of biological materials. While the residual fraction may be termed inert or inactive because it has lost its facility for self destruction (auto-oxidation), there would appear to be some room for question concerning the inertness or activity of this residual sludge as an agent for substrate removal, i.e., what proportion of this sludge (if any) contributes to the so-called "active fraction" of the activated sludge mass. The impression gained from the literature is that it is assumed that none of it does. However, there are few or no data upon which to base an unequivocal conclusion in this regard. There is little doubt that the "active fraction" (with respect to substrate removal) of the residual biomass after prolonged endogenous respiration is smaller than the active fraction of the biomass from a more conventional (sludge wasting) activated sludge process, but there is doubt that there is no "active fraction" after prolonged endogenous respiration. In addition,

it seems appropriate to point out that studies of the type reported by McWhorter and Heukelekian are of more immediate applicability to considerations of aerobic digestion as a separate unit process than to the total oxidation process in which exogenous substrates are continuously added.

From the foregoing review it can be seen that the results of some research workers indicate that there is a gradual accumulation of biologically inert organic solids which should ultimately cause functional failure of "total oxidation" plants. However, no one seems to have studied the system over a sufficiently long period to determine the time required to produce such failure. While there may be some theoretical basis for expecting an accumulation of inert and non-oxidizable organic solids, it would seem ideal from an engineering standpoint to determine the extent of the period of useful operation. The concept of combining secondary treatment and autodigestion of the sludge is indeed an intriguing one which has obvious engineering advantages, and if the process could be operated successfully for a year or so before disposal of a portion of the sludge became necessary, it would still offer an attractive alternative to the conventional practice. In view of the above considerations and the still controversial concern over the need for eventual sludge wasting, a long-term laboratory study was designed in which an extended aeration plant was operated with all solids returned to the aeration chamber except for a small, known amount used for analyses. Also, since a build-up of inert biological solids would be expected to have an adverse effect upon the ability of the system to take shock loads, the present study was initiated and the results are presented in this dissertation.

CHAPTER III

MATERIALS AND METHODS

A. Experimental Apparatus, Composition of Synthetic Waste and Procedure

Before describing the experimental equipment and procedures for the shock load studies herein reported, it is appropriate to provide a brief history of the development of the extended aeration activated sludge employed in this study. The sludge was developed by seeding the synthetic waste with sewage obtained from the effluent of the primary clarifier at the municipal sewage treatment plant, Stillwater, Oklahoma. The extended aeration unit (the total volume of aeration and settling chamber = 9.4 liters) was put into operation on March 31, 1967, and operated under continuous flow conditions with 1000 mg/l glucose as sole carbon source (30). The over-all detention time in the aeration tank and settling chamber was maintained at 24 hours. All biological solids, except a small portion (15 ml) taken every day for analysis, were returned to the aeration chamber. The solids concentration built up and on October 12, 1967 (196 days after starting the unit), half of the system, i.e. 4.7 liters, was transferred to a second unit of the same type and both halves were diluted to 9.4 liters with tap water. Since the biological solids concentration was now halved, the feed concentration was proportionally reduced to 500 mg/l glucose for each unit. One system was used for the shock load studies reported herein, and the other unit was retained for continuing studies on the long term behavior

of the extended aeration process.

1. Experimental Apparatus

Figure 1 shows the cross section of the laboratory scale total oxidation unit employed in this study. For batch operations, the adjustable baffles were removed from the reactor, since no clarifier was required for batch operation. The reactor volume was 9.4 liters for batch type operation. For continuous flow operations, the baffles were inserted, thereby dividing the reactor into an aeration chamber (5.7 l) and a clarifier (3.7 l). This corresponds to a mean residence time of 17 hours in the aeration chamber and 7 hours in the settling chamber. The adjustable baffles and clarifier walls proved to be useful in providing a "stilling" action in the settling chamber and in directing return sludge to the aeration chamber. Compressed air diffused through the mixed liquor in the aeration tank provided the dual purpose of mixing and supplying oxygen to the mixed liquor suspended solids. For continuous-flow operations, the air diffusion also provided the suction required to recycle settled solids from the clarifier. The rate of air supply was maintained at 2000 cc per liter per minute and was the same in both batch and continuous-flow systems. Figure 2 shows the flow diagram of the extended aeration system for continuous flow operation.

Shock load studies were conducted at both high and low initial solids levels. For shock load studies with high initial solid concentration, the experiments were conducted in the unit described above. For shock load studies at low initial solids concentration, special experiments were conducted separately in a 1000 ml Erlenmeyer flask. The experimental set-up used for low biological solids is shown in Figure 3.

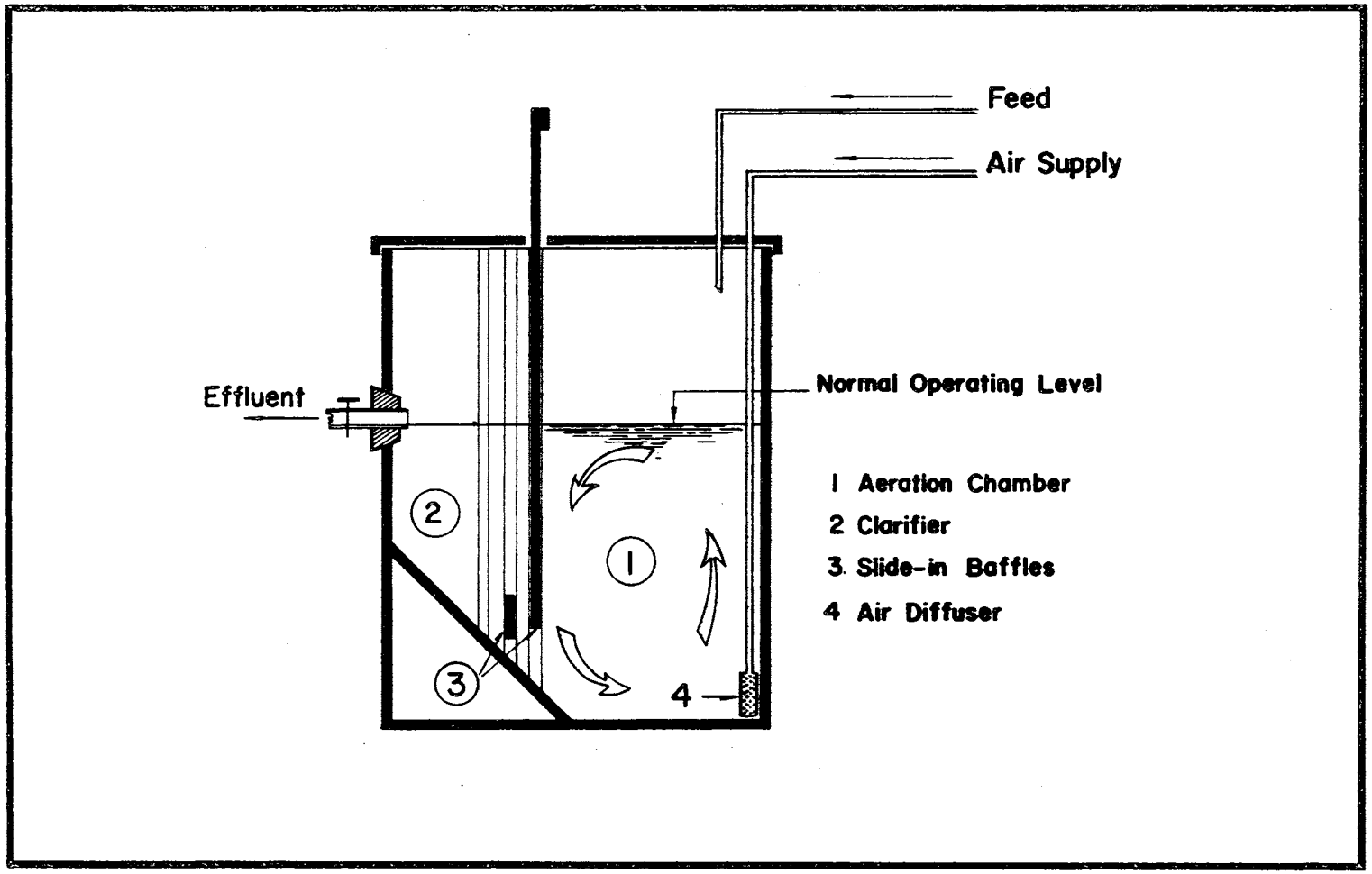

Figure 1. Laboratory Scale Continuous Flow Extended Aeration System

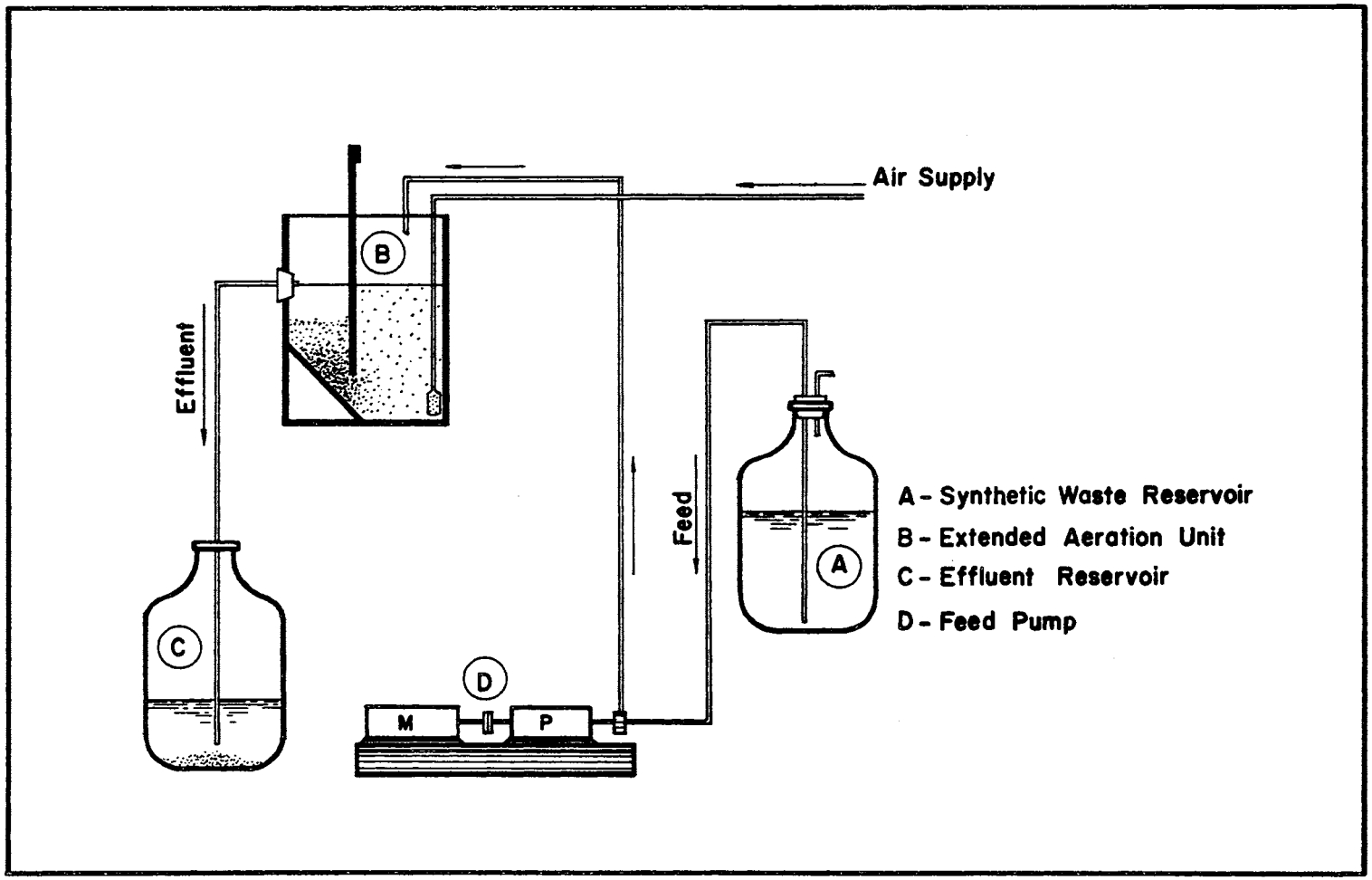

Figure 2. Schematic Flow Diagram of Laboratory Scale Continuous Flow Extended Aeration System

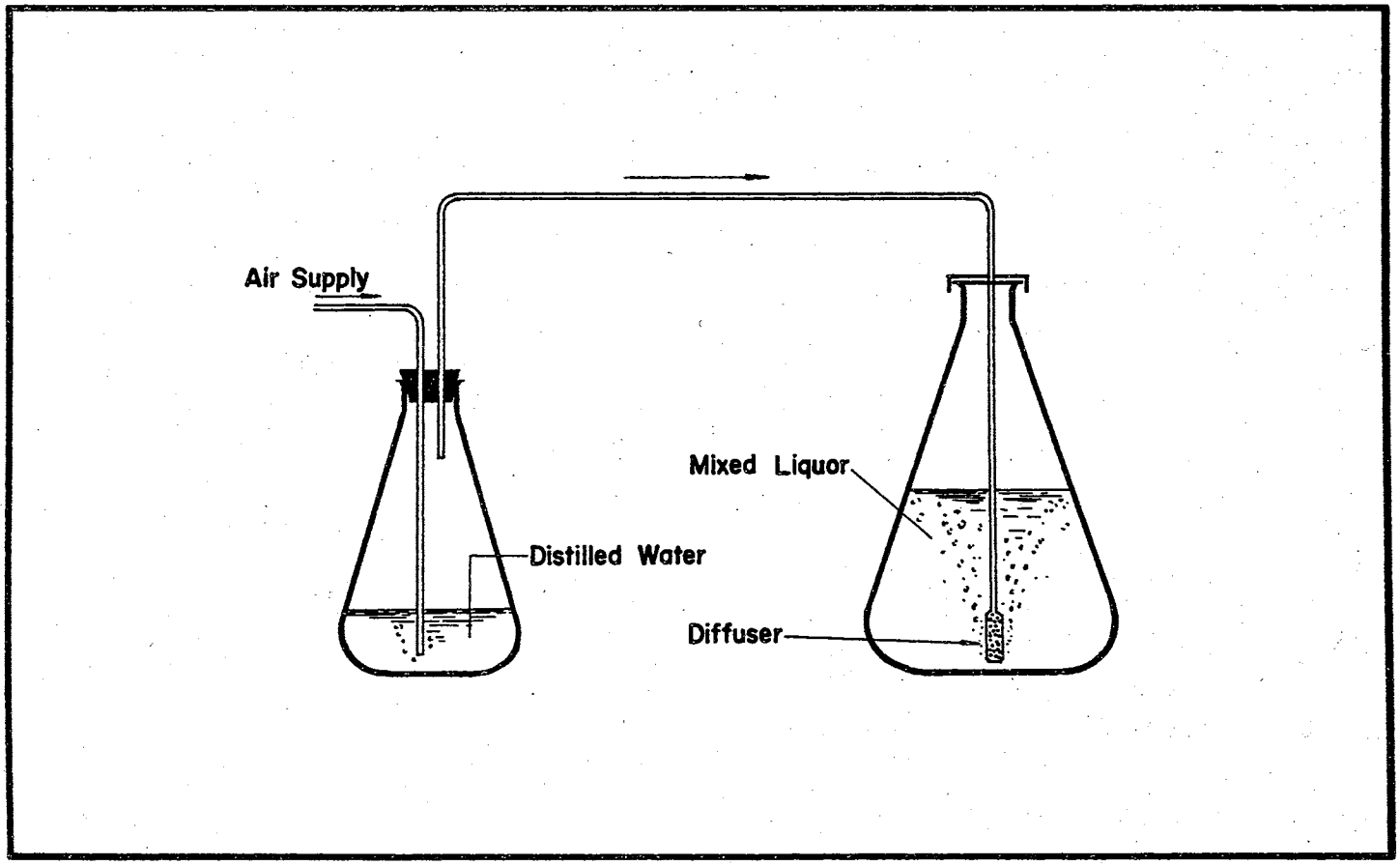

Figure 3. Experimental Set-Up for Shock Load Experiments with Low Initial Solids Concentration

2. Standard Synthetic Wastes

The synthetic waste, used in all experiments, consisted of glucose and other essential inorganic salts. The composition of the standard daily feed is given in Table I. In specific shock load experiments, higher glucose levels were employed, and the inorganic nutrients were increased proportionally. This was done in order to insure that the inorganic salts and buffer were in excess at all times and that the growth limiting factor was the carbon source (glucose). Tap water was added in order to provide trace elements.

TABLE I

COMPOSITION OF FEED FOR 500 MG/L GLUCOSE AS SUBSTRATE

Glucose	500 mg/l
$(NH_4)_2\ SO_4$	250 mg/l
$MgSO_4 \cdot 7H_2O$	50 mg/l
$Fe\ Cl_3$	0.25 mg/l
$Ca\ Cl_2$	3.75 mg/l
$Mn\ SO_4 \cdot H_2O$	5 mg/l
Phosphate Buffer, 1.0 Molar	
(KH_2PO_4, 52.7 gm/l + K_2HPO_4, 107 gm/l)	10 ml/l
Tap Water	100 ml/l

3. Procedure

The extended aeration unit was operated under both batch and continuous flow conditions. For batch-type operations, 23 hours of aeration and one hour of settling were allowed between successive

feedings. Samples of mixed liquor (15 ml) were taken daily at the end of 23 hours after feeding to determine the concentrations of suspended solids and chemical oxygen demand (COD). In order to reduce errors in sampling due to evaporation, the mixed liquor volume was brought to same level (at 9.4 liters) with distilled water before daily samples were taken. After sampling, the air supply was shut off and solids were allowed to settle. The solids were allowed to settle for one hour, after which a liter of supernatant was removed from the reactor and centrifuged, and the separated solids were returned to the aerator. The unit was then brought to aeration volume with one liter containing 9.4 times the concentration of each nutrient shown in Table I, and the aeration continued.

For continuous flow operation, feeding was regulated by a Milton Roy positive displacement pump. Feeding rate was adjusted to 24 hours over-all detention time, i.e., 17 hours in the aeration tank, and 7 hours in the clarifier. The feed solution, concentration as shown in Table I, was prepared in a 20-liter glass bottle. In order to prevent contamination in the feed reservoir, feed solution was prepared fresh each day. Daily samples were taken after the baffles were removed and solids in both chambers were allowed to mix thoroughly. When sampling was completed, baffles were put back and the normal operation was restored. The effluent from the unit was collected in a 20-liter glass carboy. At times when the continuous flow effluent exhibited a degree of turbidity (poor settling), the suspended solids carried over in the effluent were recovered by centrifugation (using a Sharples super speed centrifuge) and returned to the reactor, thus enabling positive control of sludge wastage regardless of the settling characteristics of the solids.

The pH of the mixed liquor was recorded at frequent intervals and the system was always maintained around neutral pH (6.5 to 7.2). When the pH of the mixed liquor showed considerable deviation, it was brought back to neutral value by adding alkali (NaOH) solution. The temperature of the system was maintained at room temperature (22 $\pm$ 2^{o} C).

B. Experimental Protocol

The experiments for this study were conducted in two phases:

(1) The development of "equilibrium" under batch operation and administration of shock loads of desired quantity and

(2) The development of "equilibrium" under continuous flow operation and administration of shock loads of the same magnitude as studied under batch operation.

Beginning on October 12, 1967, the unit employed for the shock load studies was operated under batch conditions and studies under Item 1 were conducted. On March 1, 1968, after studies under Item 1 were completed, continuous flow operation was again initiated and studies under Item 2 were undertaken.

1. Shock Load Studies Under Batch Operation Single Daily Feeding

In this part of the study, the extended aeration activated sludge unit was operated under batch conditions with once a day feeding as described in the preceding section. When the system approached an approximate equilibrium with respect to solids and COD concentration, the shock load experiments were conducted at both high and low initial biological solids concentrations.

Shock loads of 1000, 1500, 2000 and 2500 mg/l glucose were investigated. Before applying the desired shock load, a portion of the mixed liquor equivalent to the volume of shock load mixture to be added was

removed and centrifuged and the separated solids were put back into the reactor. The volume was then brought back to normal operating level with the desired shock load mixture. Samples were taken at zero time and at frequent intervals, usually every 15 minutes, until the substrate removal was almost complete.

In order to compare the effect of initial solids concentration in absorbing the shock load, experiments were also conducted at low initial solids concentration. Normally, the low initial solids experiments were conducted on the same day of the high solids experiment. The seed (10-15 ml) for conducting the low initial solids experiments was taken from the extended aeration reactor (prior to applying the shock load) and mixed with the synthetic waste containing the desired amount of glucose shock load. About 800 ml of this mixture was transferred to an Erlenmeyer flask (as shown in Figure 3) and aerated at the rate of 2000 cc/minute/liter of aeration volume. Twenty ml samples were taken at frequent intervals to study the rate of substrate removal and solids growth.

2. Shock Load Studies Under Continuous Flow Operation

When the experiments with batch-fed system were completed, the unit was operated with continuous addition of growth medium. Growth medium containing 500 mg/l glucose was used to obtain equilibrium conditions before shock loads were applied. To introduce shock loads into the system, the influent growth medium was changed to the desired level of glucose. Feeding at this new level was continued until a new "equilibrium" or a "steady-state" was established. During shock loads, 15 ml samples were taken periodically both from aeration and settling chambers to determine the solids concentration and COD. Sludge samples

of 5 ml were also collected simultaneously from the aeration chamber and stored in freezer for analyses on sludge composition. After sufficient data were collected at one shock load level, the feed was changed to the original glucose concentration (500 mg/l) and operated at this normal level for a few days (2-7 days). Then, the next higher level of shock load was applied. The above procedure was repeated until all of the shock load experiments (1000, 1500, 2000, and 2500 mg/l glucose media) were completed.

Before changing the feed concentration, i.e., administering a shock load, the waste inflow was momentarily turned off and the baffles were removed, allowing mixing of the solids in the aeration and settling chambers. All solids that appeared in the effluent bottle were collected by centrifugation, resuspended in a small amount of salt medium and returned to the aeration chamber. After the settling chamber wall was replaced and solids in settling chamber were well settled, the biological solids concentration in the aeration chamber was measured. Pumping of the feed at the desired shock load concentration was resumed, and sampling was begun to assess the transient behavior of the system during shock loads. Experiments with low initial solids concentration were also conducted simultaneously, as explained for batch fed system.

In addition to the studies mentioned above, the activity of the extended aeration sludge was frequently measured by conducting oxygen uptake experiments on washed cell suspension using Warburg respirometer. The "unit activity" was measured and expressed as milligrams of oxygen consumed per gram of washed cells per hour. The solids separated by centrifugation, from 20 ml of mixed liquor, were washed twice with 0.1 molar phosphate buffer and suspended in buffer solution before measuring

oxygen uptake. Forty ml of this suspension were placed in a Warburg flask and the oxygen uptake measurements were made at 25° C and 90 oscillations per minute. The remaining suspension was used to determine the solids concentration.

In shock load experiments conducted with low initial solids concentration, the carbohydrate content of the filtrate was also measured. Samples taken during shock load experiments were filtered through Millipore filter (pore size 0.45μ) and 10 ml of the filtrate was used to determine COD. The remainder of the filtrate was frozen in vials until analyses for carbohydrates were made.

C. Analytical Methods

The chemical oxygen demand (COD) test was employed to determine the total organics present in solution. The COD determinations were made in accordance with the Standard Methods (60). The carbohydrate content of the filtrates was measured using the anthrone test (61). The anthrone test was run in order to obtain information on the possible release of metabolic intermediates during the metabolism of glucose. This was accomplished by comparing the results of filtrate COD and filtrate carbohydrate on identical samples.

The biological solids concentration in the mixed liquor and effluent were determined by the membrane filter technique (Millipore Filter Co., Bedford, Mass., HA 0.45 μ) as outlined in Standard Methods (60). Aluminum dishes were used to hold the Millipore filters. Filters were dried for two hours at 103° C and equilibrated in a desiccator prior to obtaining the tare weight. Before final weighing, the same drying and cooling procedures were followed.

The protein and carbohydrate contents of the sludge were also measured in some experiments using the biuret and anthrone test respectively (61).

Oxygen utilization rate was measured in Warburg respirometer using a reaction mixture of 40 ml and 1.5 ml 20 per cent KOH in the center well. The system was maintained at 25^{o} C with 90 oscillations/minute. A ten-minute equilibration period was allowed before the manometers were closed. Dissolved oxygen concentration in the aeration and the settling chambers was measured periodically by the galvanic cell oxygen analyser in accordance with the procedures given in the operating instructions supplied with the instrument (62).

CHAPTER IV

RESULTS

The results obtained from this investigation are presented in the following order: (A) general performance of the system with normal feed (500 mg/l glucose media) under batch and continuous flow operation prior to initiating any shock load, (B) performance of the system to shock loads during batch operation, (C) performance of the system to shock loads during continuous flow operation, and (D) results of a study on sludge composition, effluent biological solids and unit activity of the sludge during the period of this investigation. Experiments under sections (B) and (C) were conducted for both high and low initial solids concentration.

A. Performance of the System Prior to Applying any Shock Load

The daily performance of the system fed with 500 mg/l glucose under both batch and continuous flow operations is shown in Figure 4. The system was operated under batch conditions for 45 days before shock loadings were administered. The same procedure was done for the continuous flow conditions in which the system was fed continuously at the same feed concentration for 23 days before applying shock loads. Even though the continuous flow study followed that under batch conditions, they are shown in the same figure for comparative purposes. No sludge was wasted throughout the experimental period, however, a small amount was taken each day (15 ml or 0.16 per cent of the aeration volume) for

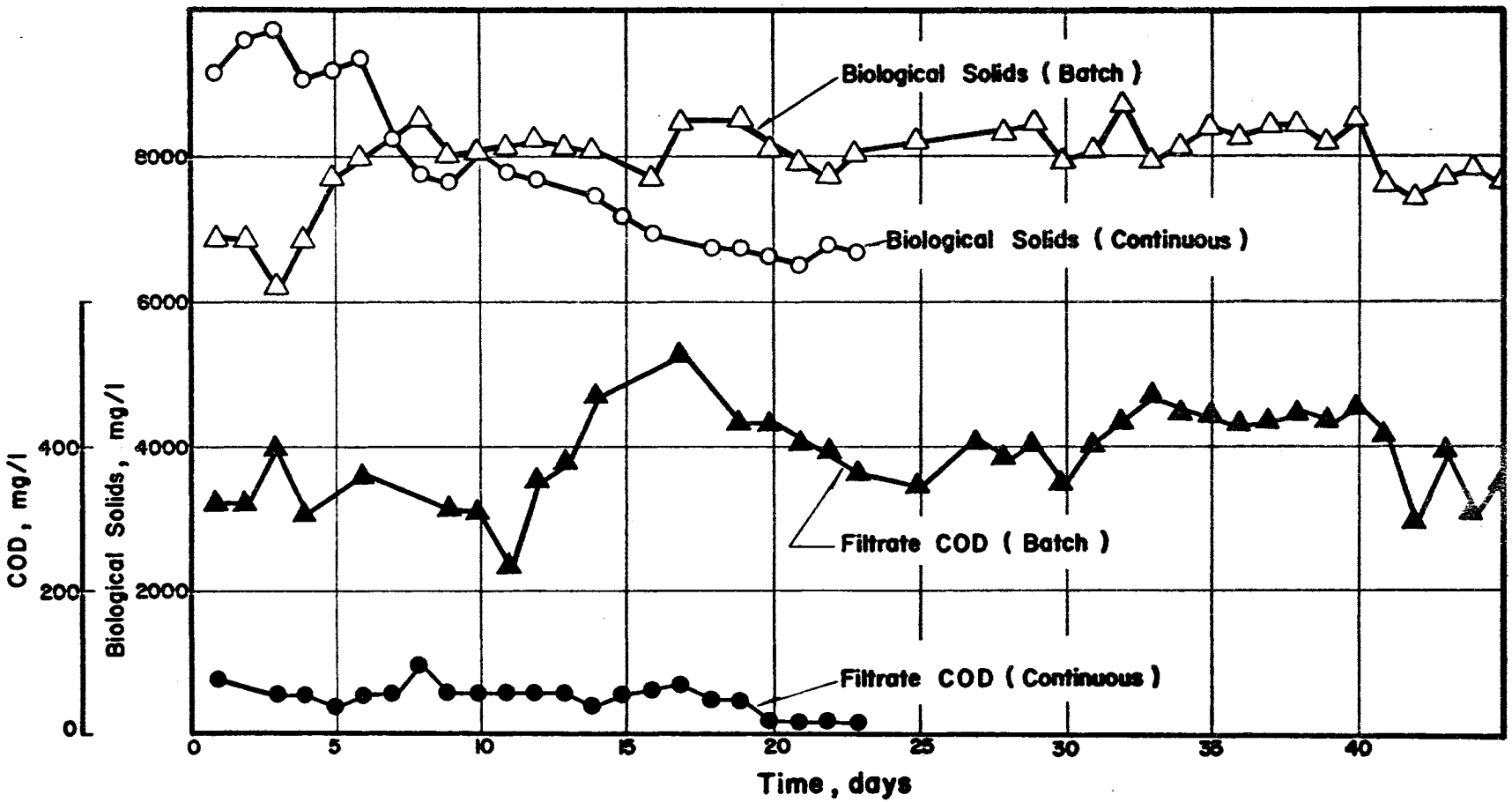

Figure 4. Biological Solids and Effluent COD Concentration in an Extended Aeration Process Under Batch and Continuous Flow Operation. Normal Feed = 500 mg/l Glucose; No Shock Loading Applied

analyses. In the batch system, the sample was taken at the end of the 23-hour aerattion period after feeding. For the continuous flow system, samples were normally taken at every 24 hours. The age of sludge was 196 days when batch operation was started and it was 336 days for continuous flow operation. It can be seen from Figure 4 that both the concentrations of biological solids and filtrate COD remained at higher values in the batch system than in the continuous flow system. During the early part of the batch operation the solids level raised rapidly from approximately 6800 mg/l to about 8500 mg/l, thereafter the solids fluctuated around 8000 mg/l. It is interesting to note that the system was formerly operated for 203 days as a continuous flow system. Then it was divided into two units in which one of them was used to conduct these experiments. Even though the concentration in the feed was halved, the organic loading per unit weight of solids was the same as before. When the shock load experiments under batch operation were completed, the system was again allowed to obtain "equilibrium" under continuous flow operation with the synthetic waste containing 500 mg/l glucose substrate. It can be seen from Figure 4 that the solids as well as COD concentration decreased during continuous flow operation and reached a new "equilibrium" at lower values than during batch operation. Though only a limited amount of information was gathered during this part of the investigation, it can be said thatthe continuous flow extended aeration process performed more satisfactorily than did the batch-fed system. The mean biological solids concentration of the batch system was 8000 mg/l. In the continuous flow system biological solids concentration decreased from the maximum value of 9750 mg/l to the minimum value of 6500 mg/l during the 23 days of operation and remained

fairly constant around 7000 mg/l thereafter with a mean value of 7800 mg/l. The mean filtrate COD concentrations differed by a considerable amount; they were, respectively, 396 and 47 mg/l for batch and continuous flow operations. The average organic loadings employed were 0.062 and 0.064 lbs COD/lb SS/day for batch and continuous systems respectively.

In order to investigate the over-all performance of the system during the period of the administration of shock loads, daily samples from the unit were also collected in addition to those taken during the transient periods. Figure 5 shows the performance of both batch and continuous flow systems when shock loads were applied. The days on which shock loads were applied are indicated by arrows in Figure 5 and the labeled numbers indicate the magnitude of each shock load. A detailed analyses of responses to individual shock load are shown in subsequent figures. "Day zero" on Figure 5 on the time scale corresponds to the last day plotted for each system in Figure 4. Thus, the unit operated as a batch system for a total period of 118 days, and as a continuous flow system for 77 days during the experimental period. However, it is relevant to point out that the sludge was almost one year old before these experiments were initiated, having been developed under continuous flow conditions without cell wastage. It can be seen from the figure that the system performance was not adversely affected by the series of shock loads which represent an increase in carbon source up to five times (from 500 mg/l glucose to 2500 mg/l glucose). The average daily performance, before and after shock loads were applied, was relatively constant, i.e., within the normal fluctuations in the system parameters (compare Figures 4 and 5). However, during batch operation, the biological solids concentration showed an increase (Figure 5) while

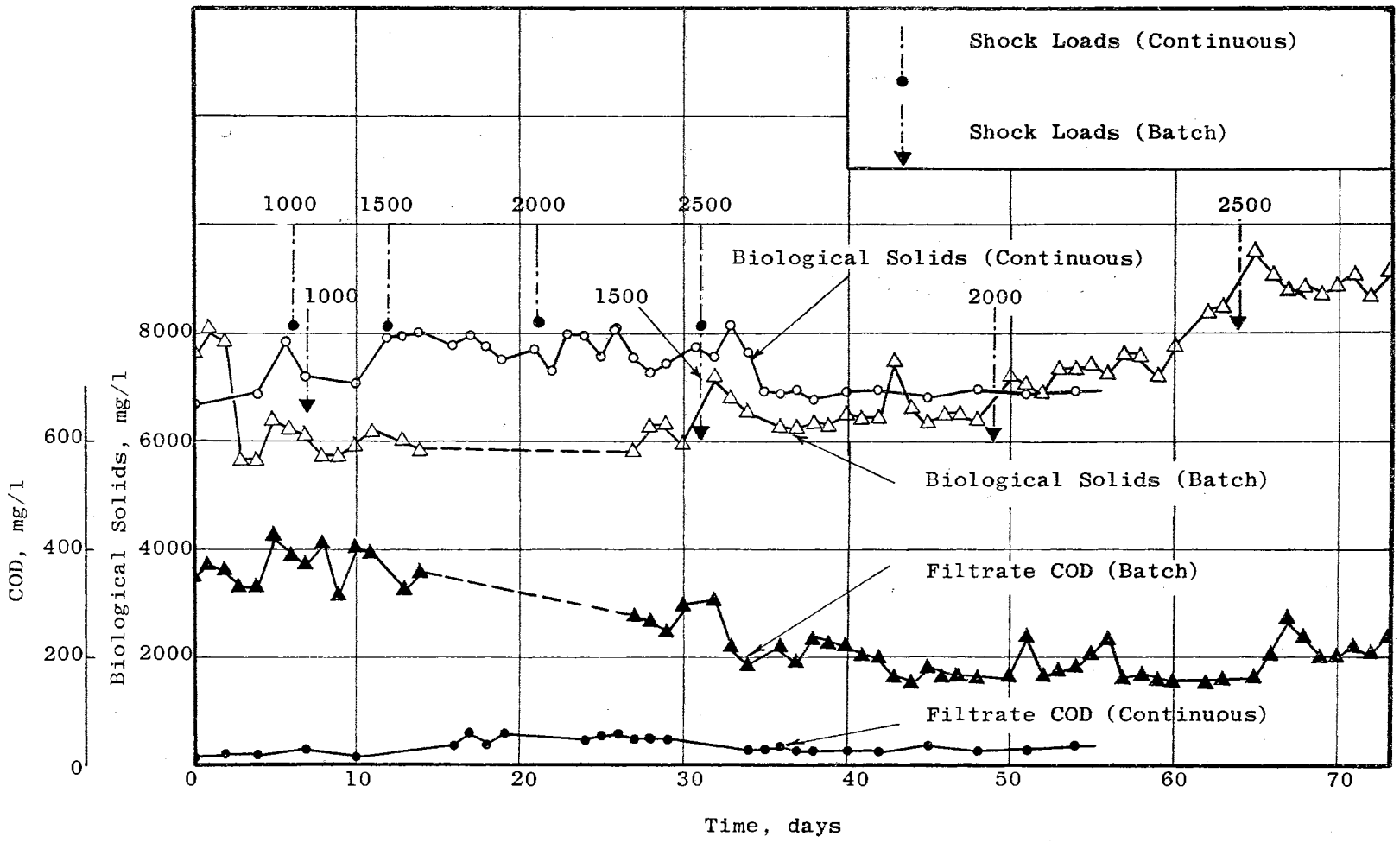

Figure 5. Biological Solids and Effluent COD Concentration in an Extended Aeration Process under Batch and Continuous Flow Operation. Normal Feed = 500 mg/l Glucose; Shock Loadings Applied as Indicated

the COD level did not. In continuous flow system neither the biological solids concentration nor the COD value showed an increase. As it has been previously mentioned, the continuously operated system performed better than the batch-fed system with respect to over-all effluent quality. The filtrate COD of the effluent from the continuous-flow system never exceeded 60 mg/l even under the highest value of shock load (2500 mg/l) applied during this investigation. The COD values of the unfiltered effluent were generally 50 to 80 mg/l higher than the filtrate COD, attesting to the generally good settling characteristics of the sludge. At times when poor settling of sludge was encountered the unfiltered effluent COD was considerably in excess of this range. This condition occurred when the shock load was increased to 2000 mg/l glucose. It is important to re-emphasize that the solids lost in the effluent were collected and returned to the aeration tank. In general, sludge settleability was as good or better than experienced with conventional activated sludge process.

B. Responses to Shock Loads Under Batch Operation

The transient responses of the extended aeration activated sludge, under batch operation, to various shock loads are shown in Figures 6 through 9. This series of experiments on quantitative shock loads was conducted directly in the unit (high initial solids) and in a separate system with low initial solids concentration.

Figure 6A shows the response of the batch-fed extended aeration sludge when the system was shock loaded with 1000 mg/l glucose. There was a rapid decrease in COD concentration and in 75 minutes it attained a terminal value of approximately 400 mg/l, which is consistent with the rather high residual COD concentration seen in Figures 4 and 5 under

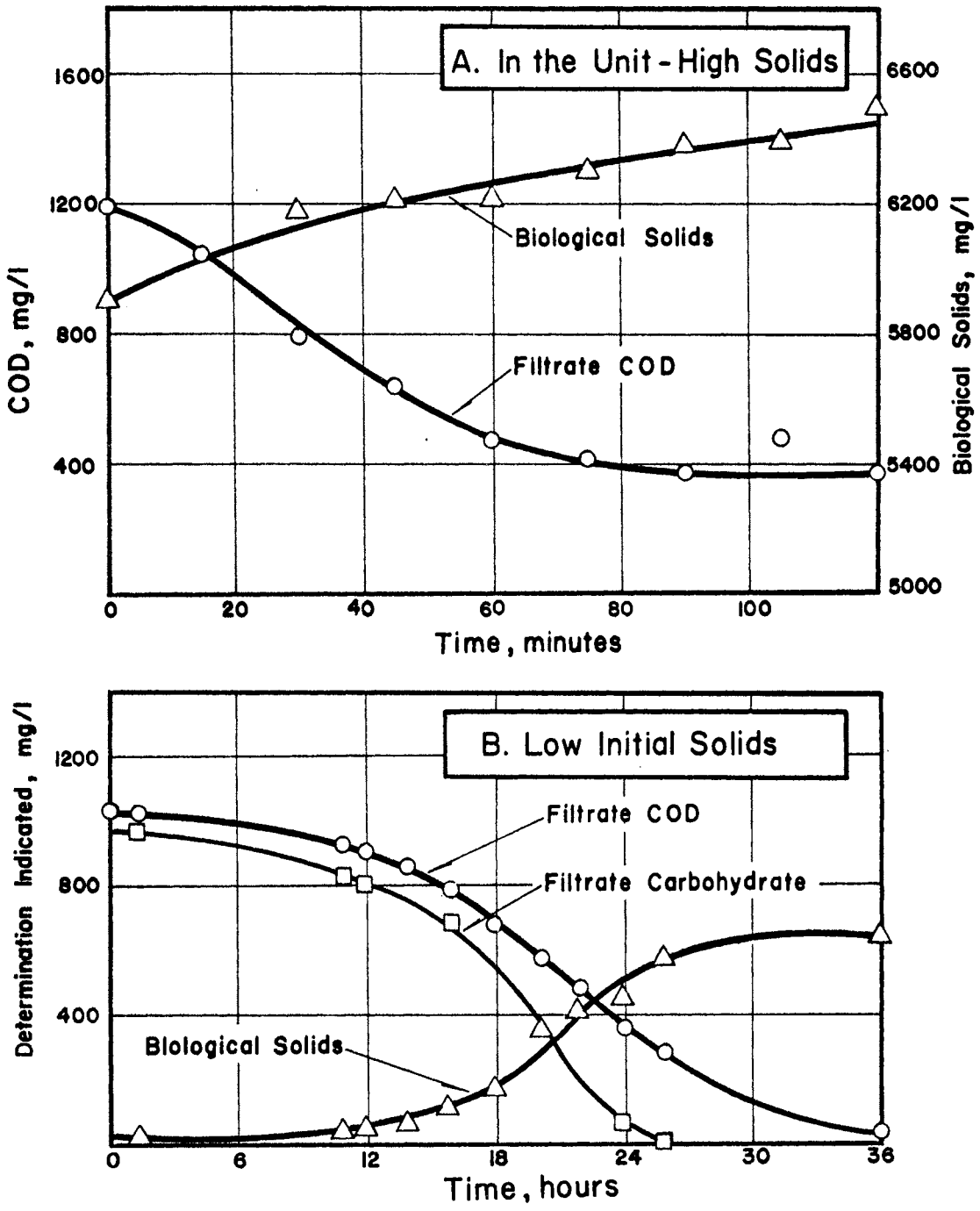

Figure 6. Response of Batch-Operated Extended Aeration Activated Sludge to Quantitative Shock Loading with 1000 mg/l Glucose

batch operation. The decrease in COD was accompanied by a corresponding increase in biological solids concentration (from 5900 mg/l to 6500 mg/l).

The response of the same sludge, at low initial solids concentration, to 1000 mg/l glucose shock is shown in Figure 6B. It can be seen from the figure that glucose COD was reduced from the initial value of 1000 mg/l to 40 mg/l in 36 hours. It took almost 12 hours before any appreciable removal of COD could occur. This is due to the low inoculum of solids (35 mg/l) used in this experiment. The solids concentration rose up to 650 mg/l at the end of the experiment. The carbohydrate curve indicates that a maximum of 300 mg/l metabolic intermediates and/or end products were produced during glucose metabolism, and a large portion of these products was subsequently utilized.

When the shock load concentration was increased to 1500 mg/l glucose, the applied COD was rapidly reduced to pre-shock conditions (approximately 275 mg/l) attesting to the ability of the system for assimilation of the shock load (see Figure 7A). The rapid removal of COD was also accompanied by an increase in solids concentration from 6550 to approximately 7850 mg/l.

The results obtained from a separate batch system with low initial solids concentration are shown in Figure 7B. In general the response of the system was similar to that obtained under 1000 mg/l glucose shock. Analysis for filtrate carbohydrate indicated that very little, if any, metabolic intermediates and/or end products were released during the assimilation of 1500 mg/l glucose. Because of the higher initial solids concentration (130 mg/l) used in this experiment, the lag time was lower (8 hours) than that with 1000 mg/l glucose shock load. The COD value decreased from 1440 mg/l at zero time to 200 mg/l at the end of 27 hours.

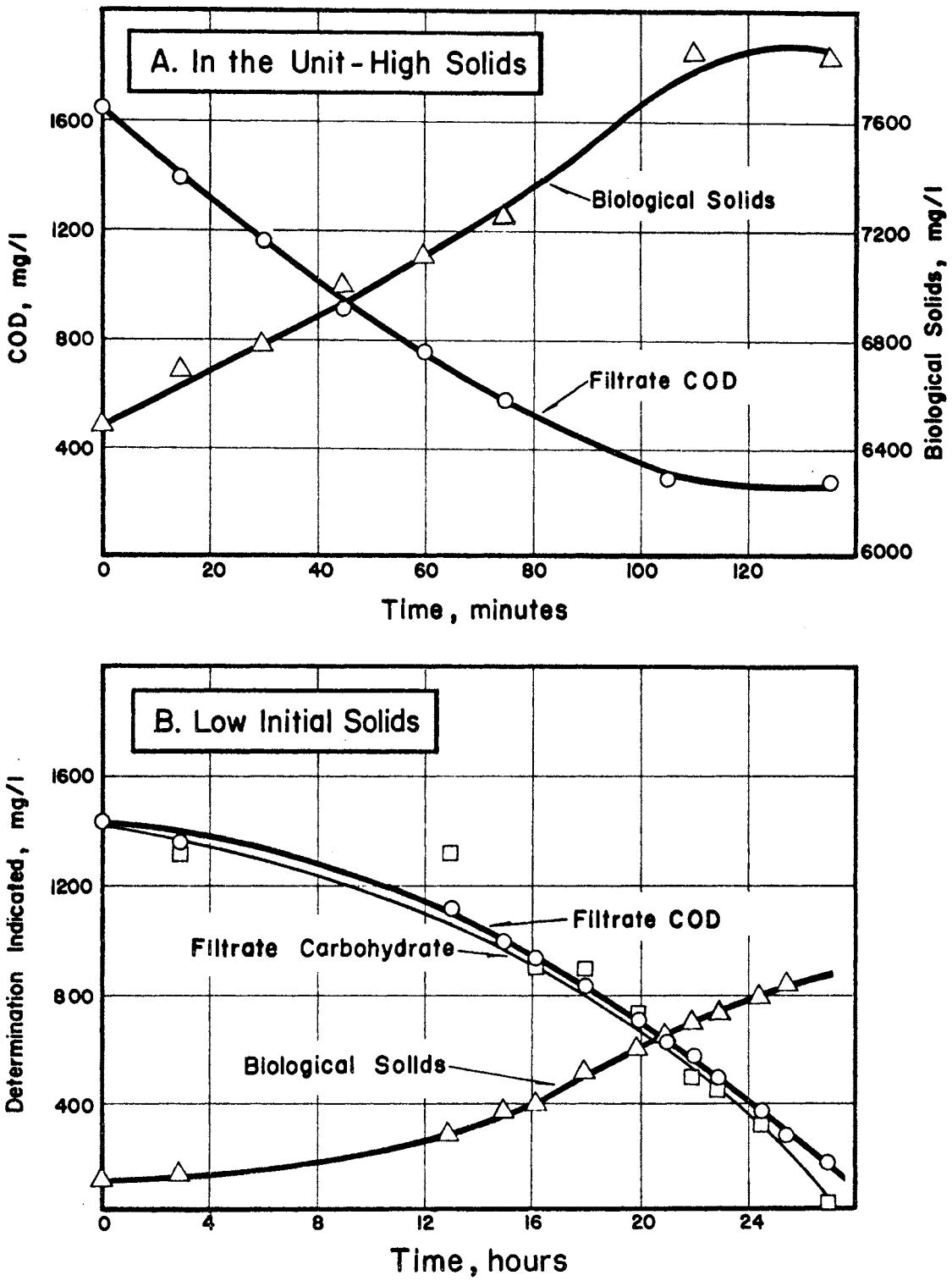

Figure 7. Response of Batch-operated Extended Aeration Activated Sludge to Quantitative Shock Loading with 1500 mg/l Glucose

The biological solids concentration increased to 850 mg/l at the termination of the experiment.

Figure 8 shows the shock load response of the system to 2000 mg/l glucose. It can be seen from Figure 8A that the initial COD of 1950 mg/l was reduced to 300 mg/l in approximately 160 minutes. The observed COD value (300 mg/l) at the termination of the experiment was higher than the COD value prior to applying the shock load (166 mg/l). However, the residual COD dropped to 166 mg/l at the end of 24 hours after applying the shock load. The biological solids concentration increased from 6700 mg/l to 8000 mg/l during the shock load and dropped back to 7250 mg/l at the end of 24 hours. Figure 8B shows the response of the same sludge, at low initial solids concentration, to 2000 mg/l of glucose. Approximately 32 hours were required to utilize the entire COD at this initial solids concentration (200 mg/l). It can also be seen that metabolic intermediates, which were subsequently utilized, were produced during the removal of glucose. At this shock load, the color of the mixed liquor changed from brown to dark brown and remained dark thereafter.

Figure 9 shows the results of the shock load experiment with the highest concentration of glucose used in this study, i.e., 2500 mg/l glucose which represents a five-fold increase in the concentration of substrate. It can be seen from Figure 9A that the system still responded successfully. The COD in the system was removed rapidly from the initial value of 2450 mg/l to approximately 200 mg/l within 120 minutes. The biological solids increased from 8200 mg/l at zero time to around 9600 mg/l at the end of the experiment (160 minutes). The response of the same sludge, at low initial solids concentration, is

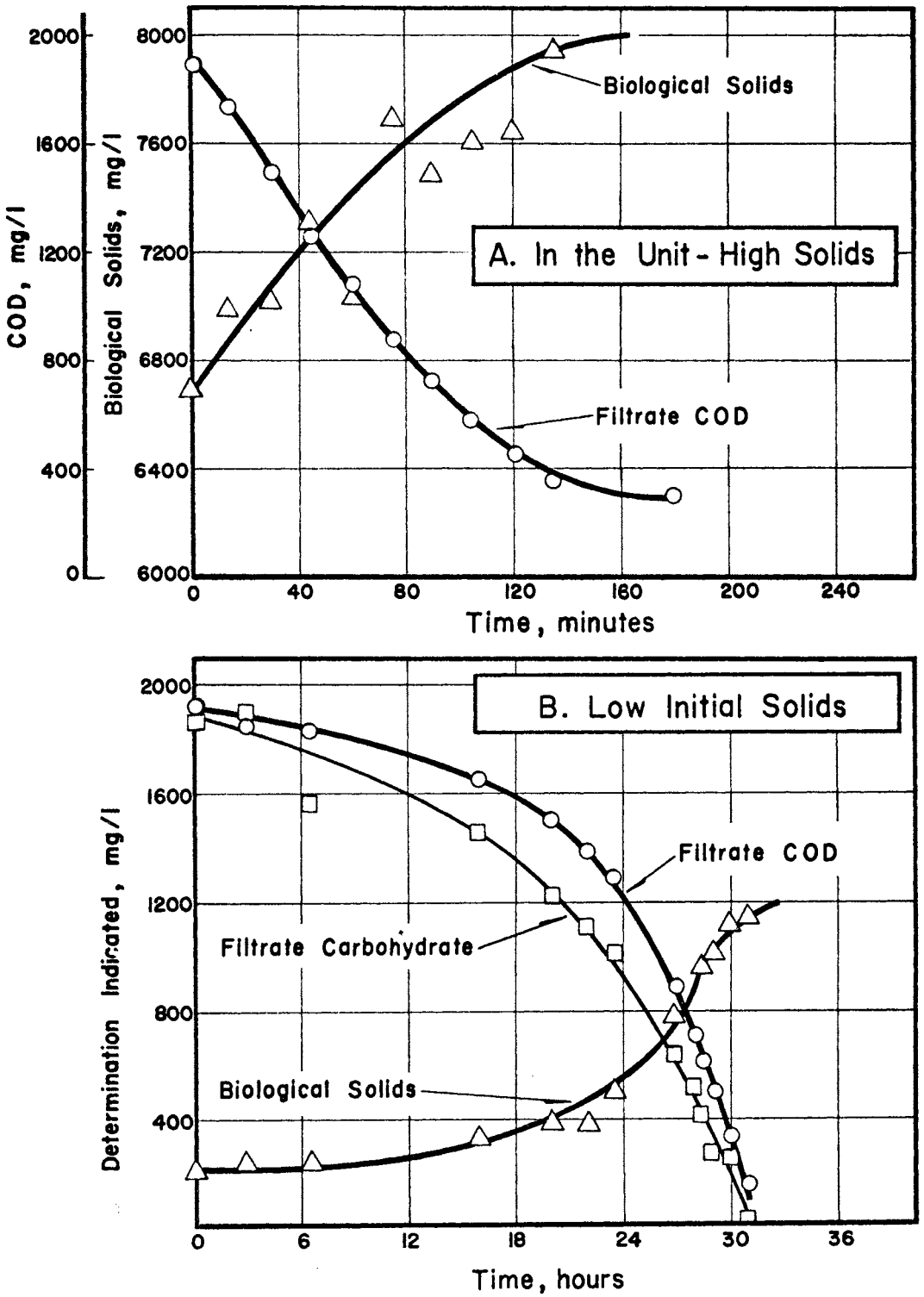

Figure 8. Response of Batch-operated Extended Aeration Activated Sludge to Quantitative Shock Loading with 2000 mg/l Glucose

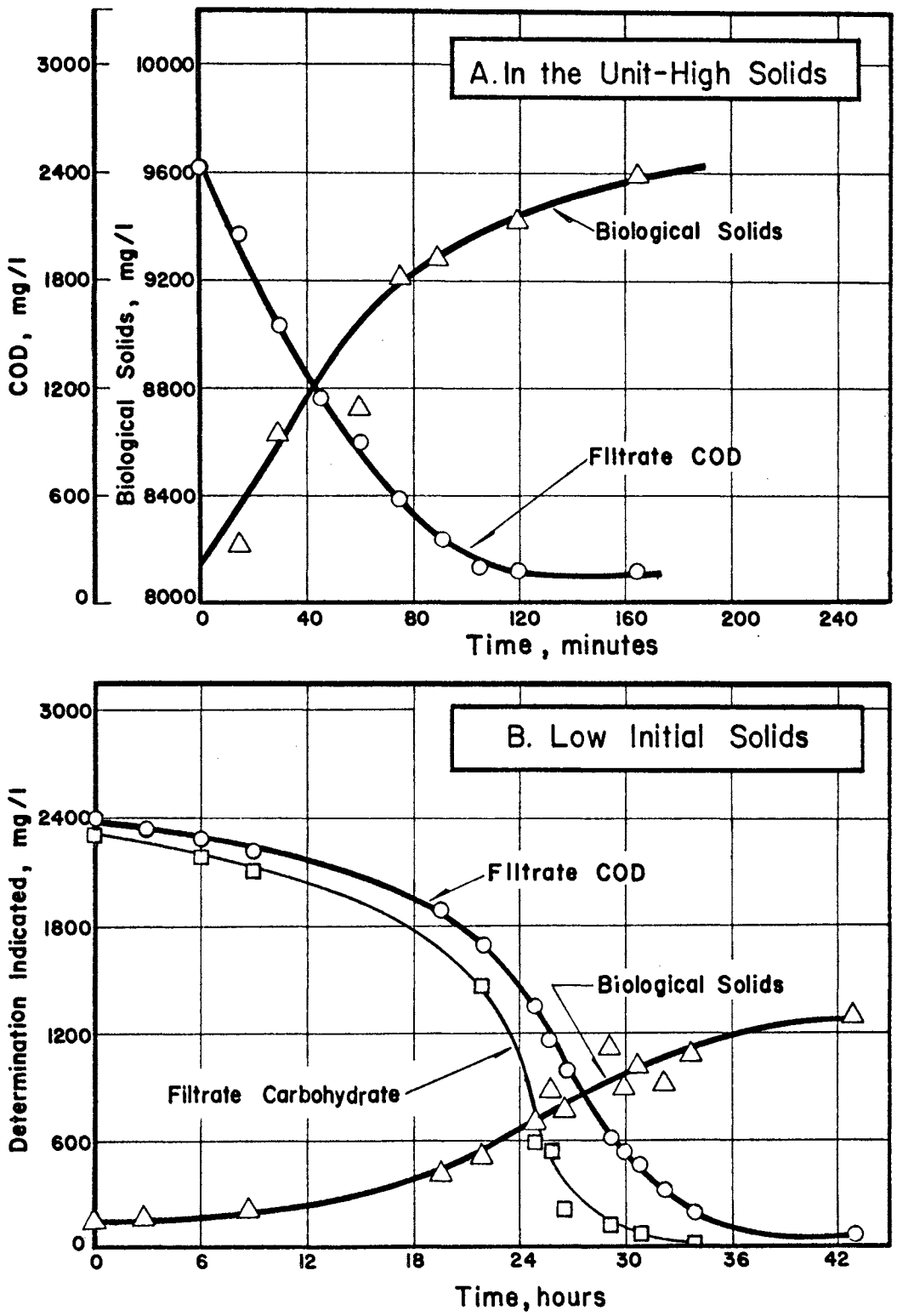

Figure 9. Response of Batch-operated Extended Aeration Activated Sludge to Quantitative Shock Loading with 2500 mg/l Glucose

shown in Figure 9B. It can be seen that the COD concentration decreased from an initial value of 2400 mg/l to around 80 mg/l in 40 hours. The biological solids concentration increased from 150 mg/l to approximately 1300 mg/l in 42 hours. The filtrate COD and the filtrate carbohydrate curves indicate that approximately 600 mg/l of metabolic intermediates and/or end products were released during this shock load but they were subsequently utilized during the terminal phase of the experiment.

When the shock load concentration was increased beyond 2000 mg/l glucose, a drop in the pH value from the neutral point to 6.3 was also noted. However, the pH was later brought back to neutral point with 20 per cent NaOH during the next feeding. Another characteristic change observed, when the shock load was increased to 2000 mg/l glucose, was occurrence of foaming. The sludge settleability was also poor at this shock load and the supernatant became turbid. However, the solids removed with the supernatant were recovered by centrifugation and returned to the system, thus insuring positive control on sludge wastage.

C. Responses to Shock Loads Under Continuous Flow Operation

The second series of experiments on quantitative shock loads were conducted under continuous flow condition. The shock loads were applied by changing the feed to desired concentrations of glucose media. The over-all detention time was kept at 24 hours for all continuous-flow experiments, and the magnitudes of shock loads were kept at the same value as for batch-fed system. For the continuous-flow experiments the composition of sludge, i.e., the protein and carbohydrate content of sludge were also measured in order to investigate the variations in cellular composition during shock loads. Biological solids concentration in the effluent was also determined to measure the effect of shock

load upon the settling characteristics of sludge.

Figure 10A shows the response of the continuous flow extended aeration sludge to gradual shock loading when the influent waste was changed from 500 mg/l to 1000 mg/l glucose. It can be seen that this shock load has essentially no effect on the performance of the system. There was little or no change in biological solids concentration and no interference of substrate removal efficiency. The results of a separate batch experiment for low initial solids concentration are shown in Figure 10B. The COD value decreased from 1000 mg/l to 30 mg/l in approximately 23 hours. The biological solids increased from an initial value of 220 mg/l to approximately 700 mg/l after 26 hours. No significant quantity of metabolic intermediates and/or end products were released during this experiment.

Figure 11A shows the response of the system to 1500 mg/l glucose shock load. It can be seen from the figure that the system responded successfully to this shock load. Neither the solids concentration nor the COD showed an increase even after 40 hours. The COD value (Figure 11A) remained steady at approximately 35 mg/l. From Figure 11B, it can be seen that the response of the same sludge at low initial solids concentration showed no significant difference from that observed under 1000 mg/l glucose shock load. Approximately 200 mg/l of metabolic intermediates and/or end products were released during the metabolism of glucose and were then subsequently utilized by microorganisms. In approximately 24 hours the entire COD fed was almost removed.

Figures 12 and 13 show results for similar experiments when the sludge was subjected to shock loads of 2000 and 2500 mg/l glucose, respectively. It can be seen from Figure 12A that, at 2000 mg/l glucose

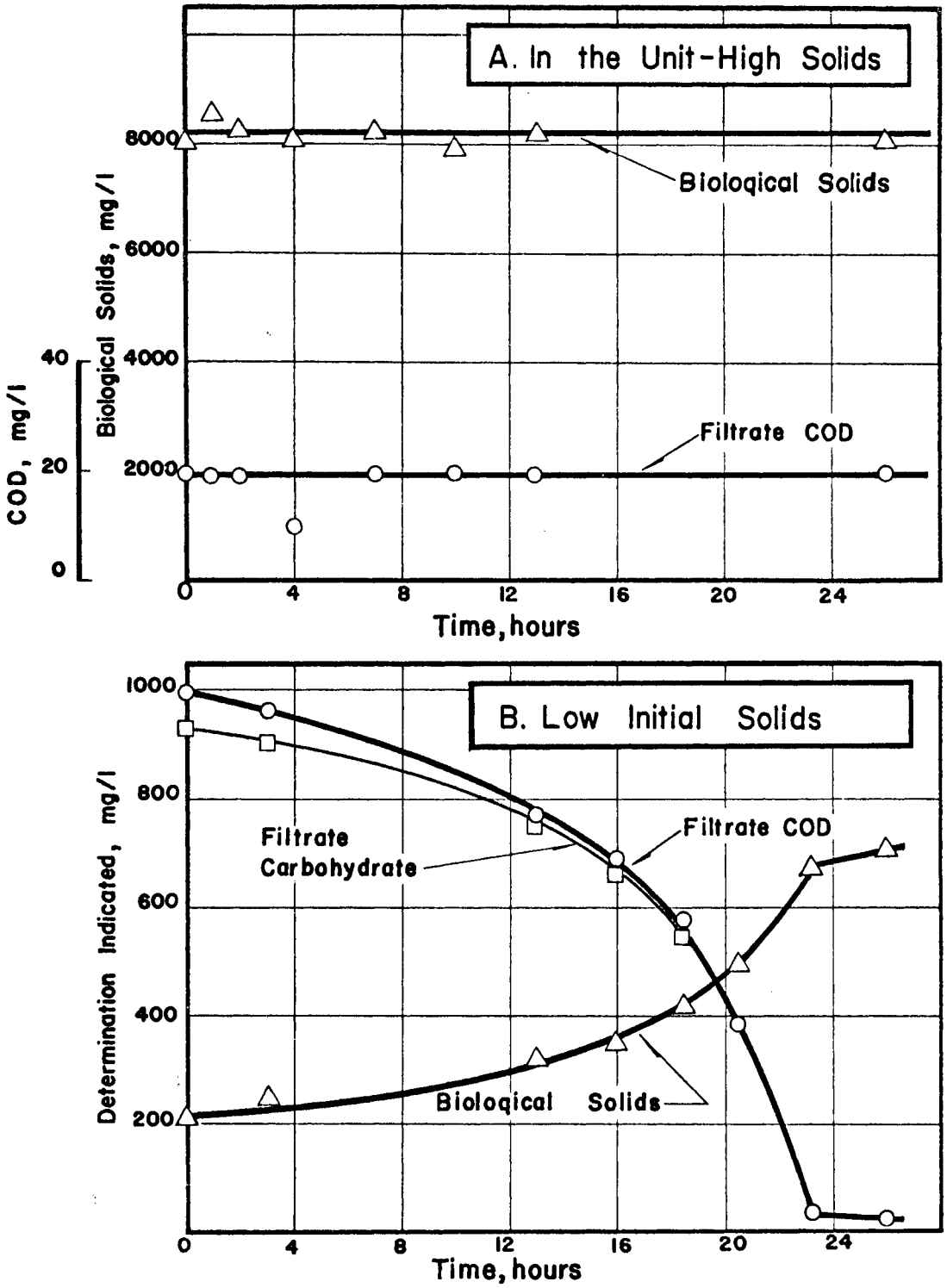

Figure 10. Response of Continuous Flow Extended Aeration Activated Sludge to Quantitative Shock Loading Applied as an Increase in Feed Concentration from 500 to 1000 mg/l Glucose

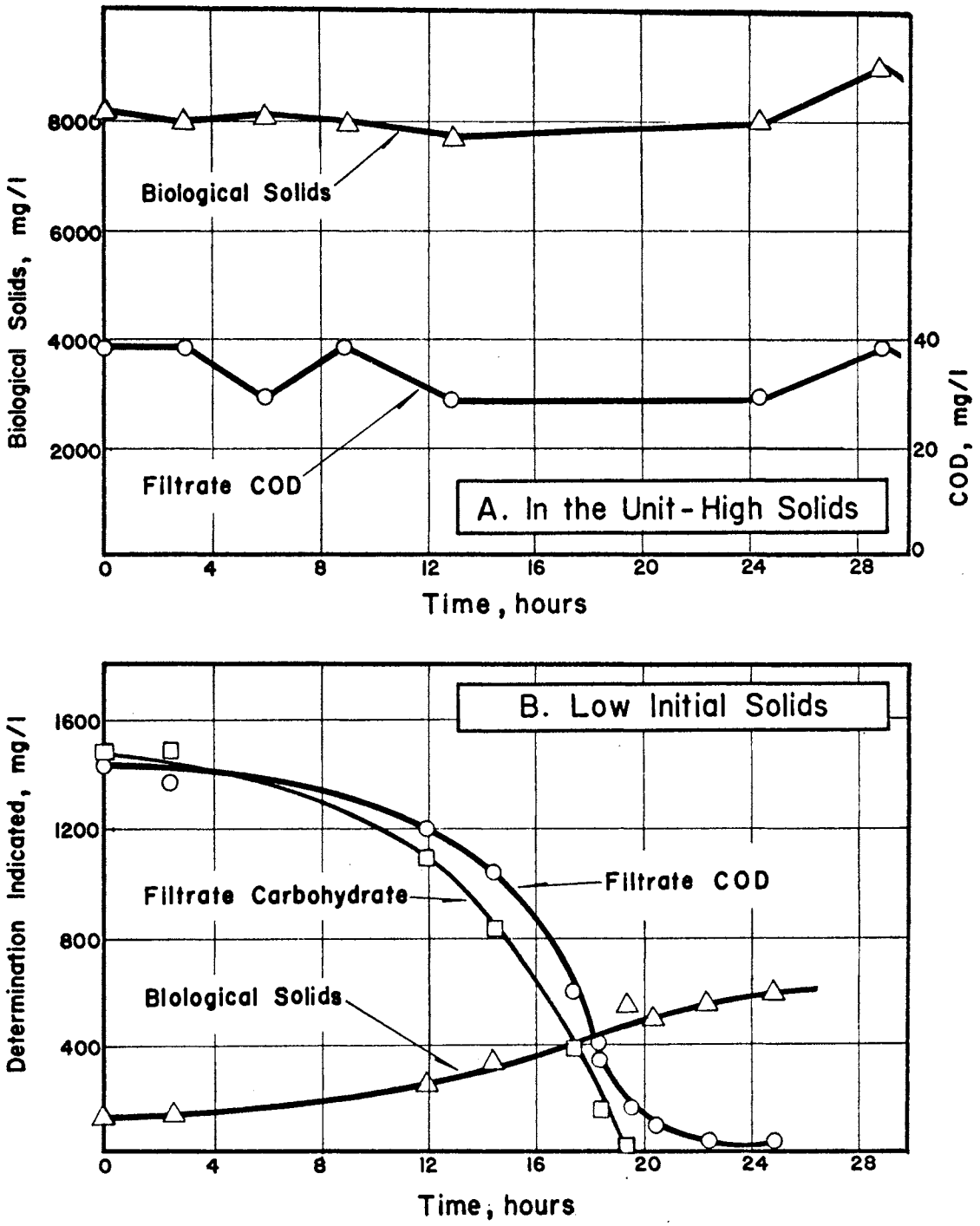

Figure 11. Response of Continuous Flow Extended Aeration Activated Sludge to Quantitative Shock Loading Applied as an Increase in Feed Concentration from 500 to 1500 mg/l Glucose

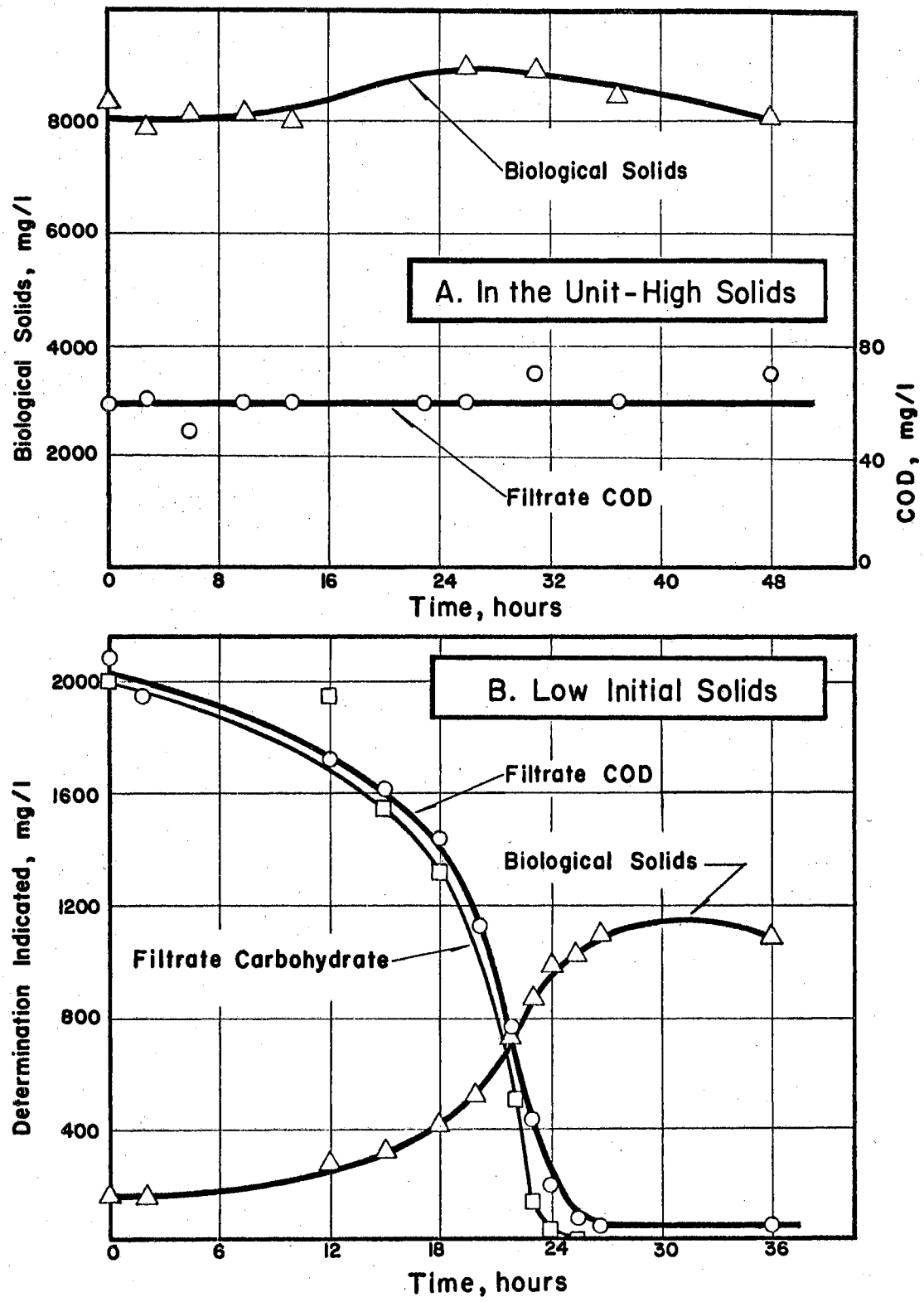

Figure 12. Response of Continuous Flow Extended Aeration Activated Sludge to Quantitative Shock Loading Applied as an Increase in Feed Concentration From 500 to 2000 mg/l Glucose

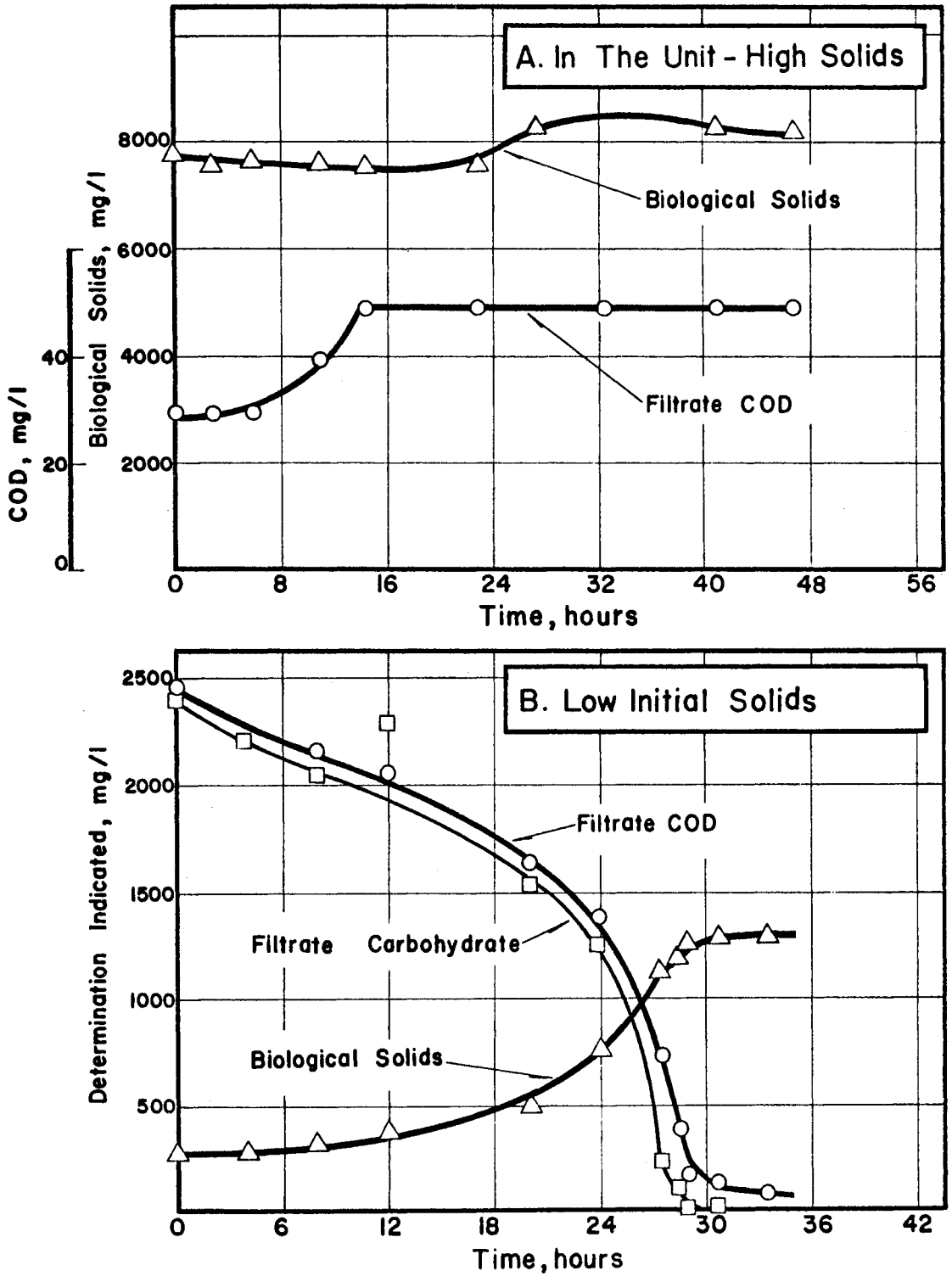

Figure 13. Response of Continuous Flow Extended Aeration Activated Sludge to Quantitative Shock Loading Applied as an Increase in Feed Concentration from 500 to 2500 mg/l Glucose

shock load, an increase in the biological solids concentration was observed (from approximately 8000 mg/l to 9000 mg/l). However, the COD of the mixed liquor remained low (60 mg/l) during the entire period of shock load. Within 48 hours the biological solids concentration returned to its pre-shock load level of 8000 mg/l. Figure 12B also shows that there was no significant retardation in the removal of COD at low initial solids concentrations. The glucose COD was removed from 2000 mg/l to about 60 mg/l and the biological solids increased from the initial value of 155 mg/l to approximately 1100 mg/l in 27 hours. The COD and carbohydrate curves indicate no or very little release of intermediates at 2000 mg/l glucose shock.

When the shock load was increased to 2500 mg/l glucose (Figure 13A) both biological solids and filtrate COD concentration showed an increase. However, the increase in filtrate COD was not significant (from only 30 to 50 mg/l). Biological solids concentration increased from 7400 to about 8500 mg/l. Figure 13B shows the response of the same sludge with low initial solids concentration. The COD value decreased from 2450 mg/l to about 190 mg/l in 33 hours of aeration with a corresponding increase in biological solids concentration from 280 mg/l to approximately 1300 mg/l. Presence of intermediates (about 200 mg/l) was also observed at this shock load.

D. Results of a Study on Sludge Composition, Effluent Solids, Unit Activity and Specific Substrate Utilization Rate

Even though the studies conducted in this research are concerned more with the biochemical efficiency of the sludge to shock loads, it is appropriate to present some of the observed changes in sludge characteristics and the change in effluent biological solids during the

period under study. It was believed that an investigation of the changes in the biochemical composition of the cells and a measure of their activity may be of considerable value in analyzing the observed responses to shock loads. In the second series of experiment or in the shock loads experiments under continuous flow operation, cells harvested from the aeration chamber during the shock load period were analyzed for protein and carbohydrate contents. Figures 14 and 15 show the results of sludge composition, expressed as a percentage of dry weight, and effluent biological solids concentration obtained during shock loads. It can be seen from Figure 14A that at 1000 mg/l glucose shock load all parameters remained relatively constant throughout the experimental period. Protein and carbohydrate content of cells were approximately 50 and 26 per cent respectively. The mean effluent biological solids concentration was approximately 50 mg/l. At 1500 mg/l glucose shock load (Figure 14B), the biological solids concentration in the effluent showed a slight increase from an initial value of 60 mg/l to 180 mg/l after 40 hours. The mean protein and carbohydrate content of sludge were around 55 and 28 per cent respectively. When the shock load concentration was increased above 2000 mg/l glucose (Figure 15), the carbohydrate content of sludge showed no significant change. It remained fairly constant at about 25 per cent. However, the mean protein content of sludge, during 2000 and 2500 mg/l glucose shock loads, was higher than that during 1000 and 1500 mg/l glucose shock loads. They were, respectively, 58 and 63 per cents. The effluent biological solids concentration remained fairly constant at pre-shock load level indicating that the settling characteristics of the sludge were not adversely impaired during these shock loads. The mean values of

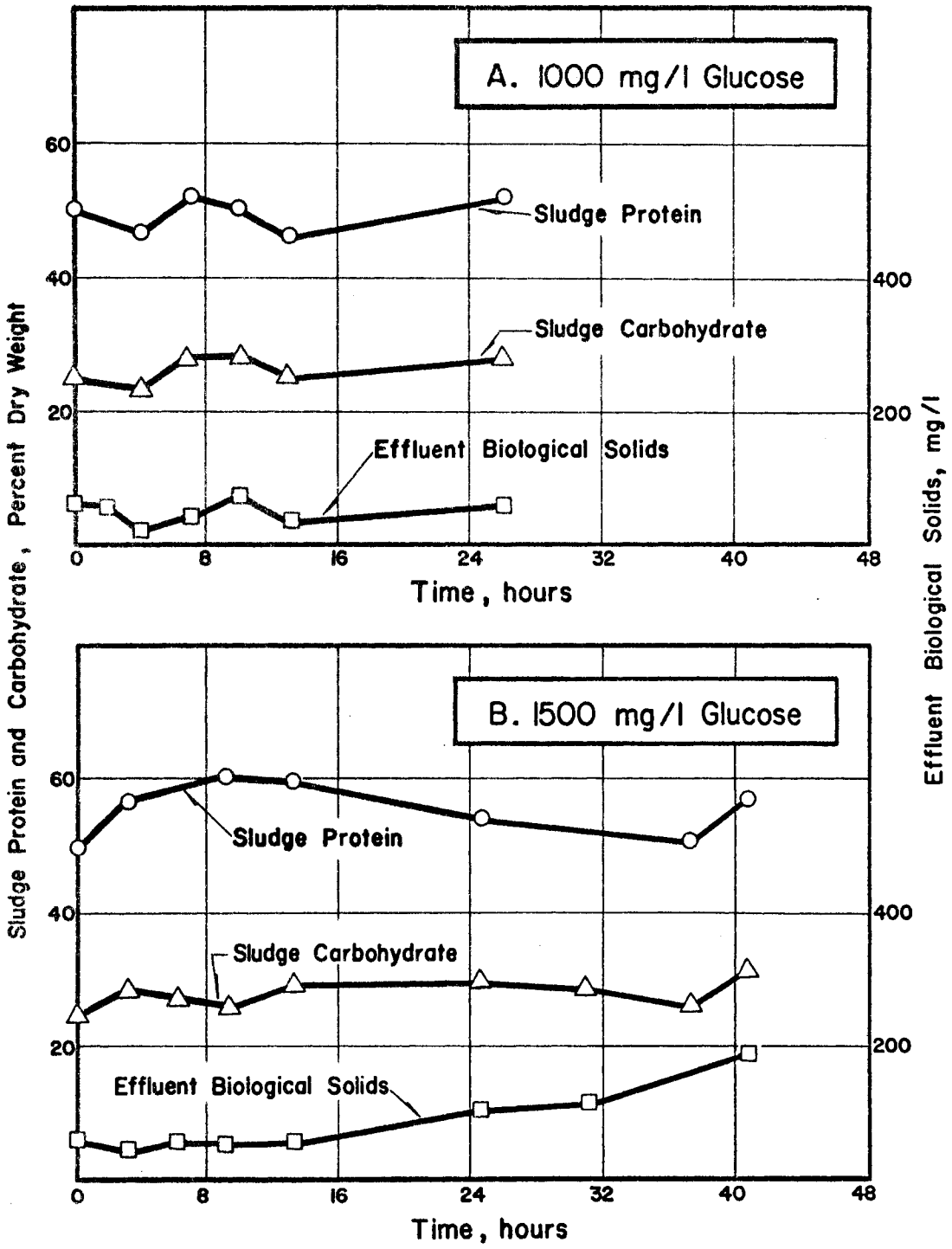

Figure 14. Effect of 1000 and 1500 mg/l Glucose Shock Loads on Effluent Solids and Sludge Composition (Continuous Flow)

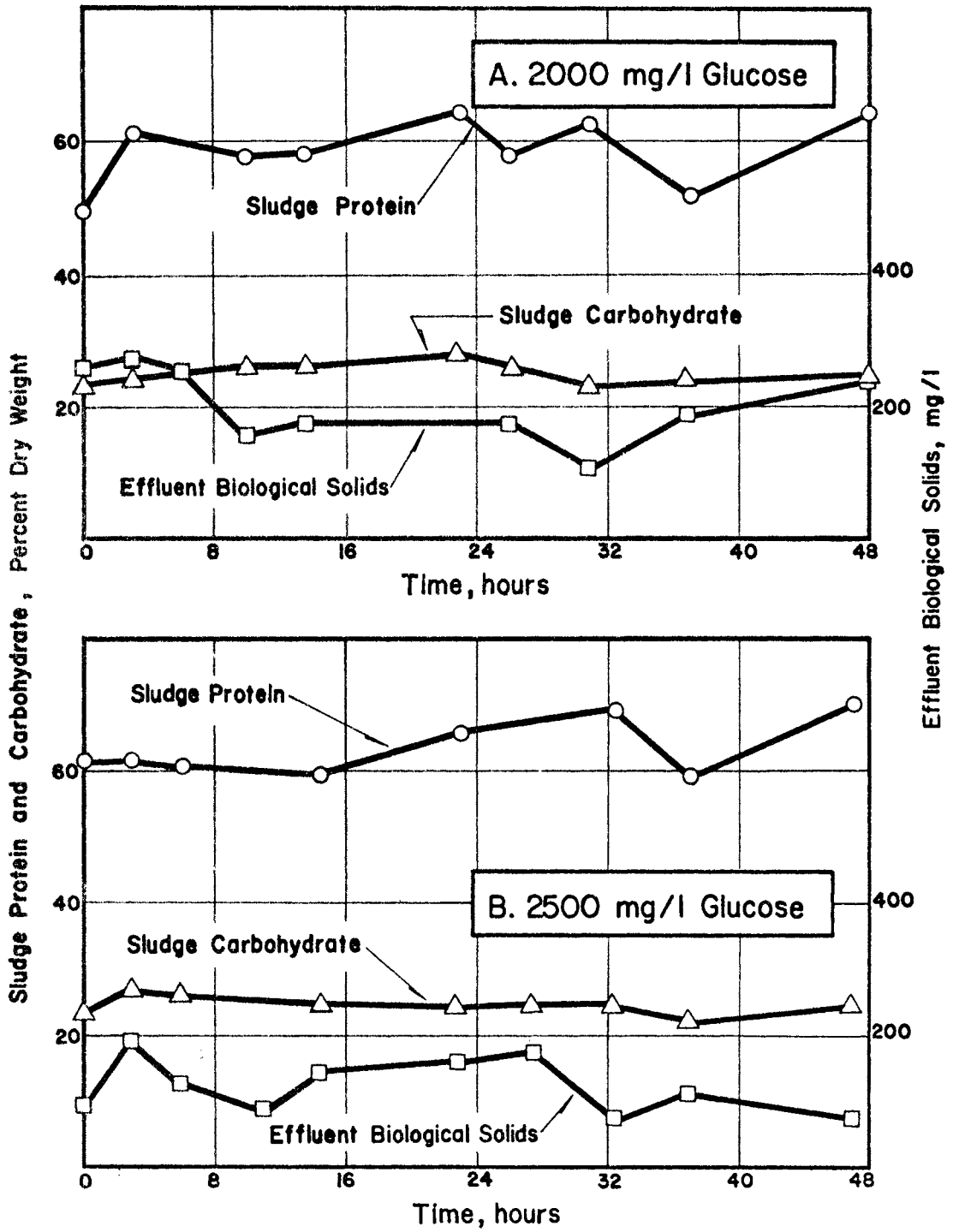

Figure 15. Effect of 2000 and 2500 mg/l Glucose Shock Loads on Effluent Solids and Sludge Composition (Continuous Flow)

biological solids concentration during 2000 and 2500 mg/l glucose shock loads were approximately 190 and 124 mg/l respectively.

In Figures 14 and 15 the results of per cent protein and carbohydrate content of sludge were shown for the individual shock loads. In order to compare these values during various degrees of shock loading, they are shown together in Figure 16. It can be seen that per cent protein content of sludge showed an increasing trend with the increase in glucose concentration while carbohydrate content of the cells remained relatively constant at about 25 per cent.

In the preceding section, the responses of the sludge to various magnitudes of shock loads were presented considering only the over-all performance of the system. Even though these parameters are sufficient to measure the system responses with regard to the purification efficiency of the system, it was felt that the factors affecting the activity of the sludge, under extended aeration, should also be investigated during the period of this investigation. Therefore, specific substrate utilization rate values were calculated for both high and low initial solids systems and a comparative analysis was made on the substrate utilization capacity of the sludge at different periods and various magnitudes of shock loads.

Table II shows the value of specific substrate utilization rate calculated for each shock load experiment. The specific substrate utilization rate values for batch experiments were obtained by dividing the amount of COD removed by the product of the average value of biological solids concentration and the time required to remove the COD.

The specific substrate utilization rate for the continuous flow unit was calculated as follows:

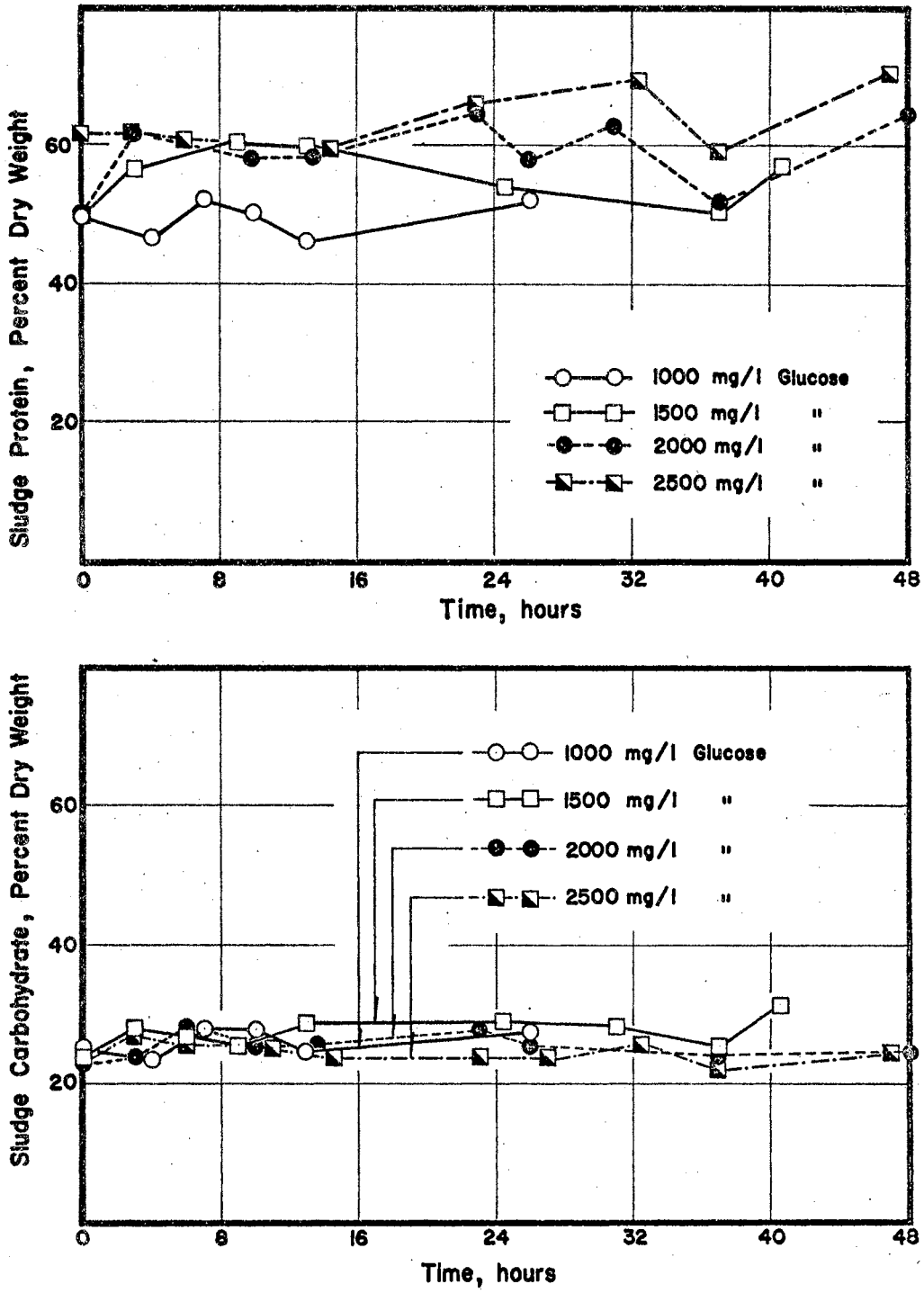

Figure 16. Effect of Various Magnitudes of Glucose Shock Load on Sludge Composition

$$\text{Specific substrate utilization rate} = \frac{COD_f - COD_e}{\bar{t} \cdot \bar{s}}$$

where

COD_f = COD in the feed in mg/l

COD_e = COD in the effluent in mg/l

$\bar{s}$ = mean value of biological solids concentration in the reactor in g/l

$\bar{t}$ = mean residence time in the unit in hours

TABLE II

SPECIFIC SUBSTRATE UTILIZATION RATE

Figure Number	Date	Age of Sludge* Days	In the Unit (High Solids) mg COD/gram SS/Hour	Separate Batch (Low Solids mg COD/gram SS/Hour
		Batch Operation		
5	12-14-67	259	99.6	90.0
6	1-6-68	282	97.2	83.3
7	1-24-68	300	98.6	82.0
8	2-9-68	316	126.8	94.0
		Continuous Flow Operation		
9	3-28-68	364	4.9	92.2
10	4-4-68	371	7.6	153.0
11	4-12-68	379	9.8	141.0
12	4-25-68	392	13.6	99.8

*Time in days since startup of the extended aeration unit

From Table II it can be seen that the specific substrate utilization rate did not deteriorate during the entire period of this investigation. The low values of specific substrate utilization rate under continuous flow operation are due to the fact that the entire detention period (24 hours) in the unit was used in the calculation, and the

shock load was applied gradually, i.e, a step increase in organic loading. Comparison of the results obtained from the identical low solids batch studies indicated that the sludge under continuous flow operation removed shock load substrate at a faster rate than the sludge under batch operation. The separate batch experiments with low initial solids also indicate that the activity of the sludge did not decrease during the experimental period (12-14-67 to 4-25-68).

The oxygen uptake values measured on washed cell suspensions are shown in Table III. It can be seen that the activity of the sludge, as measured by unit oxygen uptake, exhibited a somewhat decreasing trend, however, the specific substrate removal rates (Table II) did not exhibit a corresponding decrease. Therefore, it could appear that unit oxygen uptake cannot be used as a sole parameter in assessing the ability of a biological suspension to assimilate organic substrate.

TABLE III

OXYGEN UPTAKE VALUES OF WASHED EXTENDED AERATION ACTIVATED SLUDGE

Date	Age of Sludge* Days	Unit Activity mg O_2/gram SS/hour
11-30-67	245	3.7
12-14-67	259	2.6
1-6-68	282	3.7
1-24-68	300	3.5
2-14-68	321	3.1
3-4-68	340	3.1
4-2-68	369	2.6
6-7-68	435	2.1

*Time in days since start up of the extended aeration unit.

CHAPTER V

DISCUSSION

The studies undertaken in the present investigation were intended to throw some light on efficiency, reliability and duration of successful operation of extended aeration activated sludge plants. The results reported in this dissertation are primarily concerned with the effects of quantitative shock loads on the over-all efficiency of the system. It was felt that the results obtained from this study may help in understanding the basic response of the extended aeration sludge to shock loads, since factors such as age, accumulated inert materials in an extended aeration plant have often been thought to diminish the ability of the system to remove carbon source during such environmental changes.

Performance of the System Under Batch and Continuous Flow Operation Before Applying Shock Loads

It is evident from Figure 4 that during 45 days of batch operation, the solids concentration in the extended aeration activated sludge system reached a "pseudo-equilibrium" value at approximately 8000 mg/l. However, the COD values fluctuated widely during the early part of this period (up to 25 days) and then remained fairly constant around 400 mg/l. The "equilibrium" value of solids concentration was approximately 16 times the concentration of substrate in the influent. The organic loading at equilibrium solids level was 0.062 lbs COD/lb SS/day. Taking

0.67 as an approximate factor to convert substrate COD to BOD values (63), BOD loading is estimated to be as 0.042 lbs BOD/lb SS/day. This value agrees well with those reported for laboratory and full-size extended aeration plants (63). For equilibrium state in the continuous flow system the COD values were below 60 mg/l and biological solids concentration were approximately 7000 mg/l which is equivalent to 14 times the substrate concentration in the feed.

Comparison of solids concentration and COD values for both batch and continuous systems (see Figures 4 and 5) indicate that the continuous flow extended aeration system performed more satisfactorily than the batch operated system. Solids concentration and COD values in the continuously-fed system remained at a lower value than in the batch-fed system. When the batch operation was changed to continuous flow operation, both COD and biological solids concentration dropped and reached new equilibrium values at a lower level. The decrease in biological solids concentration may possibly be due in part to controlled addition of nutrients during continuous flow operation which restricts the growth of new population. That is to say most of the substrate addition was channelled to respiration rather than synthesis. On the contrary, during batch operation, the substrate was added in slug dose every day, thereby enabling the biological population to channel a portion of the substrate to synthesis. However, the rise in biological solids reaches a limiting value which can be supported by the amount of substrate addition. The high residual COD observed during batch operation cannot be attributed to the low efficiency of the system since the sludge possessed the ability to respond successfully at higher magnitudes of shock loads (see Figures 6 through 9). The high residual COD

in the batch system may be explained as due to gradual accumulation of soluble biologically inert end products of metabolism. The mode of operation of the batch unit was one which did not permit escape of the product in the effluent. Komolrit (4) determined the COD of the waste medium consisting of all inorganic salts (without organic carbon source), used in the medium shown in Table I, and found that the COD value due to these inorganic salts varied between 30 and 50 mg/l. Therefore, it can be said that part of the residual COD may be due to a build up of inorganic salts from the synthetic waste, since only a small amount of supernatant was discarded during batch operation. When the continuous operation was restored after batch experiments, the residual COD dropped to below 60 mg/l. This finding supports the above explanation since the mixed liquor had a mean turnover once every 24 hours during continuous flow operation. During batch operation, the most common problem encountered was foaming. This problem was especially acute when shock loads of 2000 and 2500 mg/l were applied. During continuous flow operation foaming problem was minimal and did not cause any operational difficulties. In general, the continuous flow system performed more satisfactorily than the batch-operated system.

Response of Batch and Continuously Fed Extended Aeration Sludge to Glucose Shock Loads

From the results shown in Figures 6A through 9A, it can be seen that the general response associated with each shock loading is the rapid increase in the biological solids and the decrease in substrate concentration. When the substrate was almost exhausted, the rate of increase in biological solids concentration slowed down. Comparison of

the COD values before and after the administration of shock loads indicates that 95 per cent of the COD value added as shock load was removed in all experiments during the experimental period. Also, comparison of COD removal rates even under the highest shock load concentration (2500 mg/l glucose) and the aeration times employed suggests that the system could take much higher shock load concentration than those employed in this study.

The results from continuous flow operation (Figures 10A through 13A) further indicate that the shock loads employed in this investigation did not markedly affect the over-all performance of the system. At 1000 and 1500 mg/l glucose shock, both COD and biological solids concentration values remained constant. At 2000 mg/l glucose shock there was a slight increase in biological solids concentration from approximately 8000 to 9000 mg/l but the COD values remained unchanged. Only at 2500 mg/l shock load, both biological solids concentration and COD values increased to a new steady state. However, the increase in COD value was not significant to cause failure of the system. The COD removal efficiency was 97 per cent even at highest shock load of glucose (2500 mg/l). Further, specific substrate utilization rates of sludge (Table II, High Solids) showed an increase with increasing shock load concentration. This clearly indicates the successful capability of the system in absorbing the shock loads. The above results collectively indicate that with respect to their biological efficiency of substrate utilization, "total oxidation" process can withstand rather severe quantitative shock loads.

Additional insight with the shock load response under continuous flow operation was gained by the result shown in Figures 14 and 15. It

can be seen from these figures that during these shock loads, composition of the sludge as measured by protein and carbohydrate content (per cent of dry weight) did not significantly change at the shock load levels employed in this investigation. Per cent carbohydrate varied from 22.2 to 31.6 and did not increase with the increasing glucose shock loads. However, per cent protein of sludge showed an increasing trend with increasing shock load concentrations (see Figure 16). It therefore appears that the excess carbon source supplied during shock loads was used in the main for synthesis of viable cells.

It can also be seen from Figures 14 and 15 that there was no significant change in the concentration of effluent solids during the period of shock loads. This indicates that settleability of the sludge was not adversely disrupted as result of applying quantitative shock loads. It is also important to point out here that the high effluent solids concentration observed at certain periods was primarily due to the high solids concentration in the mixed liquor rather than due to poor settling characteristics of the sludge. In general, the continuous flow extended aeration system responded successfully to the various magnitudes of shock load used in this study. The dissolved oxygen concentration in the aeration chamber was always above 4 mg/l and in the settling chamber averaged slightly above 1 mg/l.

Comparison of Batch and Continuous Flow Extended Aeration Sludge to Glucose Shock Loads

Figures 6B through 13B show in general the patterns of the removal of glucose shock load with low initial solids concentration. The substrate removal and growth curves for both sludges (batch and continuous

flow) were similar, i.e., followed the typical growth and substrate utilization curves of the microorganisms. However, comparison of Figures 6B through 13B shows that for identical shock loads the sludge, during periods of continuous flow operation, responded more successfully than under the period of batch operation. The difference between the responses of sludge under the two systems is such that the batch-fed sludge released metabolic intermediates and/or end products in greater amount than the continuous-flow system. The batch-fed sludge required comparatively longer periods in assimilating the same shock load than continuously fed sludge. This finding is substantiated by comparison of the specific substrate removal rates calculated for the low initial solids studies (see Table II). In general, the specific substrate removal rate was somewhat higher for sludge tested during the period of continuous flow operation. This result would seem reasonable, since under batch operation the sludge was subjected to a feed-rest-feed cycle and, as seen previously, the feed was metabolized rapidly (e.g., see Figure 6A) and there was a very long resting (or endogenous) period wherein it would be expected that cell function and capability might be retarded. Furthermore, the data presented in Table II indicate that the continuously fed systems could handle higher gradual quantitative shock loads than those employed in this study. This is evident from the fact that the specific substrate utilization rate values obtained for the high initial solids system were lower than those for low initial solids system (Table II, Continuous Operation). Even at the most severe shock load (2500 mg/l glucose), the specific substrate utilization rate for the continuous flow system sludge was only one seventh of the value obtained for the same sludge at a lower initial solids concentration.

This indicates that the substrate removal capacity of the sludge was much higher than that indicated under this shock load.

CHAPTER VI

SUMMARY AND CONCLUSION

1. The continuous flow extended aeration activated sludge system operated more satisfactorily than the batch operation system. "Equilibrium" state with respect to biological solids and residual COD was lower in continuous flow operation than in the batch-fed system.

2. Since the severity of the applied shock loadings increased as the sludge aged but the response was nonetheless successful, it can be tentatively concluded that the successful response of extended aeration sludge does not depend on cell age.

3. Because of the long detention time employed and relatively high biological solids concentration in the extended aeration activated sludge process, the effect of glucose shock loading up to 2500 mg/l (a five-fold increase) did not appear to cause upsets in the bio-chemical efficiency of the system. Over 95 per cent COD removal efficiency was obtained throughout the entire period of investigation.

4. Extended aeration sludge grown under continuous flow operation removed substrate at a faster rate than sludge grown under batch-fed operation when subjected to quantitative shock loads.

5. Analyses for sludge composition, conducted during shock loads under continuous-flow operation, indicate that the per cent protein content of sludge increased with increasing shock loads of glucose, whereas the carbohydrate content of sludge remained at a constant level

(approximately 25 per cent). However, the protein content dropped back to the original value after removal of the shock load.

6. The unit activity measured from endogenous oxygen uptake values does not truly reflect the changes in the biological activity of the extended aeration sludge. The specific substrate utilization rate value appears to describe the activity of sludge better than does the oxygen uptake values.

CHAPTER VII

SUGGESTIONS FOR FUTURE WORK

Based on the results of this investigation, the following suggestions are made for future work.

1. The results of this study reflect only the general performance of the extended aeration system subjected to quantitative shock loads. It would be desirable to see whether different environmental conditions (e.g., change in chemical structure of the waste, pH, and temperature) have any effect on the biochemical efficiency as well as the settleability of extended aeration sludge.

2. Since past studies have shown that concurrent removal of substrate occurs when old cells were fed with multi-substrate feed, it would be interesting to study multiple-substrate systems with extended aeration sludge.

3. Besides organic loading, detention time is an important aspect in the over-all performance of the extended aeration activated sludge process. Hence, it would be useful to study what effects the hydraulic loads may have on extended aeration systems.

4. Since biologically resistant polysaccharide accumulation has been reported for nitrogen deficient wastes, it would be interesting to extend the present investigation to shock loads of glucose alone without increasing other nutrients.

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VITA

Wisut Ragthaidee

Candidate for the Degree of

Master of Science

Thesis: RESPONSES OF EXTENDED AERATION ACTIVATED SLUDGE TO QUANTITATIVE SHOCK LOADS

Major Field: Civil Engineering

Biographical:

Personal Data: Born December 14, 1942, in Prae, Thailand, the son of Mual and Somboon Ragthaidee.

Education: Attended Triem Udom Sueksa School in Bankok, Thailand (1959-1961); completed requirements for the degree of Bachelor of Engineering from Chulalongkorn University (Bangkok, Thailand) in June, 1965. Completed requirements for the degree of Master of Science at Oklahoma State University in May, 1969.

Professional Experience: Served as an Engineer in the Department of Health, Bangkok, Thailand, from 1965-1967.