BIOCHEMICAL RESPONSE OF CONTINUOUS FLOW ACTIVATED SLUDGE PROCESSES TO QUANTITATIVE SHOCK LOADINGS

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CHAPTER I

INTRODUCTION

Water is a strategic element in the daily activities of people and industry. As the population and industries grow, water will be used at an increased rate and the necessity of conserving the water supplies becomes increasingly important. To meet this situation, Congress passed Public Law 87-88 in July, 1961, amending the Federal Water Pollution Control Act and directing the Secretary of Health, Education and Welfare to "develop and demonstrate practicable means of treating municipal sewage and other waterborne wastes to remove the maximum possible amounts of physical, chemical, and biological pollutants in order to restore and maintain the maximum amount of the nation's water at a quality suitable for repeated re-use." (1)

As industries grow up to meet the demands of modern society, the pollutional problem is bound to increase. Industries use enormous amounts of water for their successful operation, and discharge considerable amounts of waste water. It is estimated that industry consumes about one gallon of water for every fifteen it withdraws, and returns the other fourteen gallons to a body of water (2). Research has not caught up with the ever-increasing pollutional problem. The following statement clearly indicates the need for further research: "Our luxury of relying on dilution by pristine waters and on purification by the great hydrological cycle must inevitably end. We are approaching the time at which something better than the present methods for treating waste water must be used." (1)

During recent years considerable interest has been shown in maintaining the standards of the water course, with the result that pollution abatement is given serious consideration. It is estimated that the demand for water in 1980 will be 600 bgd and the supply 600 bgd. These predictions are debatable, as they fail to take into account the re-use of water. Of greater significance is the fact that water is a local problem, and any prediction made on a national basis is not meaningful. To solve this problem a large number of treatment plants are being built, and the cost of pollution abatement is on the increase. From 1950 to 1963 federal funds available for water pollution control in the Public Health Service increased more than a hundred times, from slightly over a million dollars in 1953 to more than 120 million dollars in 1963.

The construction of treatment plants does not solve the problem unless functional efficiency, reliability, and flexibility of the treatment plants are also achieved simultaneiously. These aims can be achieved only when the designing engineers and operators have gained better insight into the operational criteria and basic concepts concerning the purification process. One treatment process which has been extensively used by industries and municipalities is the activated sludge process. This may be due to the fact that it has relatively high efficiency, requires less space for treatment of the same waste quantity than do other biological treatment processes, and provides a high degree of operational flexibility.

During recent years considerable attention has been focussed on combining the treatment of domestic and industrial wastes in a centralized treatment plant. There are several advantages that can be gained through combined treatment (3)(4). The most important advantages of joint treatment are: 1) Municipal sewage contains sufficient nutrients to offset the nutrient deficiencies of industrial

waste, and 2) it may afford enough dilution to make the waste less concentrated. But joint treatment has created several operational problems, mainly rapid changes in the environmental conditions. These are referred to as shock loading to biological treatment processes (5). Three main types of shock load that are commonly encountered are 1) quantitative shock loads, 2) qualitative shock loads, and 3) toxic shock loads.

The purpose of this study is to investigate the effects of quantitative shock loads on the performance of completely mixed activated sludge systems. These were studied with and without sludge recirculation using three detention times of 4, 8, and 12 hours, respectively. The following types of shock loading were studied using glucose as substrate:

1) effect of gradual shock load
2) effect of slug shock load
3) effect of shock load under nitrogen deficient conditions, and
4) release of intermediates during shock load.

These studies were undertaken to determine the effect of disruption of steady state conditions due to the environmental changes brought about by introduction of shock loads of the types listed above.

Since most of the treatment plants receive wastes of varying strength and also wastes deficient in nitrogen, it is felt that this type of study is comparable to the conditions encountered by any treatment plant. It is felt that the results of this study will contribute significantly toward the understanding of the behavior of activated sludges under shock loading conditions.

CHAPTER II

REVIEW OF LITERATURE

Activated Sludge Process and Its Recent Development.

The treatment of wastes by the activated sludge process has been practiced for over fifty years, and this process enjoys ever-increasing popularity as a major means of biological treatment. The important milestones in the development of the activated sludge process have been excellently reviewed by Sawyer (6). This process was developed at a time when the major consideration was the treatment of domestic wastes. Attempts to apply the process to industrial wastes or mixtures of domestic and industrial wastes containing abnormal amounts of soluble and readily-oxidizable organic matter often met with the failure of the process. These failures occurred primarily because engineers did not yet fully understand that the process was essentially biochemical in nature rather than a mere application of physical principles (7). The conventional activated sludge process consists of aerating wastes in the presence of 2000 - 3000 mg/l of activated sludge for a period of 6 to 8 hours. The operation of the process has revealed several of its limitations. According to Sawyer (7) the various limitations of the process are: "1) BOD loadings are limited to 35 lbs/1000 cft aeration volume; 2) there is a high initial oxygen demand; 3) there is a tendency to produce bulking sludge; 4) the process is unable to produce an intermediate quality of effluent; 5) high sludge recirculation ratios are required for high BOD wastes; 6) solids loading on final clarifier is high; and 7) air requirements are high." Various modifications of the conventional process

have been advanced to overcome some of the disadvantages. These modifications have been brought about by actual observation of the operation of full scale treatment plants and through more basic engineering research. The various modifications of the activated sludge process are: 1) step aeration; 2) tapered aeration; 3) Kraus process; 4) biosorption process; 5) dispersed aeration; and 6) high-rate activated sludge process.

Step aeration was developed by Gould and first applied to plant scale operation at Tallman's Island plant in New York City (8). This process was developed to provide adequate "sludge age" in the aeration tank while maintaining a low suspended solids entering the final settling tank. This was possible by controlling the rates and points of application of the waste to the aeration tank. The main advantage of this process was that the oxygen demand was kept at a fairly uniform level throughout the aeration tank, due to the multiple addition of waste. This process was successful in the New York plant, due to the fact that the BOD and suspended solids concentrations of the waste were almost the same. It is doubtful that this process would give satisfactory performance when the waste is high in BOD and low in suspended solids concentration.

Tapered aeration is a modification in which the oxygen supply to the aeration tank is gradually reduced toward the outlet end. This arrangement allows more air to be supplied at the inlet end where the oxygen demand is the greatest. The modification consists of merely placing more diffusers at the inlet end of the aeration tank, and decreasing the number progressively toward the outlet end.

The Kraus process represents an attempt to control sludge bulking problems associated with the activated sludge process. This process was developed by Kraus (9) (10) at Peoria, Illinois, to decrease the high "sludge volume index." Bulking is due to the failure of the solids to

settle in the final settling tank. The degree of bulking is measured in terms of sludge volume index. Sludge volume index measurement is based on the settling of a liter of sludge for 30 minutes; a good settling sludge will have an index of 100-150. The process involves separate aeration of a mixture of digestion tank supernatant, digested sludge, and activated sludge, to produce a well nitrified sludge with excellent settling characteristics. The process serves two purposes: 1) addition of weight to the sludge thereby producing a sludge with good settleability, and 2) addition of nitrates which serve as a reserve source of oxygen to help maintain "aerobic" conditions at the inlet end of the tank. By the addition of aerated digester sludge and digester liquor in proper proportion to the return activated sludge and modifying the method of aeration, Kraus (11) was able to control the sludge volume index in addition to increasing the organic loading up to 175 lbs/1000 cft aeration volume. The ability of this process to handle higher organic loads was due primarily to the increased solids concentration in the aerator.

All of these three modifications were designed to overcome high initial oxygen demand which caused anaerobic conditions to develop in the front end of the aeration tank.

The biosorption process takes advantage of the high "adsorptive" capacity of sludge. This process was developed by Ulrich and Smith (12) to solve a difficult treatment problem at Austin, Texas. This process consists of contacting a well-conditioned sludge with unsettled waste for a period of 30 minutes under intense aeration. The solids are then separated and stabilized in a separate aerator to continue the purification process. BOD loadings in the range of 150 lbs/1000 cft aerator volume have been successfully treated. This process operates satisfactorily when the waste is colloidal in nature. Another modification of this process is contact stabilization where settled

wastes are treated. Many plants have been successfully converted to contact stabilization (13)(14). It has been claimed that such modification has provided a greater flexibility of operation and better protection against shock loadings imposed by industrial waste discharges (15). The rapid removal of waste (as BOD) was attributed to adsorption as it was considered unlikely that biological purification could proceed so rapidly. However, Gaudy and Engelbrecht (5) have shown that purification of soluble wastes by activated sludge is biochemical in nature rather than adsorptive.

Dispersed aeration and high rate activated sludge processes are designed to produce a partially purified effluent. Dispersed aeration is a process which is used where only 30 to 50% purification is desired. This process is suitable for wastes containing dissolved organics, and it also eliminates sludge disposal facilities since all of the solids are discharged along with the effluent. The purification achieved in this process is primarily due to the respiratory activity of the sludge. The main disadvantage of this process is that a considerable amount of the oxygen demand of the waste may be exerted in the receiving stream. This process is applicable when the amount of waste to be treated is small, and sufficient dilution is available in the receiving stream.

The high rate activated sludge process was developed to increase the loading capacity of activated sludge units, and also to reduce aeration time. The high rate activated sludge process is a modification of the conventional activated sludge process in which a shortened aeration period (2-3 hours) is employed using a reduced amount of solids in the mixed liquor. Wuhrmann (16) has indicated that a loading of 190 lbs/1000 cft of aeration volume could be successfully treated with an efficiency of about 80%. The success of the high rate process was made possible due to the development of high intensity aeration devices to supply oxygen at very high rates.

Although all of these processes have been advanced to overcome some of the shortcomings of the conventional activated sludge process, the main drawback of all of these modifications is that the organisms are not subjected to constant loading during the entire aeration period. Busch and Kalinske (17) have indicated that certain conditions have to be satisfied for the best operation of the activated sludge process. They are: 1) a young flocculent sludge in the logarithmic stage of growth; 2) maintenance of the log growth state by controlled sludge wasting; 3) continuous organic loading to the organisms; and 4) elimination of anaerobic conditions at any point in the oxidative treatment.

The process in which all of the above mentioned principles may be incorporated is known as "complete mixing" activated sludge; however, a "complete mixing" system can be operated on the basis of high synthesis of sludge with controlled wasting of sludge, or on the total oxidation principle with no intentional wastage of sludge. McKinney (18) defines complete mixing as a basic process in which the incoming wastes are completely mixed with the entire contents of the aeration tank. He felt that the aeration tank acts as a surge tank and tends to level out wide fluctuation in the organic load, and that the use of the entire mass of activated sludge to stabilize the organic load distributes the load uniformly over the entire aeration tank and permits better utilization of the air blown into the mixed liquor.

Eidsness (19) was the first to report on the significance of intense mixing in activated sludge plants. Pilot plant studies indicated that with complete mixing it was possible to produce an effluent of 25 mg/l BOD in a 2.5 hour contact time with domestic sewage.

McKinney (20) has proposed a process to overcome the shortcomings of conventional activated sludge process. This process is called "hi-lo" activated sludge; the

wastes are introduced along the entire length of the aeration tank. Biological solids are allowed to build up to 20,000 ppm. This process also serves to absorb variable organic contents of the waste, and effect dilution on mixing with the contents of the aeration tank. Hence no high initial oxygen demand is exerted. The high solids concentration also serves as a buffer against incoming wastes with a pH below 6.5 and above pH 9.0. This process closely approximates the more general present day concept of completely mixed systems.

The key to the successful operation of complete mixing activated sludge systems would appear to be intense aeration and/or agitation. Intense aeration serves the dual purpose of supplying oxygen to the growing organisms and effecting complete mixing in the aerator. Grieves, et al. (21) studied the effect of shortcircuiting in the completely mixed activated sludge process. They indicated that the effect of a stagnant zone is equivalent to that of an increase in loading which increases the effluent BOD by an amount proportional to the amount of shortcircuiting.

The use of completely mixed activated sludge processes has made possible the treatment of many industrial wastes which could not be treated in a conventional activated sludge process without some form of pre-treatment. The following few references will show the importance of this process for the treatment of industrial wastes.

McKinney, et al. (22) have reported on the treatment of highly alkaline textile wastes without preneutralization in a completely mixed system. They indicated that it was possible to produce an effluent of less than 50 mg/l BOD and that variations in organic load do not upset the process as severely as they do a conventional activated sludge system. Hatfield (23) used complete mixing in preference to a conventional activated sludge process for the treatment of toxic wastes. He indicated that higher organic

loadings could be handled by this system. Busch and Kalinske (17) have reported an average treatment efficiency of 89% with BOD loadings up to 350 lbs/1000 cft aerator volume in an "aero accelator" pilot plant. The "aero accelator" is an aeration tank manufactured by the Infilco Company. In addition to the turbulence created by air, complete mixing is further achieved by a rotor which provides for intense agitation and insures complete mixing of the contents of the aeration tank. The great advantage of the aero-accelator is that the final clarifier is part of the unit.

Coe (24) studied the treatment of petroleum wastes in a laboratory size activated sludge unit. His results indicate BOD reduction of 90-95% at organic loadings up to 140 lbs BOD/1000 cft aerator volume/day.

Ross, et al. (25) made use of an aero accelator to remove phenol from petroleum waste. Their results indicate that this plant can successfully treat up to 600 lbs. of phenol/day with an efficiency of 99.9%. They indicated that phenol was oxidized to CO_2 and water, although no mention was made as to how the residual phenol concentration was measured.

Taylor, et al. (26) used a homogeneously mixed aerator to treat complex wastes from orlon manufacturing. The waste contains predominantly dimethyl formamide, acrylonitrile, and finish. This waste was successfully treated at BOD loadings of 0.4 lbs/lb MLSS/day. The system was exposed to pH's of 4.5 to 10.5 without much adverse effect.

The treatment of wastes from synthetic resin manufacture has been reported by Jenkins, et al. (27). In their studies 1000 mg/l of the waste (as permanganate value) was reduced by 91.4% using an 18-hour detention time. They also indicated that an increase in detention time up to 35 hours did not significantly increase the purification efficiency. Although the waste had a high formaldehyde content, there was no indication by the authors that physi-

cal stripping of formaldehyde could have been responsible for the high efficiency observed.

Gehm (28) has indicated the desirability of using a commercial fermentor for the treatment of wastes high in BOD. He reported that it is possible to treat boardmill wastes up to BOD loadings of 400 lbs/1000 cft aeration volume/day at an efficiency of over 90% using these aerators.

Treatment of dairy wastes using a completely mixed system has been studied by Hoover and Porges (29). Their results indicate that in a waste containing 0.1% dry skim milk 50% was oxidized and 45 to 48% was assimilated. The effluent COD from the unit was primarily due to suspended solids.

Completely mixed systems have been extensively used to obtain design data for the treatment of industrial wastes containing aniline, nitrobenzol, phenol, and 2,4-dichlorophenol, chemical wastes containing antibiotics, synthetic vitamins, and cortisone and pharmaceutical wastes (30)(31)(32)(33). The great advantage of the complete mixing system lies in the fact that the size of the unit is not a factor in getting useful information for design purposes. The only criterion to be satisfied either in lab scale unit or full scale treatment plant is that of complete mixing. Once this condition is satisfied, the shape and size of the aeration unit is of little importance.

Tenney, et al. (34) have used a completely mixed system to study the effect of high organic loading at a 6-hour detention time. The organic loading employed varied from 60 lbs to 1690 lbs COD/1000 cft aerator volume/day. They indicated that 88% of the influent COD was biologically processed either to CO_2 and H_2O or resultant solids. Of the COD utilized, 48% was lost from the system, and the remainder converted to solids. Solids yield was found to be independent of loading.

The completely mixed systems have been quite extensively reviewed here to show the importance of this process

for the treatment of wastes, and because this type of system was used in the present study.

Many attempts have also been made to translate data obtained from a batch operated activated sludge process to the design of completely mixed systems. Weston and Stack (35) have indicated that batch data can be used for the prediction of the behavior of completely mixed systems by calculating an apparent BOD transfer coefficient from batch data. Garrett and Sawyer (36) felt that the completely mixed system was the same as the conventional activated sludge system, and used the mathematical analysis of the complete mixing system to evaluate the conventional activated sludge process. However, Busch (37) (38) (39) has indicated that the design of a complete mixing system on the basis of batch grown solids is hazardous. He has indicated that batch experiments using cells grown in continuous flow units will yield information on the rate of waste purification and that the settling characteristics of batch grown cells are a function of solids age while in the continuous system the applied surface loading determines the settling characteristics of the solids. Gaudy (40) has used cells grown in a completely mixed system to evaluate the effect of qualitative shock loading under batch aeration.

Another modification of the completely mixed activated sludge process which has been mentioned previously is the so-called total oxidation system. In this process advantage is taken of a relatively long detention time to oxidize the cells. In the development of this process it was reasoned that in a total oxidation unit the new growth of sludge would be balanced by the oxidation of cells so that there would not be any problem of sludge disposal. However, studies on the operation of these units have indicated a buildup of biologically inert solids. Kountz and Forney (41) using dry skim milk as a source of organic matter, have indicated that total oxidation of sludge was

not possible, and found about 20-25% of the new activated sludge remained unoxidized. McCarty and Broderson (42) also indicated that total oxidation of sludge is not feasible. They studied the effect of three different loadings, 40, 80, and 120 lbs/1000 cft/day on the performance of total oxidation systems over a period of 48 days. Their results indicated that a total oxidation system operates satisfactorily at a loading of 40 lbs/1000 cft aerator volume/day. The problem of rising sludge due to denitrification in the secondary settling tank was also indicated by their work. By employing radioactive labeling techniques, Washington and Symons (43) found that volatile solids accumulated at about 10 to 15% of the ultimate BOD of the waste when the carbon source was fatty acid or carbohydrate in nature, but less sludge accumulated for amino acids. 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 content of sludge underwent decomposition, while carbohydrate did not. Ludzack (44) observed that incomplete aerobic digestion of solids during extended aeration treatment produced a high solids concentration in the effluent, and that periodic wasting of aeration solids reduced the suspended solids concentration in the effluent. Trebler and Harding (45) indicated the importance of temperature in aerobic digestion of solids in an extended aeration plant treating whey wastes. Endogenous oxidation appeared to be maximum at 86°F., and it was concluded that even at this temperature the microorganisms build cell materials which are resistant to oxidation.

Although a considerable amount of indirect information is available on the effect of shock loading in activated sludge processes, very few studies have been made to assess directly the effect of shock loading in completely mixed

activated sludge systems. Komolrit (46) has studied the effect of qualitative shock loading in a completely mixed activated sludge system. He indicated that the continuous flow unit is not free from the deleterious effects of this type of shock load. The ability to respond to a shock load was dependent on the system dilution rate, the sludge concentration in the system, the sludge activity, and the quantity as well as the rate of inflow of the shock substrate. He also indicated that successful response to shock loading is dependent on an adequate amount of nitrogen in the incoming waste.

Extreme variations in brewery waste characteristics and their effect on the completely mixed activated sludge process have been investigated ty O'Rourke and Tomlinson (47). The COD of the hourly composite samples varied from 128 to 8420 mg/l. Their results indicated a definite detrimental effect on the biological treatment of waste manifested by an increase in the sludge volume index and increase of the BOD of the effluent due to solids discharge.

The effect of sudden discharge of highly concentrated milk waste to a treatment plant has been reported by Gault (48). The discharged milk waste had a BOD of 37,000 mg/l. As a remedial measure the return sludge was increased to 63% and the air supply to 2 cft/gal of sewage. It took five days for the BOD of the effluent to return to the normal value.

The data of McNary and Wolford (49) on the treatment of citrus waste by the activated sludge process seem to indicate that an increase in BOD of citrus wastes does not materially affect the BOD removal. The reason for the same BOD removal in spite of increased BOD of the waste could be attributed to the provision of a surge tank which served to level out wide fluctuation in BOD of the incoming waste.

Effect of Oxygen Tension in Activated Sludge Process.

Considerable research has been expended in the study of the effect of oxygen tension on the activity of microorganism. Smith (50) observed that the degree of BOD removal was not affected by variation in oxygen concentration provided that a residual existed in the mixed liquor at all times. Emde (51) showed that oxygen utilization is largely independent of oxygen tension. However, he concluded that "the oxygen content in the aeration tank should be at least 2 ppm, since below this value the purification effect will decrease." His conclusion seems to contradict his own finding, and probably is influenced by Pasveer's (52) work which indicates that oxygen transfer is the limiting factor in biological purification. Wuhrmann (53) has reported that at low or medium mixed liquor solids concentrations an increase of oxidation occurs with increasing oxygen tension, while at high sludge concentrations this effect disappears. He also indicated that complete anaerobiosis for a period of 0-270 min caused no significant change in the respiration rate of the sludge. Westgarth, et al. (54) have also observed that prolonged anaerobiosis in the clarifier of the activated sludge process is not detrimental to the process. The importance of increasing oxygenation capacity in the activated sludge process is indicated by the work of Pasveer (52). His results indicate that it is possible to treat a loading of up to 3750 lbs BOD/1000 cft aerator volume/day with an efficiency of 93%. The capacity of the activated sludge process to handle such high load could very well be due to the maintenance of a high solids concentration of about 12,000 ppm in the aerator. Gaudy (55), in studying the effect of air flow rate on the response of activated sludge to quantitative shock loading, indicated that the value of oxygen tension which affects metabolic rates lies below 0.5 mg/l of dissolved oxygen and that short term absence of dissolved

oxygen will not seriously affect the substrate removal rate of the process.

Although most of the studies have attempted to find the limits of oxygen concentration for successful operation of activated sludge, the drop in oxygen concentration in the aerator that accompanies a shock load is more important from the operational point of view. Kraus (11) has shown that loss of clarifying ability corresponds to a period of low dissolved oxygen concentration in the aerator. Gault (48) observed that dissolved oxygen in the final clarifier dropped from a value of 2.6 mg/l to 0.3 mg/l due to a sudden discharge of milk wastes. It took five days for the dissolved oxygen to return to the normal value of 2.2 mg/l which corresponded to the recovery of BOD removal efficiency during the same period.

Nutritional Aspects in Waste Treatment.

The nutritional aspects were generally overlooked until the recent increase in industrial expension and the required treatment of industrial wastes either separately or jointly with the municipal sewage. Most of the industrial wastes are deficient in nitrogen and phosphorus which are essential for their successful treatment by biological processes. Many nutritional studies have centered around determination of optimum nitrogen and phosphorus in relation to the strength of the waste measured in terms of BOD. Sawyer (56) suggested that where it was desirable to produce a biological growth with maximum nitrogen and phosphorus content, the ratio of 5-day BOD to nitrogen and phosphorus should be maintained at 17 to 1 and 90 to 1, respectively. Value of BOD:N and BOD:P ratio of 19:1 and 81:1 respectively have been reported by Hattingh (57) for maximum nitrogen and phosphorus content in the sludge. Helmers, et al. (58) have indicated that percent nitrogen content of activated sludge based on volatile matter is a good index of nitro-

gen deficiency. A value of less than 7.5 per cent is indicative of nitrogen deficiency.

In addition to these studies, a considerable amount of work has been accomplished in delineating the basic differences in substrate removal capacity of activated sludge devoid of nitrogen or supplied with inadequate amounts of nitrogen. Gaudy and Engelbrecht (59) showed that substrate removal rate in a respiring (or non-proliferating) system was comparable with that in a growth system. The major difference in the biochemical composition of the two sludges was that under non-proliferating conditions carbohydrate was the major constituent synthesized while under growing conditions the major synthetic product was protein. Similar conclusions were reached by Van Gils (60). In a study by Symons and McKinney (61) regarding the biochemistry of nitrogen in the activated sludge process in which sodium acetate was used as substrate, it was found that a decrease in the nitrogen in the system was usually accompanied by a buildup of biological solids. They found that these solids were not metabolically degradable during a long period of endogenous respiration. Microscopic examination of sludge with Alcian blue stain indicated a high content of extracellular polysaccharide.

The effect of nitrogen deficiency on the behavior of complete mixing activated sludge systems was investigated by Bechir and Symons (62). They indicated the following relationship on the basis of their results: (% organic nitrogen in volatile sludge) (% soluble COD remaining)$^{\frac{1}{2}}$ = k. Where k is a constant dependent only on the form of nitrogen used for supplementation. The value of k was found to be relatively independent of the substrate form and was also not affected by a change of solids retention time. They also reported an increase of solids in the unit with low amounts of nitrogen as compared with the system with high amounts of nitrogen.

The amount of nutrients that must be added will also vary with the degree of endogenous respiration adopted in the system. Simpson (63) has indicated that in the extended aeration plant the addition of nitrogen and phosphorus could be limited to one-third of the amount normally required (i.e., 1/3 of BOD:N = 17:1 and BOD:P = 90:1). Eckenfelder and McCabe (64) have shown that the addition of nitrogen as a supplementary nutrient was eliminated in the treatment of pulp and paper mill waste in an aerated lagoon where a long aeration period permitted the re-use of nitrogen after autooxidation.

A modification of the conventional activated sludge process for the treatment of nitrogen deficient waste was proposed by Rama Rao, Speece and Engelbrecht (65). The modification consists of channelling the effluent from the primary settling tank to activated sludge plants operated in parallel. It was proposed that one of the activated sludge units could be supplemented with nitrogen and treated in the conventional manner. A portion of the sludge from the settling tank of this unit could then be used as return sludge for the aerator, while the remainder was mixed with the waste to which no nitrogen was added and treated in the second aerator. The sludge from this unit would be wasted. Nitrogen savings of 30-50% were predicted for this modification. Another modification was proposed by Komolrit, Goel, and Gaudy (66). In this modification the nitrogen deficient waste was treated in the aerator in the usual manner without nitrogen supplementation. Under this condition the main synthesis product of the sludge will be carbohydrate. The sludge is separated and aerated with the addition of nitrogen in a second aerator. In this aerator the carbohydrate content of the sludge is converted to protein during endogenous oxidation. The sludge from this aerator is recycled to the first aerator to continue the purification process. The main advantage of this system

is that no nitrogen is lost from the system. In addition, it eliminates the need for a second activated sludge unit as proposed by Rama Rao, et al. (65). The authors cautioned against indiscriminate use of such a system and indicated that it should apply to carbohydrate wastes such as those for pulp and paper manufacture and sugar beet processing.

It is clear from a review of the literature that not much information is available regarding the effect of nitrogen deficiency in the completely mixed activated sludge process.

Sludge Bulking.

One of the most difficult operating problems encountered with the activated sludge process is the bulking of sludge.(7). It can rightfully be said that the success of any biological treatment plant depends on the efficiency with which the solids are separated in the final clarifier. Overloading, lack of nutrients, waste predominantly carbohydrate in nature, and insufficient aeration are some of the causes of sludge bulking. Smit (67) has indicated that overloading with carbohydrate waste causes bulking. The possible reason for this is that overloading could reduce the dissolved oxygen concentration in the aerator or may cause a pH drop, creating conditions favorable for the predominance of filamentous organism. The growth of filamentous organism could cause sludge bulking. However, Logan and Budd (68) have indicated that bulking could be caused not only by overloading, but also by underloading. The influence of chemical composition of waste as a factor in causing bulking is indicated by the work of Genetelli and Heukelekian (69) and Skrinde and Dustan (70). The importance of nitrogen and phosphorus deficiency as a factor which could contribute to bulking is indicated by Hattingh (71). He observed that bulking was severe when the BOD:N

and BOD:P of the waste were greater than 37:1 and 420:1, respectively. The deficiency of phosphorus in relation to waste-strength in causing bulking is indicated by Greenberg, et al. (72). The role of filamentous organisms in activated sludge processes was reviewed by Pipes (73). He surmised that filamentous organisms probably grow as unicellular form in normal activated sludge, but if the sludge is not given the opportunity to oxidize, most of the organic matter which it removes from the waste, or if nitrogen and phosphorus are deficient, the filamentous organisms accumulate large amounts of lipid which reduces the density of sludge and causes bulking. All of the studies mentioned above are primarily concerned with determining the causes of sludge bulking, but they do not offer any solution to correct it. The development of the Kraus process was aimed primarily at controlling the bulking of sludge. This process has been successfully applied at Illinois and Belleville treatment plants (11)(74). Since overloading and nitrogen deficiency have been cited as causes of sludge bulking, it is of interest to find out whether bulking occurs under shock loading conditions.

Release of Metabolic Intermediates.

The release of metabolic intermediates and/or end-products during the utilization of substrates has not received much attention in the Sanitary Engineering field. One of the possible reasons is that the release of such intermediates was not anticipated, and that special tests and instruments are required for their identification. Another factor that contributed to the lack of information in this area is the almost total reliance on the BOD test to assess the performance of biological treatment units. It is assumed that the materials present in the effluent are those which were refractory to biological treatment. Krishnan and Gaudy (75) indicated that some of the so-

called "refractory" compounds in effluents from biological treatment plants may be compounds not originally present in the waste, but compounds produced by the cells from a portion of the original carbon source.

In studying the oxidation of radioactive glucose by activated sludge, Porges, et al. (76) found that at the end of five hours of aeration 23% of the radioactivity still remained in the supernatant when carbon-1 was labeled, and 40% when carbon-6 was labeled, even though no glucose was detected by reducing test. Similar data were obtained by Clifton (77) during oxidative assimilation of glucose by Bacillus subtilis.

Brown (78) investigated the effect of trade wastes on residual impurities as compared with sewage alone. All of the wastes studied had a high residual permanganate value and BOD as compared with the sewage control.

Krishnan and Gaudy (75) observed the release of intermediates during glucose metabolism by glycerol-acclimated young cells. Studies were conducted under growing and non-proliferating conditions. Under growth conditions at the completion of glucose removal, 250 mg/l of intermediates (50% of the initial concentrations of glucose) were present in the supernatant, while under non-proliferating conditions 350 mg/l of intermediates (70% of the initial concentration of glucose) were present in the supernatant. These intermediates were metabolized after dissimilation of glucose in the growth system. In resting cell suspensions, the metabolic intermediates were not subsequently removed.

Bhatla (79) observed a plateau in the oxygen uptake curve using a pure culture of E. intermedia. The plateau was found to be due to the release of volatile acids during glucose metabolism. The second phase of oxygen uptake corresponded to the utilization of volatile acids. The pause in O_2 uptake was due to the need for acclimation before the cells could utilize the volatile acids.

Acidic components of sewage effluents were investigated by Murtaugh and Bunch (80). Effluents from four aerobic treatment plants were studied. The individual volatile acids were analyzed by gas chromatography. All of the effluents contained volatile acids from C_1 to C_6. Acetic and formic acid were predominant in normally operating plants, while longer chain fatty acids were characteristic of overloaded plants.

Pirt (81) has related the production of acetic acid in continuous culture of Aerobacter aerogenes to growth rate. Glucose was converted to acetic acid only when the growth rate was very close to the maximum growth rate. The production of acetic acid was not due to the lack of oxygen supply since acetic acid was also produced in an oxygen limited system. However, in an oxygen limited system the acetic acid was released at a lower percentage of the maximum growth rate as compared with the system supplied with excess oxygen. Oxygen limitation was detected by production of such fermentation products as acetoin. The release of acetic acid during oxidation of glucose by Aerobacter aerogenes was also observed by Hadjipetrou, et al. (82).

The release of $\mathcal{L}$-keto glutaric acid during the oxidation of glucose by a respiring cell suspension of Ps. aeruginosa was reported by Duncan and Campbell (83). The $\mathcal{L}$-keto glutaric acid which accumulated during glucose oxidation was utilized as ammonia became available from endogenous respiration. The release of $\mathcal{L}$-keto glutaric acid during glucose oxidation was also observed with Ps. fluorescens (84).

It is apparent from this review of the literature that only very little information is available regarding the effect of shock loads on the activated sludge process. The purpose of this study is to investigate in detail the effect of quantitative shock loadings on completely mixed systems.

CHAPTER III

THEORETICAL ASPECTS OF COMPLETE MIXING SYSTEM

Since all of the experiments were conducted in a steady state completely mixed system, it is pertinent to review the theoretical kinetic concepts and the relationships between various parameters which can affect operation of such systems. The steady state condition can be achieved by either internal control employing devices which measure cell density in the aerator, or by external control through the regulation of the flow rate and the concentration of limiting nutrient. The externally controlled device has been widely accepted in practice, due to its greater convenience of operation and less complex instrumentation.

A. Steady State Kinetics Without Recirculation.

Bacterial growth can be expressed by the following relationship:

$$\frac{dx}{dt} = \mu x \qquad (1)$$

where x is the concentration of organisms at time t, and μ is the exponential growth rate. According to Monod, as indicated by Herbert (85), μ is approximately proportional to the substrate concentration when this is low, but approaches a maximum value μ_m as the substrate concentration increases. This relationship can be expressed as:

$$\mu = \mu_m \frac{s}{k_s + s} \qquad (2)$$

where μ_m is the maximum growth rate. k_s is the saturation constant numerically equal to the substrate concentration at which the growth rate μ is one-half of μ_m, and s is the concentration of substrate in the reactor.

In the continuous flow unit, the mass balance equation for the concentration of cells (solids concentration) is given by

increase = growth - output, or

$$\frac{dx}{dt} = \mu x - Dx \qquad (3)$$

where D is the dilution rate which is the reciprocal of the detention time t.

Under steady state conditions there is theoretically no net change in cell concentration in the reactor; i.e.,

$$\frac{dx}{dt} = 0. \quad \text{Therefore } \mu x = Dx, \text{ or } \mu = D \qquad (4)$$

i.e., growth rate is equal to the dilution rate (D). Since the dilution rate is also equal to the inflow rate (f) divided by the volume of the reaction vessel (v), which is constant for any unit, it can be seen that under steady state conditions the growth rate is controlled mainly by the feed inflow rate (f).

The mass balance equation for the substrate is given by increase = input - output - consumption, or

$$\frac{ds}{dt} = DS_R - Ds - \mu\, x/y \qquad (5)$$

where S_R is the substrate concentration in the inflow; s is the substrate concentration in the effluent which is, under conditions of complete mixing, also equal to the concentration in the aerator, and y is the cell yield, which may be expressed as $x/S_R - s$. Since at the steady state $ds/dt = 0$, the substrate concentration may be written:

$$s = k_s \left(\frac{D}{\mu_m - D} \right) \qquad (6)$$

It is seen that in a completely mixed system under steady state conditions the substrate concentration in the effluent is independent of the substrate concentration in

the inflow. It should be noted that substrate concentration (s) and yield (y) as indicated by the equation are applicable only to a system operating under steady state conditions. It is to be realized that the growth rate equation proposed by Monod (Equation 2) is not limited only to a steady state condition. When the steady state condition is disrupted due to shock loads, as in the case of this study, the system growth rate is no longer controlled by the dilution rate and may follow the growth rate equation of Monod, in which μ is dependent upon the substrate concentration level present in the system until a new steady state is reached.

The critical dilution rate (D_c) which represents the maximum dilution rate above which the microorganisms will be completely washed out of the system, can be derived from Equation 6 by substituting: $s = S_R$ and $D = D_c$. Substituting these values, Equation 6 becomes:

$$S_R = k_s \left(\frac{D_c}{\mu_m - D_c} \right)$$

Rearranging this equation

$$D_c = \mu_m \left(\frac{S_R}{k_s + S_R} \right) \qquad (7)$$

B. Steady State Kinetics With Recirculation.

Mathematical formulae for the kinetics of the steady state with cell feedback is similar to that derived for no recirculation. In this type of system a concentrated suspension of cells is recirculated to the aerator at a predetermined concentration and rate of flow. Settled sludge is recirculated from the final settling tank at cell concentration cx_1, where c is a concentration factor equal to the ratio of the cell concentration in the return flow to that in the reactor effluent x_1. The flow rate of the return sludge is determined by the selected recircu-

lation rate (r) which is the ratio between return flow (R) and incoming flow (f); i.e., $r = R/f$; hence, the total flow to the reactor is $f(1+r)$.

The cell concentration that enters the settling tank is $(1+r)fx_1$ and the cell concentration that is returned to the reactor is $rfcx_1$. Therefore the cell concentration in the effluent from the clarifier is

$$fx_2 = (1+r)f\,x_1 - rfcx_1$$

$$x_2 = (1+r-rc)\,x_1, \text{ or}$$

$$\frac{x_2}{x_1} = (1+r-rc) = A \tag{8}$$

Since x_2 should always be less than x_1 in a normally functioning recycle system, then A should have a positive value smaller than unity.

The dilution rate for the reactor with respect to the total flow is

$$D_1 = \frac{(1+r)f}{v}$$

but the overall dilution rate related to the incoming flow is $D = f/v$

The mass balance equation for the cell concentration in the aeration tank is given by:

rate of change = rate of growth + rate of feedback - washout; i.e,

$$\frac{dx}{dt} = \mu x_1 + rDcx_1 - Dx_1(1+r) \tag{9}$$

At steady state

$$dx/dt = 0$$

$$\therefore \mu = (1+r-rc)D = AD \tag{10}$$

In this case, unlike the system without feedback, the steady state growth rate is less than the dilution rate. This indicates that for equal μ values, systems with feedback will handle higher flow rates; that is, systems with feedback can be operated at a greater dilution rate. The mass balance equation for the substrate concentration is:

Rate of change = input + feedback rate - output - consumption, or

$$\frac{ds}{dt} = DS_R + rDs - (1+r)Ds - \mu_m \frac{x_1}{y} \frac{s}{k_s+s} \qquad (11)$$

At steady state $ds/dt = 0$, therefore

$$S = k_s \frac{AD}{\mu_m - AD} \qquad (12)$$

Cell concentration leaving the aerator is given by

$$\mu_m \frac{x_1}{y}\left(\frac{s}{k_s + s}\right) = D(S_R - s), \text{ or}$$

$$\mu \frac{x_1}{y} = D(S_R - s). \quad \text{Since } \mu = \mu_m \frac{s}{k_s + s}$$

$$\therefore x_1 = D(S_R - s) \frac{y}{\mu}$$

$$= y \frac{S_R - s}{A} \quad . \quad \text{Since } \mu = AD \qquad (13)$$

In the present study a value for c of 2.5 and an r value of 0.33. was selected. These values were chosen in order that the solids concentration in the aerator with feedback would be approximately twice that of the system without feedback. However, for one experiment total recirculation was employed; (i.e., 100% sludge recycling) as shown in Figure 48.

In order to demonstrate graphically these relationships between the system parameter values of y, k_s and μ_m were assumed using values which were previously found from

batch studies. The following values were selected for demonstration purposes:

$$y = 0.50,\ \mu_m = 0.51\ hr^{-1},\ k_s = 50\ mg/l$$

$$c = 2.5, \text{ and } r = 0.33.$$

In Figure 1 is shown the relationship between s and x_1 for various values of dilution rate with and without recirculation of sludge. It can be seen from the figure that the dilution rate does not significantly affect the system until its value exceeds 0.35 hr^{-1} and 0.75 hr^{-1}, respectively, with and without recirculation. Beyond this value the solids drop down considerably with a concomitant increase in the residual concentrations of the substrate, and finally a dilution rate is reached at which no solids can be maintained in the aerator. This is due to the fact that higher flow rates or lower detention times exceed the rate at which the organisms can multiply. As a consequence of this, the solids in the aerator are merely displaced, and the system fails. This is known as "washout." It can be seen from Figure 1 that washout occurs at 0.486 hr^{-1} without recirculation, and 0.97 hr^{-1} with recirculation.

The obvious advantage of increased solids concentration in the recirculation system is its ability to handle higher organic loading. The recirculation system also reduces the aerator size, since it can handle higher flow rates.

C. Kinetics of Increase and Decrease of Glucose Concentration due to a Shock Load in the Steady State System.

In the present study two types of shock loading were used. Gradual shock loadings were administered by changing the glucose concentration in the feed to a value greater than that employed under the previous steady state condition. Slug loading was accomplished by injecting a concentrated solution of glucose directly into the aerator to

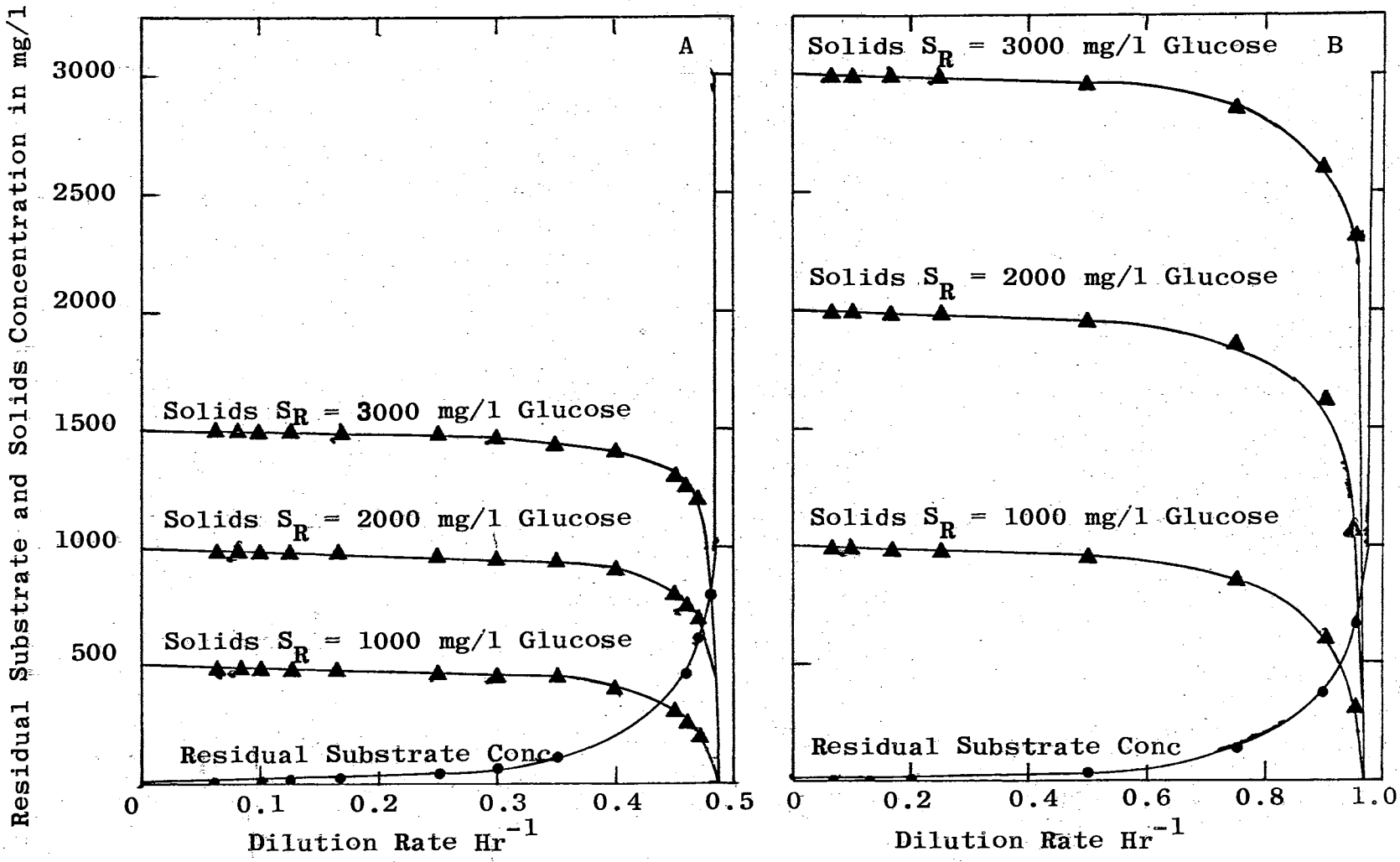

Fig. 1 - STEADY STATE RELATIONSHIP A) NO RECIRCULATION AND B) WITH RECIRCULATION

bring its concentration to a specific value. Both types of shock loading were administered without changing the flow rate. The only change was due to the increased concentration of glucose.

The rate of increase in the glucose concentration in the aerator due to a gradual shock loading can be expressed as:

$$\frac{ds}{dt} = S_R D - sD \tag{14}$$

where ds/dt is the rate of change of glucose concentration with time. S_R is the concentration of glucose in the inflow, s is the concentration of glucose in the outflow, and D is the dilution rate. Integration of this equation yields:

$$s = S_R (1 - e^{-Dt}) \tag{15}$$

This equation was also used to check whether complete mixing occurred in the aerator using methyl red as indicator. Results of such an experiment are shown in Figure 2. The application of Equation 15 to completely mixed systems have been discussed more fully by Komolrit and Gaudy (86). From the result it can be seen that essentially complete mixing was achieved in the aerator.

The kinetics of decreasing glucose concentration in the aerator due to diluting out of a slug loading is given by:

$ds/dt = DS_R - Ds$. At zero time

$S_R = 0$. Therefore

$$ds/dt = - sD \tag{16}$$

Upon integration this equation yields:

$$s = s_o e^{-Dt} \tag{17}$$

where s_o is the concentration of glucose in the aerator.

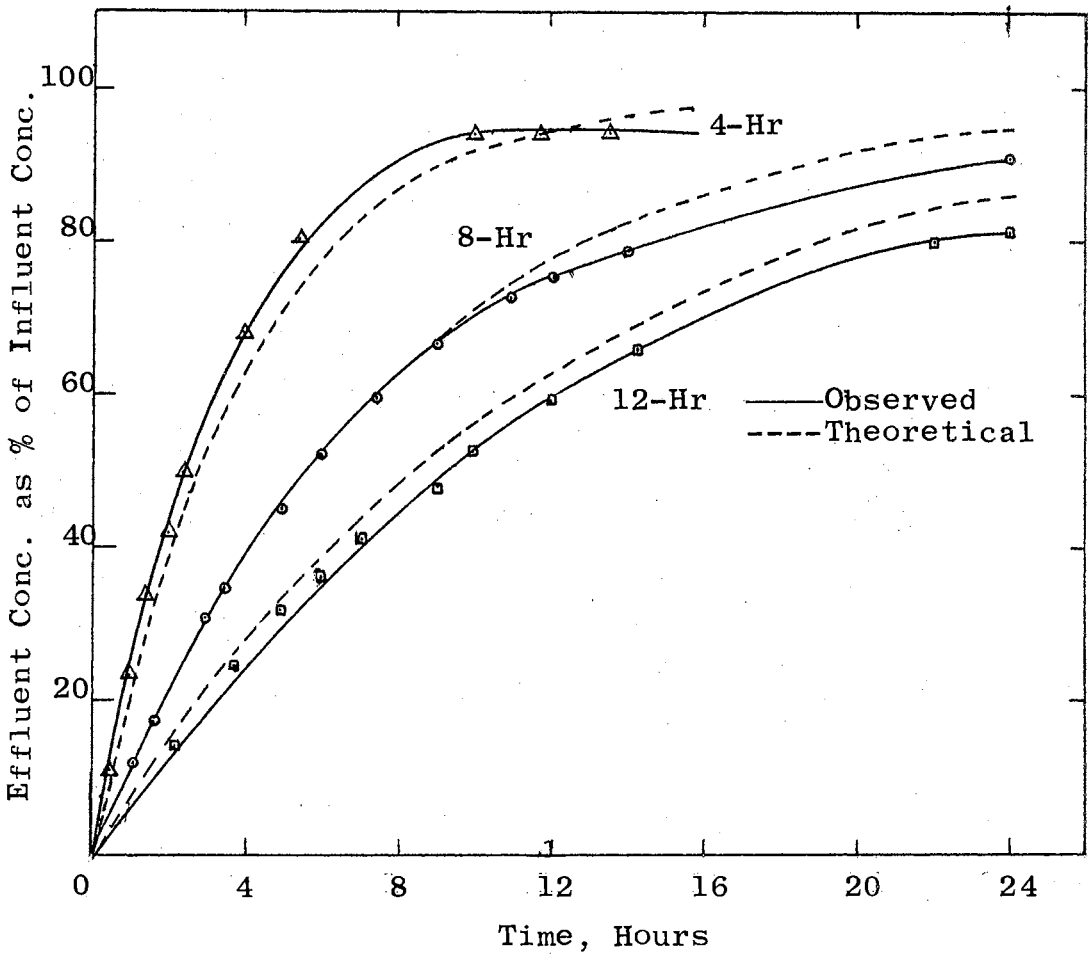

Fig. 2 - DEGREE OF COMPLETE MIXING AT DIFFERENT DETENTION TIMES USING METHYL RED AS INDICATOR

Equations 15 and 17 were developed to show the increase of glucose concentration in the aerator due to gradual shock loads and decrease of glucose concentration in the aerator after it had received a slug dose of glucose. These equations are useful in predicting the theoretical concentration of glucose at any time during shock loads. Comparison of this value with the actual concentration in the aerator provide a convenient method of evaluating the response to shock loadings. The use of these equations will be discussed more fully in a subsequent section of this report.

CHAPTER IV

MATERIALS AND METHODS

A. Description of Apparatus and Standard Synthetic Wastes:

1. Apparatus.

A photograph of the experimental activated sludge unit employed in this study is shown in Figure 3. The volume of the glass aerators was 2.5 liters, but the effective volume of mixed liquor under aeration was approximately 2.4 liters due to the displacement of mixed liquor by the diffused air. The air flow rate used was 4000 ml/min when sludge recirculation was not used. When recirculation was employed, it was found that this flow rate was insufficient to keep the solids completely mixed. Therefore, air flow rate was maintained in excess of 5000 ml/min and due to this increased air flow rate, the volume of mixed liquor was reduced to 2.2 liters. The air was supplied to the aerator through porous glass diffusers. With recirculation of sludge, air was supplied at two different levels of mixed liquor, one diffuser was placed at the bottom of the aerator, and the other was located six inches from the bottom. This was found necessary due to the increased solids concentration in the aerator.

The inflow of the synthetic waste to the aerator was regulated by a pump (Milton Roy Co., Philadelphia, Pa. Model No. 4-c-48-R), which was previously calibrated to give the desired flow rate to maintain a particular detention time or dilution rate. The mixed liquor from the aerator was collected in a glass jug and periodically wasted. When recirculation was used, the effluent from the aerator was discharged directly into a settling tank. The settling

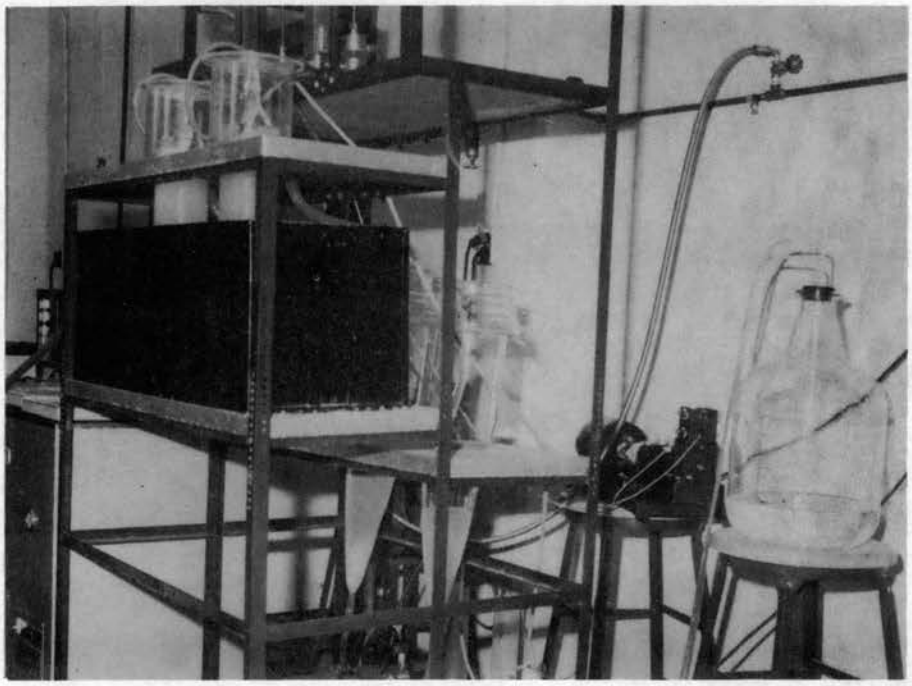

Fig. 3 - PHOTOGRAPH OF BENCH-SCALE COMPLETELY MIXED ACTIVATED SLUDGE SYSTEM

tanks are located behind the aerator in Figure 3. The settled sludge was collected and aerated. The solids concentration in the returned sludge was maintained at 2000 $\pm$ 100 mg/l except in two experiments where the average solids concentration in the return sludge was 1820 and 2290 mg/l, respectively. The temperature of the system was maintained constant throughout the experiment, and the variation in temperature for all of the experiment was 25°C. $\pm$ 0.5°C. The temperature for two experiments was not controlled.

2. Standard Synthetic Wastes.

The synthetic waste used in the present study consisted of glucose and essential inorganic salts. The inorganic salts were added to provide a nutritionally balanced synthetic waste. The amounts of inorganic salt used per 1000 mg/l of glucose were:

$(NH_4)_2 SO_4$, 500 mg/l; $MgSO_4 \cdot 7H_2O$, 100 mg/l; $MnSO_4 \cdot H_2O$, 10 mg/l; $Fecl_3 \cdot 6H_2O$, 0.5 mg/l; $Cacl_2 \cdot 2H_2O$, 7.5 mg/l; tap water, 100 ml/l, and 1.0 M potassium phosphate buffer at pH 7.0, 10 ml/l. The volume of synthetic waste was made to one liter with distilled water. Whenever the glucose concentration used was more than 1000 mg/l, the inorganic salts and buffer were proportionally increased to maintain the same amount of inorganic nutrients with respect to glucose. The ratio of COD to N and COD to P of the synthetic waste were 10:1 and 2.93:1, respectively. These ratios were much higher than the values reported in the Sanitary Engineering literature. The reason for maintaining such high ratios was to insure that the carbon source was the only limiting nutrient. When nitrogen-limiting conditions were studied, the amount of $(NH_4)_2SO_4$ was reduced to give the desired carbon to nitrogen ratio.

B. Experimental Protocol.

Initially, two liters of standard waste were made at a glucose concentration of 1000 mg/l and transferred to the

aerator. The synthetic waste was seeded with 50 ml of primary effluent from the Stillwater municipal treatment plant, and then operated as a batch unit for 24 hours. This was done in order to develop sufficient solids concentration in the aerator. After 24 hours the unit was operated under continuous flow conditions at the desired detention time. Three detention times, 4, 8, and 12 hours, were employed in the present study. Prior to any particular shock loading experiment, the unit was operated at least three days to insure steady state conditions. When recirculation was adopted normally three weeks were required before flocculated cells were developed which would settle well.

Normally during the period of equilibration samples of effluents were periodically analyzed to ensure that steady state conditions had been reached. Shock loading experiments were conducted only when the unit had reached steady state.

Normally two units were operated simultaneously. As an extra precaution prior to each experiment the contents of both units were thoroughly mixed and placed back into the system. This was done in order to ensure that conditions in both units were identical prior to a shock loading experiment.

Gradual shock loadings were administered by changing the influent feed to a new synthetic feed of desired glucose concentration. Slug doses were administered by directly injecting glucose solution into the aerator to bring the glucose concentration to the desired value. Prior to the injection of glucose, a portion of the mixed liquor equivalent to the volume of glucose to be added was removed. This was done in order to maintain a constant aeration volume. The volume of mixed liquor that was removed prior to the injection of glucose were 48 and 72 ml for 2000 and 3000 mg/l glucose slug doses, respectively.

C. Analytical Technique.

The chemical oxygen demand of the samples was determined in accordance with the procedure given in Standard Methods

(87). Potassium dichromate (0.25N) and concentrated sulfuric acid were used. Silver sulfate was always added as catalyst.

The glucose concentration in the samples was determined by the anthrone test using the procedure outlined by Gaudy (88). A modification with respect to the quantity of anthrone later proposed by Gaudy, Komolrit, and Bhatla (89) was incorporated. In addition to the anthrone test, glucose was determined by the glucostat test for some of the experiments. This test was performed in accordance with the procedure outlined in the Worthington Biochemical Corporation manual (90).

Biological solids concentration was determined by the membrane filter technique (Millipore Filter Co., Bedford, Mass., HA 0.45 μ). Very light aluminum dishes (weighing approximately 0.2 to 0.3 gms) were used to hold the Millipore filters. Filters were dried for two hours at 103^{o}C. and equilibrated in a dessicator overnight prior to obtaining the tare weight. Before final weighing, the same heating and cooling procedure was followed.

The protein and carbohydrate content of the sludges were determined by the procedure outlined by Gaudy (88). The amount of anthrone reagent added to the sample was increased, as indicated under the test for glucose by the anthrone method.

Lipid content of the sludges was determined for only two experiments. Extraction of lipids from a filtered 25 ml sample of sludge was carried out using 60 ml of 3:1 ethanol:ether (Skelly, B.P30-60) mixture (91). Lipids were extracted for six hours on a shaker at 25^{o}C. After extraction, the flask contents were filtered through a 0.45 μ Millipore filter. The filtrate was poured into a COD flask, and the ethanol-ether mixture was evaporated at 70^{o}C. The flask was then flushed with a gentle stream of air. Blanks and standards were prepared by similarly evaporating 60 ml of the ethanol-ether mixture alone and

60 ml of the mixture containing known amounts of stearic acid. After evaporation the standard procedure for COD analysis was followed. The lipid content of the sludge sample was calculated by comparing the COD values of the sample with the COD values of the standard stearic acid sample.

The carbon, hydrogen, and nitrogen contents of the sludge were determined for only two experiments. The carbon, hydrogen, and nitrogen contents of the samples were determined using a model 180 C.H.N. analyzer (F&M Scientific Company, Avondale, Pennsylvania). This instrument operates on the following principle: Any sample containing carbon, hydrogen, and nitrogen, when combusted in the presence of silver oxide as catalyst, is converted to CO_2, H_2O and nitrates or nitrites. The nitrates and nitrites are reduced to nitrogen as they pass through reduced copper in the combustion tube. The combusted sample is analyzed for C, H, and N by gas chromatography.

Volatile acids in the filtered sample were determined using the steam distillation method (87) and gas chromatography. An aliquot of the filtered sample (usually 25 ml) was made up to 50 ml with distilled water and then acidified with 2 ml of 10N sulfuric acid. Approximately 35 gm of $MgSO_4 \cdot 7H_2O$ was added and the solution was then steam distilled. Similarly, 50 ml of distilled water was also steam distilled, and this served as a blank. A volume of 450 ml of the distillate was collected and titrated against 0.05N NaOH using phenolphthalein as indicator. The amount of distillate to be collected was based on the distillation of a standard solution of sodium acetate. The procedure used was in accordance with Standard Methods (87) except that 0.05N NaOH was used instead of 0.10 N NaOH. This modification was adopted because of the low volatile acids concentration present in the sample. It was found that distillation of 50 ml distilled water consumed 0.6 ml

0.05N NaOH. Therefore all of the samples were corrected for this blank titration.

The individual volatile acids in the sample were determined by gas chromatography. A Model 810 gas chromatograph (F&M Scientific Company) equipped with a 1/4" glass column packed with 20% (weight) diethylene glycol adipate polyester and 2% phosphoric acid on 60 to 80 mesh chromosorb W adsorbent was employed. Helium was used as the carrier gas. Several trial runs were carried out to determine optimum conditions for the separation of individual volatile acids. The main object of these runs was the separation of all acids within a reasonable time. Based on the trial runs, the following conditions were adopted for the analysis of fatty acids. Helium was supplied at the rate of 140 ml/min at 60 psi pressure. Hydrogen and air were supplied at 30 psi and 33 psi, respectively. The column temperature was maintained at 120^{o}C. The detector and injector temperature were maintained at 270^{o}C. and 290^{o}C., respectively. Dual flame detection was adopted for the analysis. When a mixture of volatile acids is injected into the column, each individual acid is retained in the column for a specific period of time before it is eluted. The acids are eluted on the basis of number of carbon atom (i.e., the higher the number of carbon atoms, the greater the time an acid is retained on the column). Retention time is the basis for the qualitative identification of volatile acids. The retention times of various volatile acids are shown in Table I. It was found that after the column had been in use for a month, the retention time was considerably shortened, as indicated in Table I. It was thought that the calibration of the rotameter which controls the helium flow might have been changed in such a way as to result in greater carrier gas flow, and hence reduced retention time. In order to check the helium flow at various rotameter settings, flows were measured with a gas flowmeter; the results are shown in Fig-

TABLE I

RETENTION OF VOLATILE ACIDS IN GAS CHROMATOGRAM COLUMN

Acids	Retention Time in Minutes	
	1[1]	2[2]
Acetic	5.65	2.40
Propionic	8.15	3.50
Isobutyric	9.15	3.80
Butyric	12.10	5.10
Isovaleric	14.75	6.10
Valeric	20.30	8.40
Hexanoic	33.25	13.75

[1]Retention times for new column after break-in period

[2]Retention times for same column after 30 days.

ure 4. It can be seen from the figure that helium flow was higher for all rotameter settings than the flow suggested by the manufacturer. However, when the airflow was maintained at 140 ml/min and a chromatogram was run with the standard volatile acids, it was found that retention time obtained during the break-in period (indicated under column 1 of Table I) could not be repeated. A possible reason for this might be that the column had not been fully conditioned during the early retention time study. A mixture of standard volatile acids at different concentrations (50, 100, 150, 200 mg/l) were run through the column to determine their retention time and peak area. In all the analyses the volume of sample was kept constant at 5 µl. The areas under the peaks were measured by a planimeter and calibration curves between concentration and and peak area were plotted and are shown in Figures 5 and

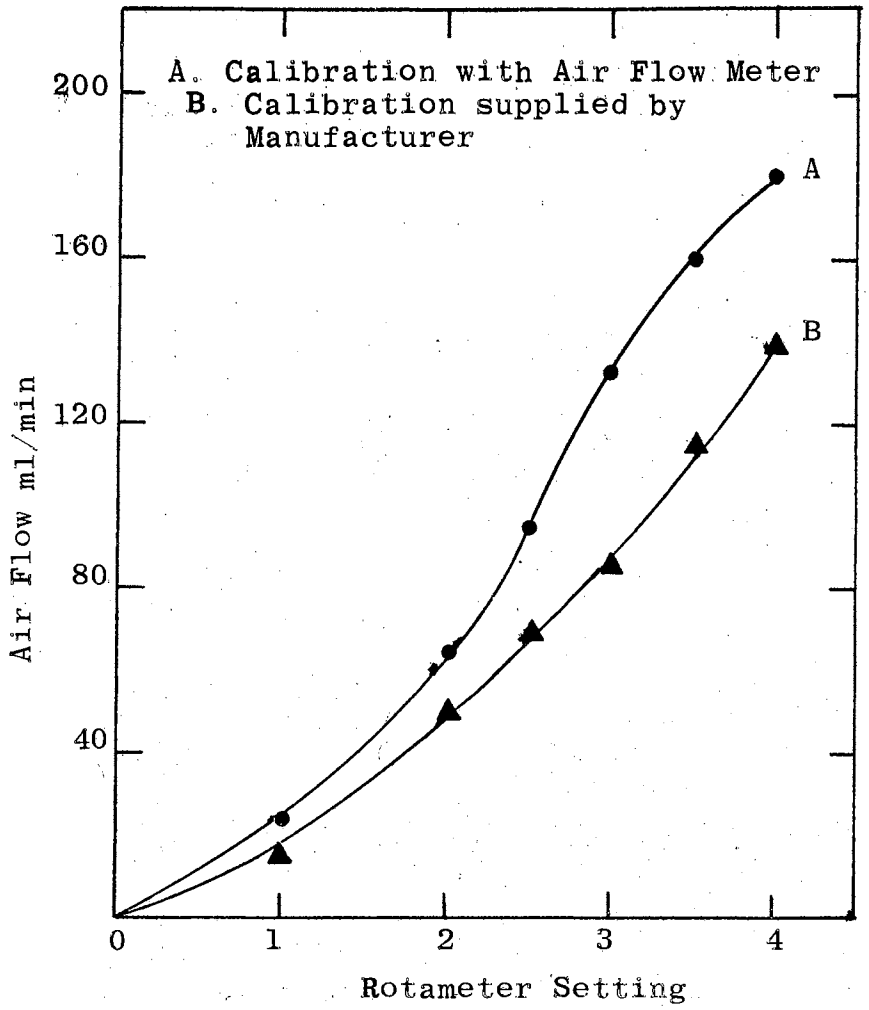

Fig. 4 - RELATION BETWEEN ROTAMETER SETTING AND AIR FLOW

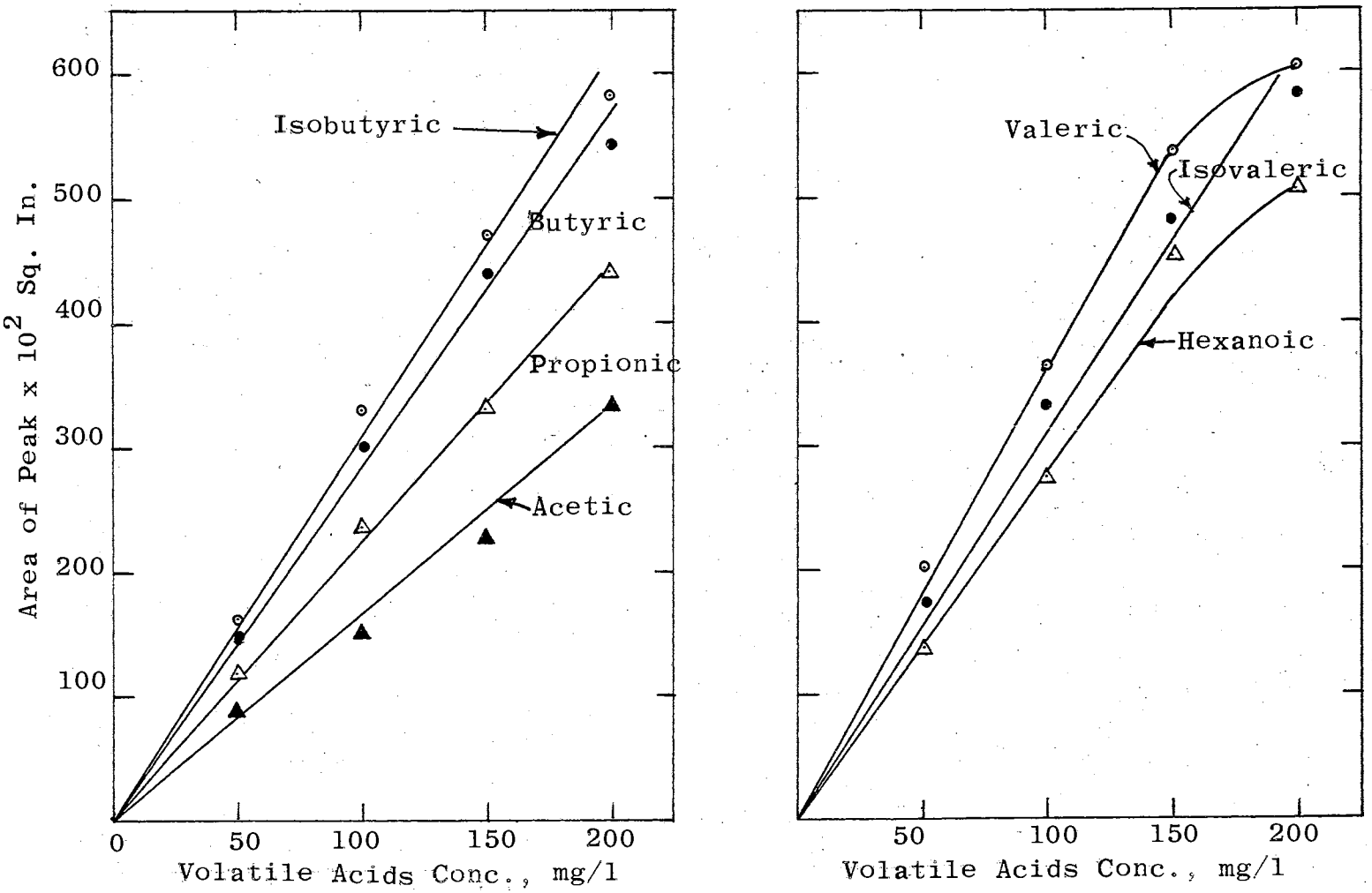

Fig. 5 - CALIBRATION CURVE FOR VOLATILE ACIDS DETERMINATION BY GAS CHROMATOGRAPHY

7. The standard gas chromatogram of 50 mg/l concentration of each acid are shown in Figures 6 and 8. The areas plotted for 50 mg/l of volatile acids in Figure 5 were obtained from Figure 6, and the areas shown in Figure 7 for 50 mg/l of volatile acids were obtained from Figure 8. When the retention time was changed. the peak area was also increased, as shown in Figures 6 and 8. These variations do not affect the results, since standard samples were run with each determination. It was found that formic acid could not be detected with the flame detector, although it was detected with thermal conductivity. The thermal conductivity was not used on account of its insensitivity to the low concentrations of volatile acids that were normally encountered in the sample. Hence, formic acid was not identified in the samples.

Dissolved oxygen in the mixed liquor was measured with the Jarrel Ash dissolved oxygen analyzer. The dissolved oxygen in mixed liquor was measured as percentage of saturation value. The percent saturation was converted to dissolved oxygen in mg/l using the saturation value of oxygen at the measured temperature. The measurement of dissolved oxygen was done in accordance with the procedure given in the Jarrel Ash manual (92).

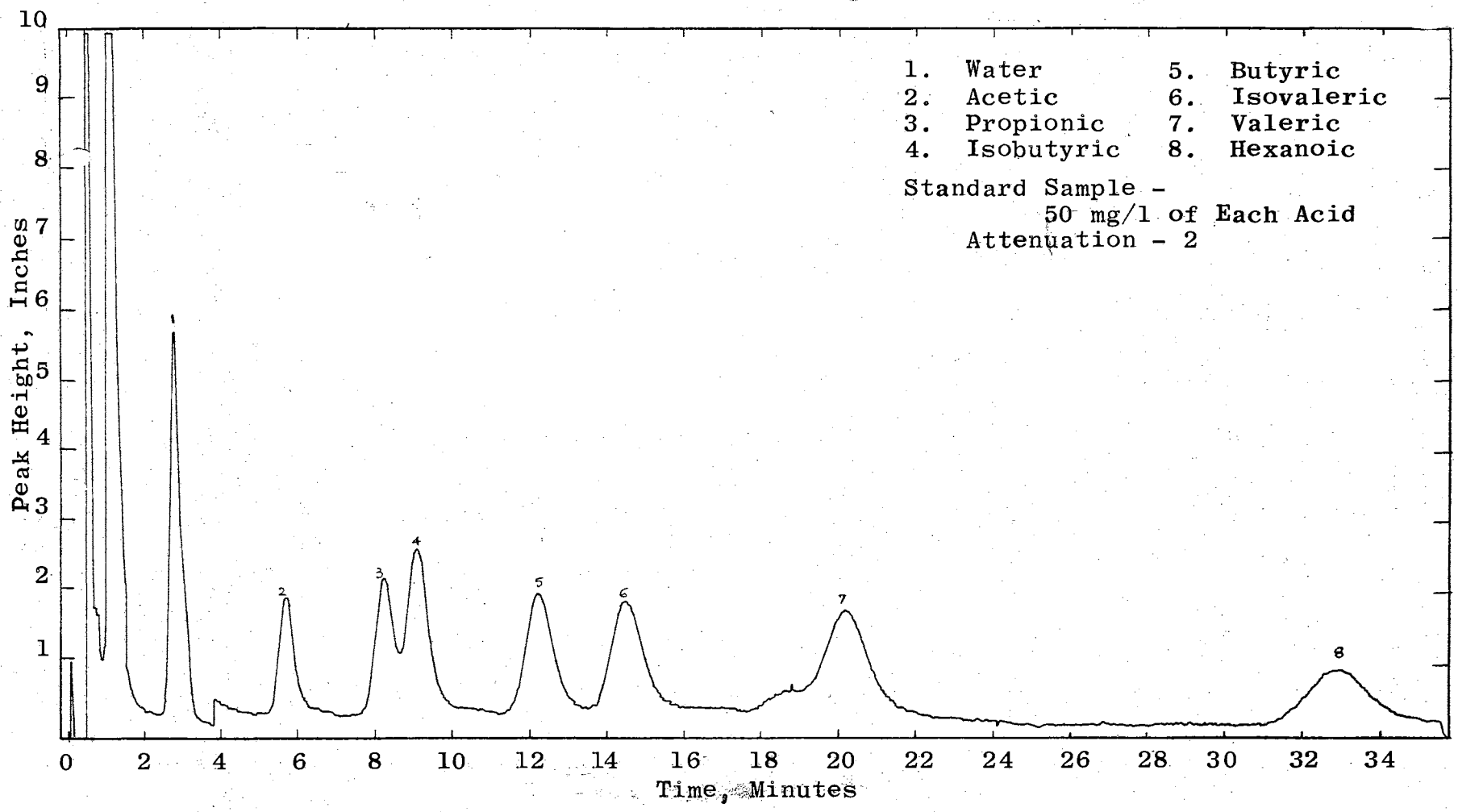

Fig. 6 - STANDARD CHROMATOGRAM OF MIXTURE OF VOLATILE ACIDS

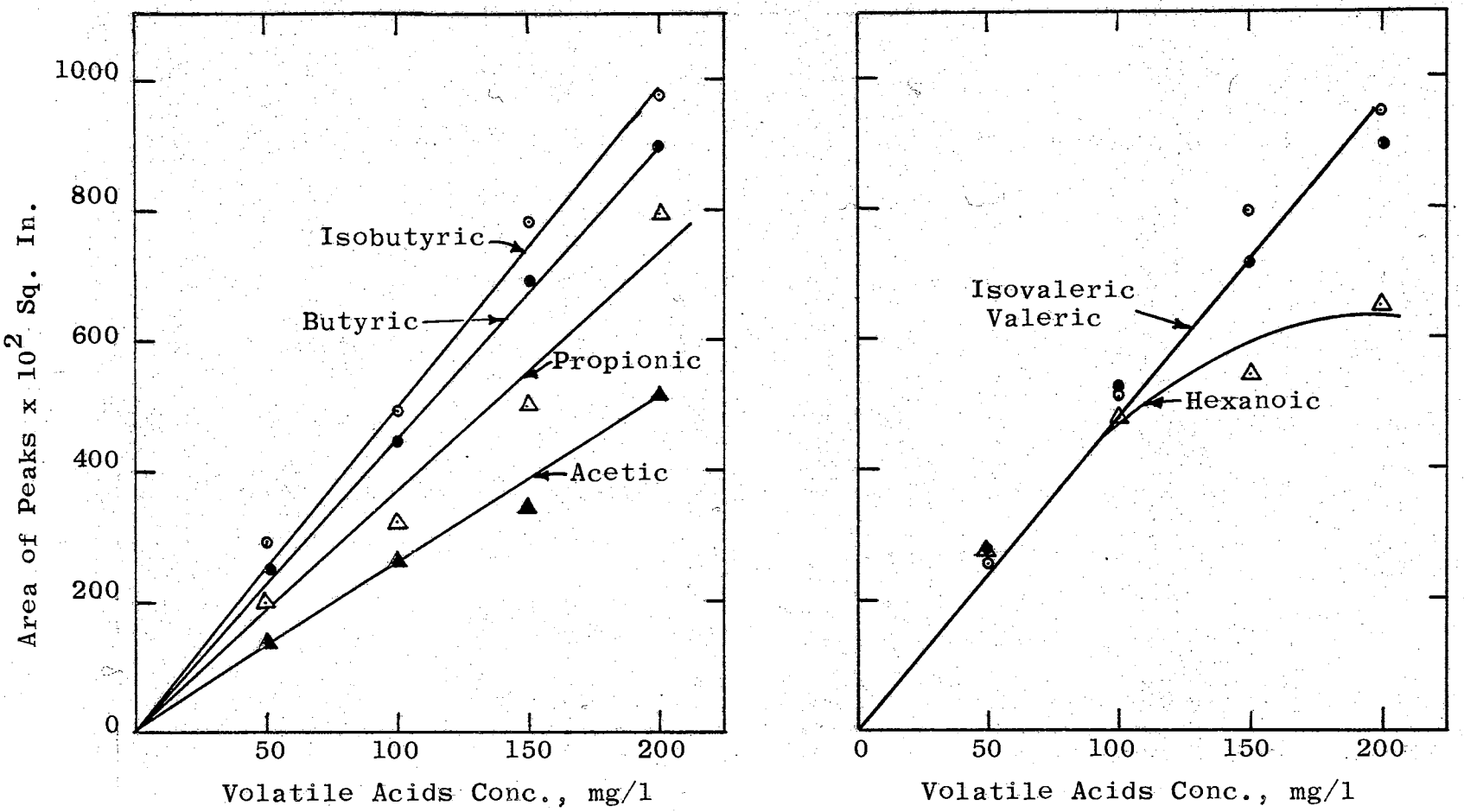

Fig. 7 - CALIBRATION CURVE FOR VOLATILE ACIDS DETERMINATION BY GAS CHROMATOGRAPHY

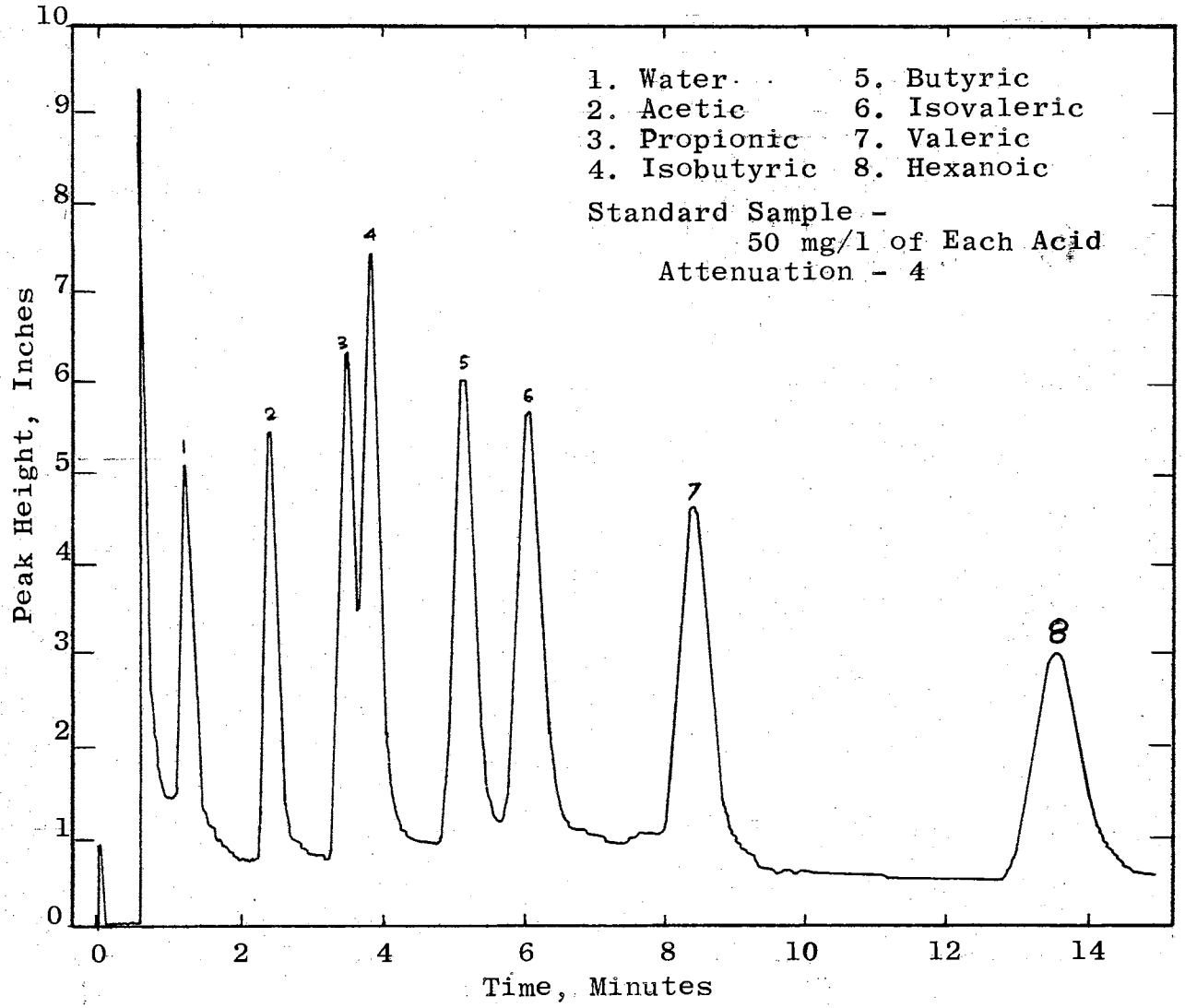

Fig. 8 - STANDARD CHROMATOGRAM OF MIXTURE OF VOLATILE ACIDS

CHAPTER V

RESULTS

The results are presented in the following four sections: (1) response to gradual shock loading; (2) response to slug shock loading; (3) response to shock loading under nitrogen deficient conditions; and (4) release of intermediates during shock loading. All experiments under sections (1) through (3) were conducted with and without recirculation of sludge. In the experiments employing sludge recirculation, the concentration of glucose in the influent was maintained at the same value as that employed for experiments without sludge recirculation. This was done to simulate the condition existing in any treatment plant. Studies on the release of intermediates were accomplished without solids recirculation at a 4-hour detention time.

1. Response to Gradual Shock Loads.

a. 4-Hour Detention Time. The steady state behavior of the continuous flow unit at 1000 mg/l glucose is shown in Figure 9. It can be seen that the solids level fluctuated somewhat although other parameters remained fairly constant. The anthrone COD in both of the systems remained at a very low level during the entire period of the experiment; however, the total COD was considerably higher in both systems, indicating the possible release of intermediates or residual compounds resistant to metabolism. The difference between the total COD and anthrone COD could not be attributed to the interference of inorganic

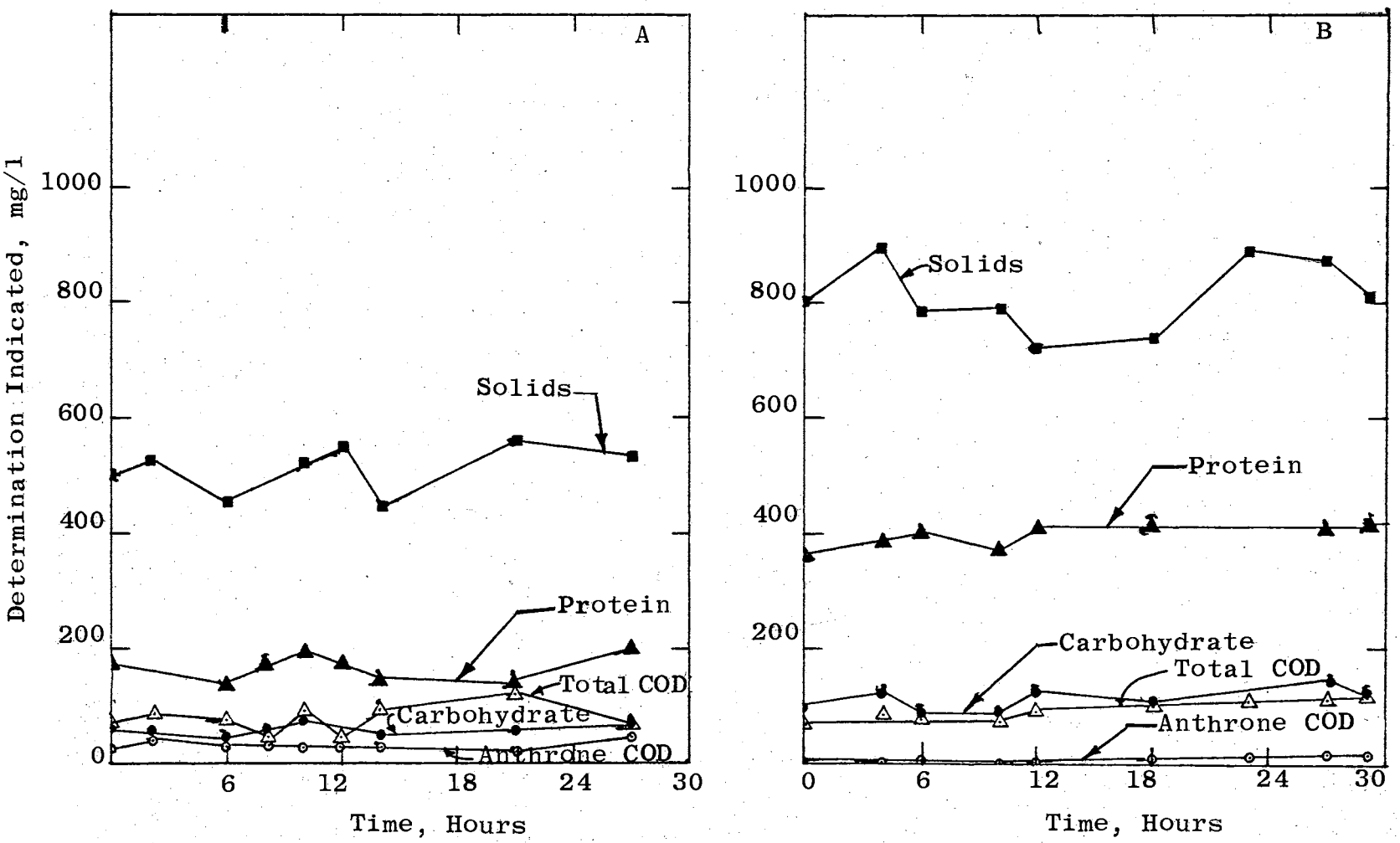

Fig. 9 - STEADY STATE BEHAVIOR OF THE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AT 1000 mg/l GLUCOSE. A) NO RECIRCULATION, AND B) WITH RECIRCULATION

salts in the influent feed which had a COD of only 16 mg/l.

The shock load response when the influent feed was changed from 1000 mg/l to 2000 mg/l glucose is shown in Figure 10. The shock load increased the total COD in the effluent from 75 mg/l to 340 mg/l in four hours. It can also be seen that there is considerable difference between total COD and anthrone COD of the effluent. The dotted line in Figure 10 represents the theoretical glucose concentration in the aerator due to the shock load if it were not removed by the activated sludge. It can be seen that the system is capable of handling a shock load of 2000 mg/l glucose; however, eight hours elapsed before the total COD value returned to the previous steady state value. It can also be seen that more COD is present in the effluent than can be accounted for by the anthrone COD.

In Figures 11 and 12 are shown the response in the continuous flow unit when the system was subjected to 3000 mg/l glucose. This represents a three-fold increase in the glucose concentration of the feed. It is obvious from Figure 11 that the biochemical efficiency of the system was seriously affected and that it could not handle this shock load successfully. The total COD of the effluent increased to a maximum of 900 mg/l. Sixteen hours were required before the COD of the effluent reached a fairly constant value. It is also interesting to note that the biological solids concentration nearly attained a steady state value at sixteen hours. The COD of the effluent was, however, higher than the previous steady state value of 50 mg/l. The anthrone COD did not increase as much as the total COD and was very low after six hours. When recirculation of solids was employed (see Figure 12), the system was not at all affected by this shock load. There was only a very slight increase in total COD over the previous steady state value of 65 mg/l.

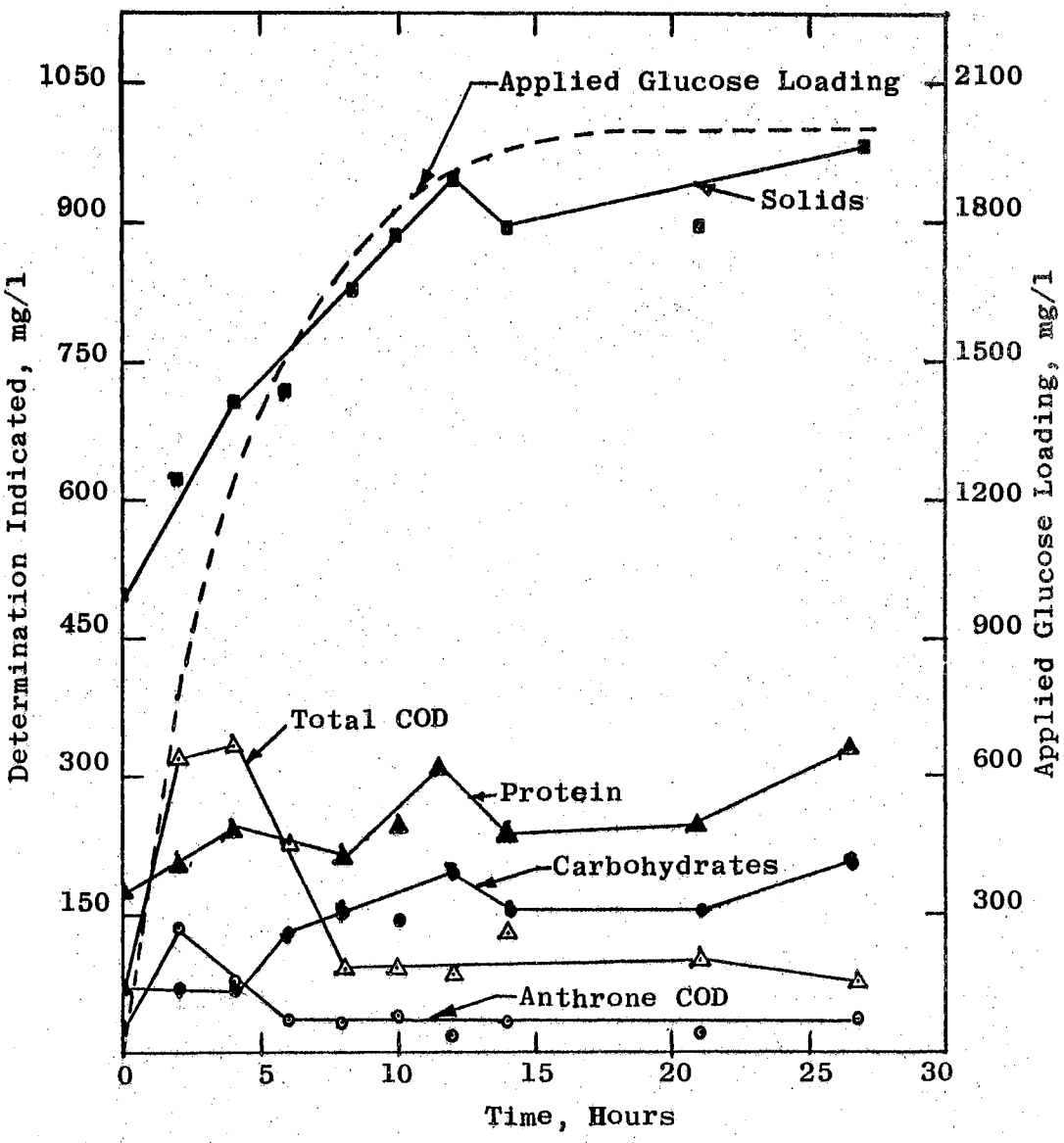

Fig. 10 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE (NO RECIRCULATION)

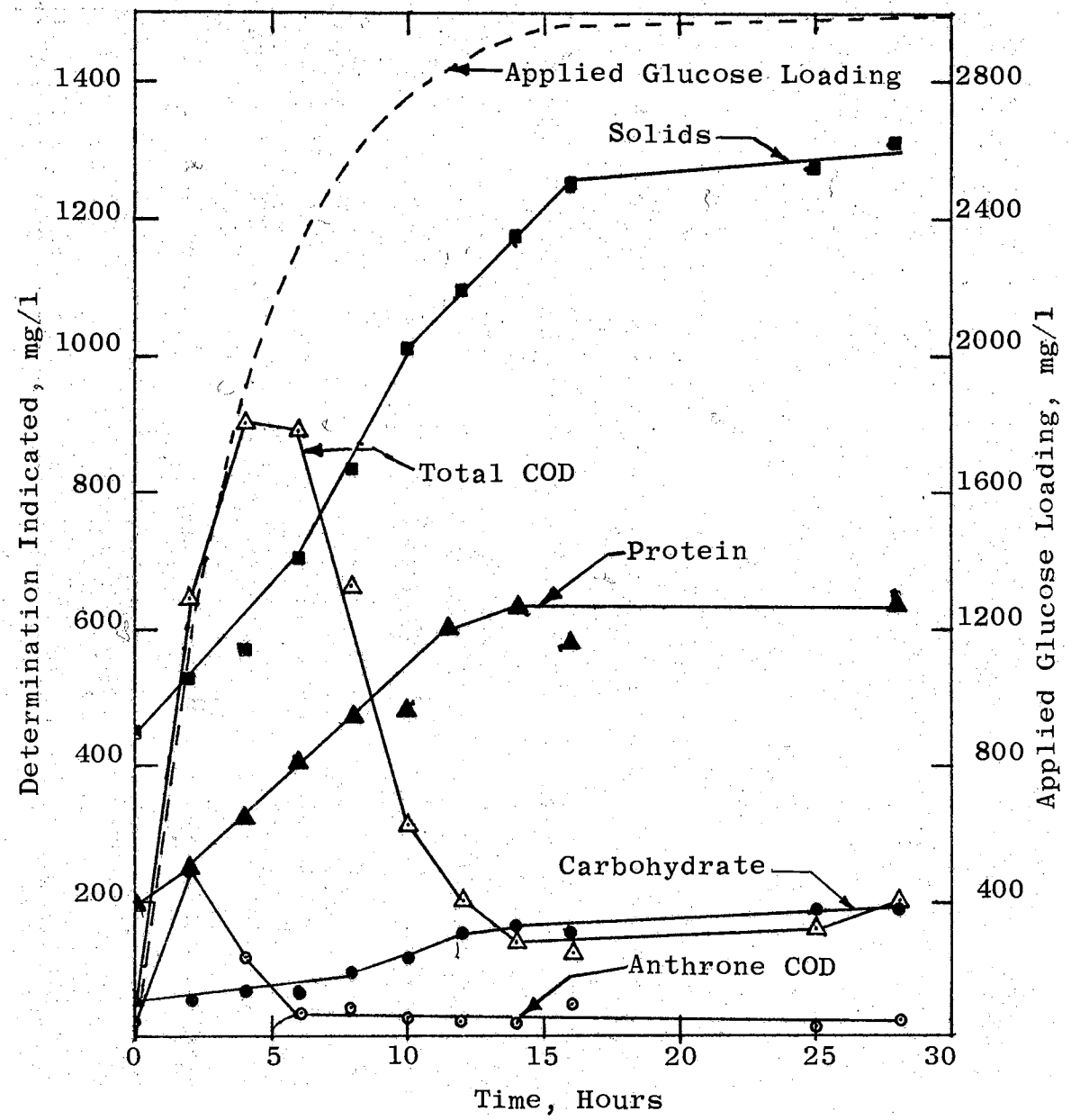

Fig. 11 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/1 TO 3000 mg/1 GLUCOSE (NO RECIRCULATION)

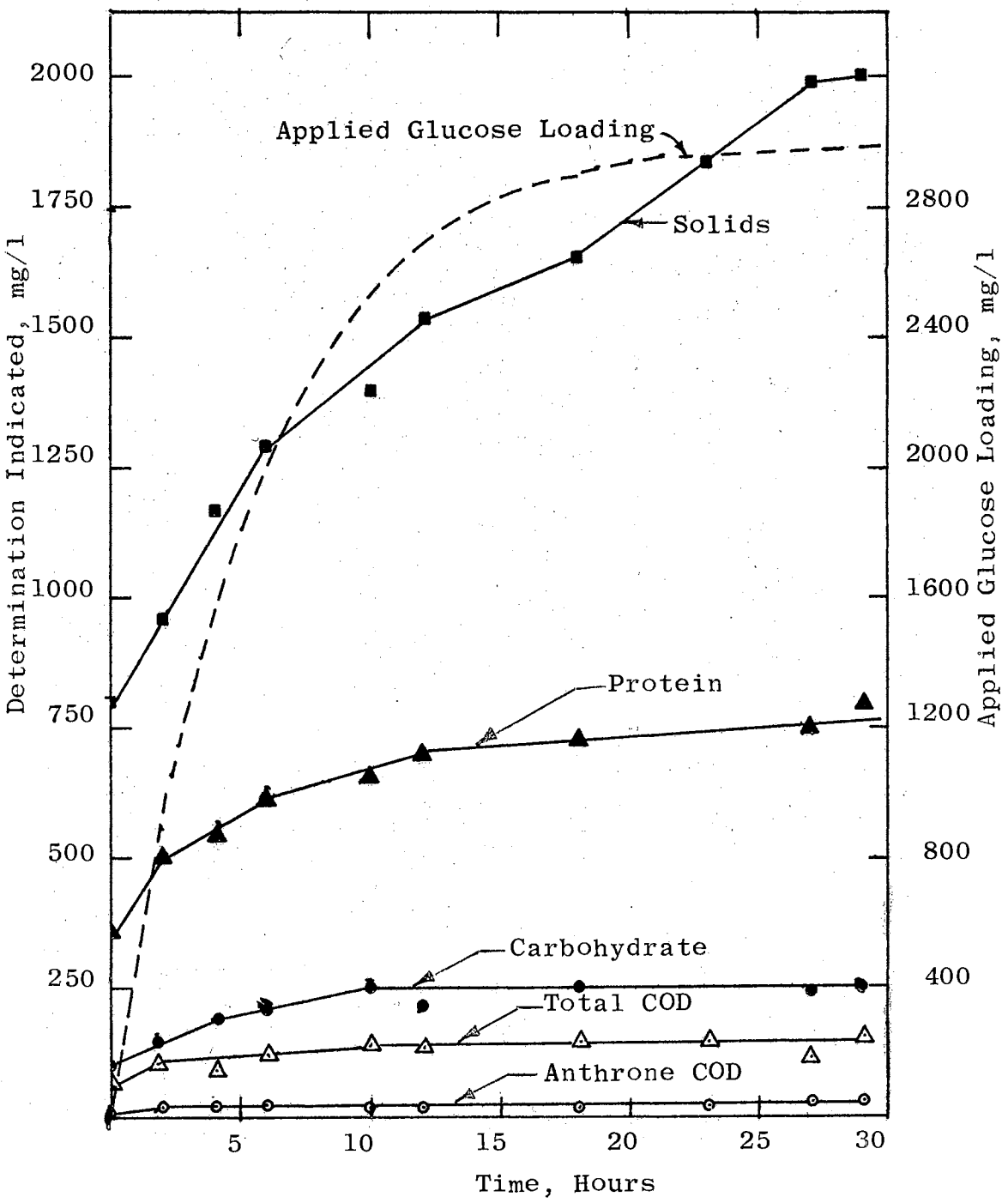

Fig. 12 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE (RECIRCULATION)

The shock load responses when the influent glucose concentration was changed from 1000 mg/l to 5000 mg/l are shown in Figures 13 and 14. It is apparent from Figures 13 and 14 that neither system was capable of handling a 5000 mg/l glucose shock loading. In both systems there was a rapid increase of total COD. It is interesting to note that approximately 50% of the theoretical glucose concentration at four hours was present in the effluent as total COD in either system. In the unit with no recirculation of solids the glucose concentration was very low after six hours. In contrast to this system, in the unit in which solids were recirculated the glucose (anthrone) COD was very high. This result indicates that release of intermediates did not occur to any great extent when solids were recirculated. It can also be seen from Figures 13 and 14 that the COD concentration reached a steady value when the solids concentration approximated a constant value. The increase in solids concentration was also accompanied by an increase in protein and carbohydrate content of the solids. The residual COD was quite high in both systems and did not return to the previous level during the entire period of the experiment. It can be seen that recirculation of solids does not seem to improve the performance at a shock loading level of 5000 mg/l glucose. Although the solids increased rapidly in both systems, the response was not rapid enough in comparison with the rapid increase in glucose concentration as shown by the dotted lines in Figures 13 and 14. Almost sixteen hours were required before total COD in the effluent reached a steady state value.

b. 8-Hour Detention Time. The steady state behavior of the continuous flow unit at 1000 mg/l glucose is shown in Figure 15. As with the 4-hour detention time, there was considerable variation in the level of biological solids although other parameters remained fairly

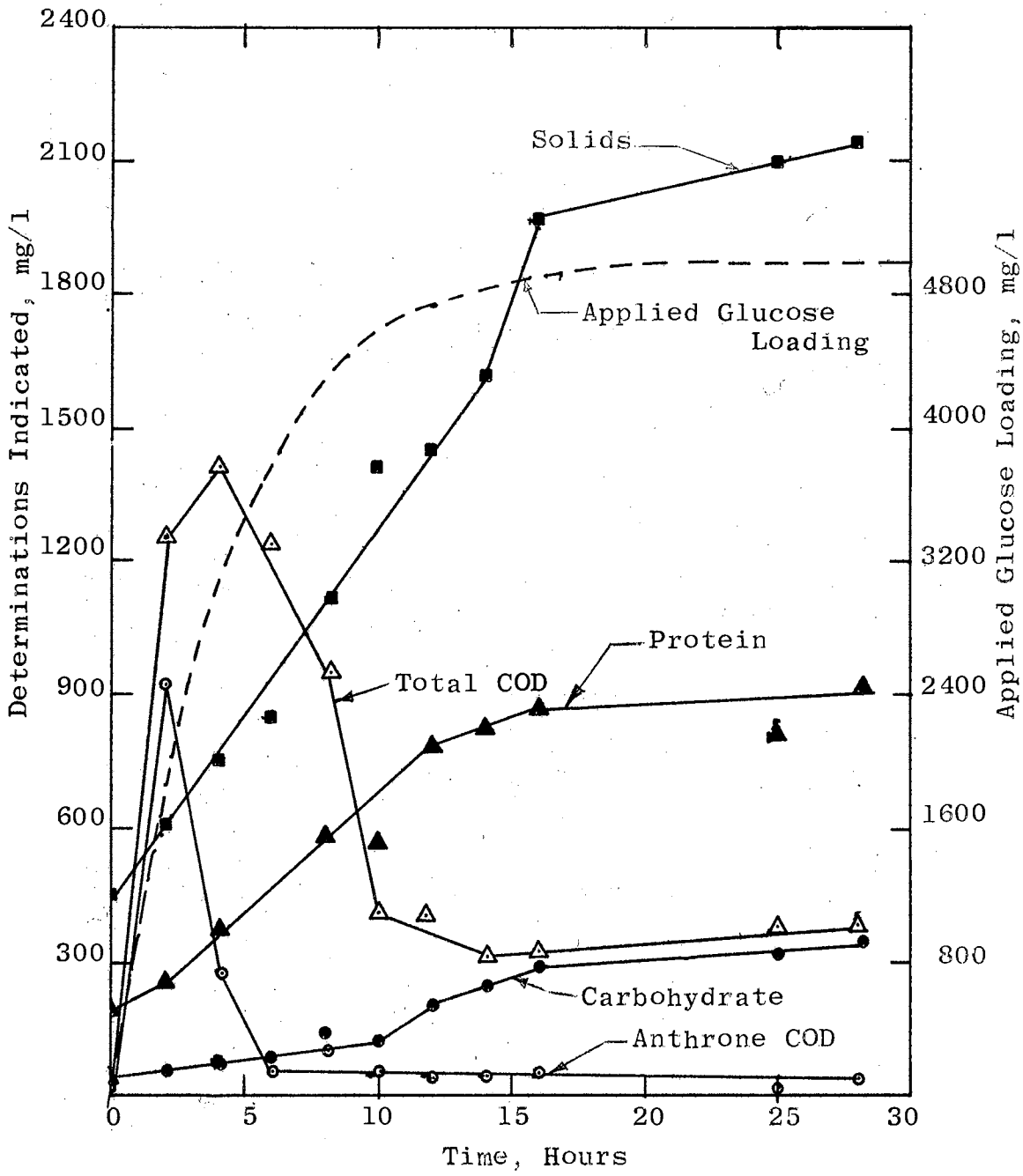

Fig. 13 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (NO RECIRCULATION)

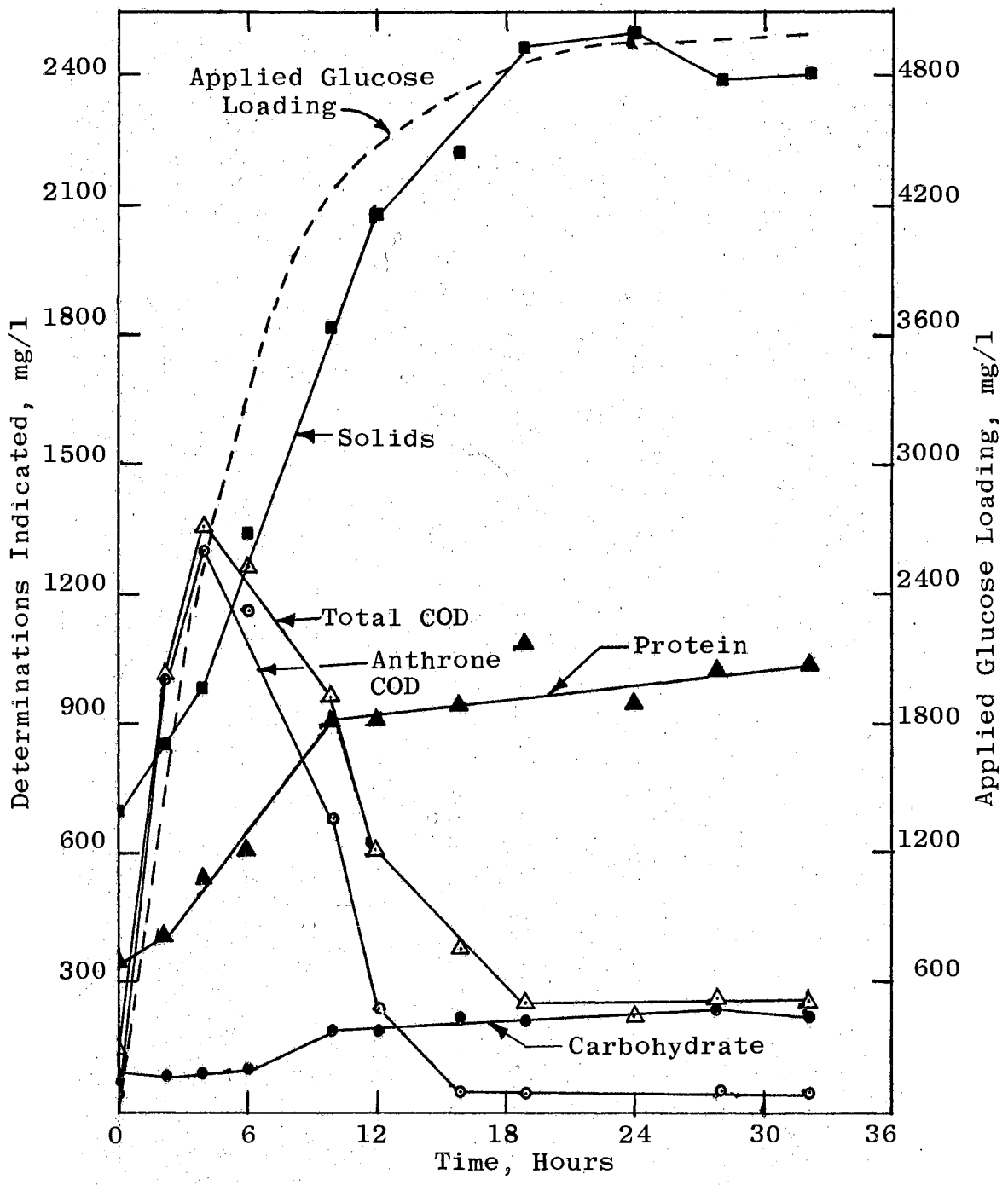

Fig. 14 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (RECIRCULATION)

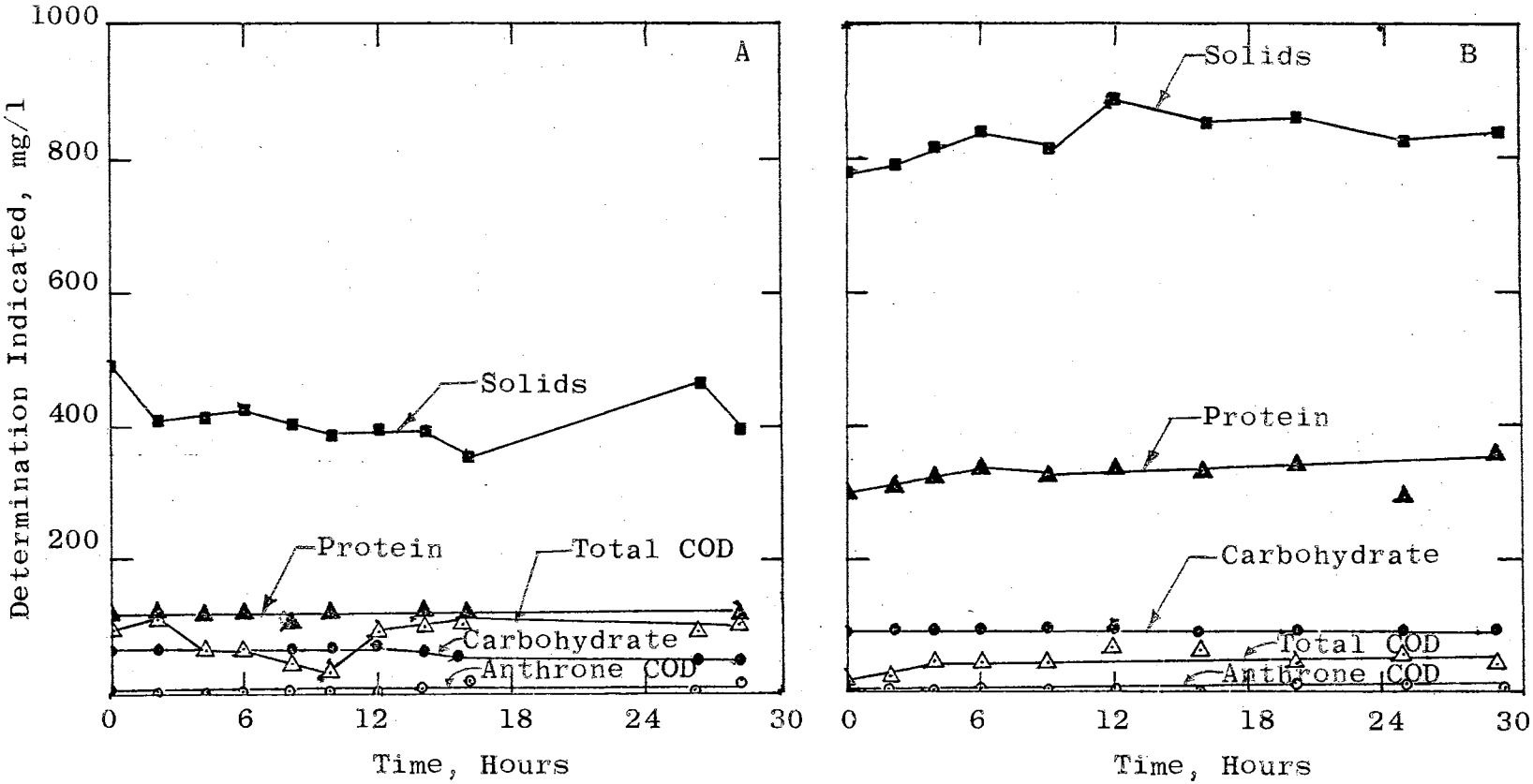

Fig. 15 - STEADY STATE BEHAVIOR OF THE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AT 1000 mg/l GLUCOSE. A) NO RECIRCULATION, AND B) WITH RECIRCULATION

constant. The anthrone COD was very low in both systems in comparison with the total COD.

In Figure 16 is shown the response in the continuous flow unit when the influent glucose concentration was changed from 1000 mg/l to 2000 mg/l, representing a two-fold increase in glucose concentration in the incoming feed. There was an increase of approximately 50 mg/l of total COD over the steady state value; however, the total COD was reduced to a value close to the previous steady state value after six hours. Although there was a slight increase in total COD, the anthrone COD remained constant throughout the experimental period. Solids concentration increased to only 835 mg/l, which is considerably less than twice the steady state solids concentration of 495 mg/l, thus indicating that doubling the substrate concentration did not double the cell yield. It can be seen from Figure 16 that the system was capable of handling a shock load of 2000 mg/l glucose.

The shock load responses when the influent glucose concentration is increased from 1000 mg/l to 3000 mg/l are shown in Figures 17 and 18. There was only a slight increase in the total COD although the data do exhibit some fluctuation. The total COD reached a fairly constant value of 200 mg/l, which was higher than the 105 mg/l obtained with 1000 mg/l glucose feed. There was also a slight increase in glucose (anthrone) COD over the steady state value. There was also a peak in solids concentration which was finally reduced to a constant value of 1260 mg/l. On the other hand, when recirculation was adopted (Figure 18) there was very little increase in the total COD and the previous steady state value was attained in nine hours. It can be seen from Figure 18 that there was not much increase in the carbohydrate content of the solids as compared with the protein content. Comparison of Figures 17 and 11 shows that a shock loading of

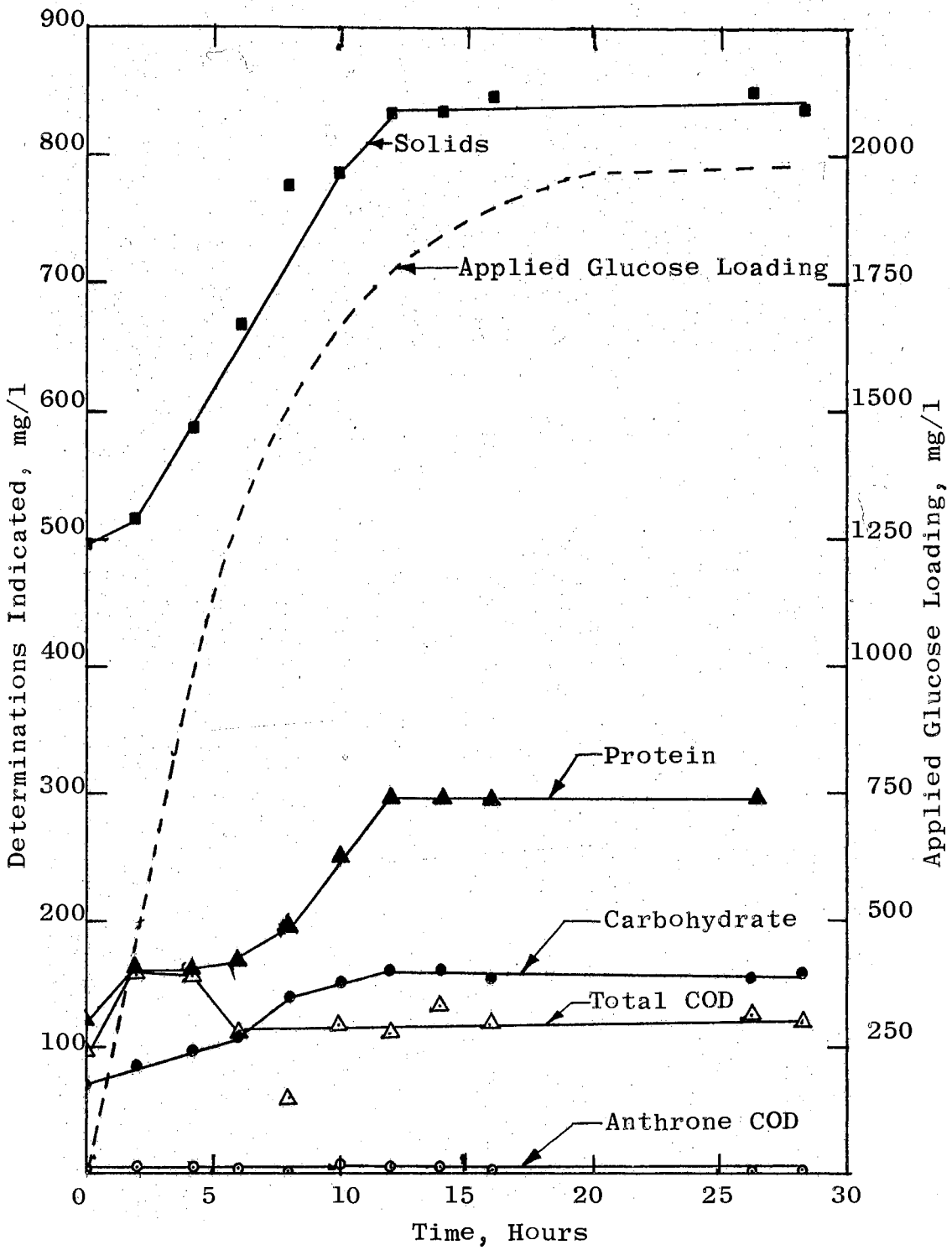

Fig. 16 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLOW FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE (NO RECIRCULATION)

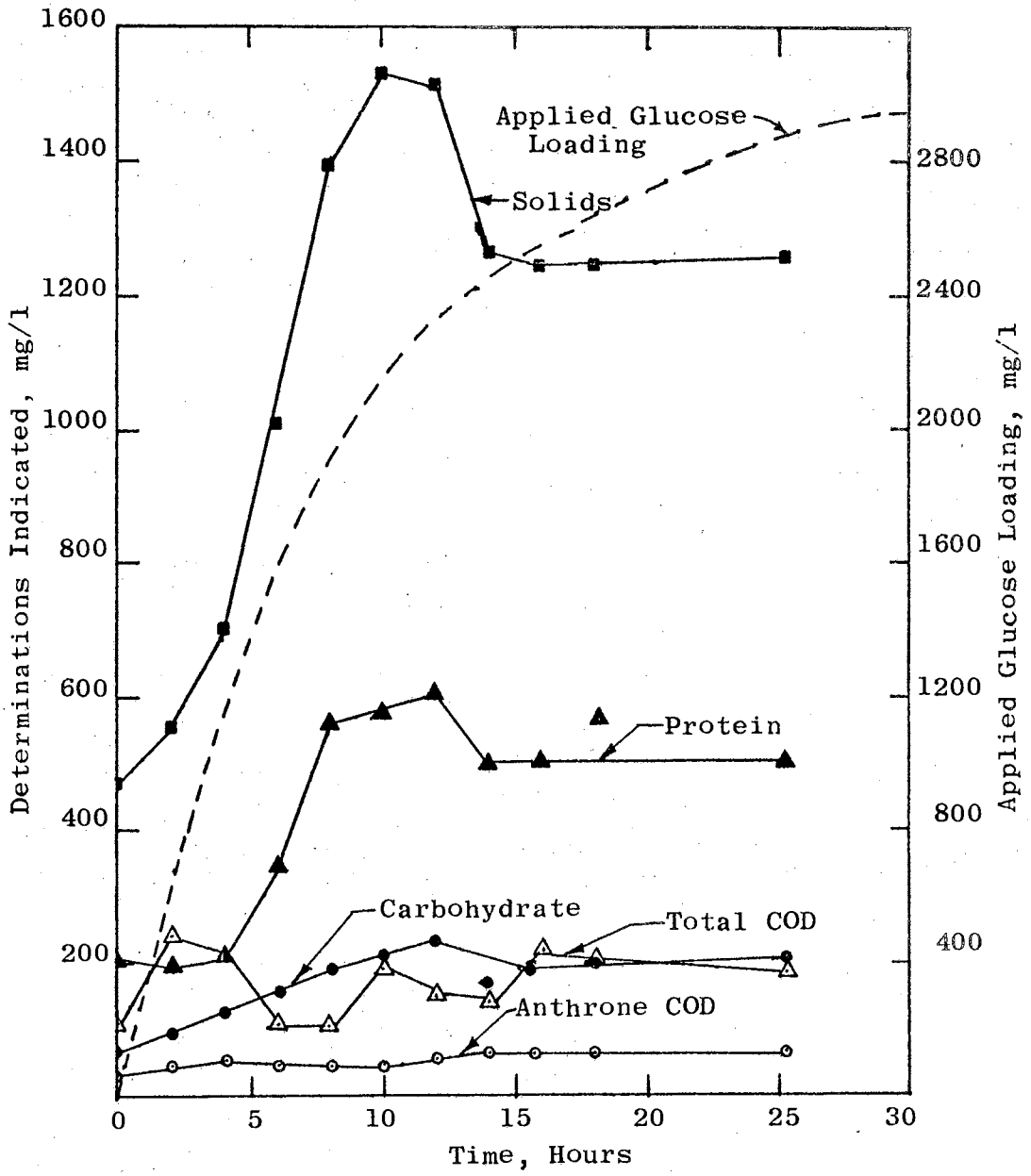

Fig. 17 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE (NO RECIRCULATION)

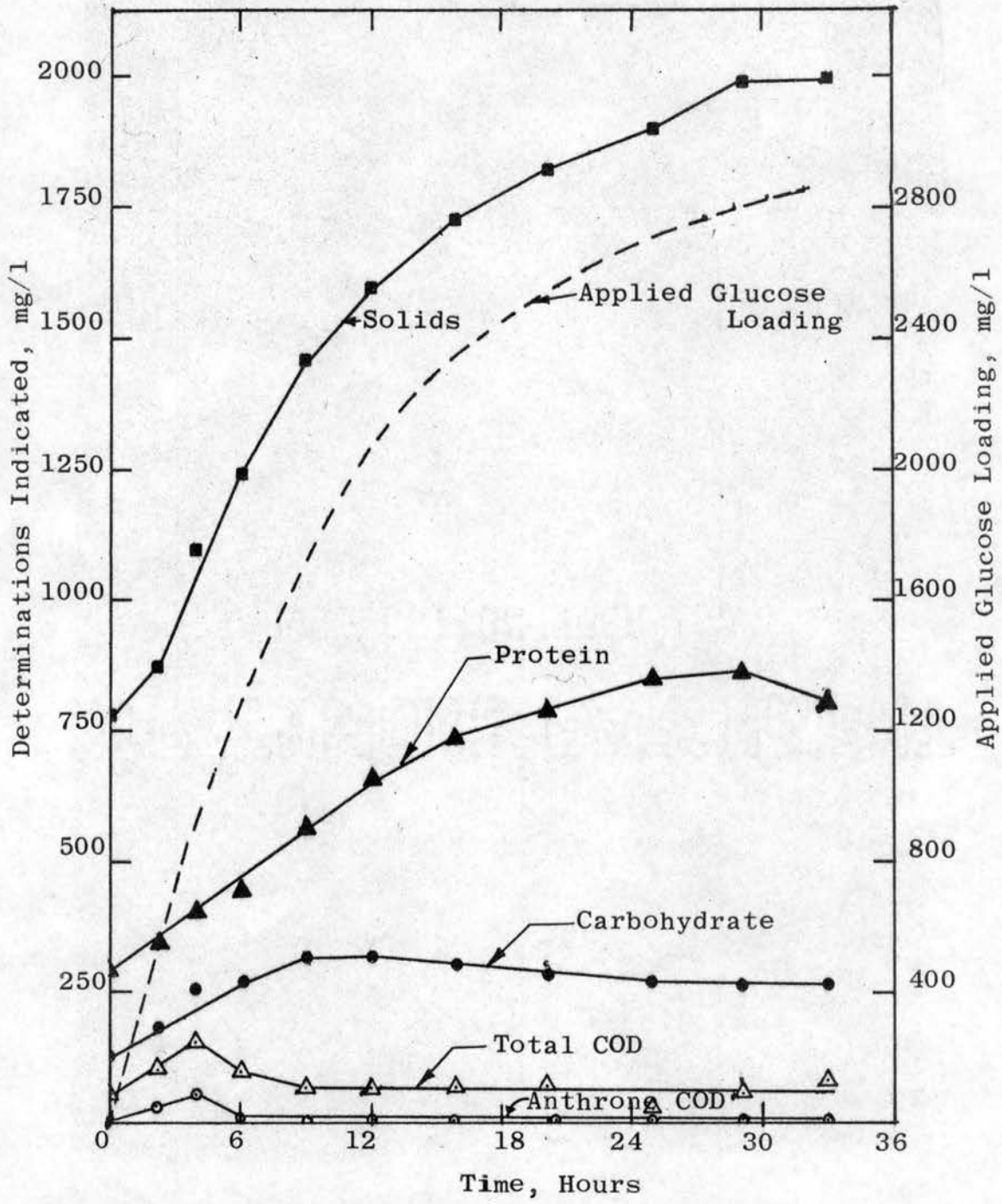

Fig. 18 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/1 TO 3000 mg/1 GLUCOSE (RECIRCULATION)

3000 mg/l glucose does not affect a system operating with an 8-hour detention time as seriously as one operating at a 4-hour detention time. When recirculation of solids was practiced, both the 8-hour and 4-hour detention systems successfully responded to glucose shock loading at the 3000 mg/l level as shown in Figures 12 and 18.

The shock load responses to 5000 mg/l glucose are shown in Figures 19 and 20. In Figure 19 it is seen that the total COD increased to 645 mg/l in two hours and was gradually reduced to a value of approximatly 270 mg/l. This value is much higher than the previous steady state value of 105 mg/l. Although there was considerable increase in total COD, there was very little increase in anthrone COD. However, as seen in Figure 20, when recirculation was used the total COD increased to a maximum of 700 mg/l. in two hours and was finally reduced to a constant value in twelve hours. It can be seen from Figure 20 that the total COD returned to the steady state value existing prior to the shock. In this system the anthrone COD increased to a maximum of 415 mg/l and was gradually reduced to a value of 50 mg/l. As with the 4-hour detention, the release of intermediates was restricted when recirculation was employed. It can also be seen that the severity of the 5000 mg/l glucose shock load was much lessened at the 8-hour detention time compared with the 4-hour detention time (Figures 13 and 14).

c. 12-Hour Detention Time. The steady state behavior of the continuous flow unit under condition of solids recirculation at a 12-hour detention time is shown in Figure 21. There appeared to be a slowly-occurring fluctuation of the biological solids although other parameters exhibited fairly constant values. The residual total COD was approximately 90 mg/l, and the anthrone COD was negligible. It can be seen from Figures 9, 15, and 21 that the solids concentration shows considerably more varia-

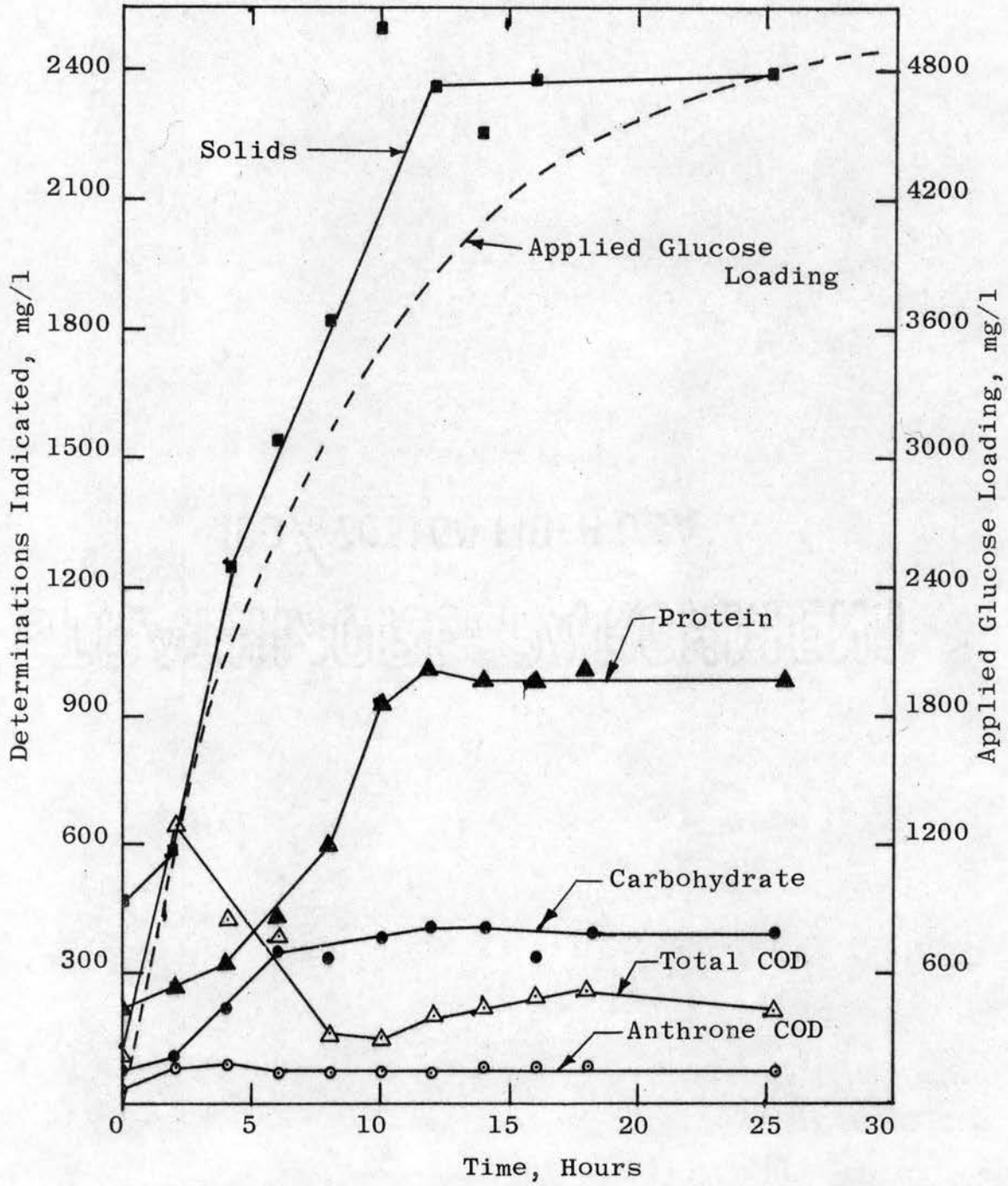

Fig. 19 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (NO RECIRCULATION)

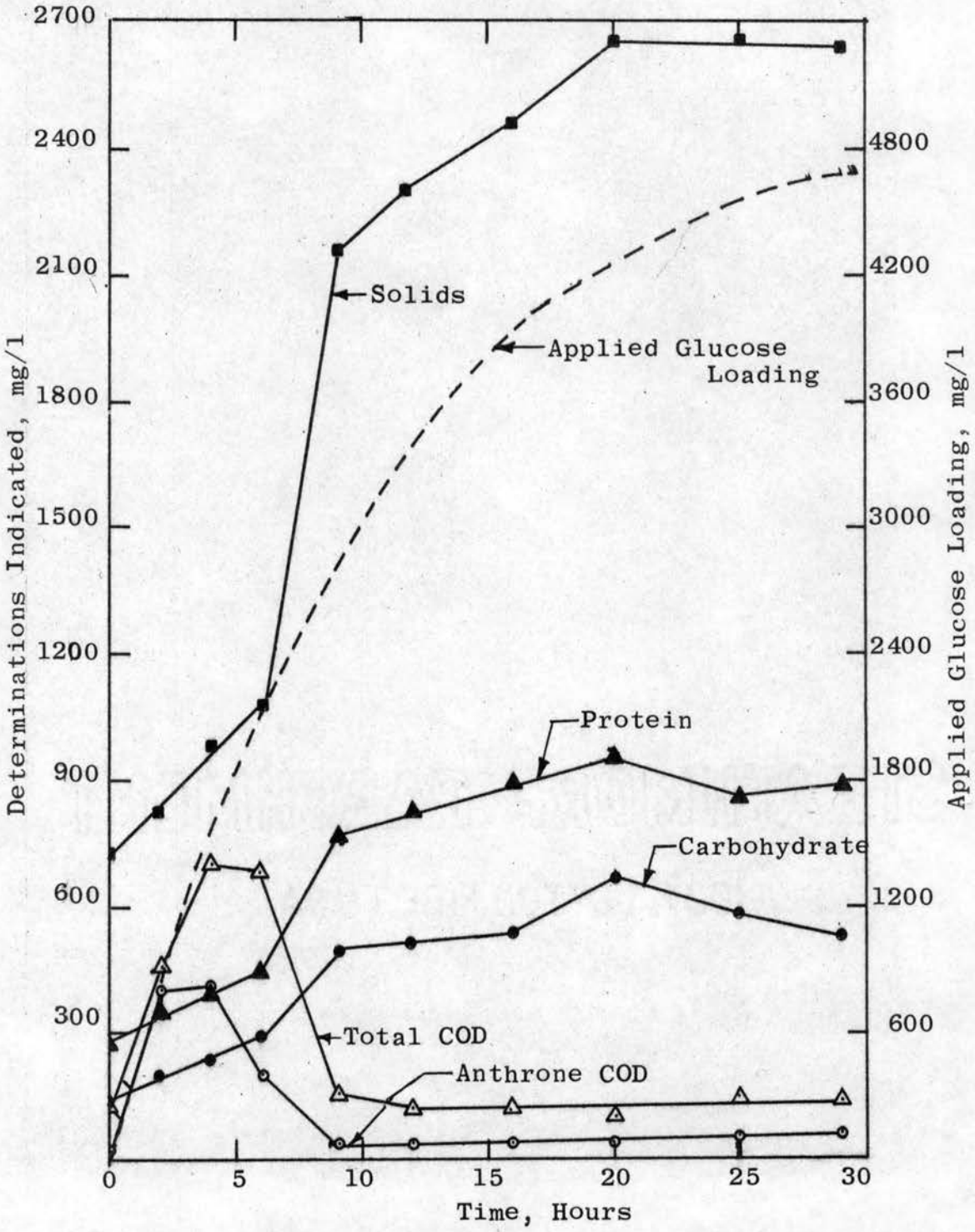

Fig. 20 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (RECIRCULATION)

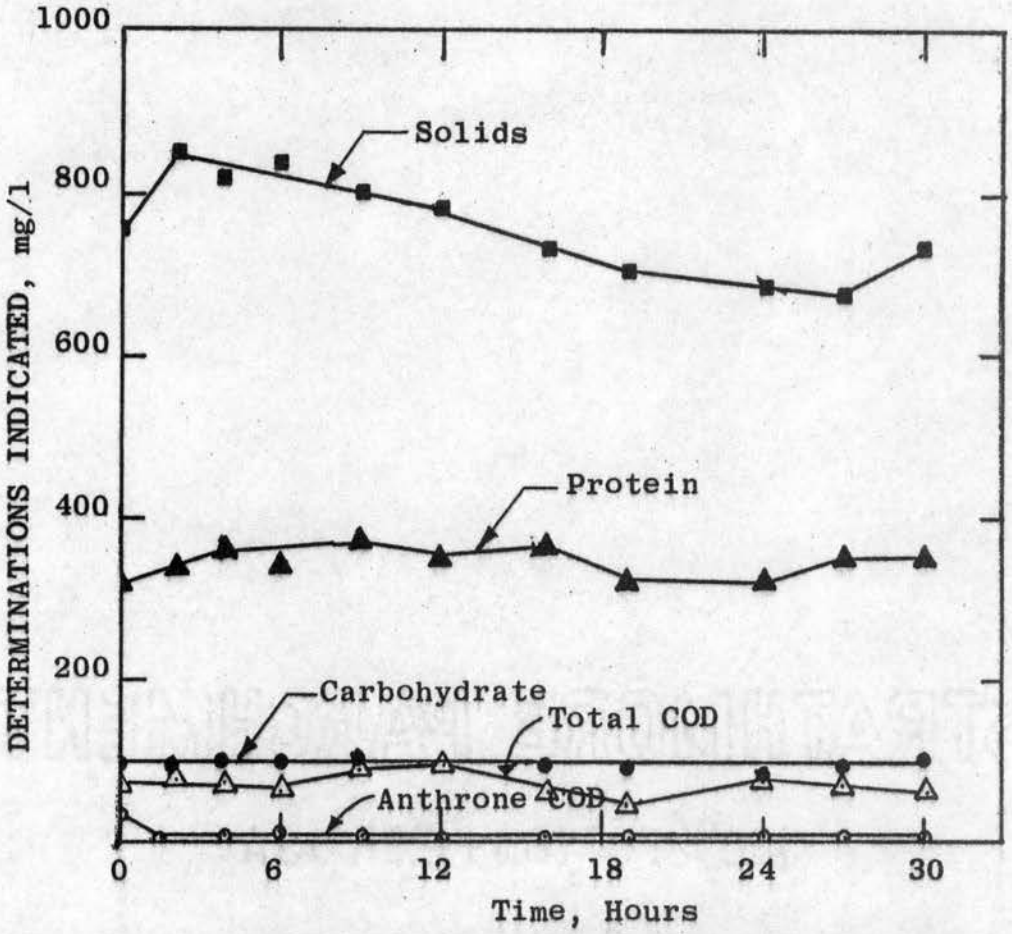

Fig. 21 - STEADY STATE BEHAVIOR OF THE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME WITH RECIRCULATION AT 1000 mg/l GLUCOSE

tion than any other parameter. This may indicate variations in cell yield, which are possibly due to changes in predominating bacterial species. Studies on the steady state response without recirculation of solids were not conducted.

The shock load response to an influent feed of glucose at 2000 mg/l is shown in Figure 22. The total COD increased to 200 mg/l during the first two hours and was gradually reduced to 80 mg/l in eight hours. Thereafter the total COD increased and finally reached a value of 155 mg/l. The final total COD was higher than the previous steady state value. The anthrone COD also increased throughout the experimental period. The response of the continuous flow unit to a glucose shock load of 2000 mg/l was not similar to that obtained with 4 and 8-hour detention times (Figures 10 and 16). It can also be seen from Figures 10, 16, and 22 that the release of intermediates is much less and anthrone COD is higher at 12-hour detention time. As shown in Figure 22, the solids concentration increased to 685 mg/l, which is less than double the steady state value of 400 mg/l; i.e., the cell yield did not appear to be directly proportional to substrate concentration.

The shock load response to 3000 mg/l glucose is shown in Figures 23 and 24. Without cell feedback (Figure 23) there was a gradual increase in total COD to 275 mg/l during the first eight hours. The COD was gradually reduced to 135 mg/l in twelve hours. As with the 2000 mg/l glucose shock load, the total COD increased after twelve hours and reached a value of 285 mg/l at the end of twenty-eight hours. The anthrone COD also showed a similar trend and reached a final value of 150 mg/l at the end of the experiment. However, when sludge recirculation was used (Figure 24), there was very little increase in total COD and anthrone COD. This result

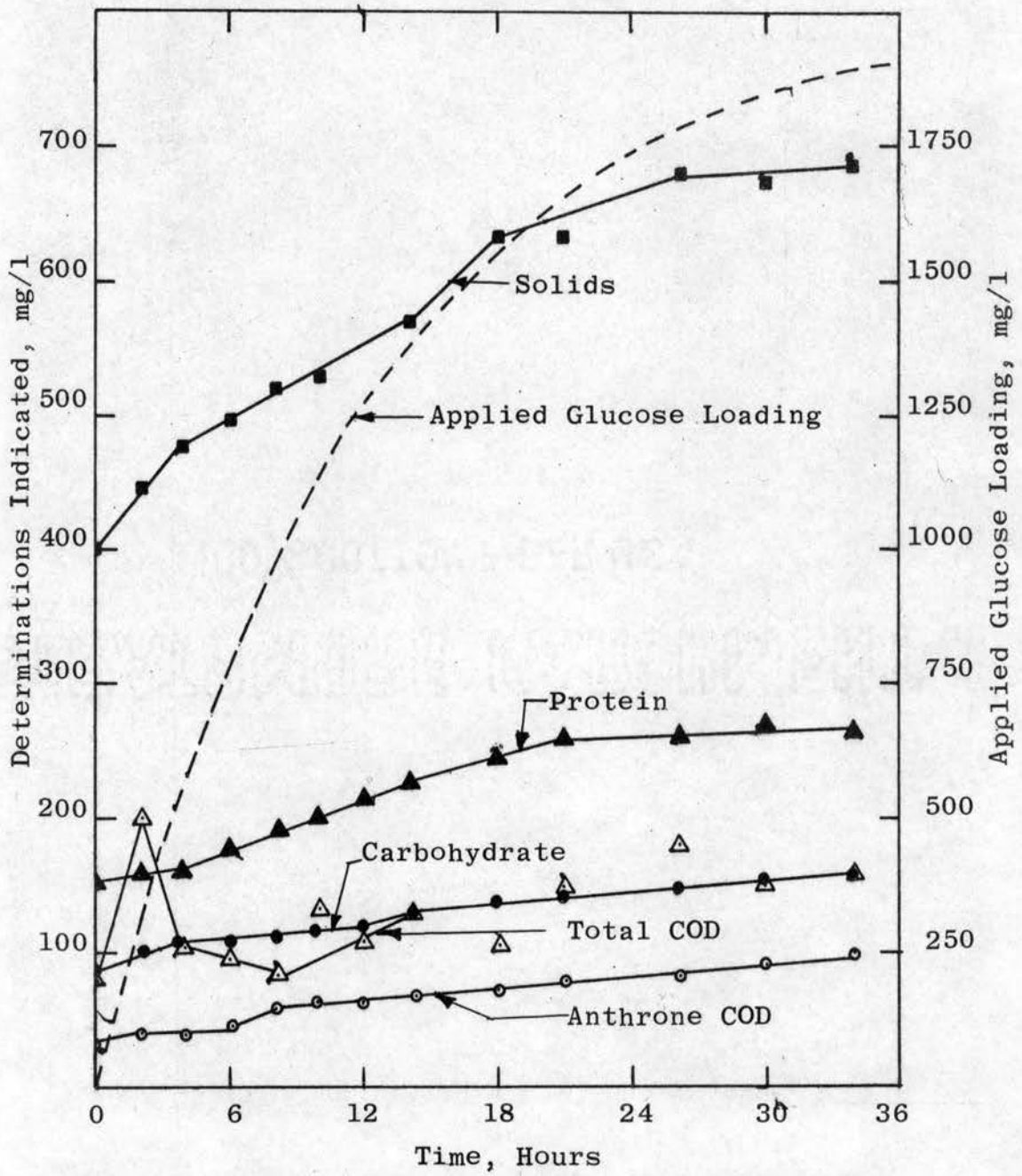

Fig. 22 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE (NO RECIRCULATION)

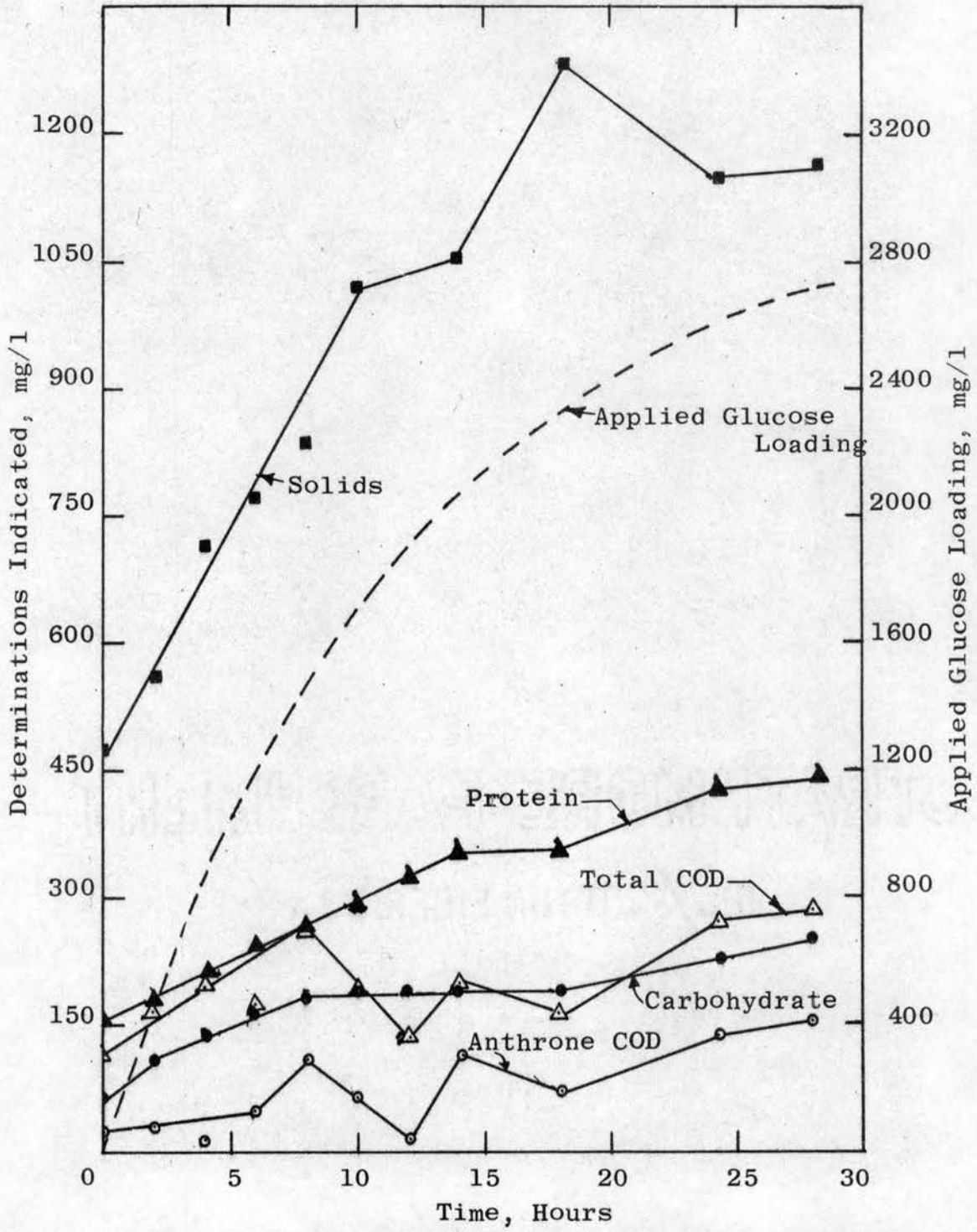

Fig. 23 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/1 TO 3000 mg/1 GLUCOSE (NO RECIRCULATION)

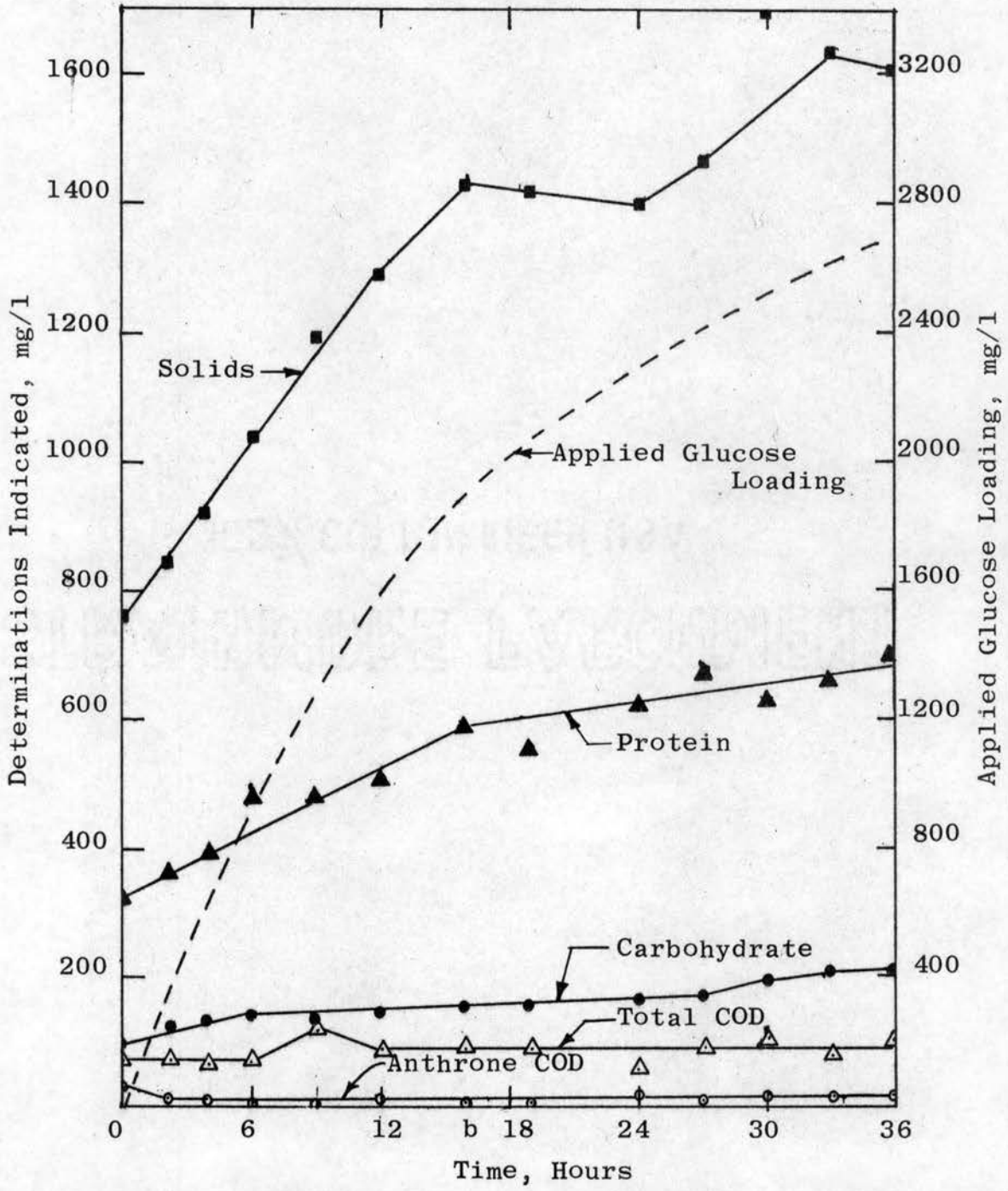

Fig. 24 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE (RECIRCULATION)

indicates that a system employing solids recirculation at the ratio herein employed can handle a shock loading of 3000 mg/l glucose very successfully.

The shock load response to 5000 mg/l glucose is shown in Figures 25 and 26. The total COD increased to a maximum value of 580 mg/l and was gradually reduced to 125 mg/l by fourteen hours. After fourteen hours the total COD again increased and reached a fairly steady value of 250 mg/l. It can be seen from Figure 25 that the final COD is approximatly four times the steady state value obtained with 1000 mg/l glucose. The anthrone COD increased to a maximum of 275 mg/l in two hours, and rapidly decreased. However, as with the total COD, it increased after four hours, and reached a final value of 140 mg/l in thirty-four hours. When recirculation was employed, the total COD increased to a maximum of 450 mg/l and was gradually reduced to the previous steady state value in twelve hours (Figure 26). The anthrone COD value also increased, and was reduced to a very low value after eight hours. It can be seen from Figures 25 and 26 that the response to a glucose shock load of 5000 mg/l is much more successful when solids recirculation is employed. It can also be seen by comparing Figures 13, 19, and 25 that the severity of disruption of the steady state at the 5000 mg/l level decreases with increasing detention time. A similar trend was also observed when solids recirculation was used, as shown by comparison of Figures 14, 20 and 26. It can also be seen that manifestation of the release of intermediates decreases with increasing detention time.

In most of the experiments the solids increase was accompanied by a considerable increase in protein content without much increase in carbohydrate content of the cells. This indicates that the response to gradual shock loading is one of true growth response rather than

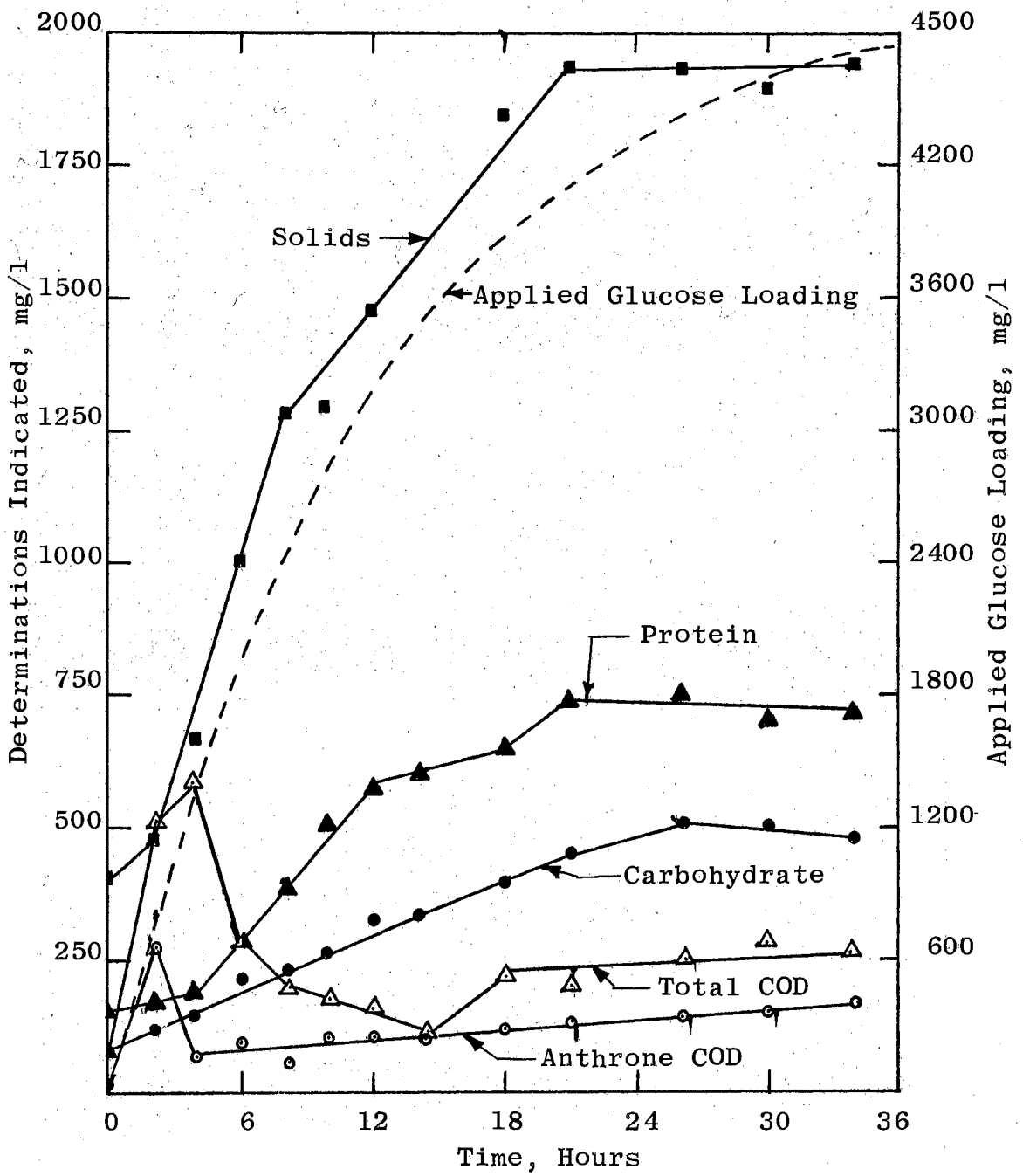

Fig. 25 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/1 TO 5000 mg/1 GLUCOSE (NO RECIRCULATION)

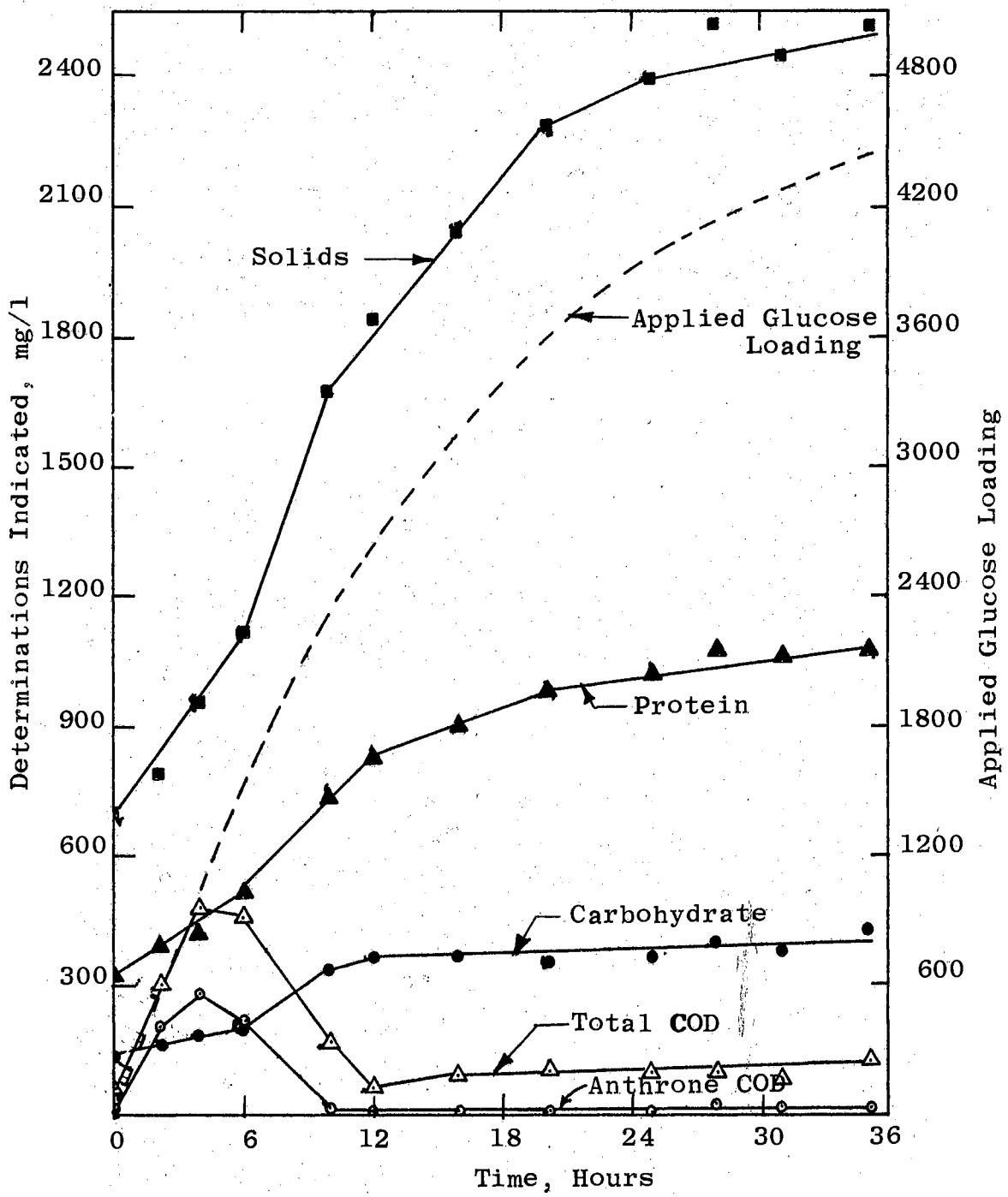

Fig. 26 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (RECIRCULATION)

accumulation of storage products like carbohydrate. In only two experiments (Figures 20 and 25) was considerable carbohydrate synthesis noted. Further, the solids increase was not accompanied by a proportional increase in protein and carbohydrate content of the sludge, indicating the synthesis of other materials, possibly ribonucleic acid (e.g., Figures 11 and 12). Rapid synthesis of ribonucleic acid content of cells during growth was indicated by Herbert (93) for several pure cultures of bacteria.

2. Responses to Slug Shock Loads.

a. 4-Hour Detention Time. The responses to a shock loading of 2000 mg/l glucose are shown in Figures 27 and 28. The influent feed was maintained at 1000 mg/l glucose and enough glucose was added to bring its concentration in the aerator to 2000 mg/l glucose. It can be seen from Figure 27 that the total COD concentration in the effluent was returned to a fairly steady state after ten hours. There was a considerable difference between total COD and the anthrone COD. The dotted line shown in Figures 27 and 28 represents the washout of the applied glucose if it were not used by the activated sludge. It can be seen from Figure 27 that there is not much removal of COD due to the shock which can be attributed to metabolism. The solids concentration increased to a maximum of 540 mg/l, and when glucose was exhausted, it dropped to a constant value of 350 mg/l. It can also be seen that the increase in solids concentration was accompanied by a rapid increase in protein content of the sludge without much carbohydrate increase. When recirculation was used (Figure 28), the total COD reached a steady state value in six hours. The anthrone COD and total COD removal curves were nearly identical. From comparison of Figures 27 and 28, cell feedback appears to

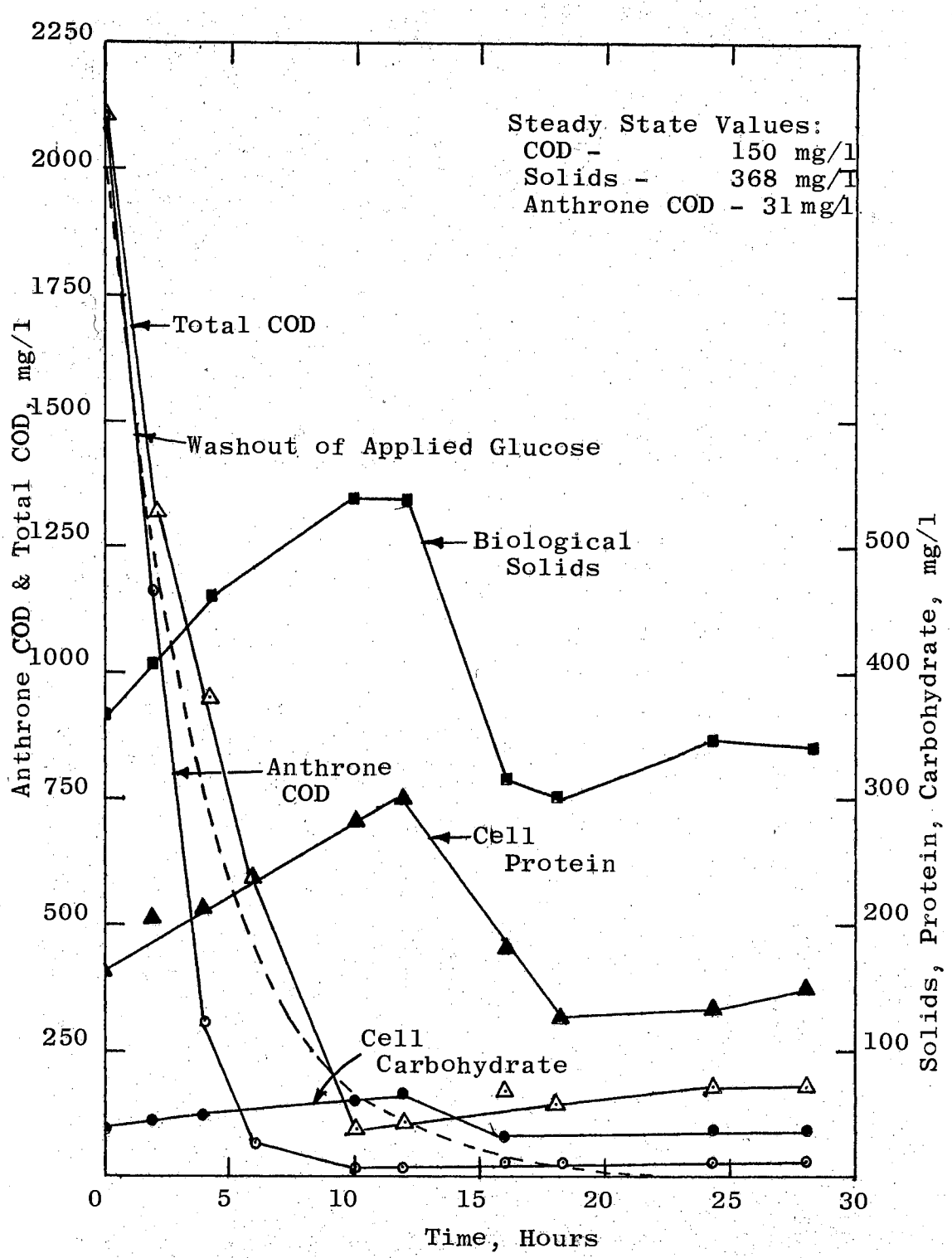

Fig. 27 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

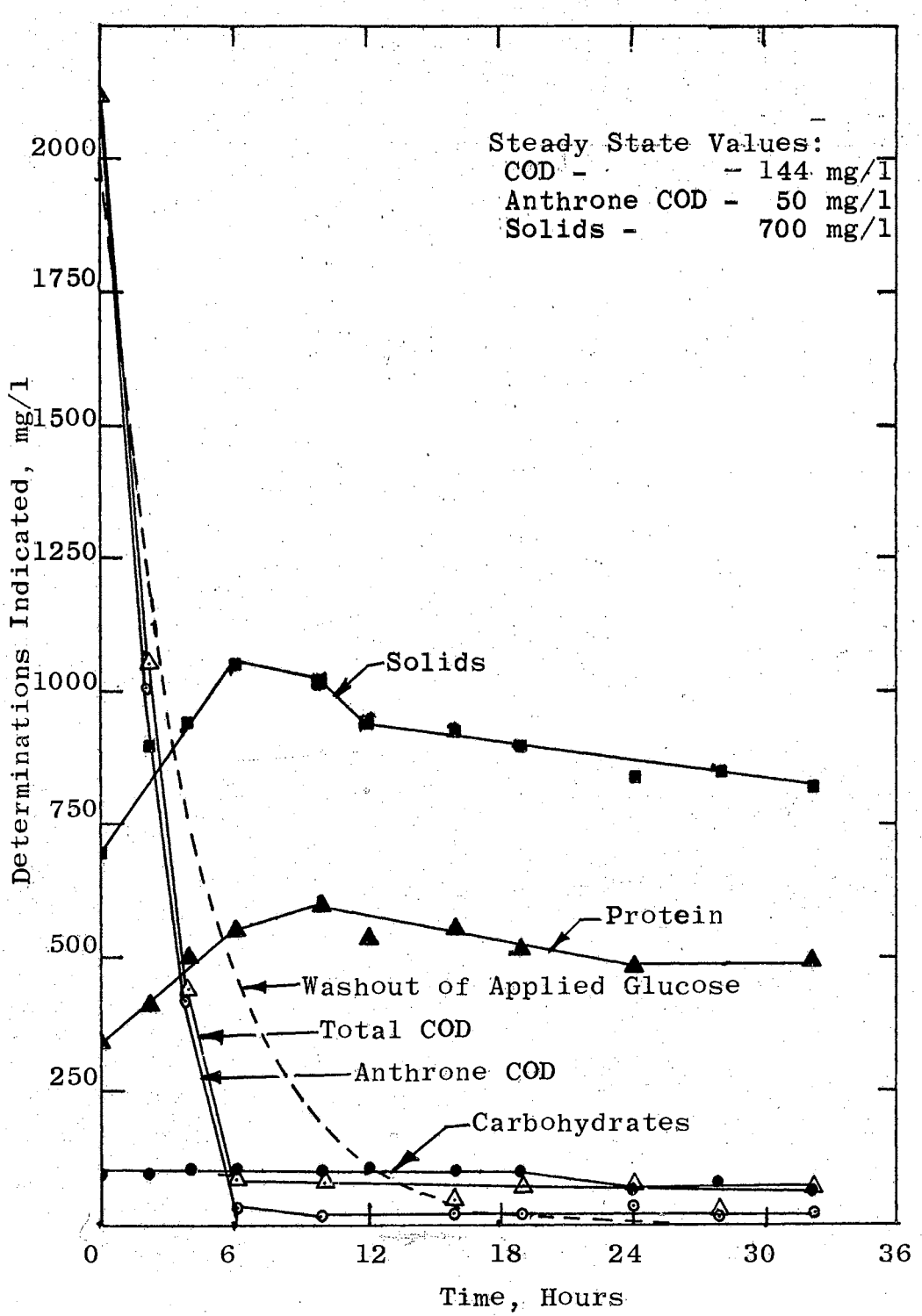

Fig. 28 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (RECIRCULATION)

enhance a more successful response to a 2000 mg/l glucose slug load. It can also be seen from Figure 28 that the increase in solids concentration was accompanied by an increase in protein synthesis and no increase in the carbohydrate content.

The response to a glucose slug shock loading of 3000 mg/l is shown in Figure 29. It can be seen that the total COD reached a steady state value after ten hours. The total COD curve follows closely the theoretical washout curve. There is considerable difference between anthrone COD and total COD after two hours. The biological solids concentration reached a maximum of 560 mg/l and finally was reduced to a fairly constant value of 450 mg/l; i.e., returned to the previous steady state value. The increase in solids concentration was not very high considering the fact that the glucose concentration in the aerator was 3000 mg/l. This would indicate that most of the applied glucose was diluted out of the system. As with the previous experiments, protein synthesis was greater than carbohydrate synthesis. Since the response at 2000 mg/l glucose slug with solids recirculation improved only slightly, it was expected that the response at 3000 mg/l glucose slug would be similar and hence no experiment was performed with the solids recirculation at this concentration. It was of interest to find whether an improved performance could be obtained when the glucose slug was also accompanied by a gradual shock of glucose. Since the response to gradual shock loading was accompanied by an increase of solids, it was felt that increasing the solids concentration in the aerator would improve the response to a glucose slug shock loading.

The shock load responses when the influent was changed from 1000 mg/l to 2000 mg/l glucose and also shock loaded with a slug dose of 2000 mg/l glucose are shown in Figures 30 and 31. In these experiments the

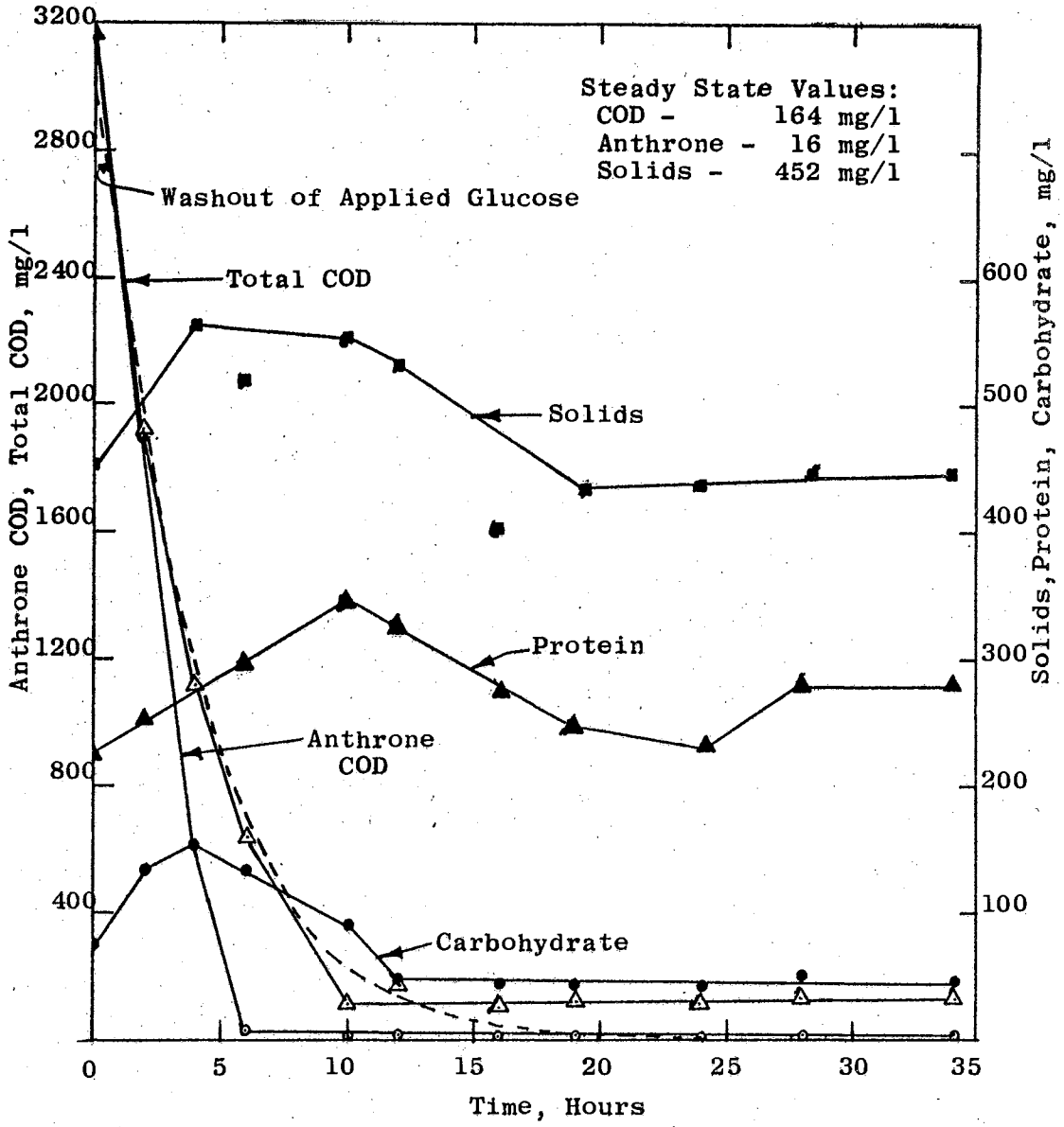

Fig. 29 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

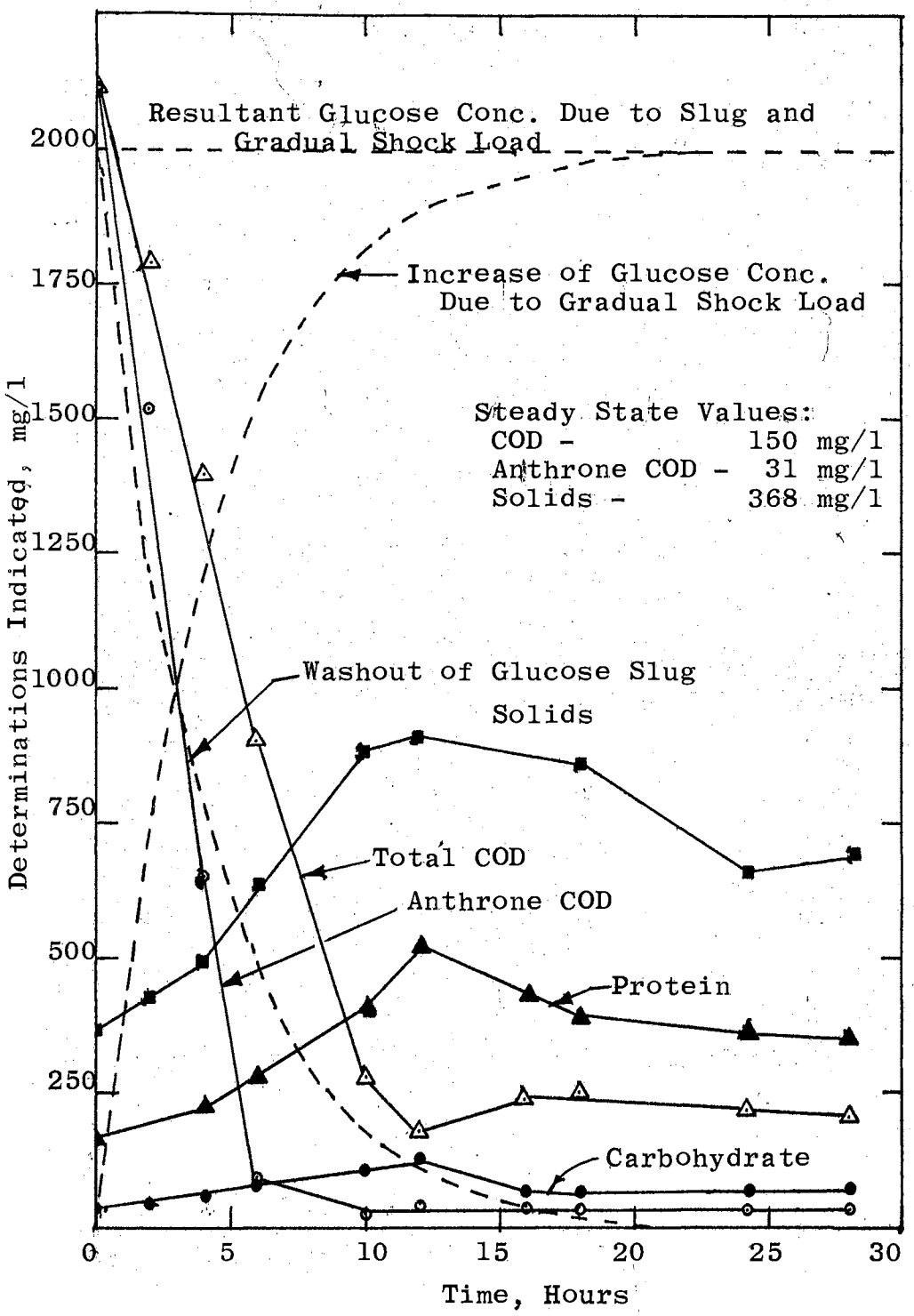

Fig. 30 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

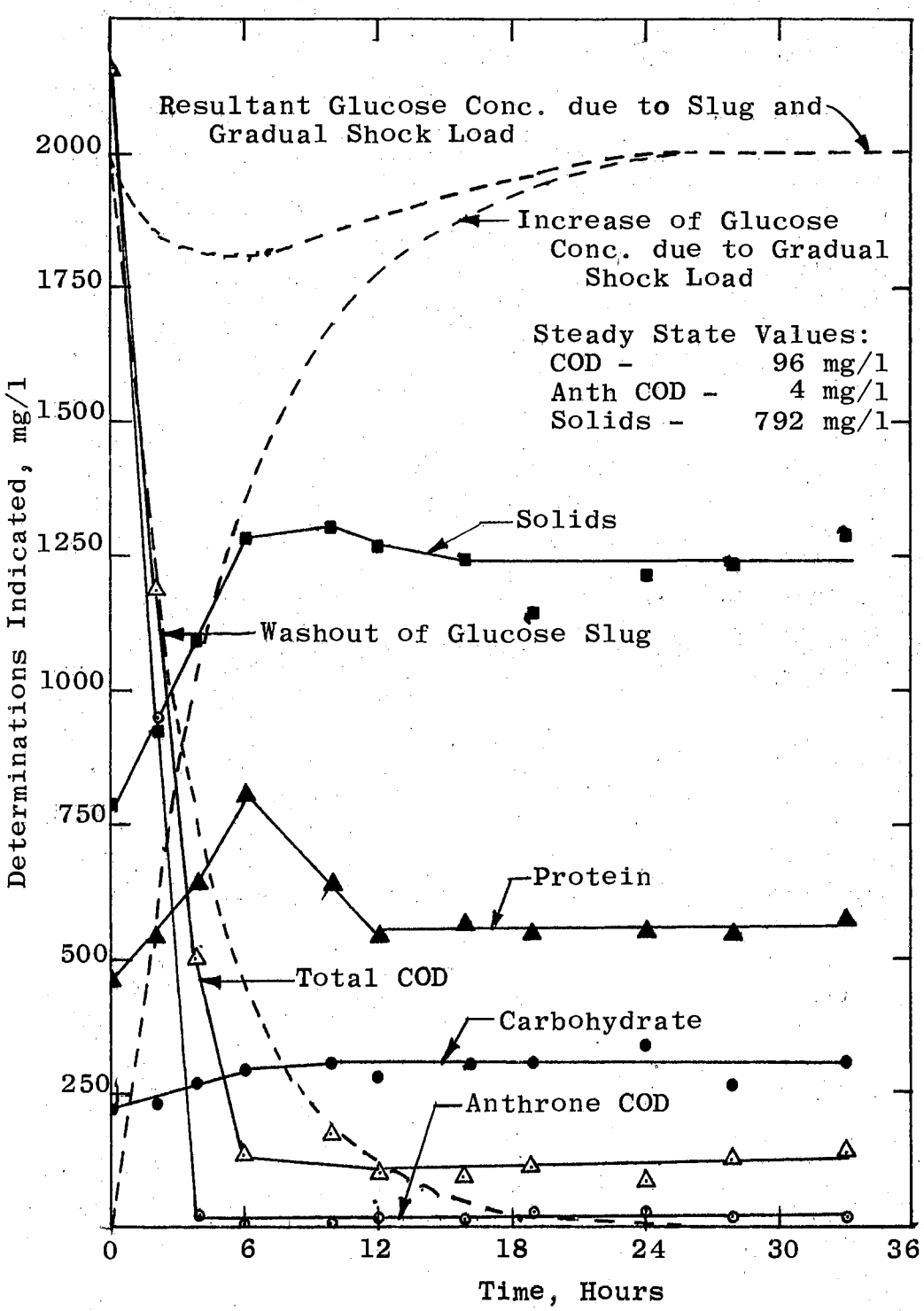

Fig. 31 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (WITH RECIRCULATION)

the units were subjected to a gradual shock loading in addition to a slug dose. The total COD concentration in the effluent was reduced to an approximate steady state value in twelve hours. However, there was a considerable difference between total COD and anthrone COD. The total COD reached a steady state value of 200 mg/l, which was slightly higher than the previous steady state value of 150 mg/l. It can also be seen that the total COD curve falls outside of the theoretical glucose washout curve. The biological solids concentration reached a maximum of 915 mg/l and was then reduced to 690 mg/l at the end of the experiment. The horizontal dotted line in Figure 30 represents the theoretical glucose concentration in the aerator, due to gradual and slug loads if the glucose were not metabolized by the activated sludge. It can also be seen that correspondingly more protein than carbohydrate was synthesized. Figure 31 shows the response to a similar shock load when solids recirculation was employed. The total COD was reduced to a constant value of 125 mg/l in six hours. It can be seen that there was no excess solids synthesis, which seems to indicate that most of the glucose slug was diluted out. The dotted curved line represents the theoretical glucose concentration in the aerator due to gradual and slug loads if it were not metabolized by the activated sludge. The resultant glucose concentration appears as a curved line because the washout of the glucose slug is greater than the increase of glucose concentration due to the gradual shock load when sludge is recycled.

The system responses to a slug dose of 3000 mg/l glucose plus a 3000 mg/l glucose gradual shock load are shown in Figures 32 and 33. It can be seen that the total COD was reduced to a steady state value of 210 mg/l in sixteen hours. It can also be seen that there

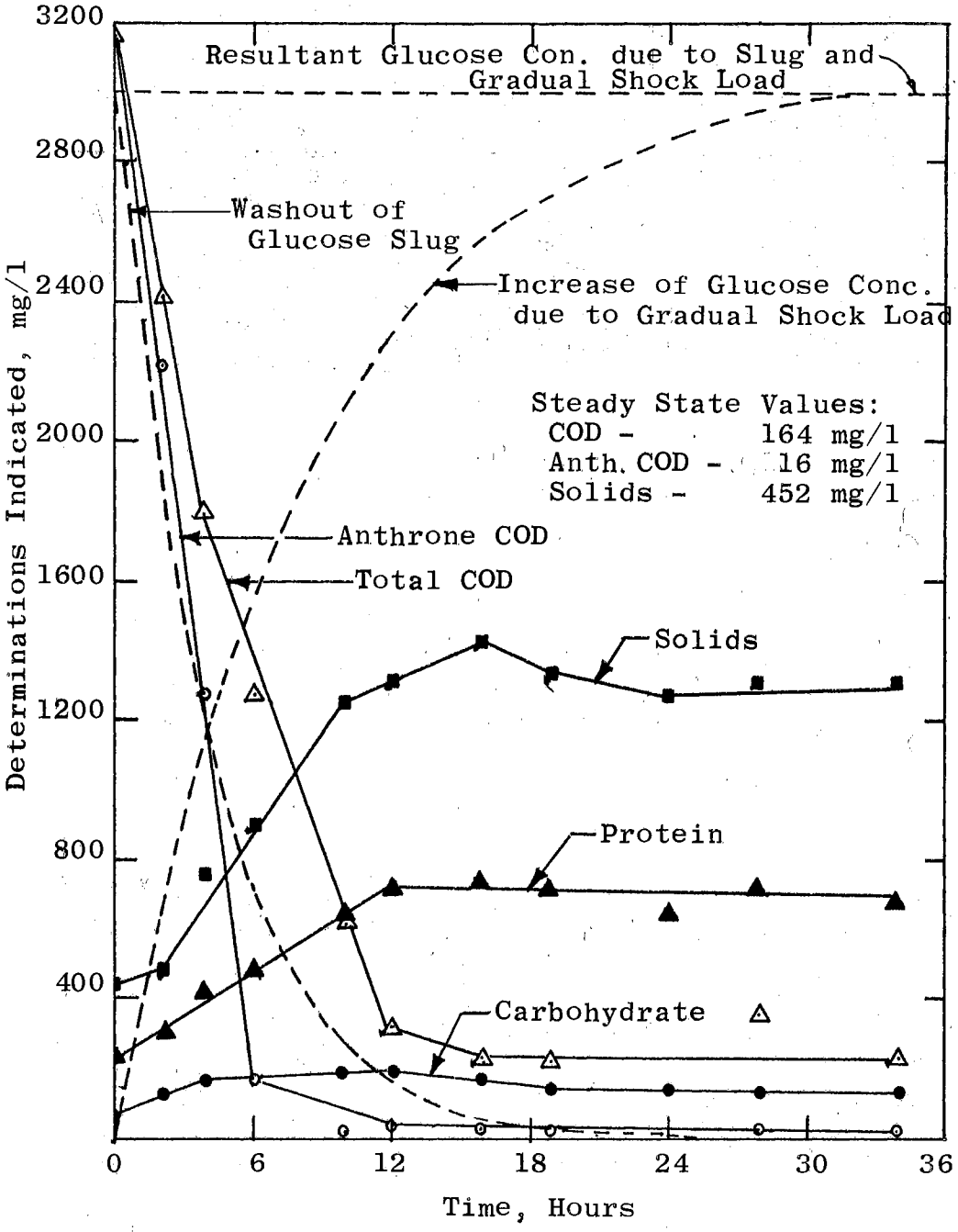

Fig. 32 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

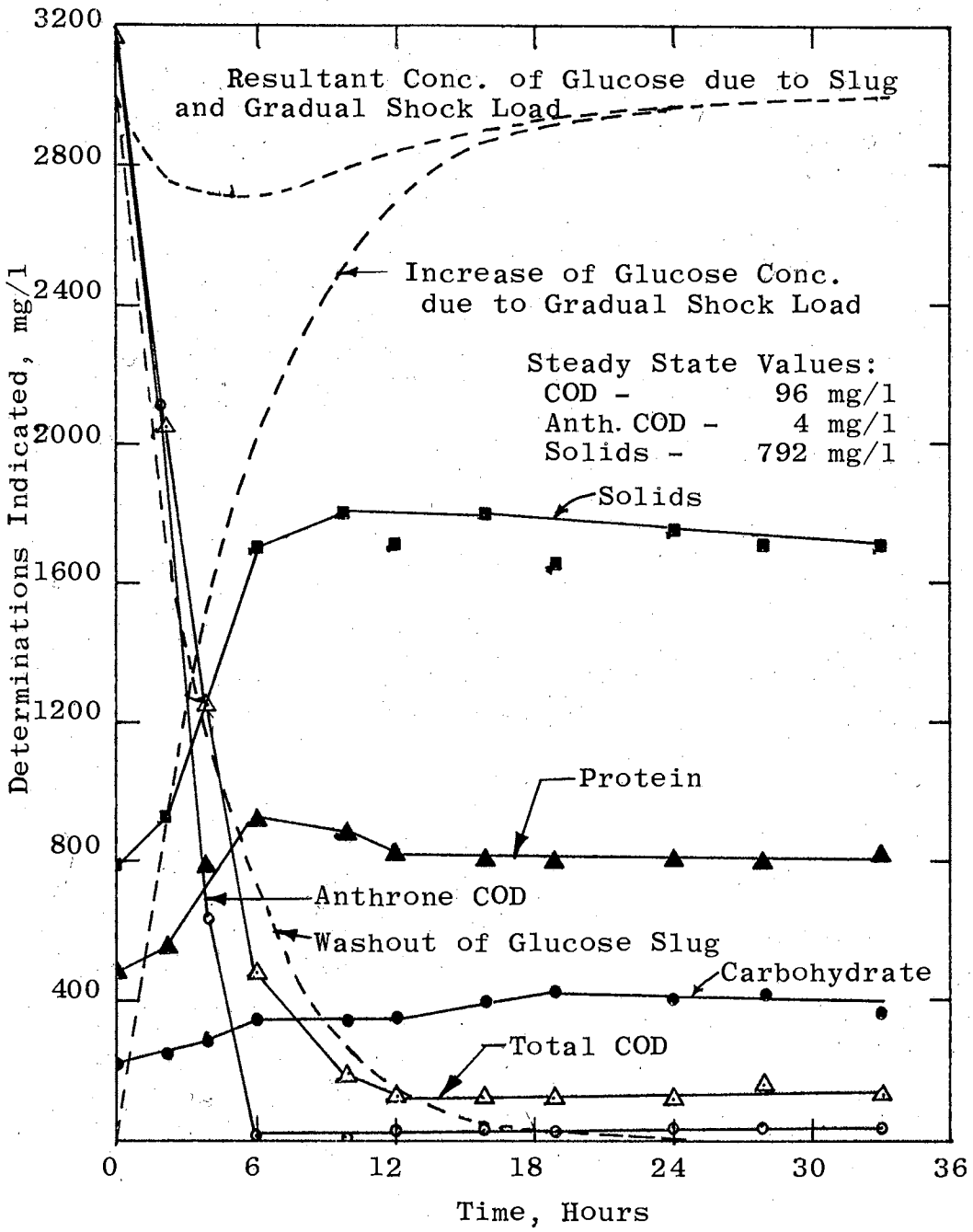

Fig. 33 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l to 3000 mg/l GLUCOSE AND ALSO SHOCKING WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (RECIRCULATION)

was considerable difference between total COD and anthrone COD, indicating the release of intermediates. As compared with the theoretical glucose washout curve, the total COD is higher at all times, and this would appear to be due to the effect of release of intermediates produced due to the combination of gradual and slug shock load. As in the previous experiment, there was no large increase in solids concentration, and the increase which was registered was probably due to the gradual shock. It can also be seen from Figure 32 that protein synthesis was considerably greater than carbohydrate production. It can be seen from Figure 33 that the total COD was reduced to a steady state value of 120 mg/l in twelve hours. Comparison of Figures 32 and 33 indicates that the response is much better when recirculation of solids is used; also less intermediates are detected in this system. There was very little excess solids synthesis as can be seen from Figure 33, which seems to indicate that most of the applied glucose slug dose was diluted out since this system is known to be capable of accepting a gradual shock of 3000 mg/l glucose (Figure 12).

b. 8-Hour Detention Time. The shock load responses to a slug dose of 2000 mg/l glucose are shown in Figures 34 and 35. The influent feed was maintained at 1000 mg/l glucose. It can be seen from Figure 34 that the total COD was reduced to a steady state value of 65 mg/l in twelve hours; the anthrone COD was almost equal to total COD at all times. Comparison of Figures 27 and 34 indicates that it takes a slightly longer time to reduce the total COD to a steady state value for the 8-hour detention time. However, when compared with the theoretical washout curve, the response at the 8-hour detention time seems to be better. It can also be seen that there is not much solids increase in the system. The response to a similar shock load with sludge recirculation is

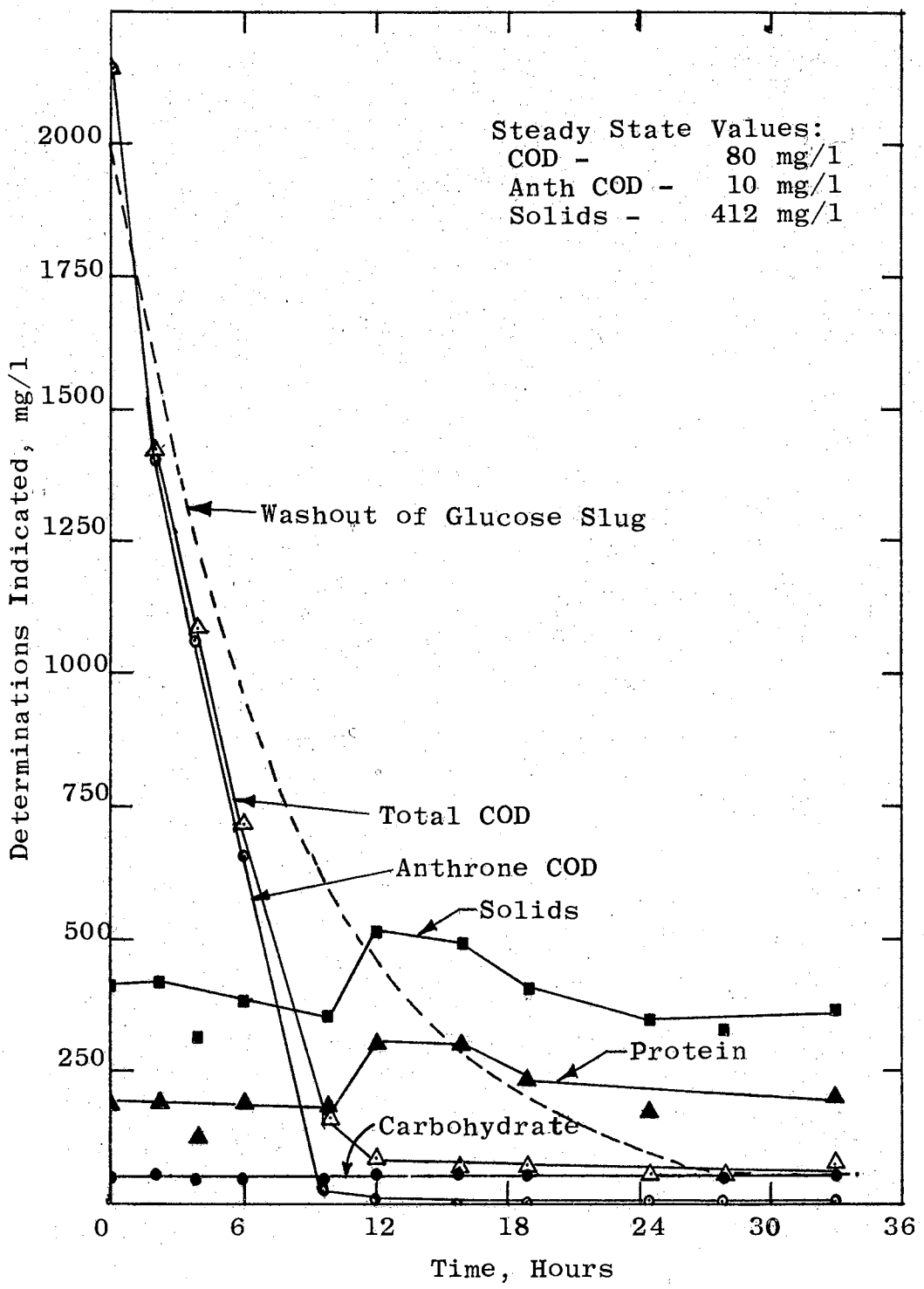

Fig. 34 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

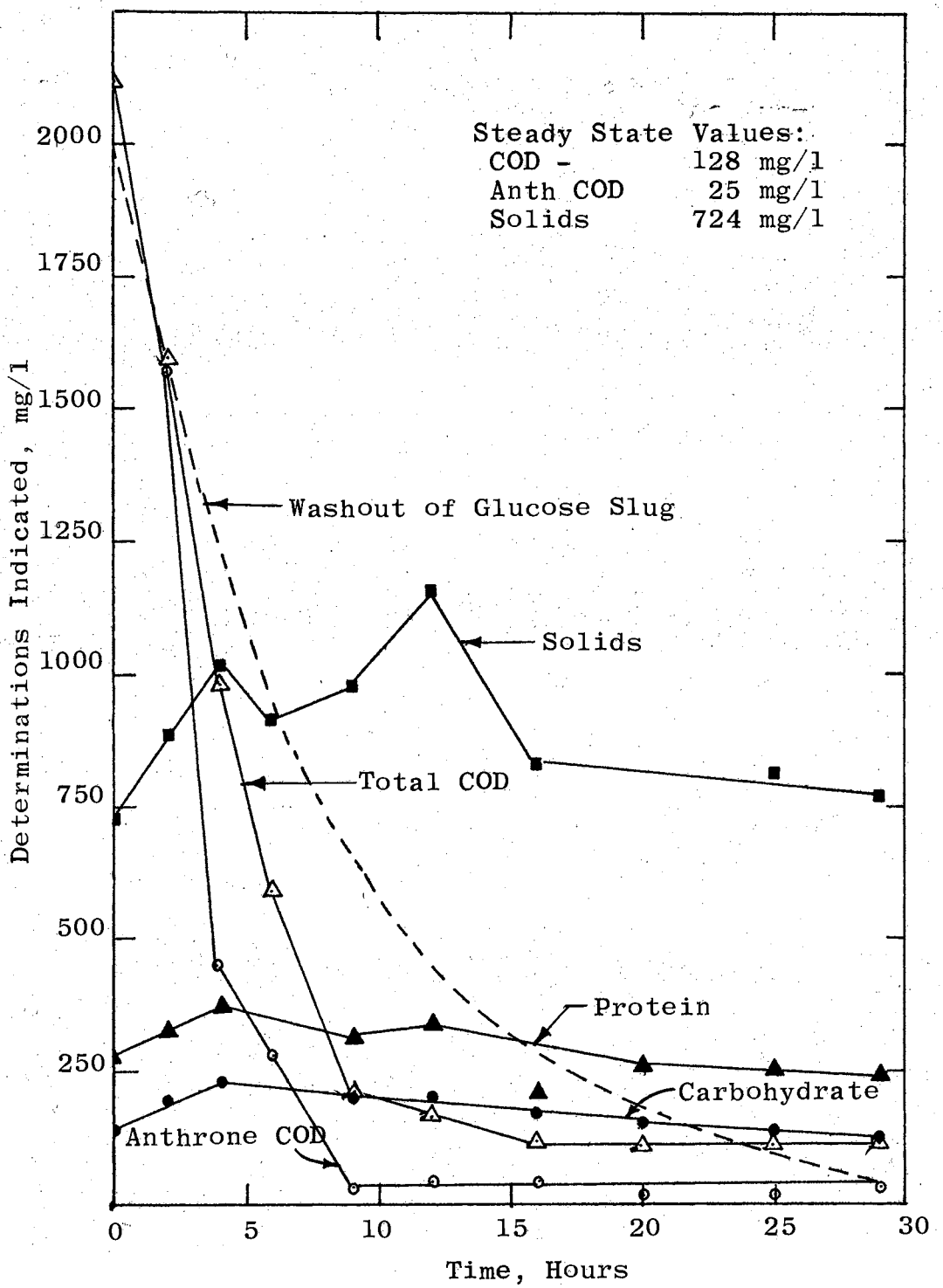

Fig. 35 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (RECIRCULATION)

shown in Figure 35. The total COD was gradually reduced to a steady state value of 120 mg/l in sixteen hours; however, the anthrone COD reached a steady state value in nine hours. The solids increased to a maximum of 1150 mg/l and was then reduced to a steady state value of 770 mg/l at the end of thirty hours. It can be seen from Figures 28 and 35 that a system operated at 8-hour detention time requires a longer time to remove the applied slug load. However, when compared with the theoretical glucose washout curve, the response at the 8-hour detention time was slightly better than at the 4-hour detention time.

The shock load response to a slug loading of 3000 mg/l glucose is shown in Figure 36. The total COD was reduced to a steady state value of 60 mg/l in sixteen hours. There is, however, a considerable difference between the values for anthrone COD and total COD. The solids level showed considerable variation during the first twelve hours, and rose to a maximum of 680 mg/l at nineteen hours. The solids concentration was then gradually reduced to 410 mg/l at the end of thirty-three hours. Comparison of Figures 29 and 36 indicates that a system operated at 8-hour detention time takes longer to remove the applied glucose load. It can also be seen that in both systems the total COD curve follows the theoretical glucose washout curve.

The shock load responses when the influent was changed from 1000 mg/l to 2000 mg/l glucose and the unit was shock loaded with a slug dose of 2000 mg/l glucose are shown in Figures 37 and 38. It can be seen from Figure 37 that the total COD reached an approximate steady state value in twelve hours. The anthrone COD was slightly lower than the total COD at all times. The solids concentration reached a maximum of 875 mg/l and was then reduced to an approximate steady state

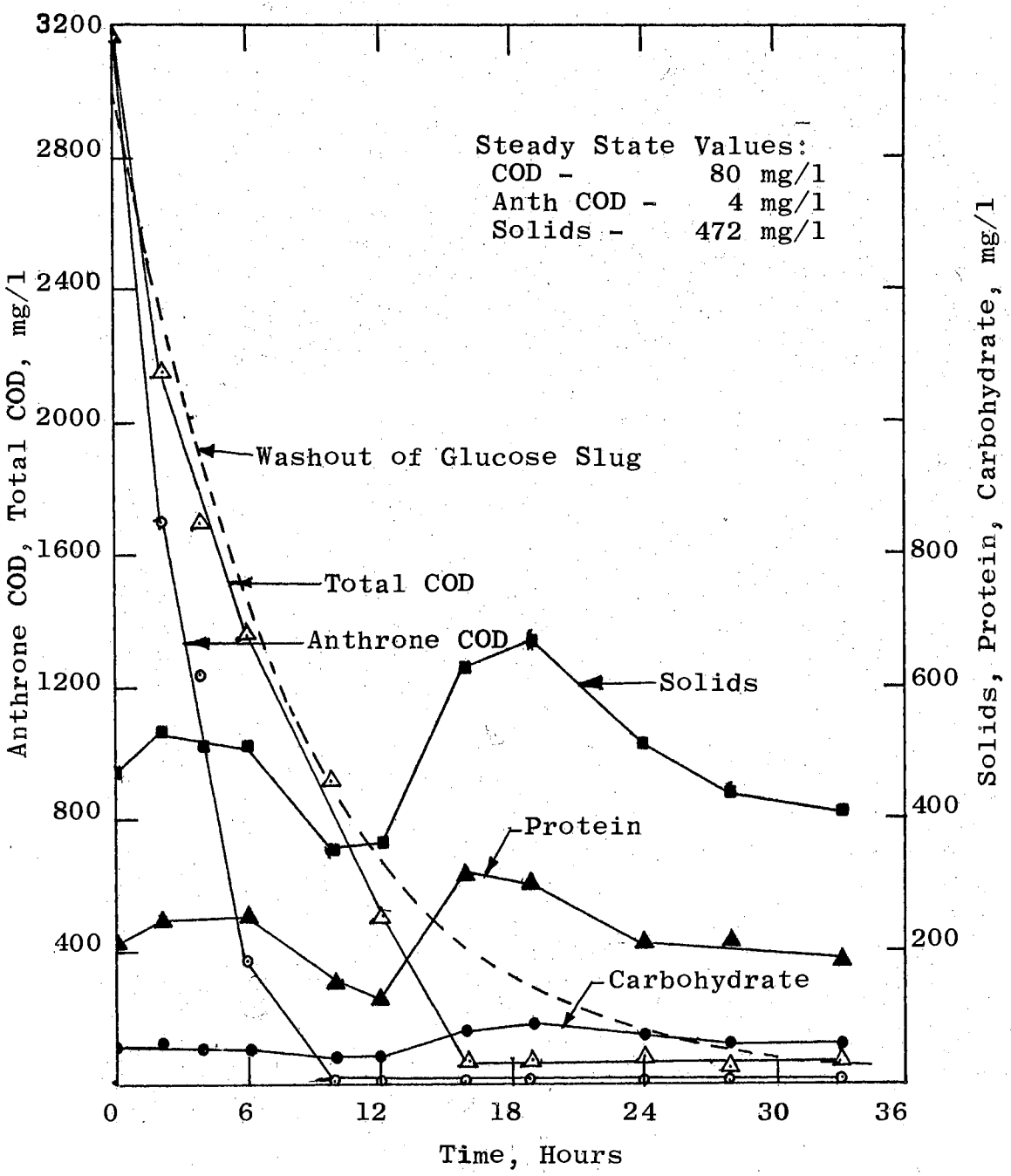

Fig. 36 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

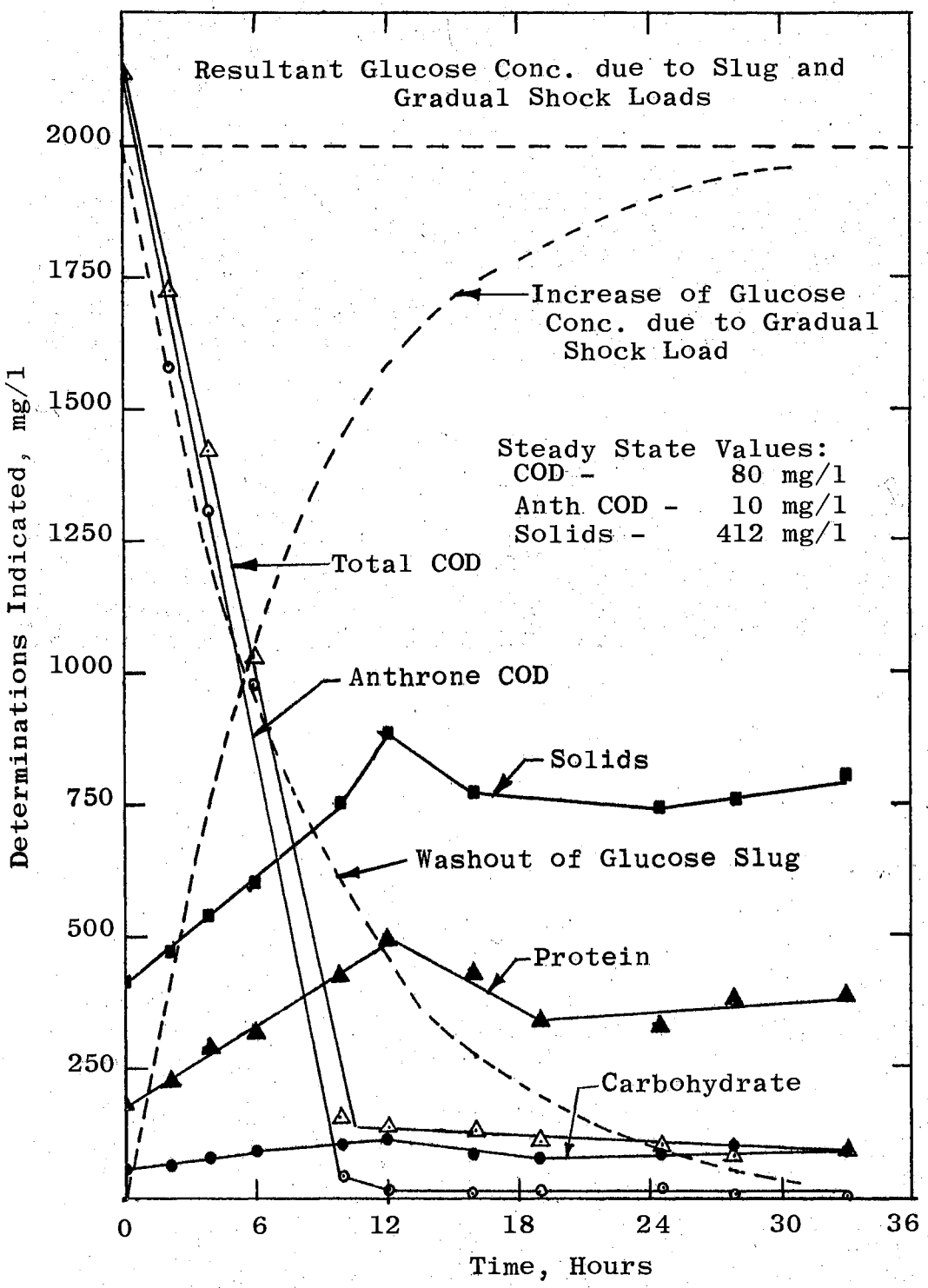

Fig. 37 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND ALSO SHOCKING WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

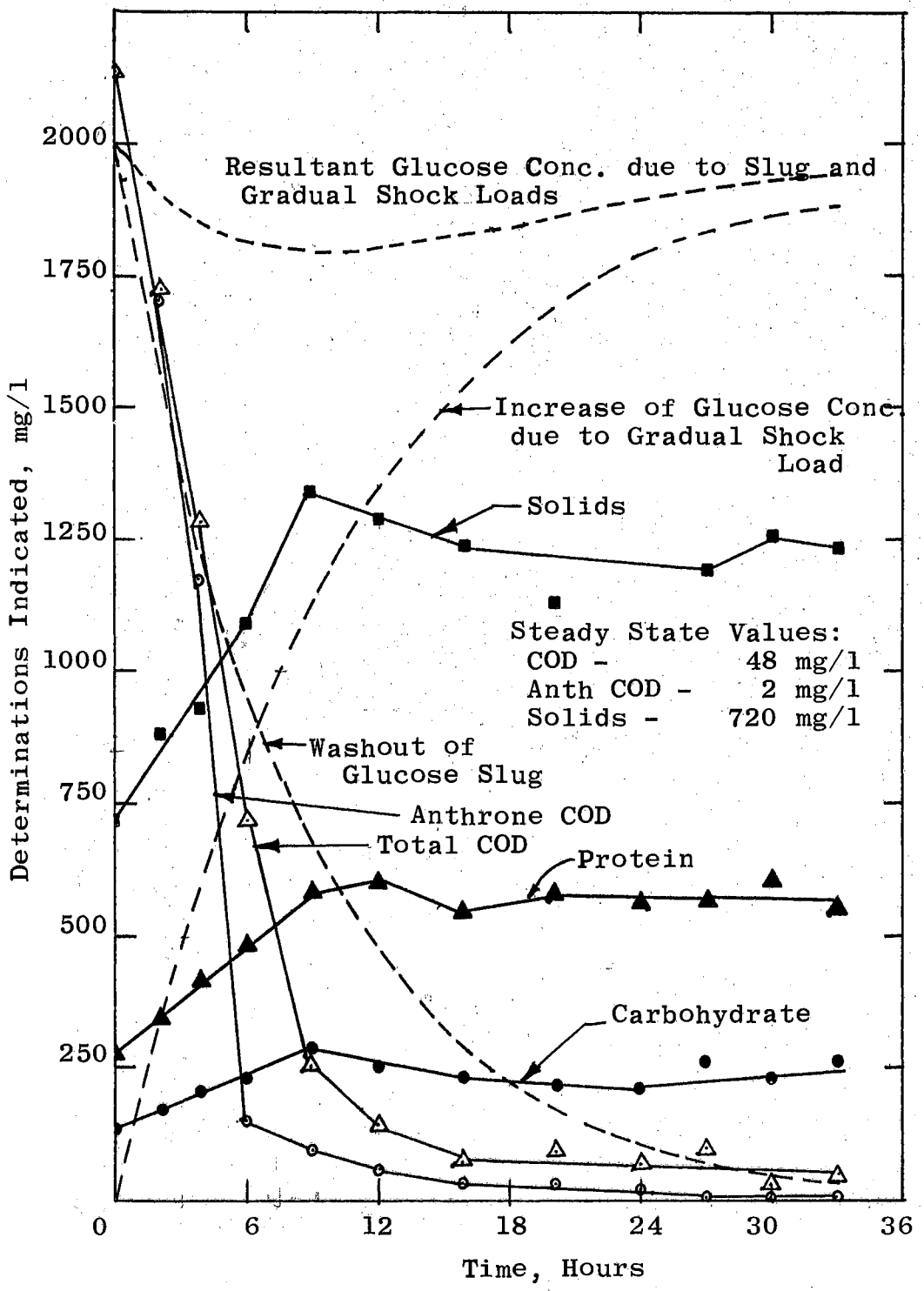

Fig. 38 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (WITH RECIRCULATION)

value of slightly over 750 mg/l at the end of thirty-three hours. It can also be seen from Figure 37 that there was considerably greater synthesis of protein than carbohydrate occurring in the system. The shock load response to a similar shock load with solids recirculation is shown in Figure 38. The total COD was reduced to a steady state value of approximately 65 mg/l in sixteen hours. There was a considerable difference between total COD and anthrone COD after four hours. The solids concentration reached a maximum of 1340 mg/l and was then reduced to 1250 mg/l at the end of the experiment. It can also be seen that there was a proportionally greater synthesis of protein than carbohydrates in response to the shock load.

The shock load responses when the influent was changed from 1000 mg/l to 3000 mg/l glucose and the unit was shocked with a slug dose of 3000 mg/l glucose are shown in Figures 39 and 40. It can be seen from Figure 39 that the total COD reached a steady state value of 100 mg/l after nineteen hours; however, there is considerable difference between the anthrone COD and total COD, indicating the release of intermediates. The solids concentration reached a maximum of 1760 mg/l and was reduced to a steady state value of 1380 mg/l at the end of twenty-eight hours. Comparison of Figures 32 and 39 indicates that the system operated at an 8-hour detention time requires slightly longer to reduce the total COD to a steady state value than one operated with 4-hour detention. In both cases there is considerable release of intermediates. The response to a similar shock load with solids recirculation is shown in Figure 40. It can be seen that the total COD reached a steady state value of approximately 120 mg/l in sixteen hours. Again, there is a considerable difference between anthrone COD and total COD. The solids

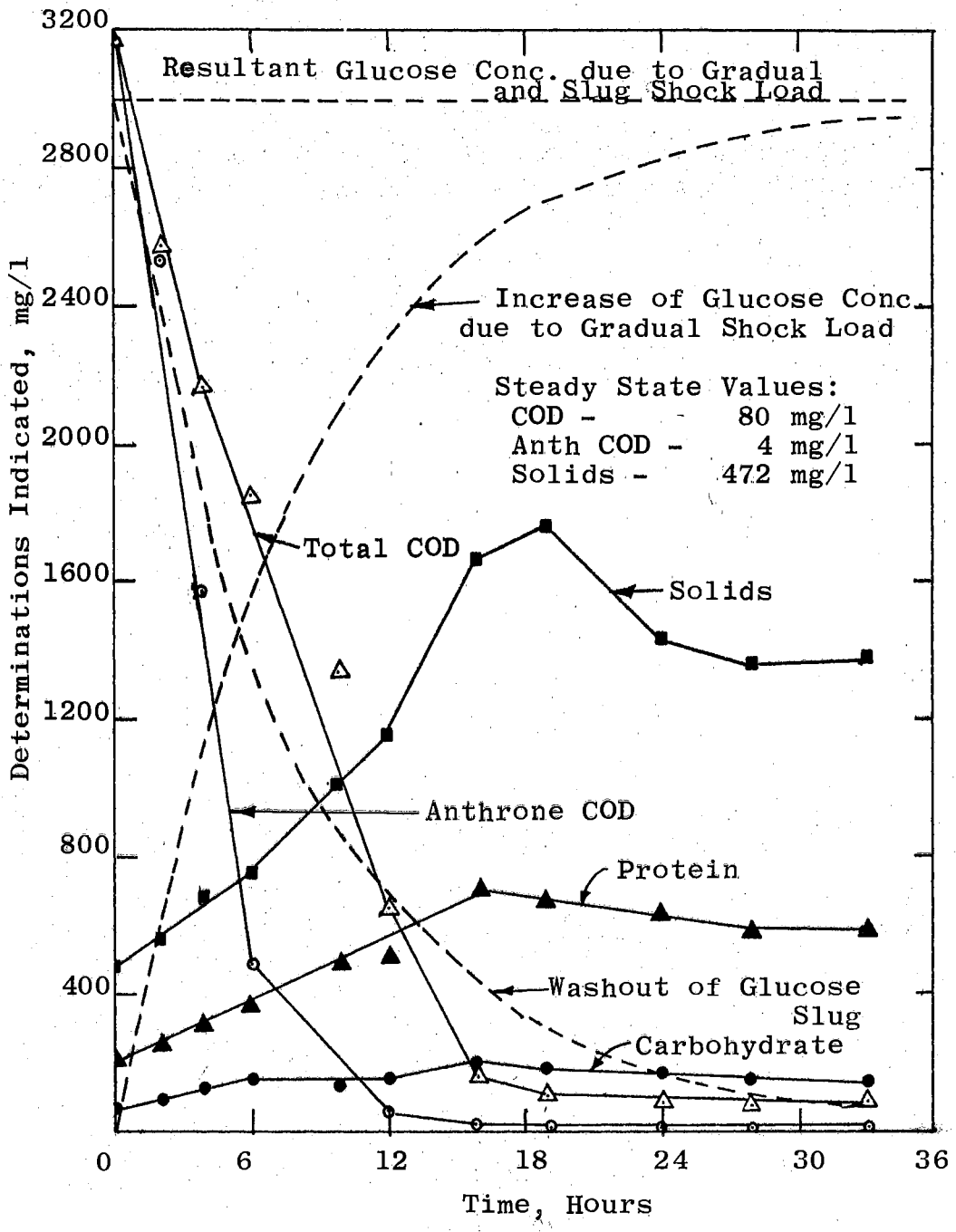

Fig. 39 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE AND ALSO SHOCKING WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

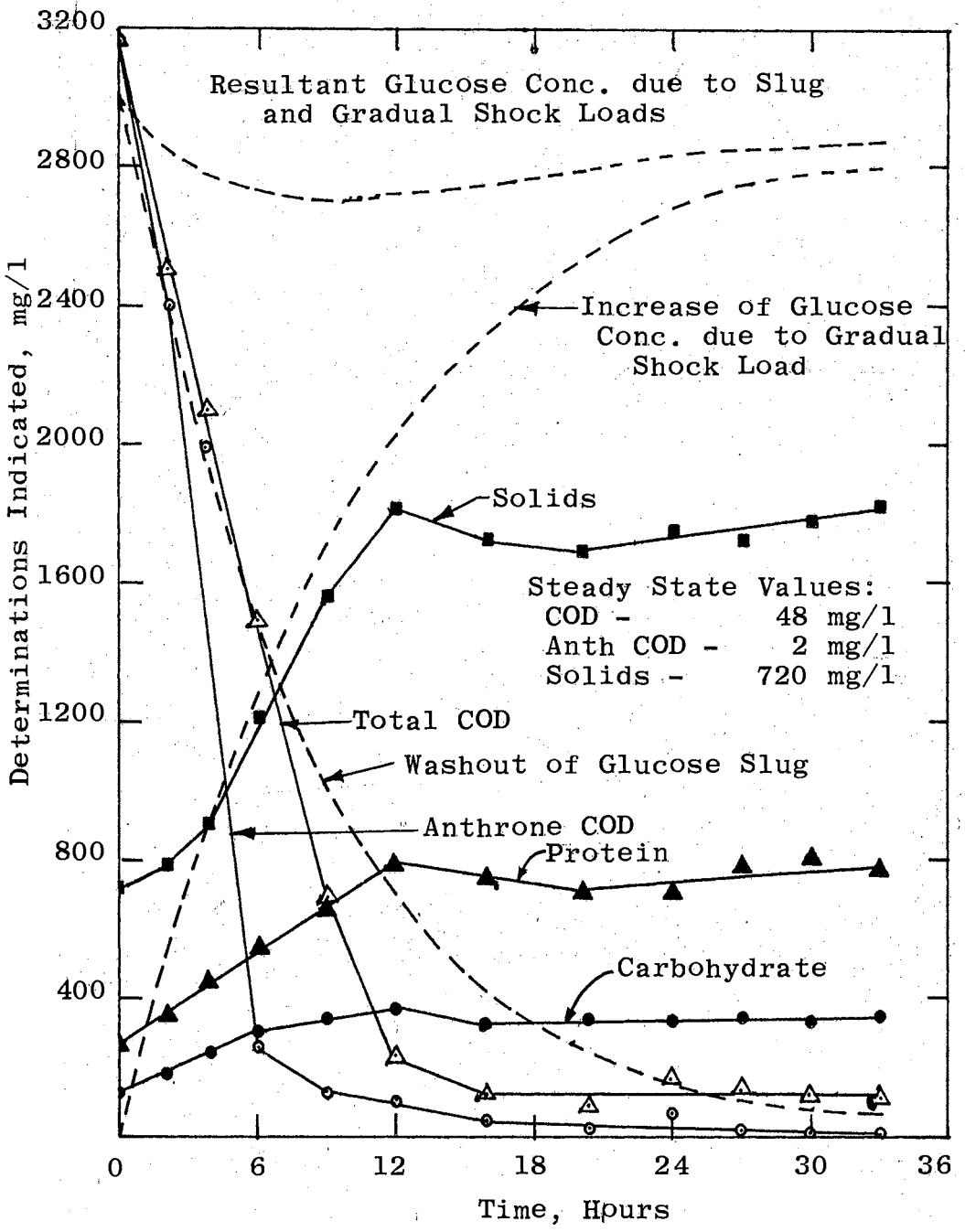

Fig. 40 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (WITH RECIRCULATION)

concentration reached a maximum of 1800 mg/l in twelve hours, and there was only a slight reduction in solids concentration thereafter. It can be seen that the total COD curve nearly follows the theoretical glucose washout curve, indicating that most of the total COD in the system was diluted out since it is known from Figure 18 that this system is capable of handling 3000 mg/l glucose as a gradual shock load. This surmise is also indicated by the solids concentration curve which does not show any solids synthesis in excess of the final steady state value. Comparison of Figures 40 and 33 indicates that a system operated at an 8-hour detention time takes longer to bring the total COD and anthrone COD to the new steady state values. It can also be seen that the general response to this shock load is similar in both systems (Figures 33 and 40).

c. 12-Hour Detention Time. The shock load responses to a slug dose of 2000 mg/l glucose while the influent was maintained constant at 1000 mg/l glucose are shown in Figures 41 and 42. It can be seen from Figure 41 that the total COD reached a steady state value of 125 mg/l in fourteen hours. However, a considerable amount of intermediates was present in the system, as shown by comparison of the anthrone COD and total COD curves. Since the total COD was always less than the dilute-out curve for the glucose, there is indication that the applied slug dose of glucose was utilized. However, no additional growth was reflected in the solids concentration curve. The response to a similar shock loading with solids recirculation is shown in Figure 42. The total COD reached a steady state value of approximately 60 mg/l in sixteen hours. It can be seen that very little release of intermediates occurred in comparison with the results shown in Figure 41. The solids concentration rapidly increased to a maximum of

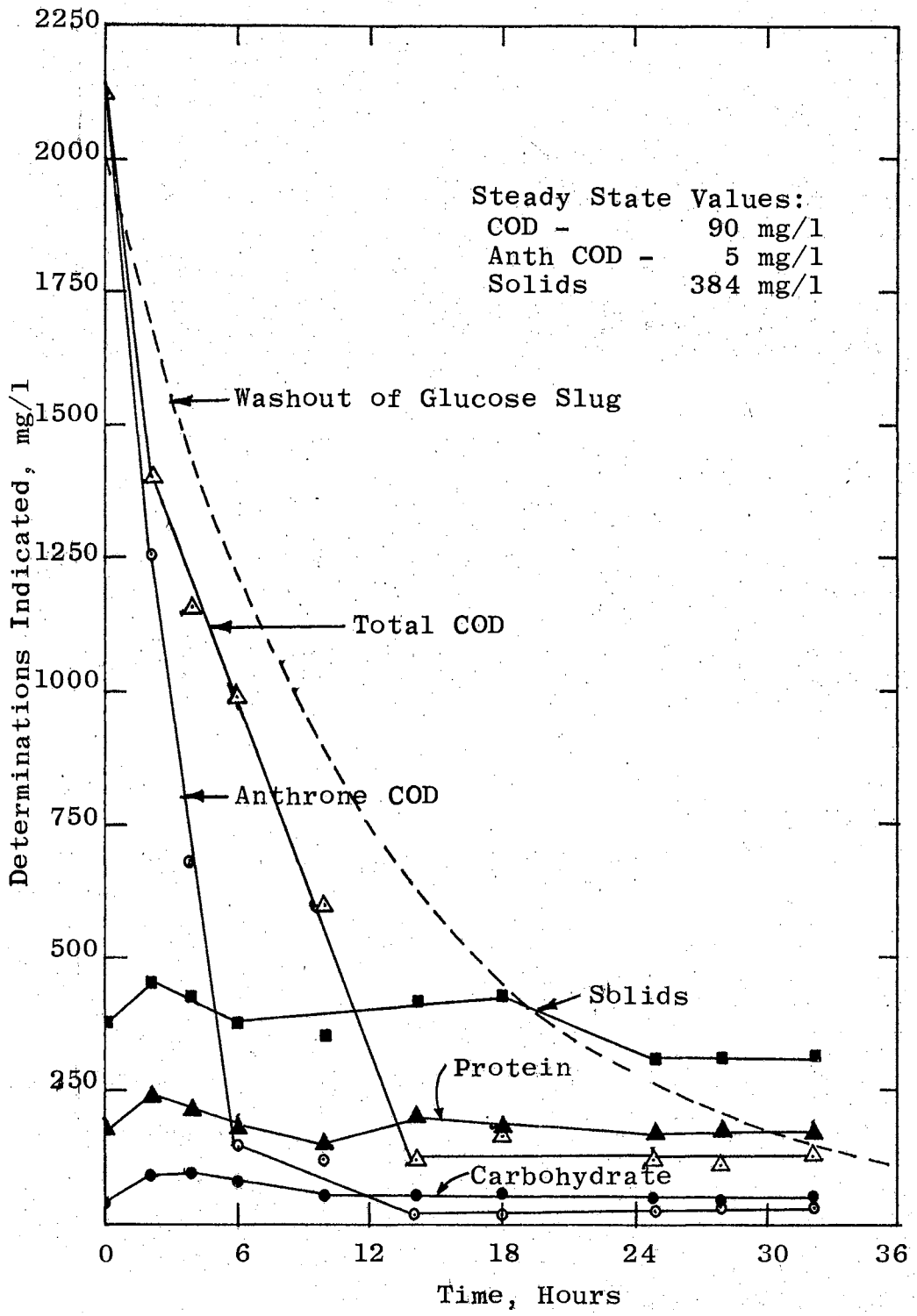

Fig. 41 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

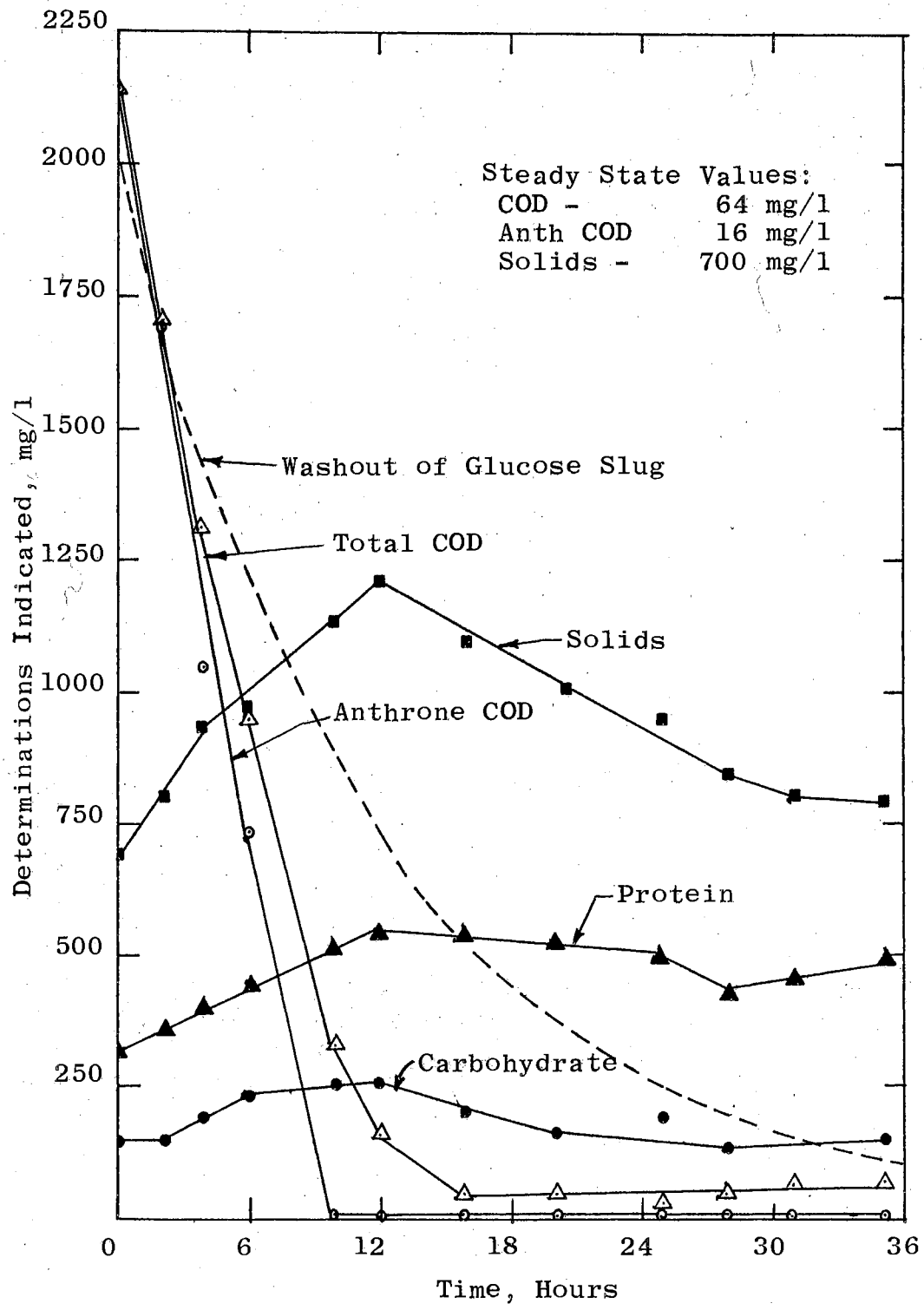

Fig. 42 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (RECIRCULATION)

1250 and was finally reduced to 790 mg/l at the end of thirty-five hours. Comparison of Figures 41 and 42 indicates a much better response to 2000 mg/l glucose slug load when sludge recirculation was employed.

The shock load response to a slug dose of 3000 mg/l glucose while the influent was maintained constant at 1000 mg/l glucose is shown in Figure 43. It can be seen that the total COD was gradually reduced to a steady state value of 80 mg/l after eighteen hours. The anthrone COD value was close to the total COD value at all times. The solids concentration increased to a maximum of 620 mg/l and was finally reduced to an approximate steady state value of 360 mg/l within twenty-four hours. Comparison of Figures 43 and 36 indicates that a system operated at a 12-hour detention time takes longer to reduce the total COD to a constant value than one operated at an 8-hour detention time; however, the release of intermediates is not apparent at the 12-hour detention time. If the response is compared with the theoretical glucose washout curve, the performance of the system operated with a 12-hour detention time appears to be much better than the response at detention time of four hours. It can also be seen from Figure 43 that the increase in solids concentration was accompanied by a rapid increase in protein synthesis.

The shock load responses when the influent was changed from 1000 mg/l to 2000 mg/l glucose and the unit was also shock loaded with a slug dose of 2000 mg/l glucose are shown in Figures 44 and 45. It can be seen from Figure 44 that the total COD reached a steady state value of 120 mg/l in twenty-five hours; however, there was a considerable difference between anthrone COD and total COD. There was very little increase in the solids concentration during the initial nine hours; thereafter there was a fairly rapid rise and a maximum

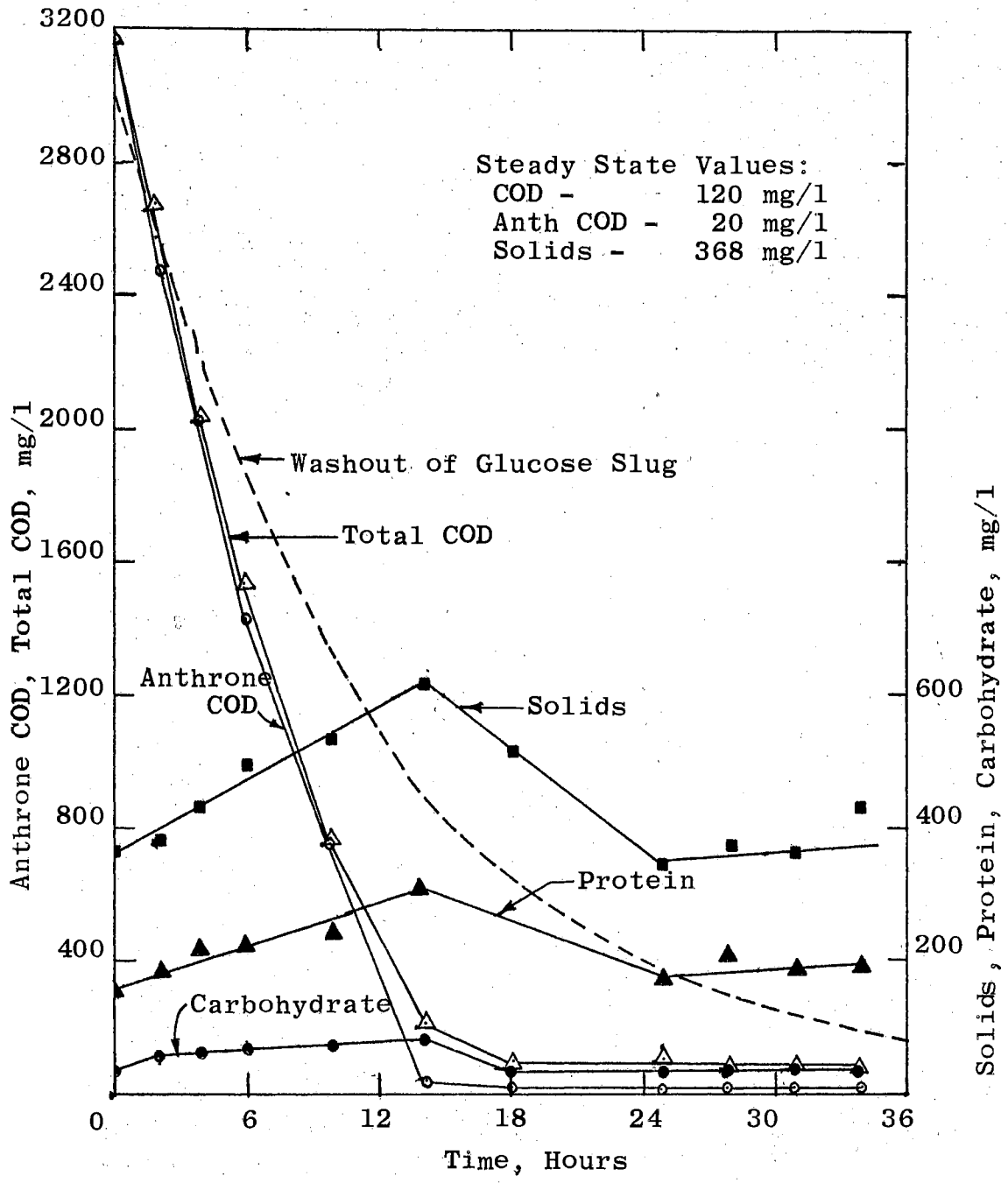

Fig. 43 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME CONTINUOUSLY FED AT 1000 mg/l GLUCOSE AND SHOCKED WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

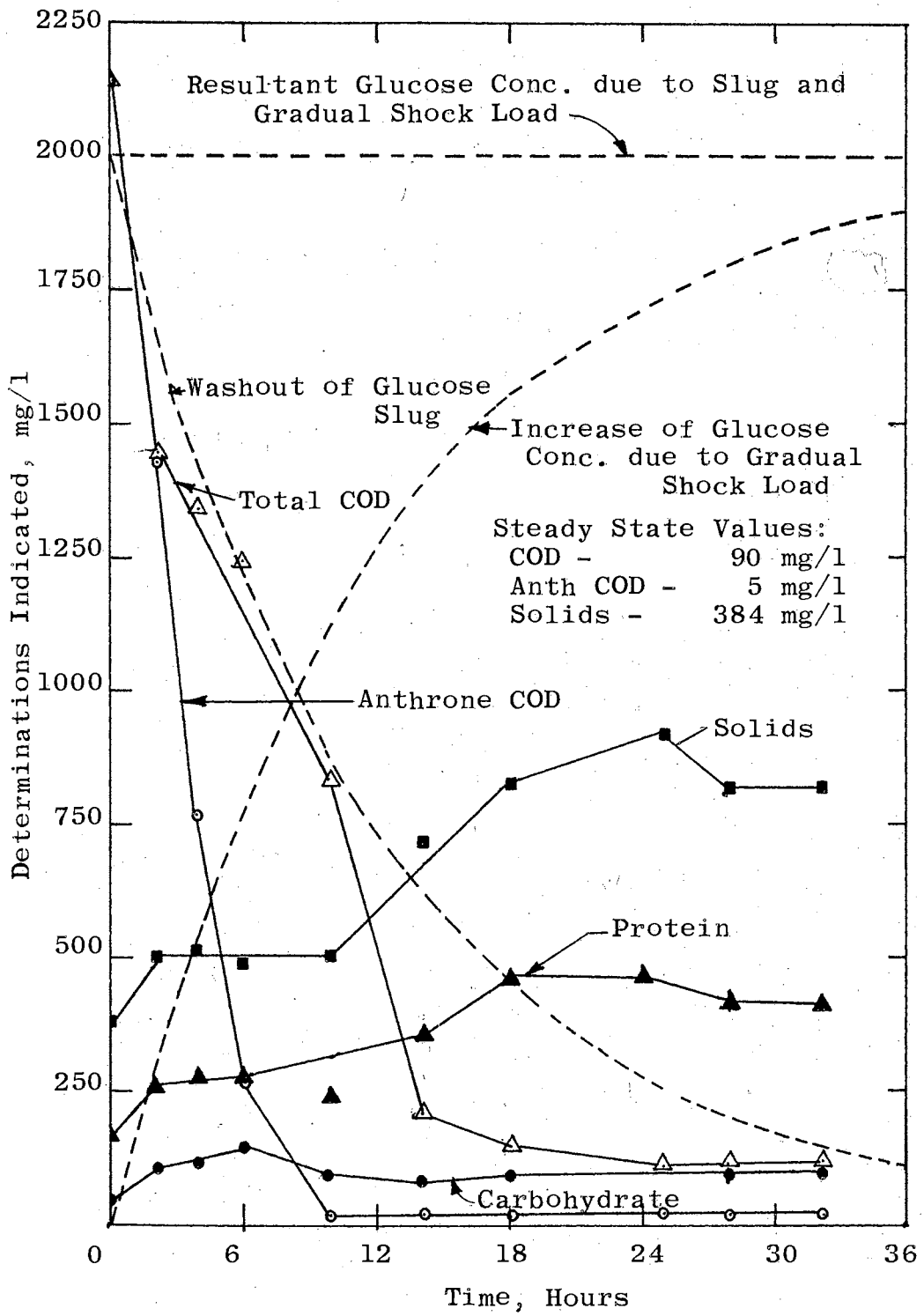

Fig. 44 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (NO RECIRCULATION)

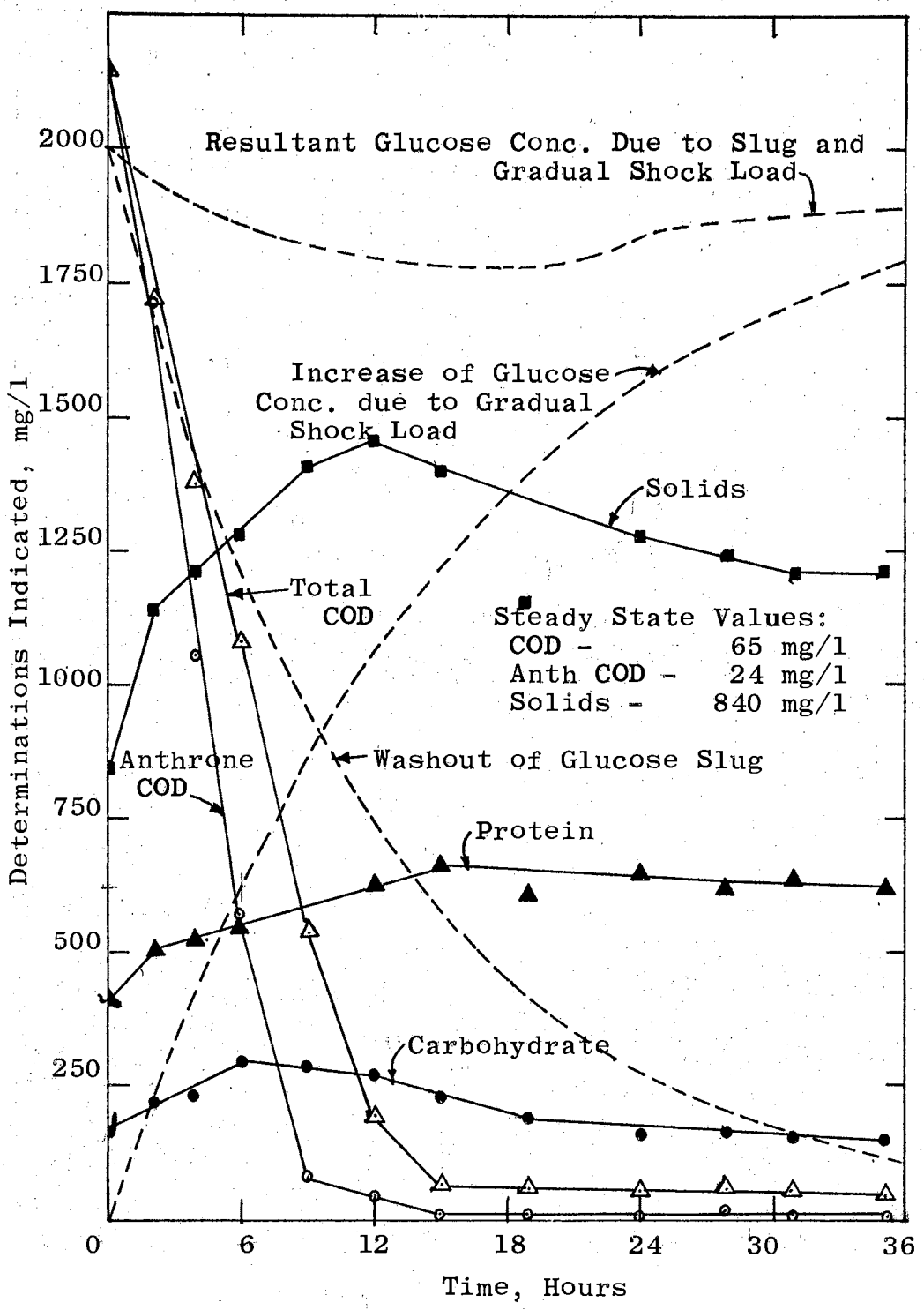

Fig. 45 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 2000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 2000 mg/l GLUCOSE (WITH RECIRCULATION)

of 920 mg/l was reached at twenty-five hours. The solids concentration attained a steady state value of 815 mg/l at the end of twenty-eight hours. It can also be seen that protein synthesis was much greater than carbohydrate synthesis. The response to a similar shock load with solids recirculation is shown in Figure 45. The total COD was reduced to a steady state value of 65 mg/l in fifteen hours. The anthrone COD was less than the total COD at all times although there was not as much release of intermediates as compared with Figure 44. The solids reached a maximum of 1350 mg/l at twelve hours and was gradually reduced to a steady state value of 1200 mg/l. It can also be seen from Figure 45 that the solids increase was accompanied by a proportionately greater protein than carbohydrate synthesis. Comparison of Figures 44 and 45 indicates a much better response when solids recirculation is employed. It can be seen from Figures 37, 38, 44, and 45 that the response of the system at the 12-hour detention time appeared to be much better as compared with 8-hour detention time.

The shock load responses when the influent feed was changed from 1000 mg/l to 3000 mg/l glucose and the unit was also shocked with a slug dose of 3000 mg/l glucose are shown in Figures 46 and 47. The total COD reached a steady state value of 160 mg/l after eighteen hours. It can also be seen from Figure 46 that there was not much release of intermediates as indicated by comparison of the anthrone and total COD curves. The solids increased rapidly during the first nine hours and thereafter increased more gradually. An approximate steady state value of 1160 mg/l was attained at the end of twenty-six hours. It can also be seen from Figure 46 that there was a rapid increase in the protein content of the sludge as compared with the carbohydrate content. Comparison of Figures 39 and 46 indicates a much better response at the 12-hour detention time for the same shock load. The response to a similar shock load with

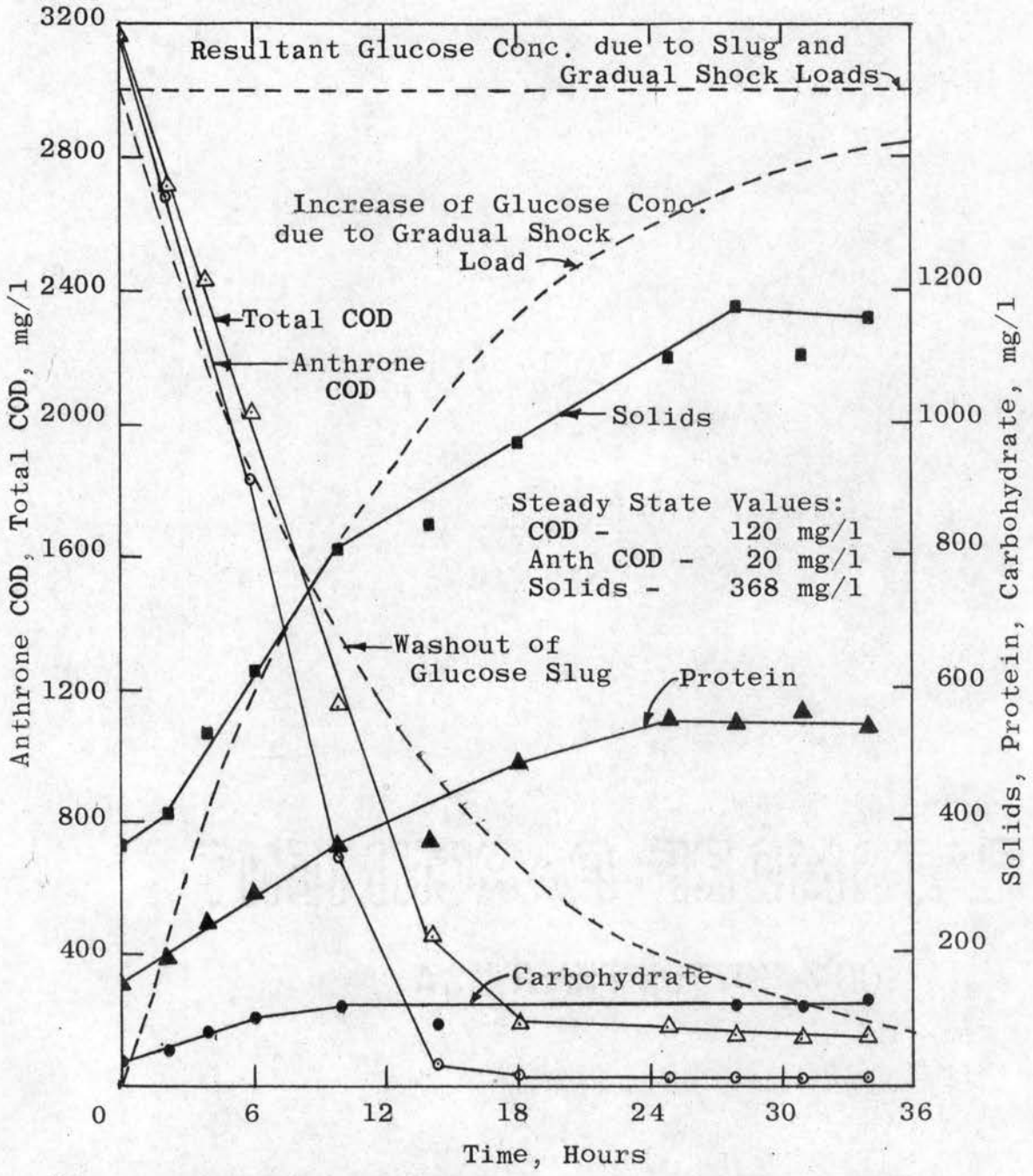

Fig. 46 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 3000 mg/l GLUCOSE AND SHOCKING WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (NO RECIRCULATION)

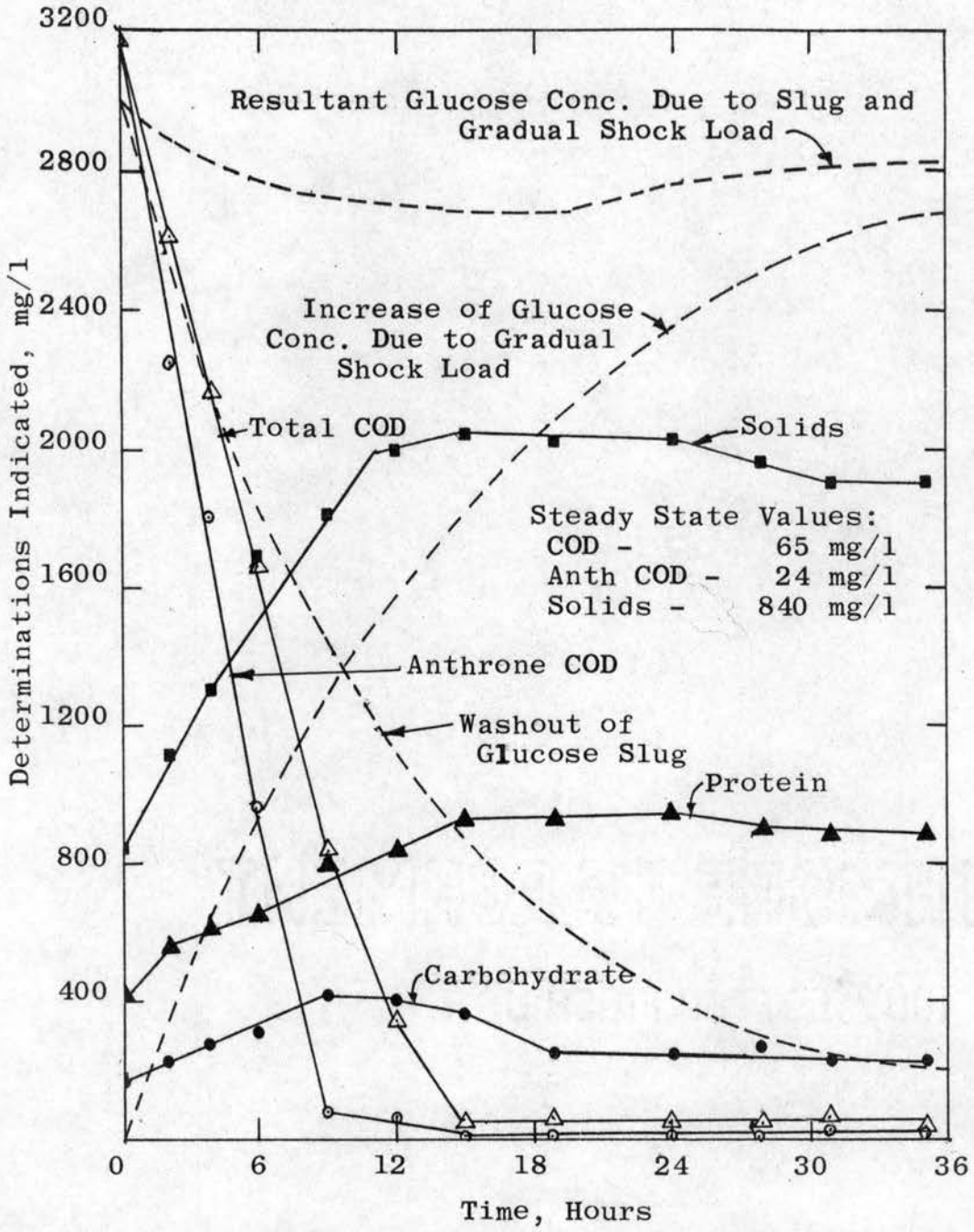

Fig. 47 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLOW FEED FROM 1000 mg/1 TO 3000 mg/1 GLUCOSE AND ALSO SHOCKING WITH A SLUG DOSE OF 3000 mg/1 GLUCOSE (RECIRCULATION)

solids recirculation is shown in Figure 47. The total COD was reduced to a steady state value of 50 mg/l in fifteen hours. It can also be seen that there was a difference between anthrone COD and total COD at all times. The solids concentration increased rapidly, reached a maximum of 2040 mg/l and was finally reduced to a steady state value of 1900 mg/l. Comparison of Figures 40 and 47 indicates a much better response to this shock load when the system is operated at 12-hour detention time.

In order to evaluate the effect of solids concentration on the response to slug shock loading, an experiment was conducted in a continuous flow system employing total recirculation (i.e., recirculation ratio = 1). The solids concentration in the system was in excess of 3000 mg/l. The result of a 3000 mg/l glucose slug to such a system is shown in Figure 48. There was a rapid utilization of the glucose slug, indicating a successful response to such a shock load. This is also clearly indicated by the difference between the total COD and washout curve. The applied glucose slug was completely removed in five hours. The utilization of the glucose slug is also indicated by the increase in the solids concentration. The increase in solids concentration was also accompanied by a similar increase in protein and carbohydrate content of the cells.

3. Response to Shock Loads under Nitrogen Deficient Conditions.

a. 4-Hour Detention Time. In this portion of the study, experiments were conducted to determine the modes of response of continuous flow steady state systems under nitrogen deficient conditions. In all of the experiments the amount of $(NH_4)_2 SO_4$ added is expressed in terms of BOD/N ratio. In order to convert the substrate concentra- to corresponding BOD values, the BOD is calculated at 0.7 of the chemical oxygen demand. The value of 0.7 was previously employed by Gaudy, et al.(94).

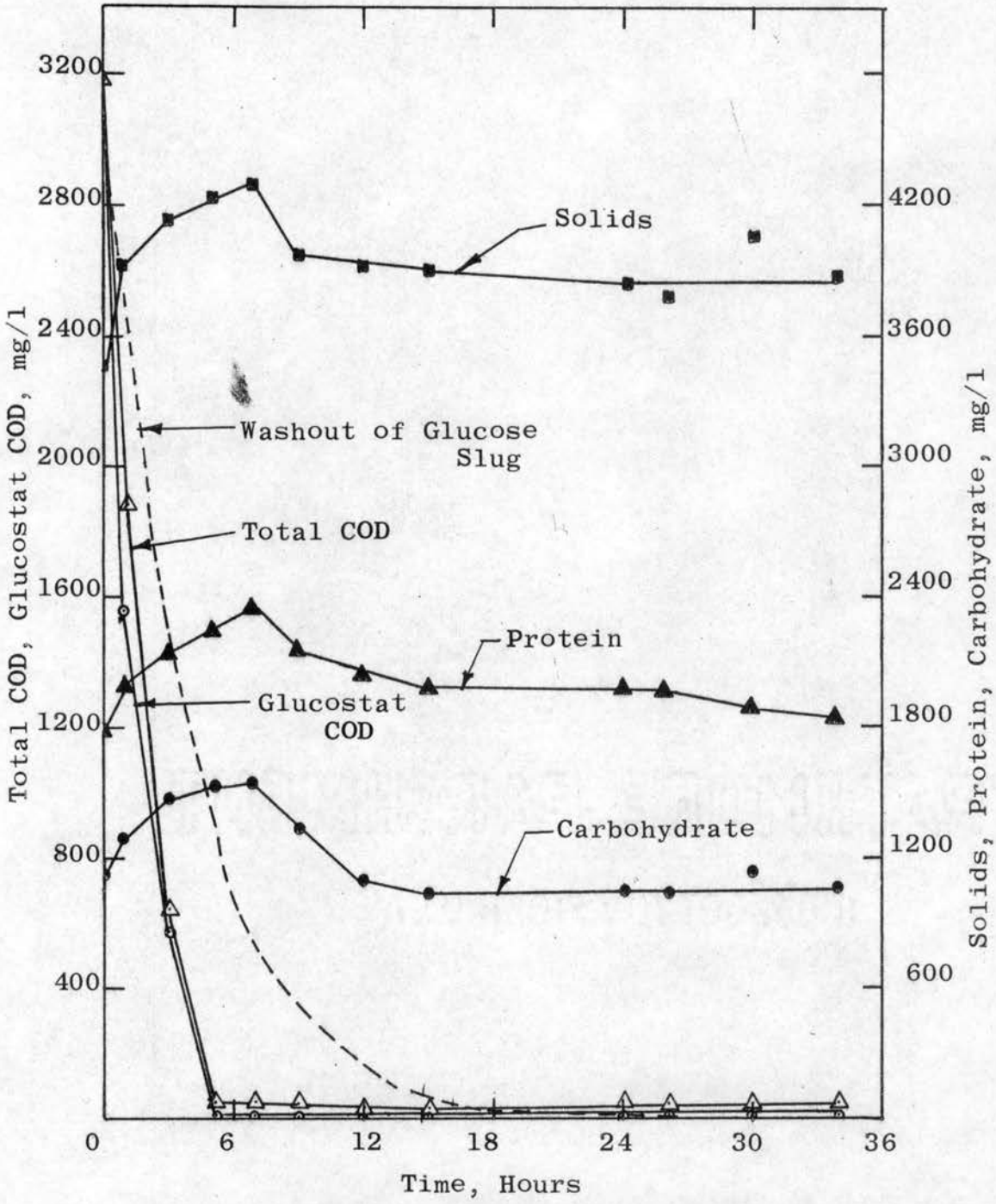

Fig. 48 - SHOCK LOAD RESPONSE OF THE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME WHEN THE INFLUENT WAS MAINTAINED CONSTANT AT 1000 mg/l GLUCOSE AND THE UNIT WAS SHOCKED WITH A SLUG DOSE OF 3000 mg/l GLUCOSE (TOTAL RECIRCULATION)

The response to a change in nitrogen content in the influent feed is shown in Figure 49. The influent feed was maintained constant at 1000 mg/l glucose. Originally, the BOD/N ratio was maintained at 7 and the amount of $(NH_4)_2SO_4$ was reduced to yield a BOD/N ratio of 30. It can be seen that the total COD increased to a maximum of 520 mg/l and was gradually reduced to 300 mg/l after thirty-two hours. The anthrone COD reached a maximum of 160 mg/l and was reduced to a steady state value of 75 mg/l. The biological solids concentration rapidly declined; however, it increased again to its previous steady state value. It can be seen that there was a marked decrease in protein content of the sludge and a delayed increase in carbohydrate content. It is apparent from Figure 49 that reduction in the nitrogen content in the influent feed caused a severe change in the biochemical efficiency of the system.

The shock load responses when the influent feed was changed from 1000 mg/l glucose with $\frac{BOD}{N} = 7$ to 3000 mg/l glucose with $\frac{BOD}{N} = 30$ are shown in Figures 50 and 51. It can be seen from Figure 50 that there was a rapid increase in the total COD during the first six hours. After this time COD removal improved, but 1420 mg/l COD remained in solution at the end of thirty-two hours. There was also a rapid increase in anthrone COD. After attaining a peak value the anthrone COD was reduced to 190 mg/l. It can be seen from these results that a considerable amount of metabolic intermediates and/or end products was released into the medium. The biological solids concentration reached a maximum value of only 850 mg/l which is less than triple the previous steady state value of 350 mg/l. It can also be seen that protein synthesis was very much retarded while the carbohydrate content of the sludge increased considerably. The response to a similar shock load with recirculation of biological solids is shown in Figure 51. In this system there was also a rapid increase in the total

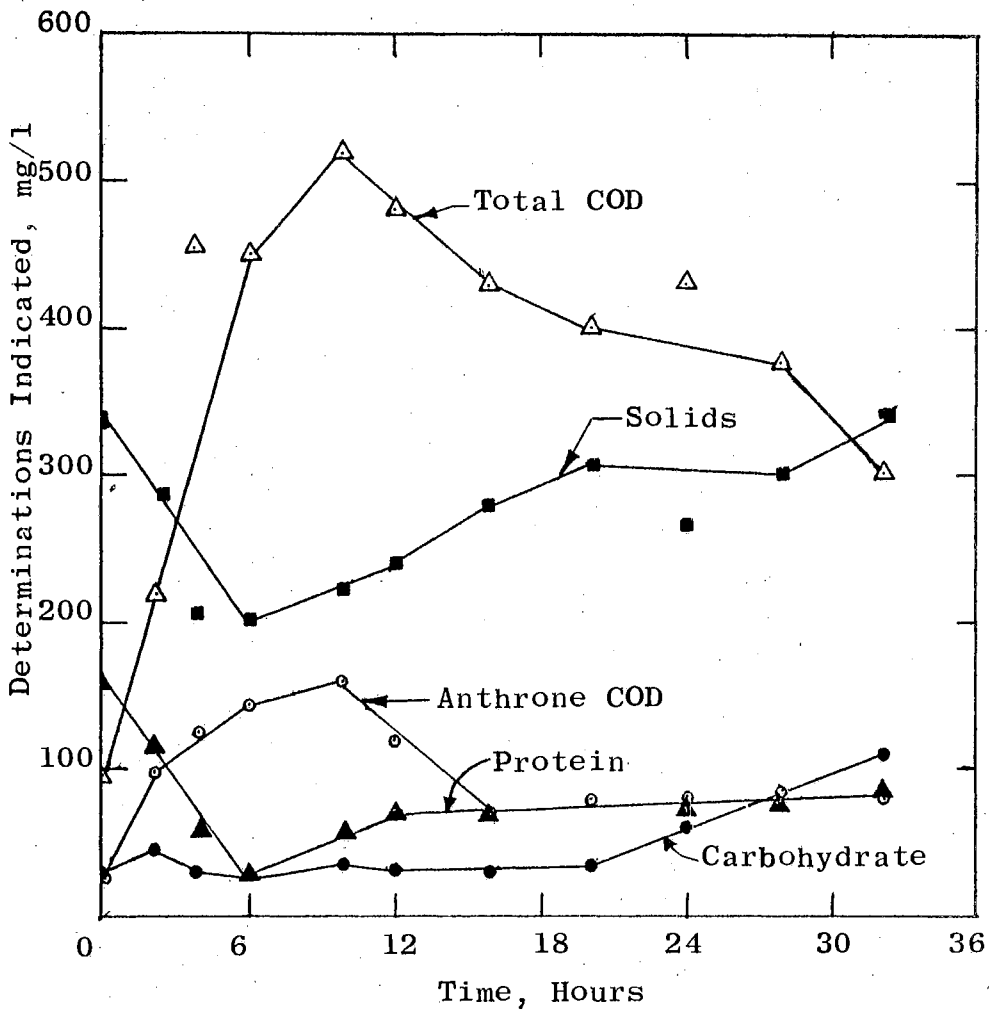

Fig. 49 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/1 GLUCOSE WITH BOD/N = 7 TO 1000 mg/1 GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

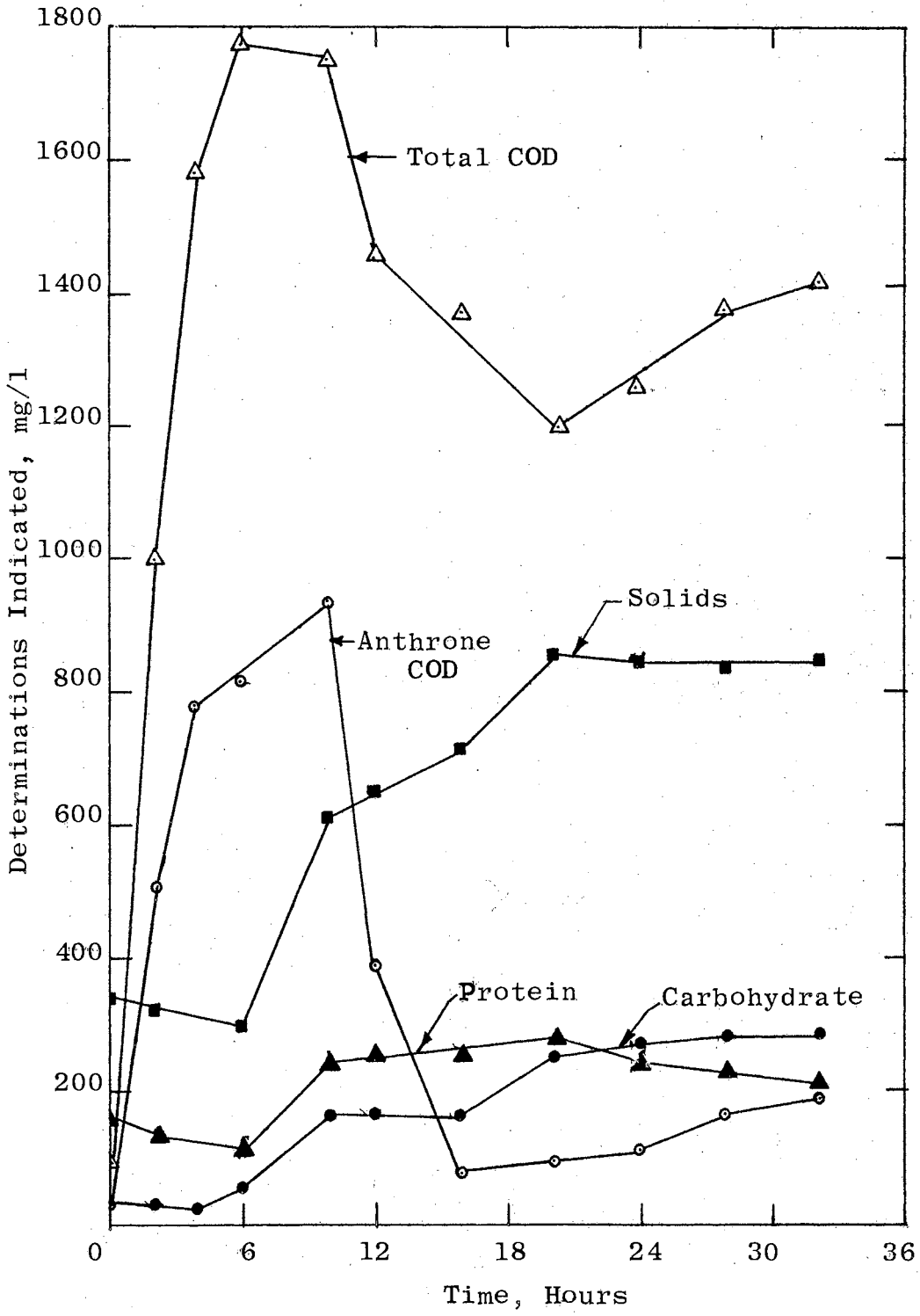

Fig. 50 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

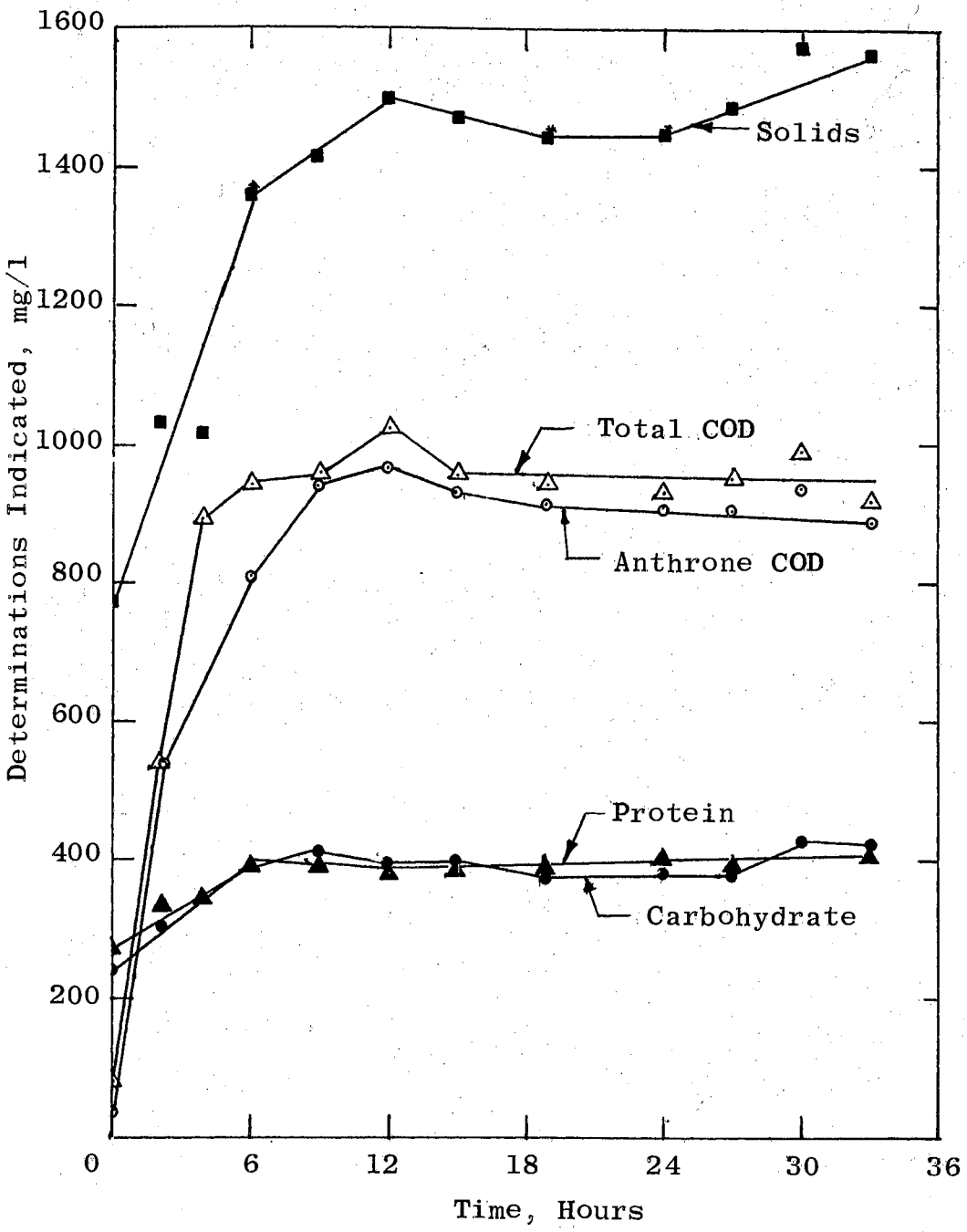

Fig. 51 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (WITH RECIRCULATION)

COD and a steady state value of approximately 930 mg/l was attained. It can be seen that the anthrone COD was very similar to total COD. The most striking difference between the systems shown in Figures 50 and 51 is the absence of intermediates when solids recirculation is used; there was also a significant difference between the protein and carbohydrate content of the sludge in both systems. This aspect will be discussed in detail in a subsequent section of this report. It can also be seen that the removal of total COD was more efficient for the system in which solids recirculation was practiced; however, for both modes of operation, biochemical efficiency was severely disrupted.

The response to a change in nitrogen content from a $\frac{BOD}{N}$ ratio of 7 to one of 40 while the influent feed was maintained constant at 1000 mg/l glucose is shown in Figure 52. There was a gradual increase in the total COD concentration in the effluent. However, there was not a comparable increase in anthrone COD which reached a steady state value of 50 mg/l. The solids concentration gradually decreased from an initial value of 520 mg/l and approached a final steady state value of 385 mg/l. A similar decrease was also noted in the protein content of the sludge; however, the carbohydrate content remained relatively constant. On a percentage basis, the carbohydrate content increased due to the reduction in solids concentration.

The shock load responses when the influent was changed from 1000 mg/l glucose with $\frac{BOD}{N} = 7$ to 3000 mg/l with BOD/N = 40 are shown in Figures 53 and 54. It can be seen from Figure 53 that the total COD increased rapidly to a maximum of 1260 mg/l and remained at a high level. However, the anthrone COD reached a maximum of only 465 mg/l. It can be noted that the total COD did not increase to as high a value as it did when BOD/N of 30 was employed (Figure 50). This may have been due to the slightly higher solids concentration in the system before the shock, but is

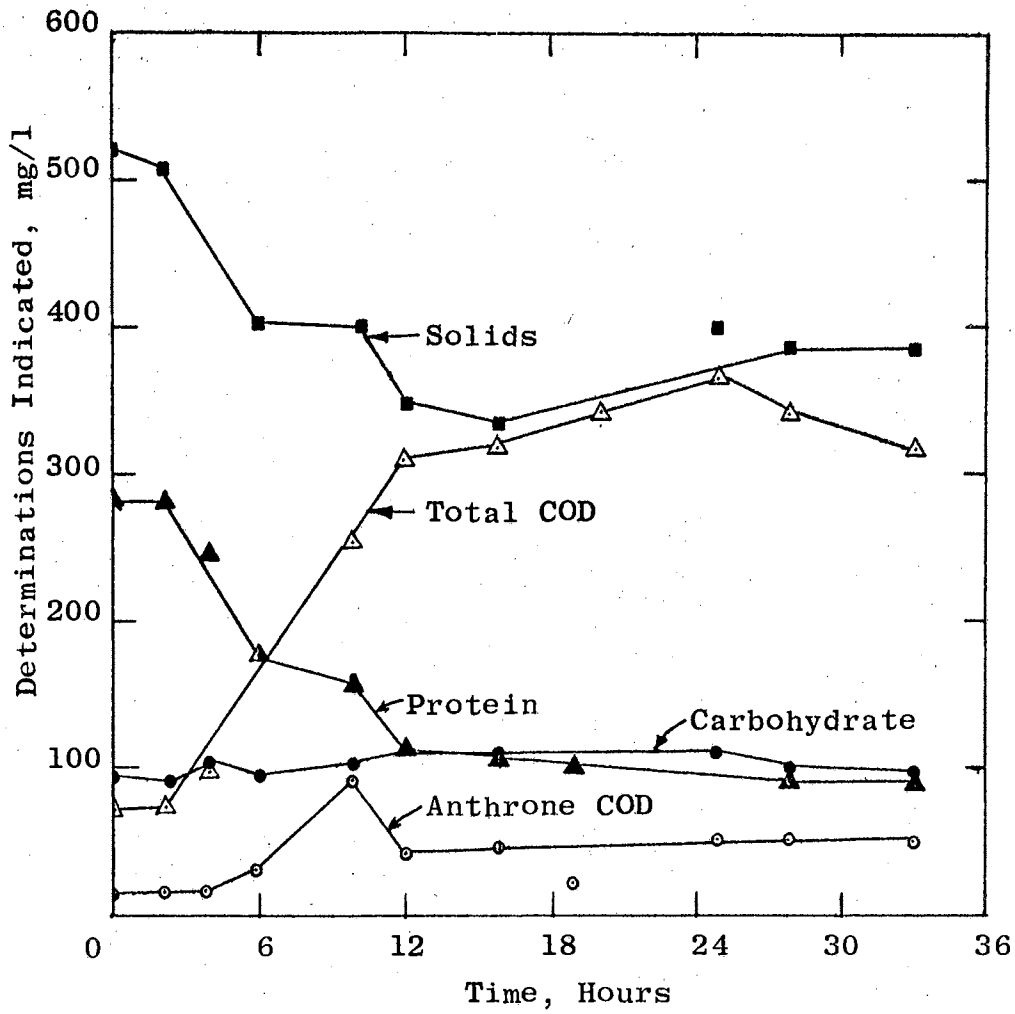

Fig. 52 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 1000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

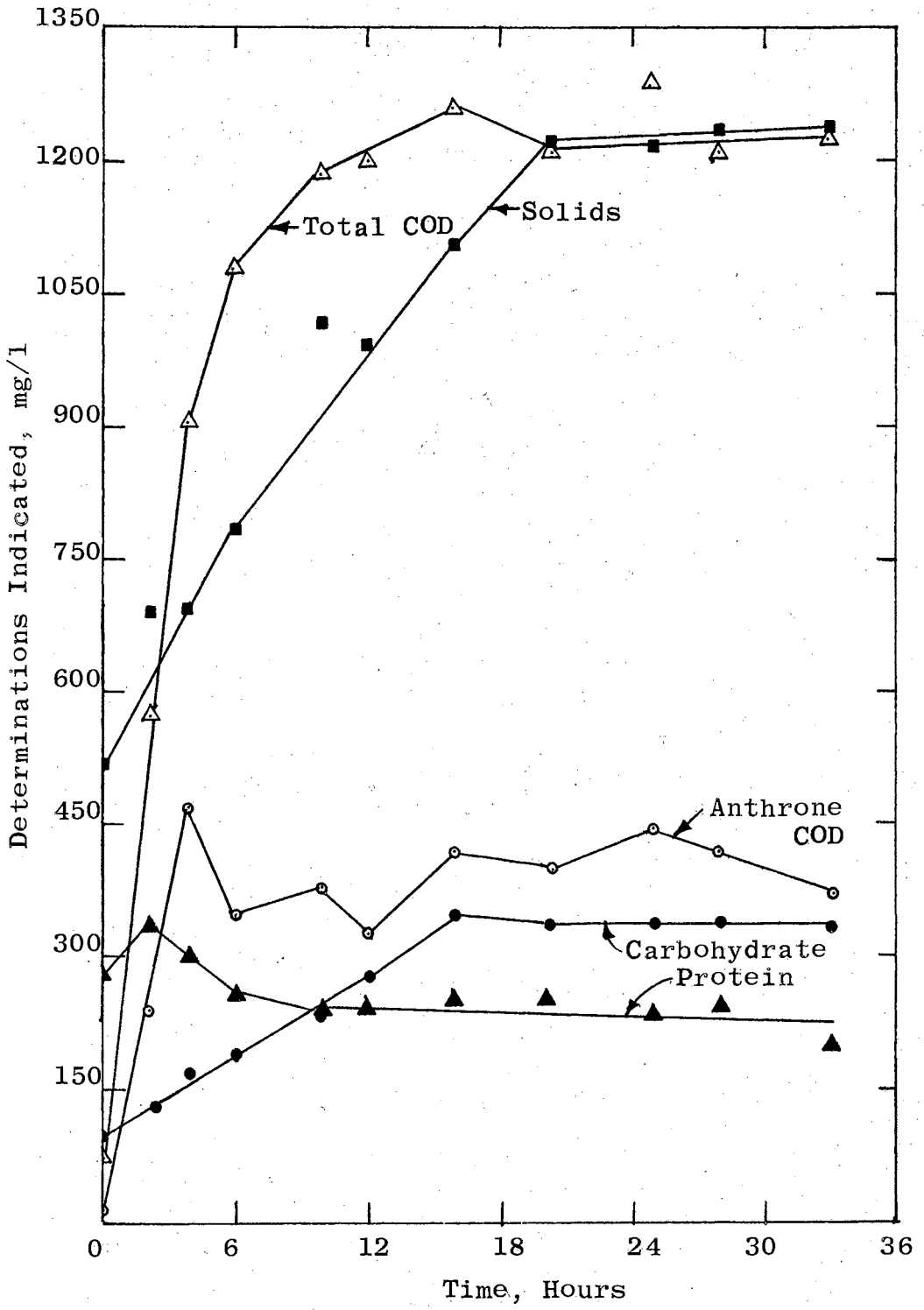

Fig. 53 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

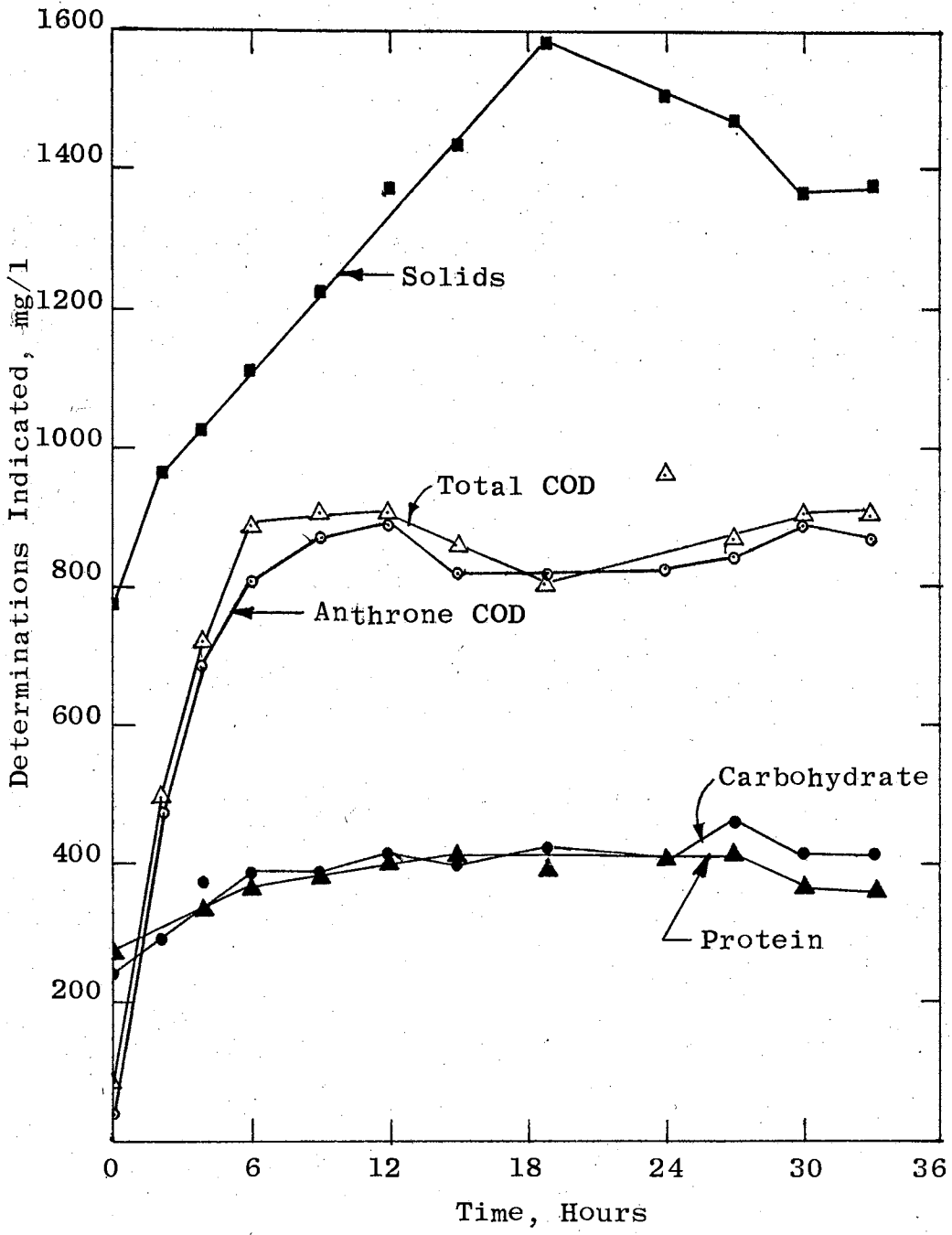

Fig. 54 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE BOD/N = 40 (WITH RECIRCULATION)

more probably due to the fact that for the experiment shown in Figure 53 the biological solids responded by an immediate growth whereas it can be seen in Figure 50 that there was a lag in sludge production of at least six hours. It can be seen in Figure 53 that there was very little protein synthesis in response to the shock load, but there was a considerable increase in the carbohydrate content of the sludge. The response to a similar shock load with solids recirculation is shown in Figure 54. The total COD increased to a maximum of 900 mg/l and was closely paralleled by the anthrone COD. The biological solids concentration increased to a maximum of 1580 mg/l and thereafter declined to a steady state value of 1360 mg/l. The values for protein and carbohydrate content of the sludge were almost the same throughout the experiment, and unlike the system shown in Figure 53, there was no excess carbohydrate synthesis in response to the shock. It can be seen from Figures 53 and 54 that the biochemical efficiency of the system was severely affected due to inadequate amounts of nitrogen in the incoming feed.

b. 8-Hour Detention Time. The response to a change in nitrogen content from a $\frac{BOD}{N}$ ratio of 7 to one of 30 while the influent feed was maintained constant at 1000 mg/l glucose is shown in Figure 55. The total COD increased to a maximum of 350 mg/l, and was finally reduced to 250 mg/l at the end of forty-eight hours. The anthrone COD remained relatively constant during the initial nine hours, and gradually increased to a maximum of 260 mg/l. Comparison of Figures 49 and 55 indicates that less total COD appeared in the effluent for the system operated at the 8-hour detention time. However, the anthrone COD was quite high. The biological solids concentration fluctuated considerably during the first nine hours, then gradually decreased and reached a value of 220 mg/l at forty-eight hours. It can also be seen that there was a gradual decrease in protein content,

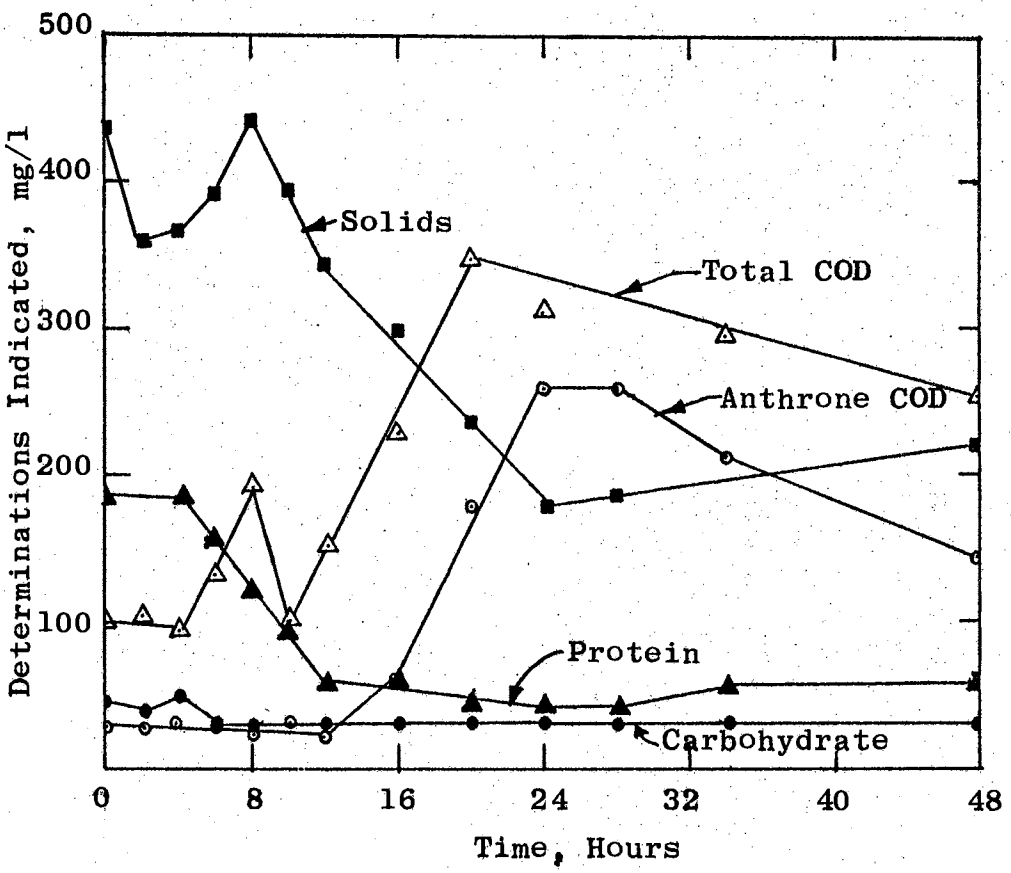

Fig. 55 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 1000 mg/l GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

although the carbohydrate remained constant. On a percentage basis, the carbohydrate content increased due to the reduction in solids concentration.

The shock load responses when the influent feed was changed from 1000 mg/l glucose with a $\frac{BOD}{N}$ ratio of 7 to 3000 mg/l glucose with a $\frac{BOD}{N}$ ratio of 30 are shown in Figures 56 and 57. It can be seen from Figure 56 that the total COD reached a maximum of 1050 mg/l at twenty-seven hours and remained relatively constant. However, the anthrone COD increased to a maximum of only 510 mg/l and was reduced to 300 mg/l at the end of forty-eight hours. The solids concentration reached a maximum of 1015 mg/l and remained approximately steady at this value. The solids level in the aerator was considerably less than three times the previous steady state value of 435 mg/l. It can also be seen that there was only a slight increase in protein content although carbohydrate content increased appreciably. The response to a similar shock load with solids recirculation is shown in Figure 57. The total COD increased rapidly to 440 mg/l six hours after the shock was applied. It can be seen that the anthrone COD curve lies close to the curve of total COD. More carbohydrate than protein was synthesized in response to the shock. It can be seen by comparison of Figures 57 and 56 that sludge recirculation improved the response. Also, it can be seen by comparison of Figures 50, 51, 56, and 57 that the systems operated at the 4-hour detention time were more seriously affected by the lack of nitrogen than were those operated at an 8-hour detention time.

The response to a change in nitrogen content from a $\frac{BOD}{N}$ ratio of 7 to one of 40 while the feed was maintained constant at 1000 mg/l glucose is shown in Figure 58. The total COD decreased during the first six hours and then gradually rose to a maximum of 320 mg/l at the end of thirty-three hours. The anthrone COD remained essentially

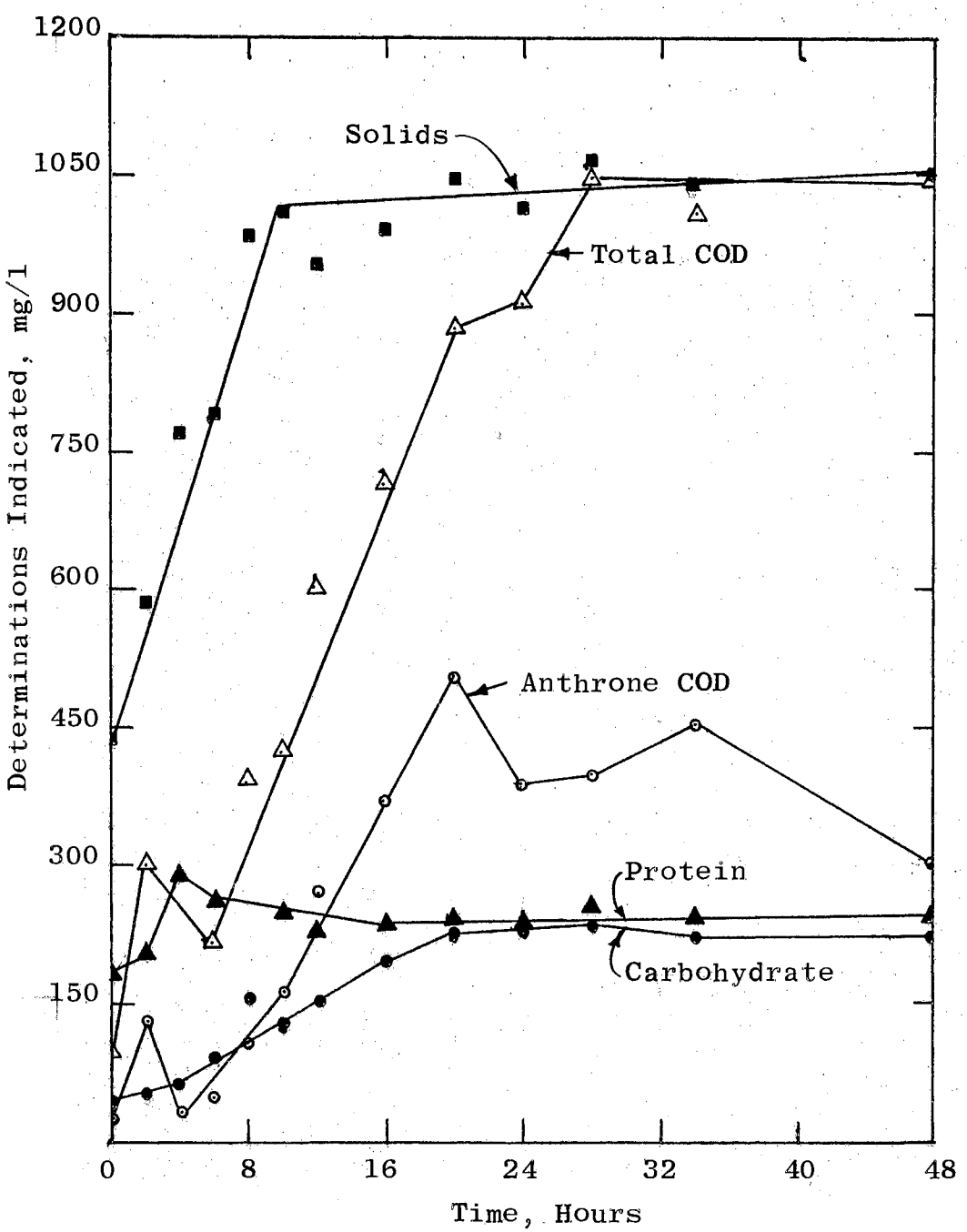

Fig. 56 – SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

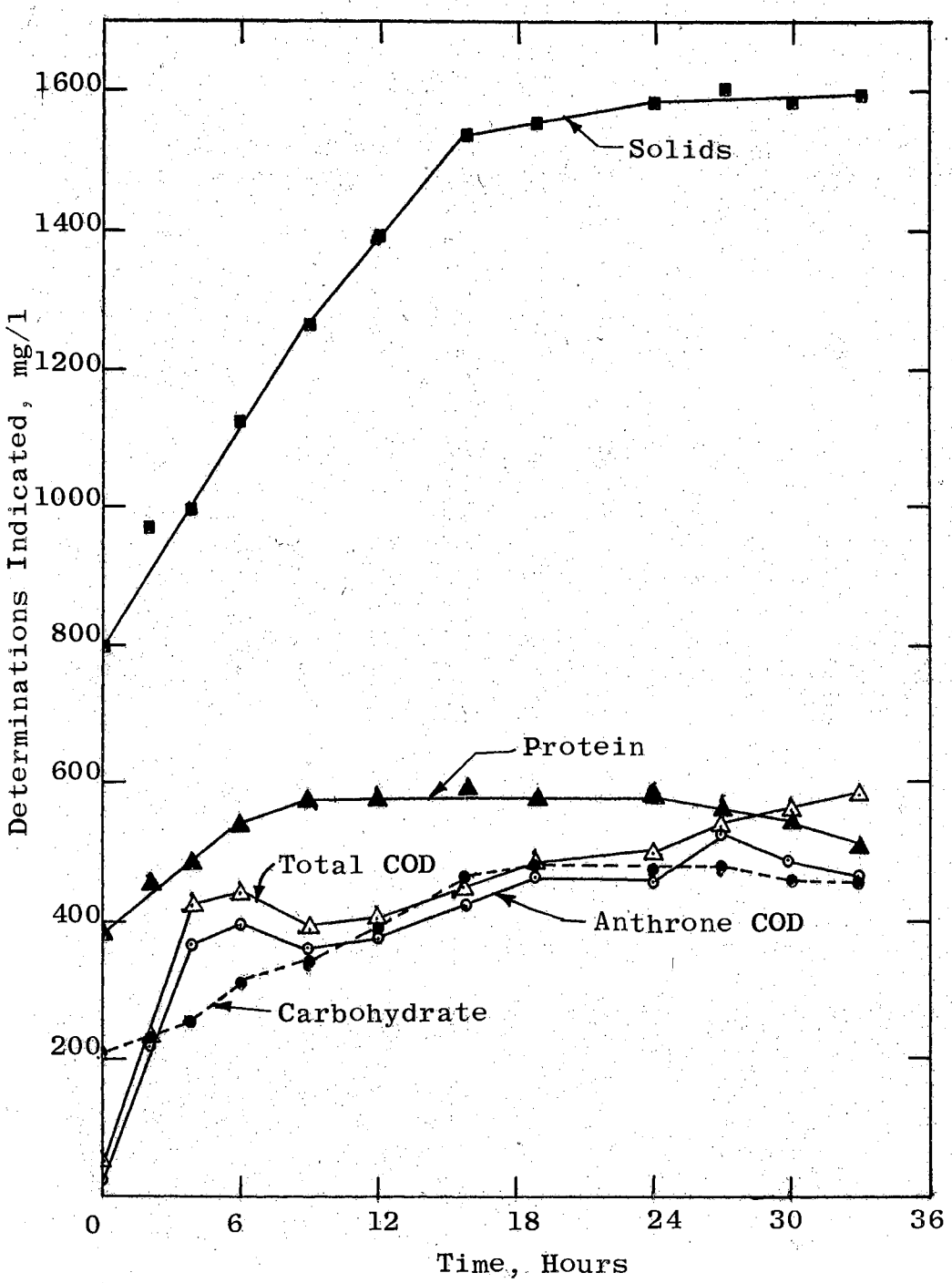

Fig. 57 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (WITH RECIRCULATION)

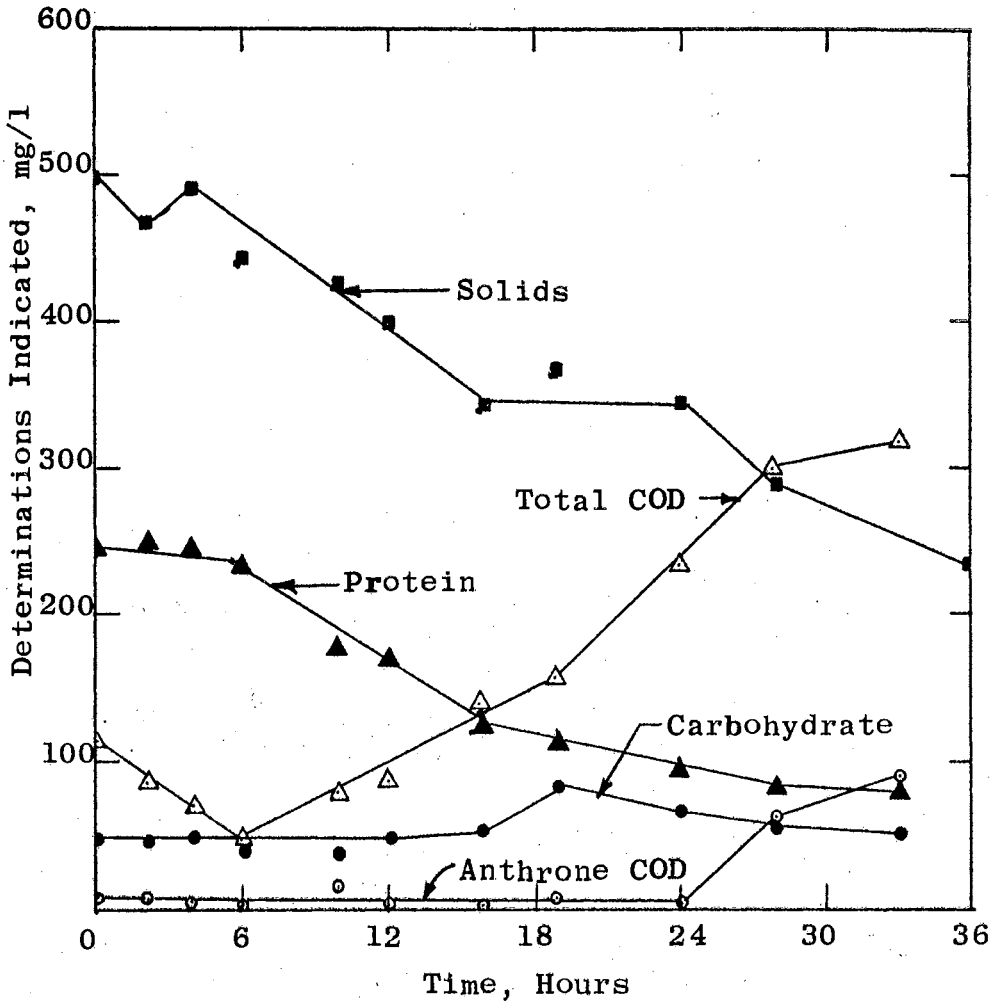

Fig. 58 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 1000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

constant up to twenty-four hours, and thereafter increased to 90 mg/l at thirty-three hours. The solids decreased throughout the experimental period and attained a final value of 225 mg/l at thirty-three hours. The decrease in solids concentration was accompanied by a decrease in protein content of the sludge while the carbohydrate content remained fairly constant, indicating an increase in the percentage of carbohydrate in the sludge.

The shock load responses when the influent was changed from 1000 mg/l glucose with a BOD/N ratio of 7 to 3000 mg/l glucose with a BOD/N ratio of 40 are shown in Figures 59 and 60. It can be seen from Figure 59 that the total COD increased to a maximum of 470 mg/l and was thereafter reduced to a steady state value of 360 mg/l. There was only a slight increase in the anthrone COD throughout the experimental period. It can be seen by comparing Figures 58 and 59 that the latter system responded in a relatively more successful manner. It was observed that the system shock loaded with 3000 mg/l glucose (Figure 59) became distinctively reddish in color after six hours although both experiments were done on the same day. This suggests that a change in predominant species may have been responsible for this improved performance. This indicates that recirculation may possibly prevent or delay changes in predominance which could really improve the performance as shown in Figure 59. However, this was the only experiment in which a change in predominance of organisms was observed under nitrogen deficient gradual shock loading. It can be seen from Figure 59 that the protein content of the sludge decreased considerably while there was a rapid increase in carbohydrates. The response to a similar shock load with solids recirculation is shown in Figure 60. The total COD increased throughout the experimental period and reached an approximate steady state value of 920 mg/l. The increase in total COD was accompanied by a similar

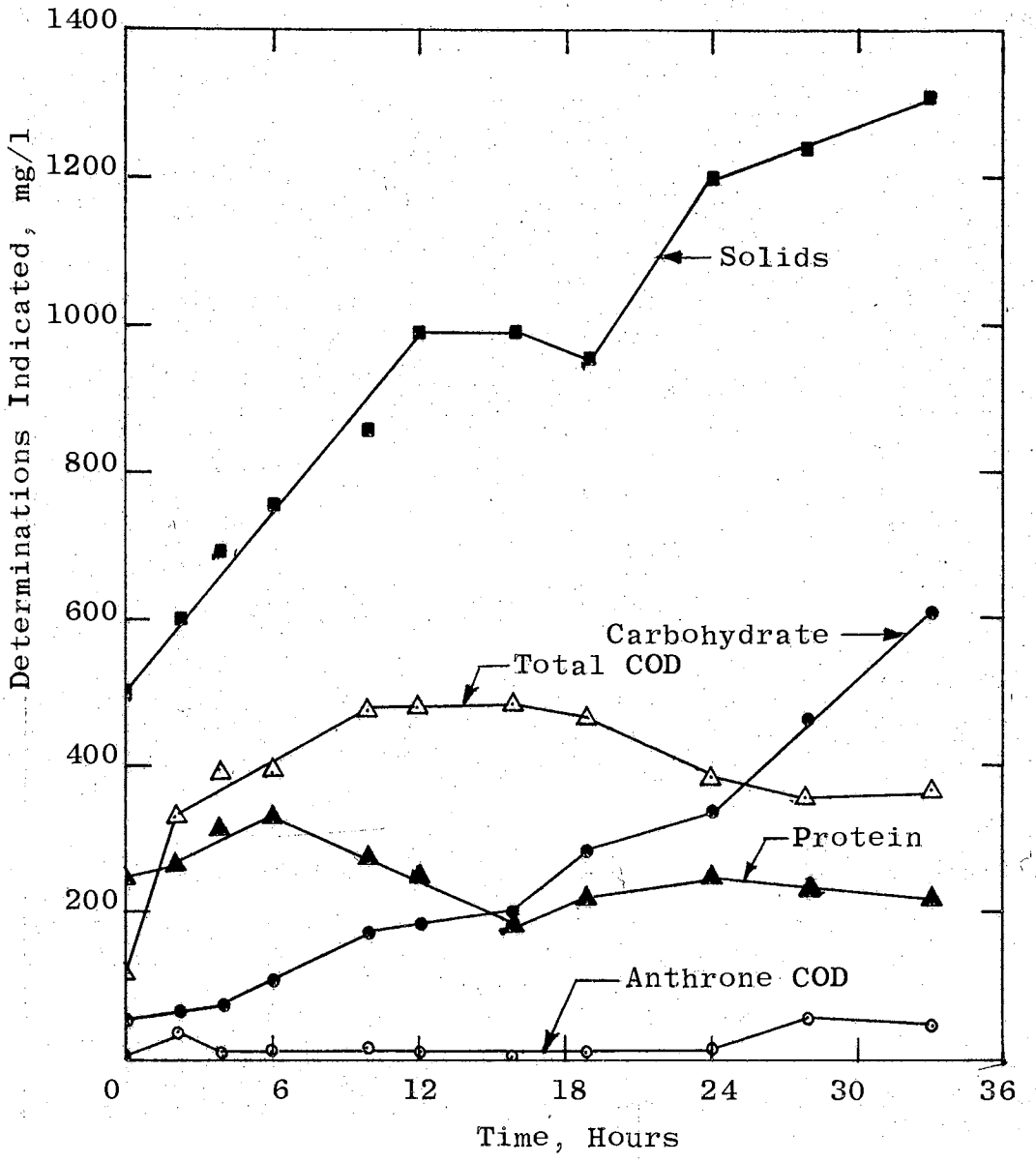

Fig. 59 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

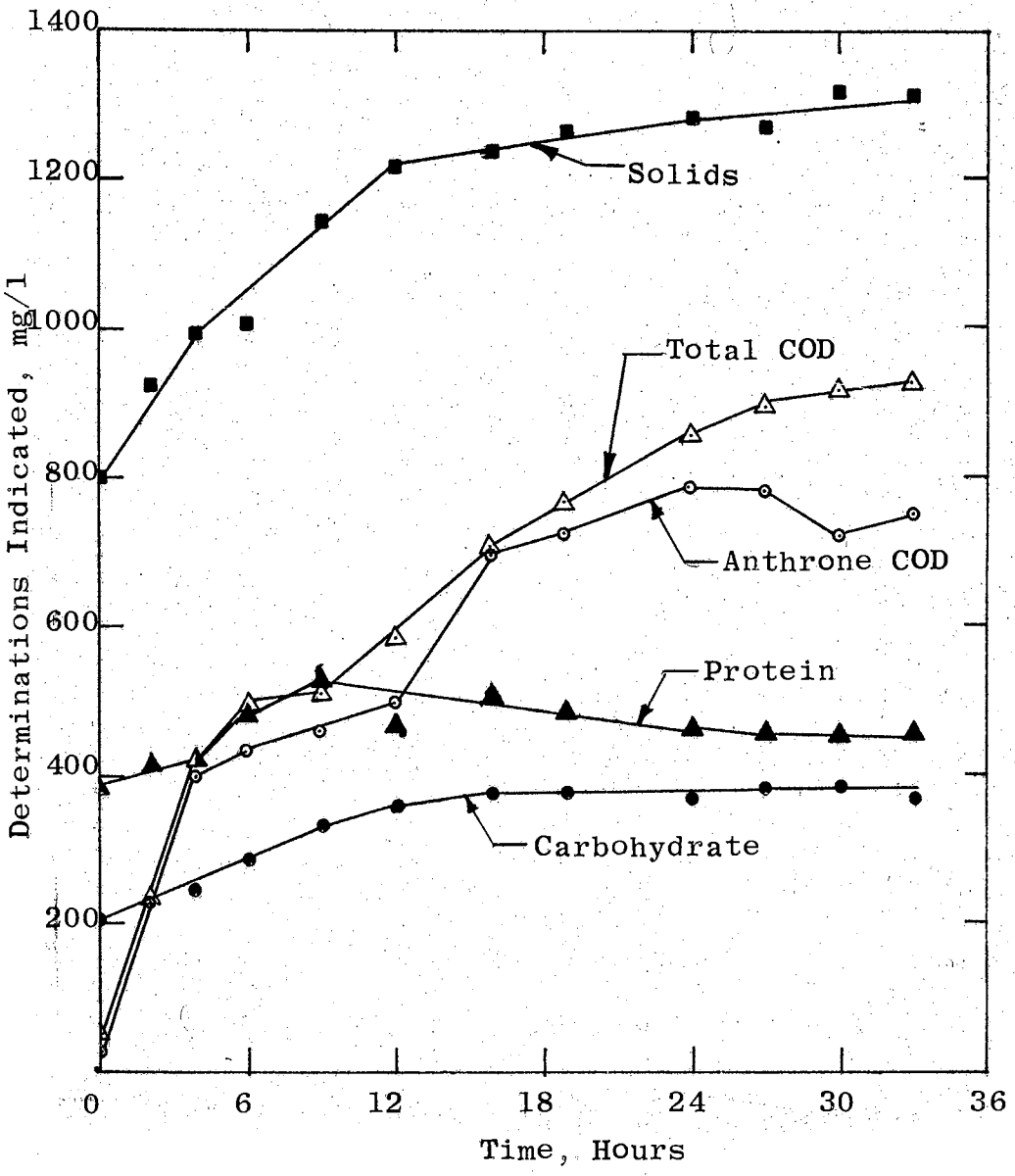

Fig. 60 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (WITH RECIRCULATION)

increase in anthrone COD. Comparison of Figures 57 and 60 indicates that the response of the system is more seriously affected at a $\frac{BOD}{N}$ ratio of 40 than at 30; it can also be seen the solids level was considerably lower than in the system operated at a BOD/N ratio of 30.

c. 12-Hour Detention Time. The response to a change in the nitrogen content while maintaining the influent feed at 1000 mg/l glucose is shown in Figure 61. The total COD fluctuated considerably during the first twelve hours and thereafter it remained at approximately 100 mg/l. The anthrone COD was fairly low at all times. There was also considerable variation in the solids curve. It can be seen that the system was not affected to any appreciable extent due to this particular change in nitrogen content.

The shock load response when the influent was changed from 1000 mg/l glucose with $\frac{BOD}{N} = 7$ to 3000 mg/l glucose with BOD/N = 21 is shown in Figure 62. It can be seen that there was very little increase in total COD or anthrone COD in the system. The solids increased rapidly and reached an approximate steady state value of 1125 mg/l. It can also be seen that carbohydrate synthesis was approximately equal to protein synthesis. The result seems to indicate that a change in nitrogen content from BOD/N = 7 to 21 does not severely affect the response of the system to a gradual shock load of 3000 mg/l glucose.

The response of the system when the influent was changed from 1000 mg/l glucose with BOD/N = 20 to 1000 mg/l glucose with BOD/N = 30 is shown in Figure 63. It can be seen that anthrone COD and total COD increased slighty after eighteen hours. The solids level increased slightly; however, it returned to the previous steady state value. It can also be seen that more carbohydrate was synthesized than protein. Comparison of Figures 49, 55, and 63 indicates that the response at a $\frac{BOD}{N}$ ratio of 30 is definitely better at the 12-hour detention time.

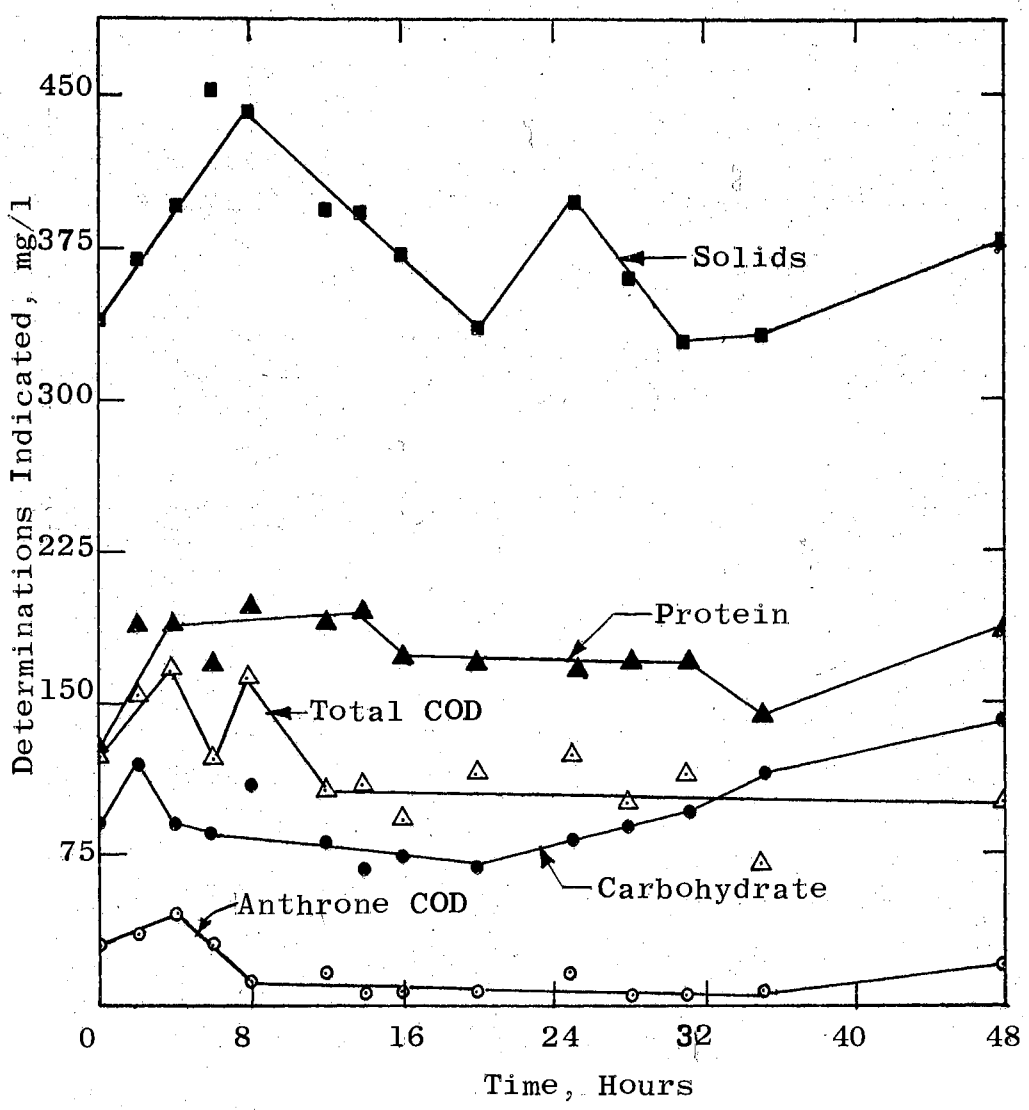

Fig. 61 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 1000 mg/l GLUCOSE WITH BOD/N = 21 (NO RECIRCULATION)

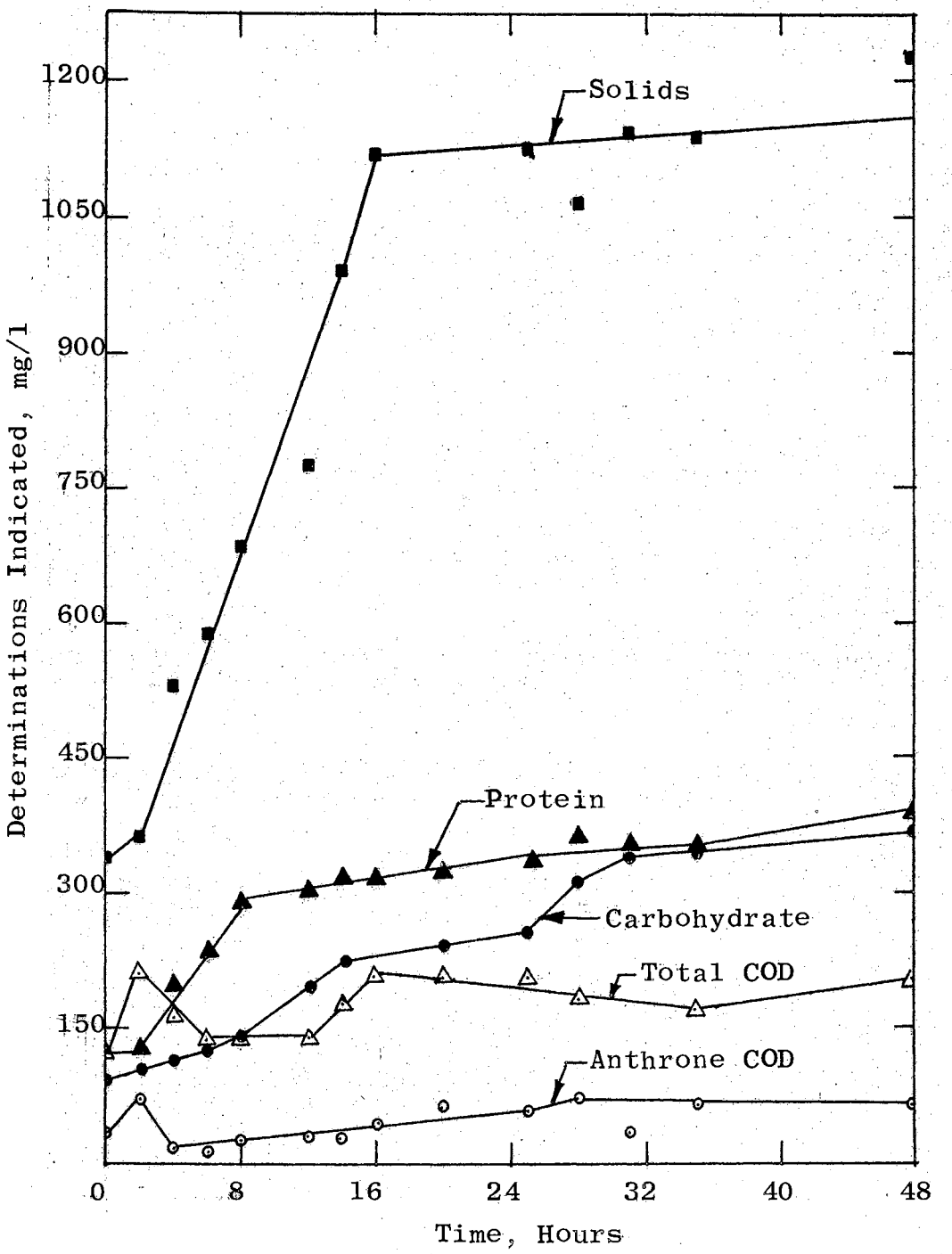

Fig. 62 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 21 (NO RECIRCULATION)

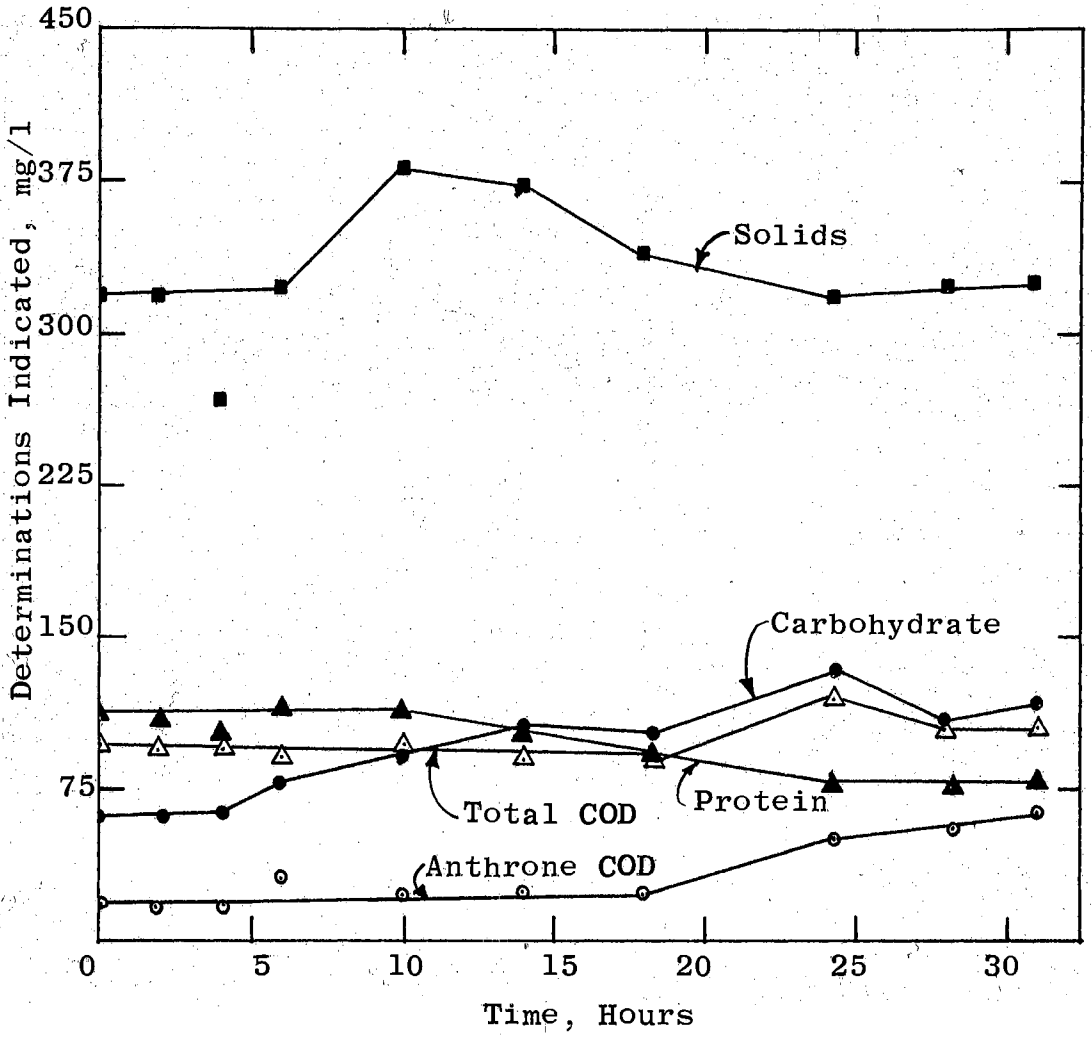

Fig. 63 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 1000 mg/l GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

The shock load response when the influent feed was changed from 1000 mg/l glucose with $\frac{BOD}{N}$ = 20 to 3000 mg/l glucose with BOD/N = 30 are shown in Figures 64 and 65. The total COD reached a maximum of 450 mg/l and was then gradually reduced to an approximate steady state value of 200 mg/l. However, the anthrone COD remained fairly constant throughout the experiment. It can be seen that there was considerably higher solids synthesis in the system. The solids level reached a maximum of 1540 mg/l. While the protein content did not increase greatly, there was considerable increase in the carbohydrate content of the sludge. Comparison of Figures 50, 56, and 64 indicate a definite improvement in system response at the 12-hour detention time. The response to a similar shock load with solids recirculation is shown in Figure 65. There was very little change in total COD and anthrone COD in the effluent. Comparison of Figures 51, 57, and 55 indicates that the system which was operated at the 12-hour detention time responded much better to this shock loading situation.

The response of the system when the $\frac{BOD}{N}$ ratio is changed from 20 to 40 while the influent feed is maintained at 1000 mg/l glucose is shown in Figure 66. The total COD reached a maximum of 260 mg/l and was then reduced to its previous steady state value of 140 mg/l. The anthrone COD remained fairly constant for eighteen hours, and then increased to a maximum of 45 mg/l at the end of twenty-eight hours. The solids concentration fluctuated considerably, and reached a steady state value of 230 mg/l. It can also be seen that carbohydrate synthesis was higher than protein synthesis.

The shock load responses when the influent was changed from 1000 mg/l glucose with a $\frac{BOD}{N}$ ratio of 20 to 3000 mg/l glucose with a $\frac{BOD}{N}$ ratio of 40 are shown in Figures 67 and 68. It can be seen from Figure 67 that the total COD increased rapidly and finally reached a value of 825 mg/l at

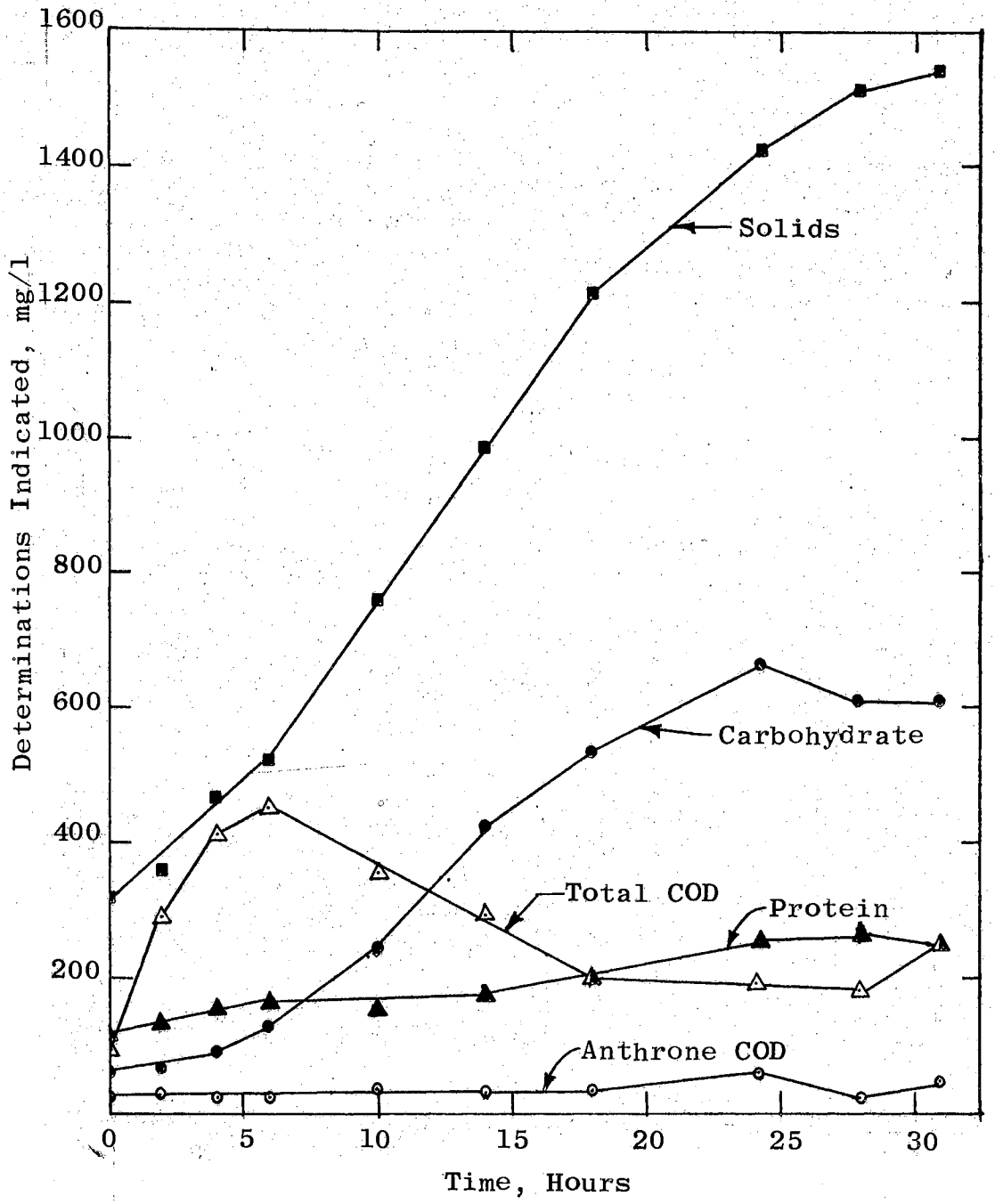

Fig. 64 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (NO RECIRCULATION)

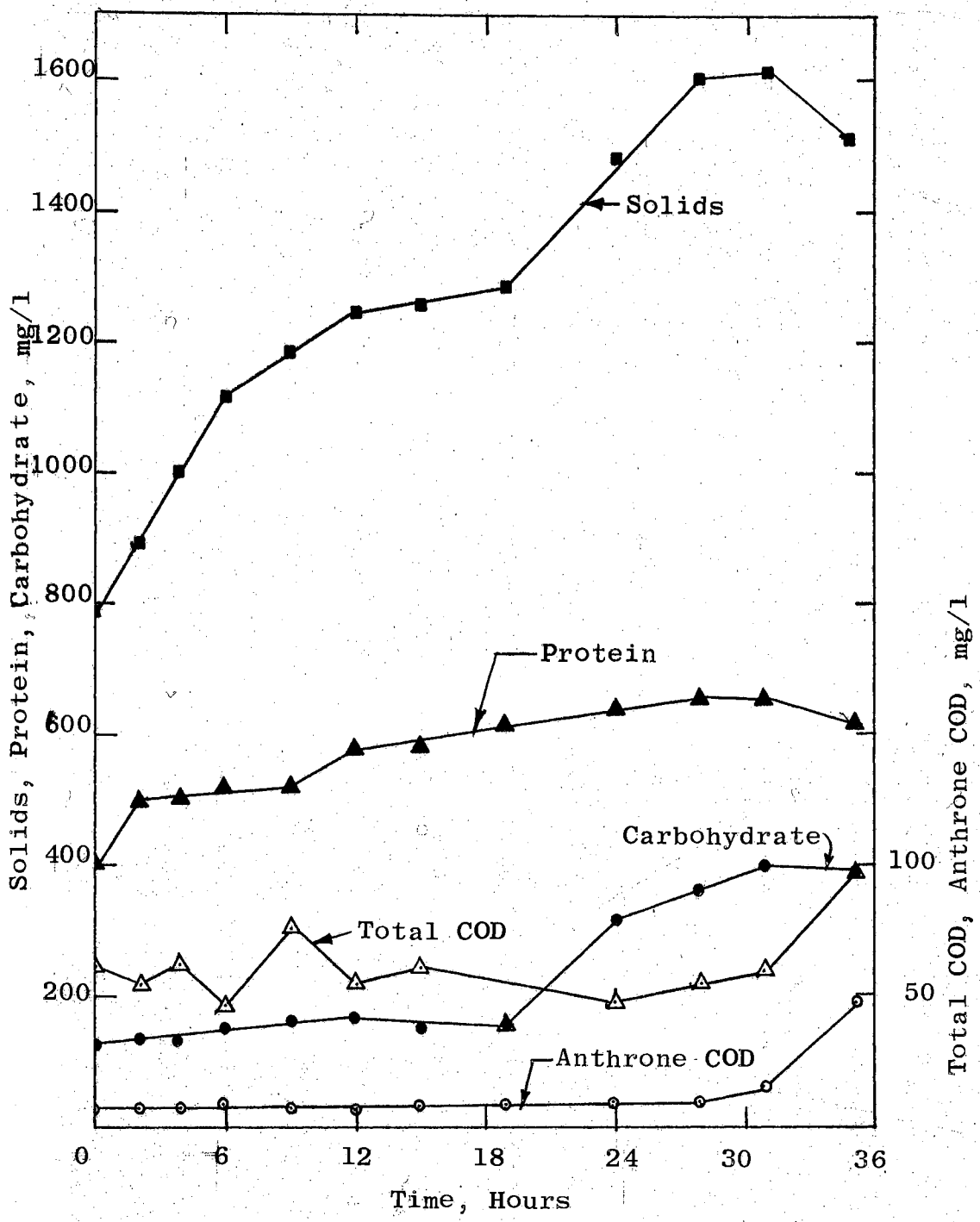

Fig. 65 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l WITH BOD/N =20 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (WITH RECIRCULATION)

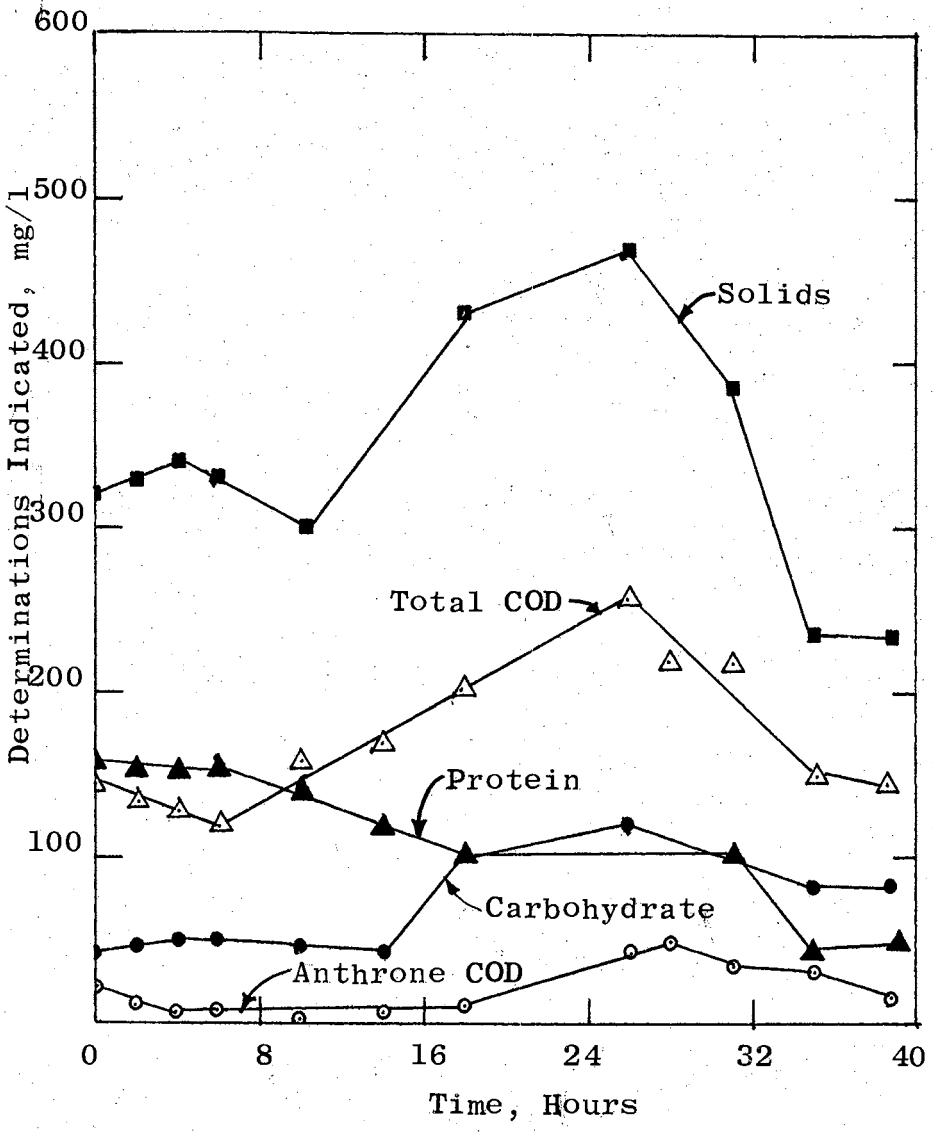

Fig. 66 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 1000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

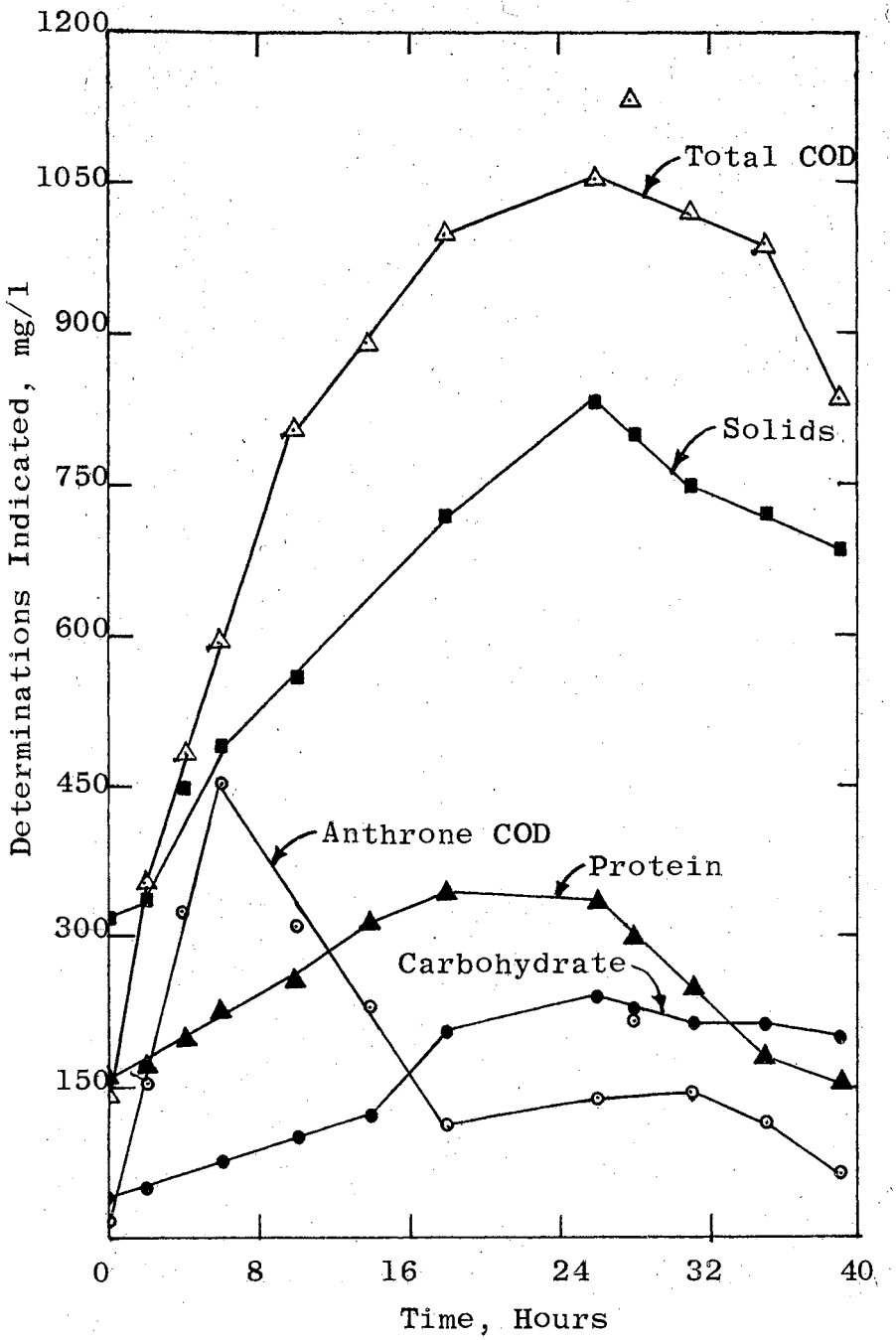

Fig. 67 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l WITH BOD/N = 20 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

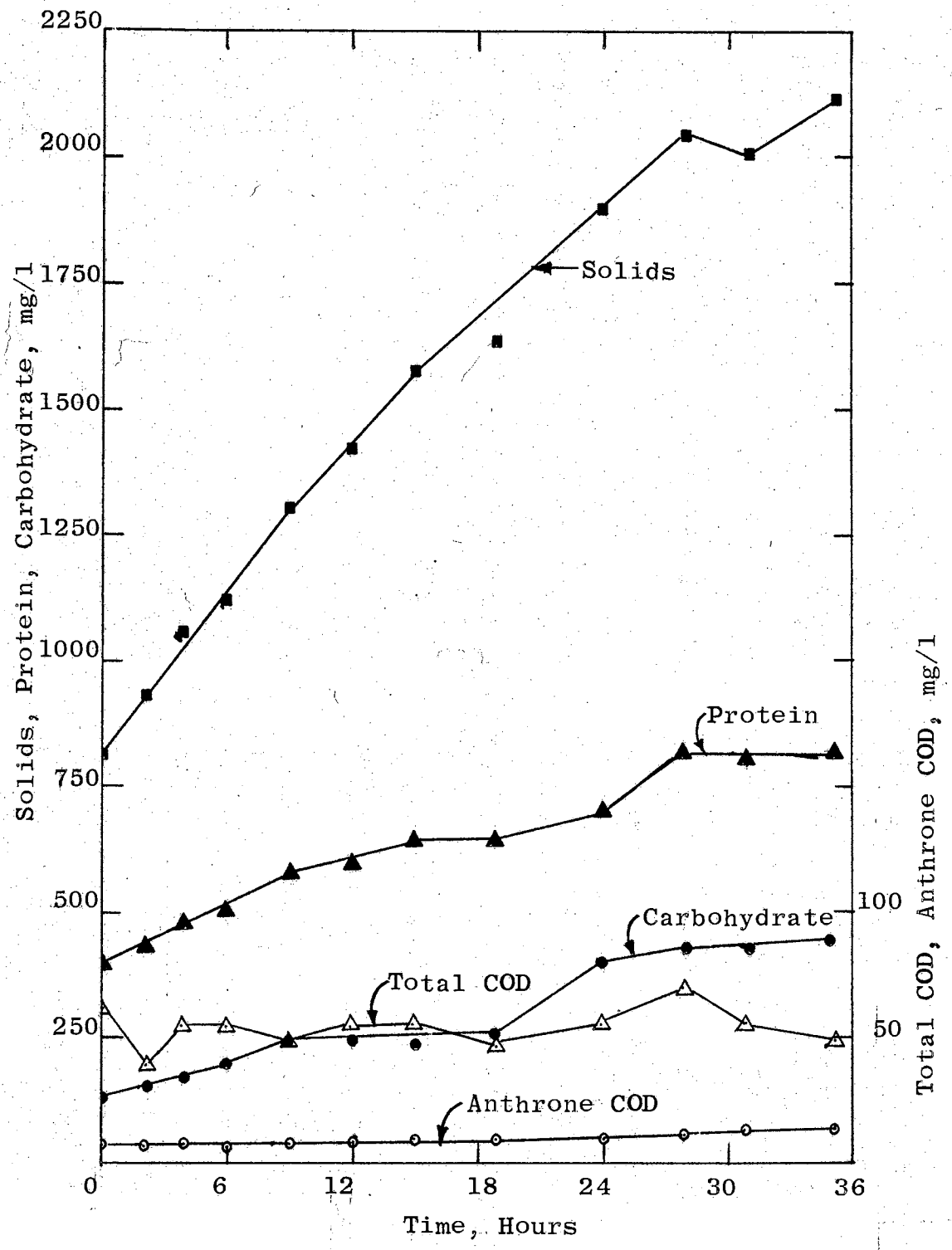

Fig. 68 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 12-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (WITH RECIRCULATION)

the end of thirty-nine hours. The anthrone COD reached a maximum of 450 mg/l and was then reduced to 70 mg/l at the end of thirty-nine hours. It can be seen that there was not as much increase as expected in the solids concentration. It can also be seen that there was a greater synthesis of carbohydrate than protein after the peak in the solids concentration. The response to a similar shock load with solids recirculation is shown in Figure 68. It can be seen that there was very little change in total COD or anthrone COD of the system. It is apparent from Figures 65 and 68 that solids recirculation greatly improved the response of the system to a 3000 mg/l glucose shock load.

It is clear from Figures 65 and 68 that with solids recirculation the system can successfully handle a gradual shock load of 3000 mg/l glucose at a $\frac{BOD}{N}$ ratio of either 30 or 40. It was decided to detemine whether the same response could be obtained at another detention time. Hence, similar experiments were conducted at a detention time of eight hours. The system was previously acclimated to 1000 mg/l glucose with a $\frac{BOD}{N}$ ratio of 20. The shock load responses are shown in Figures 69 and 70. It is clear from Figures 69 and 70 that the system operated at 8-hour detention time could not handle this shock load successfully. It can also be seen that the system operated with BOD/N ratio of 40 had more total COD and anthrone COD than the system which was operated with a BOD/N ratio of 30. It is interesting to note from Figures 57, 60, 69, and 70 that the response to a shock load of 3000 mg/l glucose at $\frac{BOD}{N}$ ratios of 30 and 40 are more severe when the systems were previously acclimated at a BOD/N ratio of 20 than when operated at a ratio of 7 before the shock.

4. Release of Intermediates Under Shock Loading Conditions.

This portion of the study was conducted using a 4-hour detention time without solids recirculation. The shock load

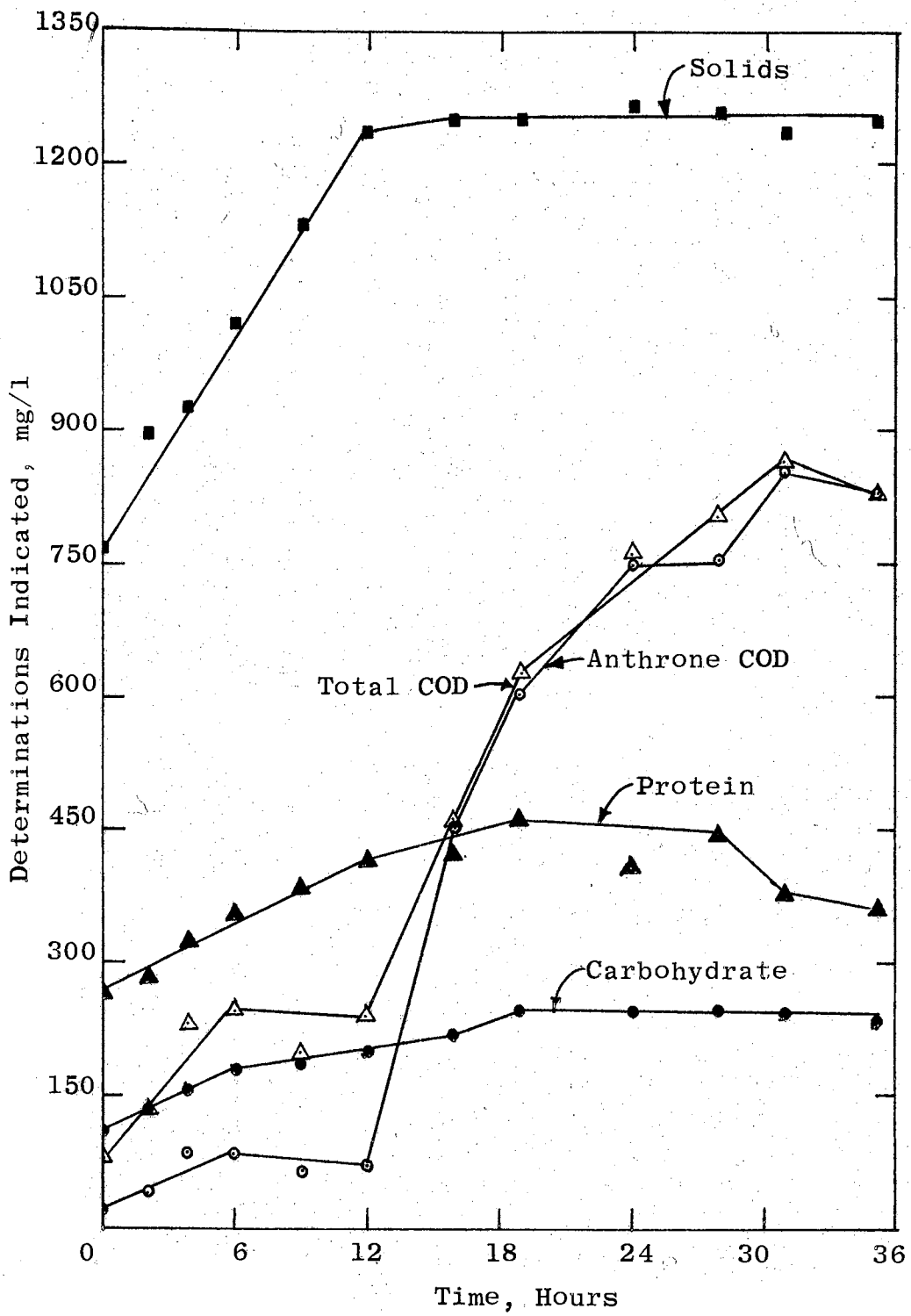

Fig. 69 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 3000 mg/l GLUCOSE WITH BOD/N = 30 (WITH RECIRCULATION)

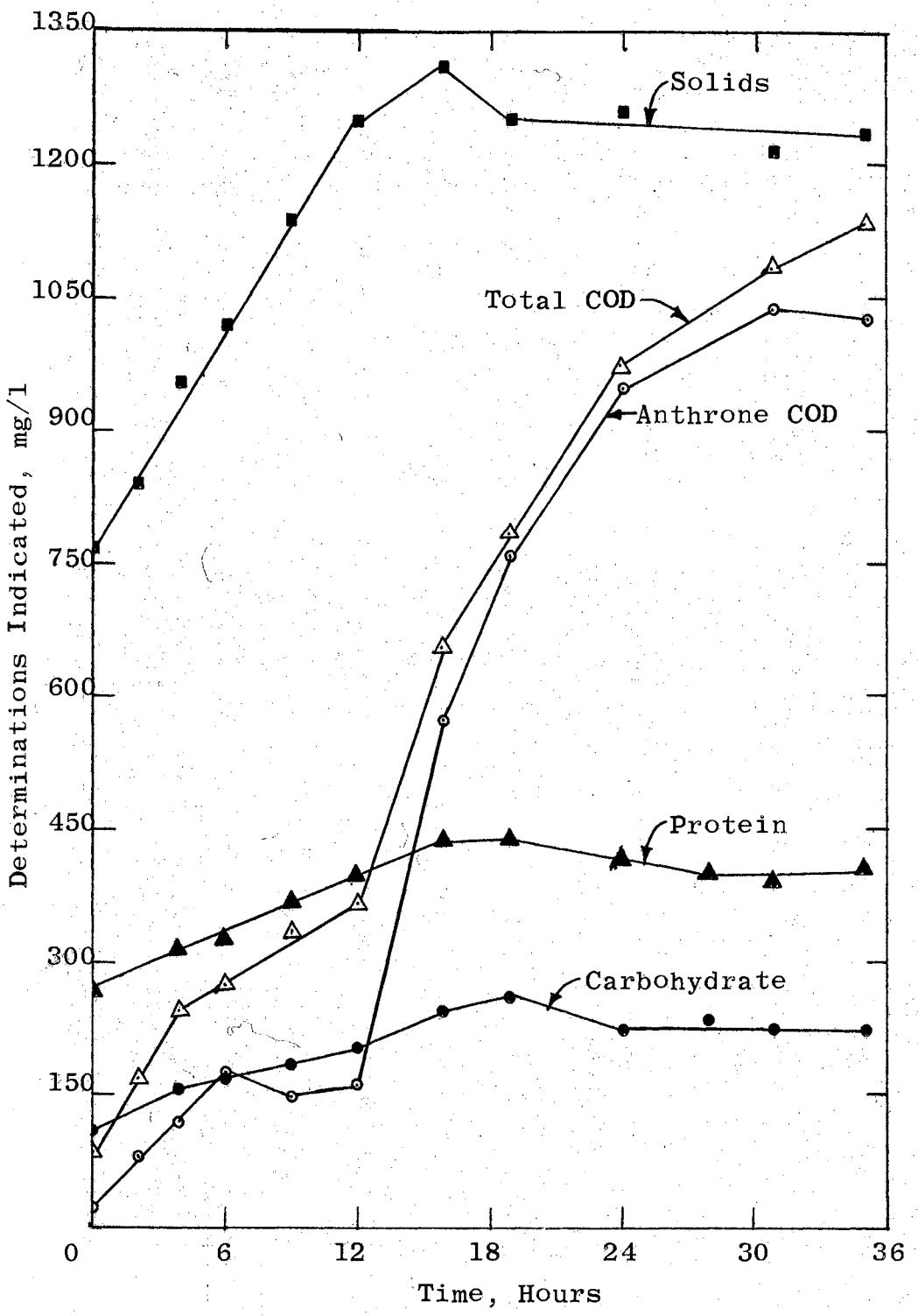

Fig. 70 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 8-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 20 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (RECIRCULATION)

response when the influent is changed from 1000 mg/l to 3000 mg/l glucose is shown in Figure 71. The total COD increased rapidly to a maximum of 950 mg/l and was then reduced to a steady state value of 180 mg/l; however, there was very little increase in anthrone COD. The glucose was also determined by the glucostat test. It can be seen that the glucostat COD was very low at all times. Volatile acids increased to a maximum of 370 mg/l and were finally reduced to an approximate steady state value of 50 mg/l. It can also be seen that considerably more COD was present in the system than could be accounted for by the anthrone and volatile acids values. Gas chromatographic analyses of the samples for individual volatile acids are shown in Table II. It can be seen that the predominant volatile acid in the samples is acetic although small concentrations of other acids are present. It can also be seen that total volatile acids as determined by distillation was higher than the total detected by gas chromatography. A possible reason is that formic acid was not detected.

In order to investigate the effect of increased organic loading on the release of intermediates, the unit was initially operated at 500 mg/l glucose and shock loaded with 3000 mg/l glucose, representing a six-fold increase in the glucose concentration in the influent. The response to such a shock load is shown in Figure 72. It can be seen that the total COD reached a maximum of 1100 mg/l and was then reduced to 140 mg/l at the end of thirty-five hours. The anthrone COD increased to a maximum of 420 mg/l and was then reduced to a steady state value of 20 mg/l at thirty-five hours. The glucostat COD was only slightly lower than anthrone COD. The volatile acids concentration reached a maximum of 288 mg/l and was then reduced to an approximate steady state value of 35 mg/l. It can be seen from Figures 71 and 72 that increased loading did not have an appreciable effect on the release of intermediates. It

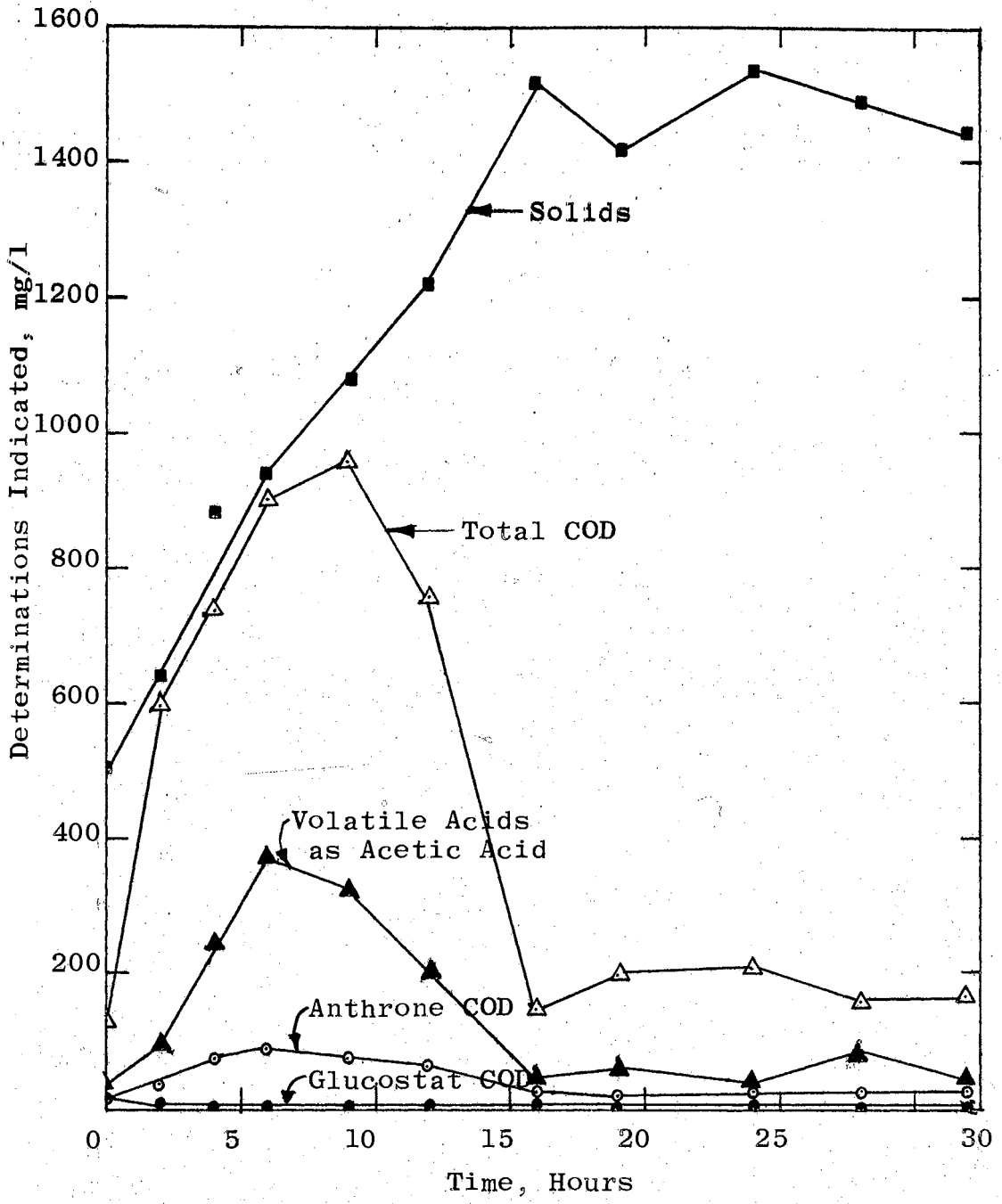

Fig. 71 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE TO 3000 mg/l GLUCOSE (NO RECIRCULTATION)

TABLE II

ANALYSIS OF INDIVIDUAL VOLATILE ACIDS BY GAS CHROMATOGRAPHY DURING SHOCK LOADING

Time Hrs	Acetic mg/l	Propionic mg/l	Iso Butyric mg/l	Butyric mg/l	Iso Valeric mg/l	Valeric mg/l	Hexanoic mg/l	Total Vol. Acids As Acetic Acid, mg/l Gas Chro.	Distil.
0	12.5	-	2	-	-	5	-	17	36
2	95	-	5	5	-	5	7.0	108	96
4	215	-	-	-	-	-	7.5	219	246
6	285	-	-	-	-	-	8.0	289	378
9	210	-	-	-	-	-	20.0	220	324
12	135	-	10	-	-	-	17.0	150	204
16	20	-	-	-	-	4	-	22	48
19	18	-	-	-	-	-	-	18	60
24	16	-	-	-	-	-	-	16	36
28	10	-	-	-	-	-	-	10	84
32	15	-	-	-	-	-	-	15	48

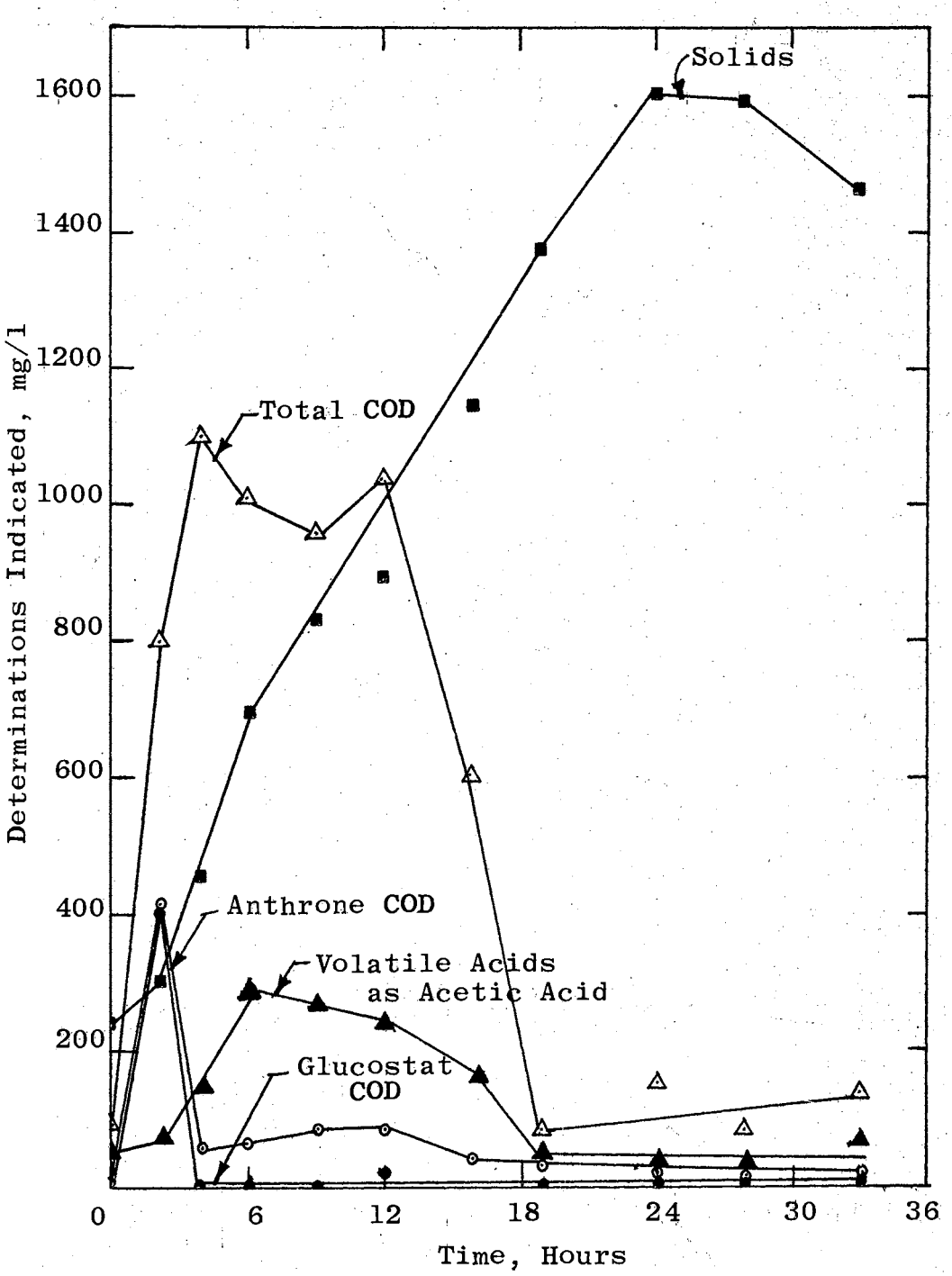

Fig. 72 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 500 mg/l GLUCOSE TO 3000 mg/l GLUCOSE (NO RECIRCULATION)

can also be seen from Figure 72 that a considerable amount of organic material is present in the system which was not detected by the anthrone and volatile acids determinations. The gas chromatographic analyses of the samples are shown in Table III. It can be seen that acetic acid is the main component present in the samples. It can also be seen that a higher concentration of acid is detected in the volatile acid sample than in the sample for gas chromatographic analysis.

The shock load response when the influent was changed from 1000 mg/l to 5000 mg/l glucose is shown in Figure 73. The total COD increased rapidly to a maximum of 1250 mg/l and was then reduced to a steady state value of 80 mg/l. There was only a slight increase in anthrone and glucostat COD. The volatile acids concentration reached a maximum of 460 mg/l and was then reduced to a steady state value of 60 mg/l. It can be seen that a considerable amount of material reactive to the COD test was present which was not detected by the anthrone and volatile acids determinations. The gas chromatographic analyses for individual volatile acids are shown in Table IV. Again it can be seen that the predominant volatile acid is acetic although other acids are present in small amounts. It can be seen from Figure 73 that there was not much lipid and carbohydrate synthesis although the protein concentration of the sludge increased considerably. Elemental analyses of sludge samples are shown in Table V. The percent carbon, hydrogen, and nitrogen varied only slightly.

The shock load response when the influent is changed from 1000 mg/l glucose with BOD/N = 7 to 3000 mg/l glucose with a BOD/N ratio of 40 is shown in Figure 74. The total COD increased rapidly, reached a maximum of 1440 mg/l and was gradually reduced to 950 mg/l at the end of thirty-five hours. Although there was considerable increase in total COD, there was not a considerable increase in anthrone and glucostat COD. The volatile acids concentration reached a

TABLE III

ANALYSIS OF INDIVIDUAL VOLATILE ACIDS BY GAS CHROMATOGRAPHY DURING SHOCK LOADING

Time Hrs	Acetic mg/1	Propionic mg/1	Iso Butyric mg/1	Butyric mg/1	Iso Val eric mg/1	Val eric mg/1	Hexa noic mg/1	Total Vol. Acids As Acetic Acid, mg/1 Gas Chro.	Distil.
0	15	2.5	-	-	-	-	-	17	54
2	45	10.0	-	-	-	-	12.5	64	75
4	75	10.0	-	-	-	-	20.0	93	150
6	188	7.5	-	-	-	-	7.5	198	288
9	205	2.5	-	-	-	3.0	17.5	218	270
12	177.5	5.0	-	-	-	3.0	-	183	246
16	165	2.5	2.0	-	-	4.0	7.5	173	168
19	10	2.0	-	-	-	8.0	-	16	42
24	8	2.0	2.0	-	-	10.0	-	16	36
28	10	-	-	-	-	2.0	-	12	30
33	12.5	-	-	-	-	-	-	12.5	72

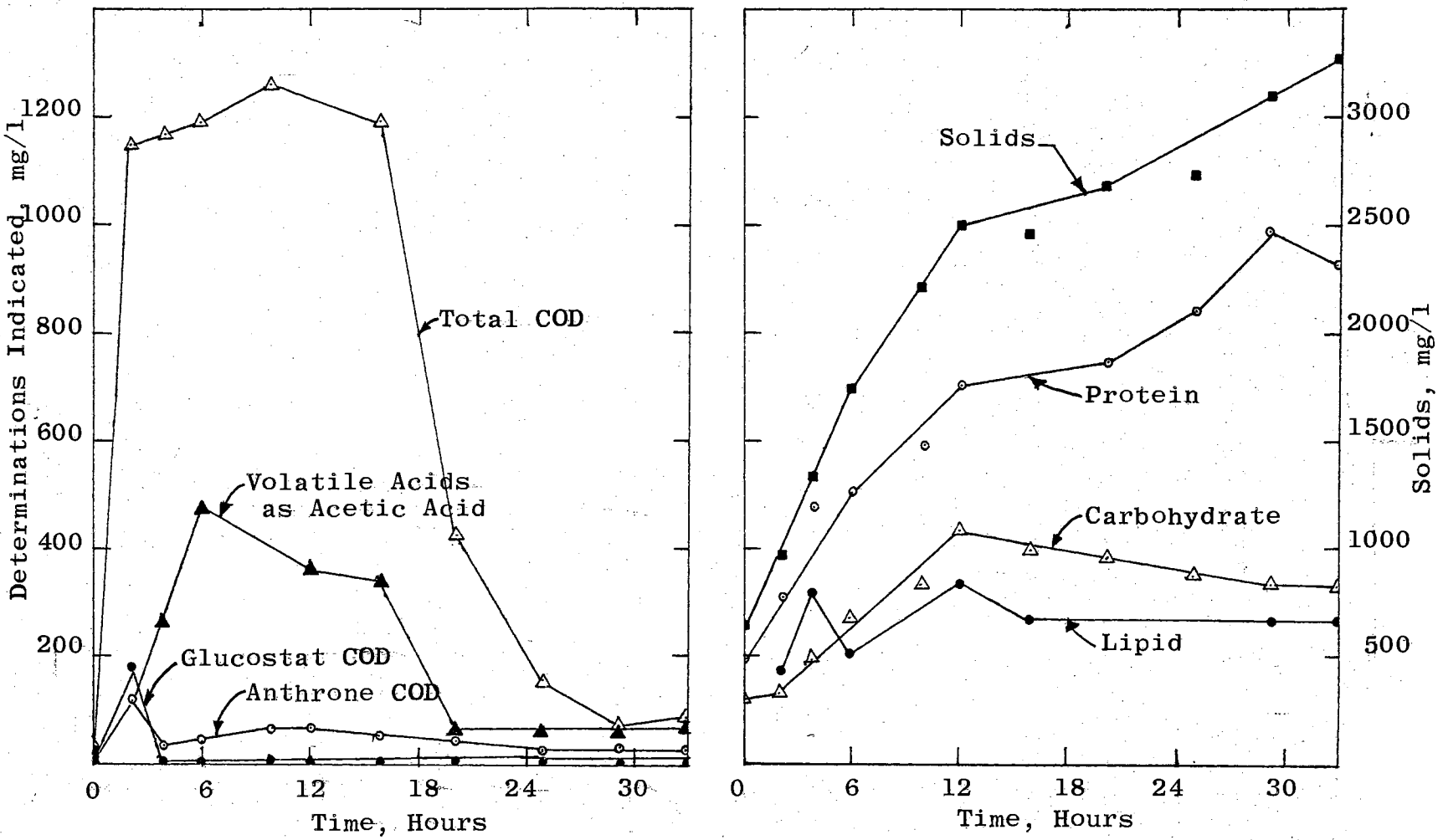

Fig. 73 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l TO 5000 mg/l GLUCOSE (NO RECIRCULATION)

TABLE IV

ANALYSIS OF INDIVIDUAL VOLATILE ACIDS BY GAS CHROMATOGRAPHY DURING SHOCK LOADING

Time Hrs	Acetic mg/l	Propionic mg/l	Iso Butyric mg/l	Butyric mg/l	Iso Val eric mg/l	Val eric mg/l	Hexa noic mg/l	Total Vol. Acids As Acetic Acid, mg/l Gas Chro.	Distil.
0	30	8	-	4	-	3	-	39.5	-
2	27.5	14	-	-	-	10	-	45.5	120
4	164	8	-	-	-	11	17.5	187.0	262
6	350	5	-	-	-	13	-	362.0	480
12	262.6	10	-	-	-	30	-	288.0	360
16	300	10	-	16	-	17.5	-	329.0	340
20	22	8	-	10	-	13.0	-	43.0	65
25	27.5	9	-	5	-	10.0	-	44.0	60
29	25.0	10	-	7	-	10.0	-	44.0	70
33	25.0	8	-	-	-	11.0	-	39.0	60

TABLE V

CHANGES IN ELEMENTAL COMPOSITION OF SLUDGE DURING GRADUAL SHOCK LOADING OF 5000 mg/1 GLUCOSE

Time Hrs.	% Carbon	% Nitrogen	% Hydrogen
0	45.6	10.45	7.95
2	43.2	9.38	7.43
4	47.0	9.70	8.12
6	46.4	9.38	8.40
10	41.3	7.28	6.80
12	40.0	7.28	6.60
16	38.4	6.78	6.50
20	39.0	7.28	6.45
25	42.0	8.35	7.02
29	40.0	8.35	6.40
33	45.6	9.38	7.70

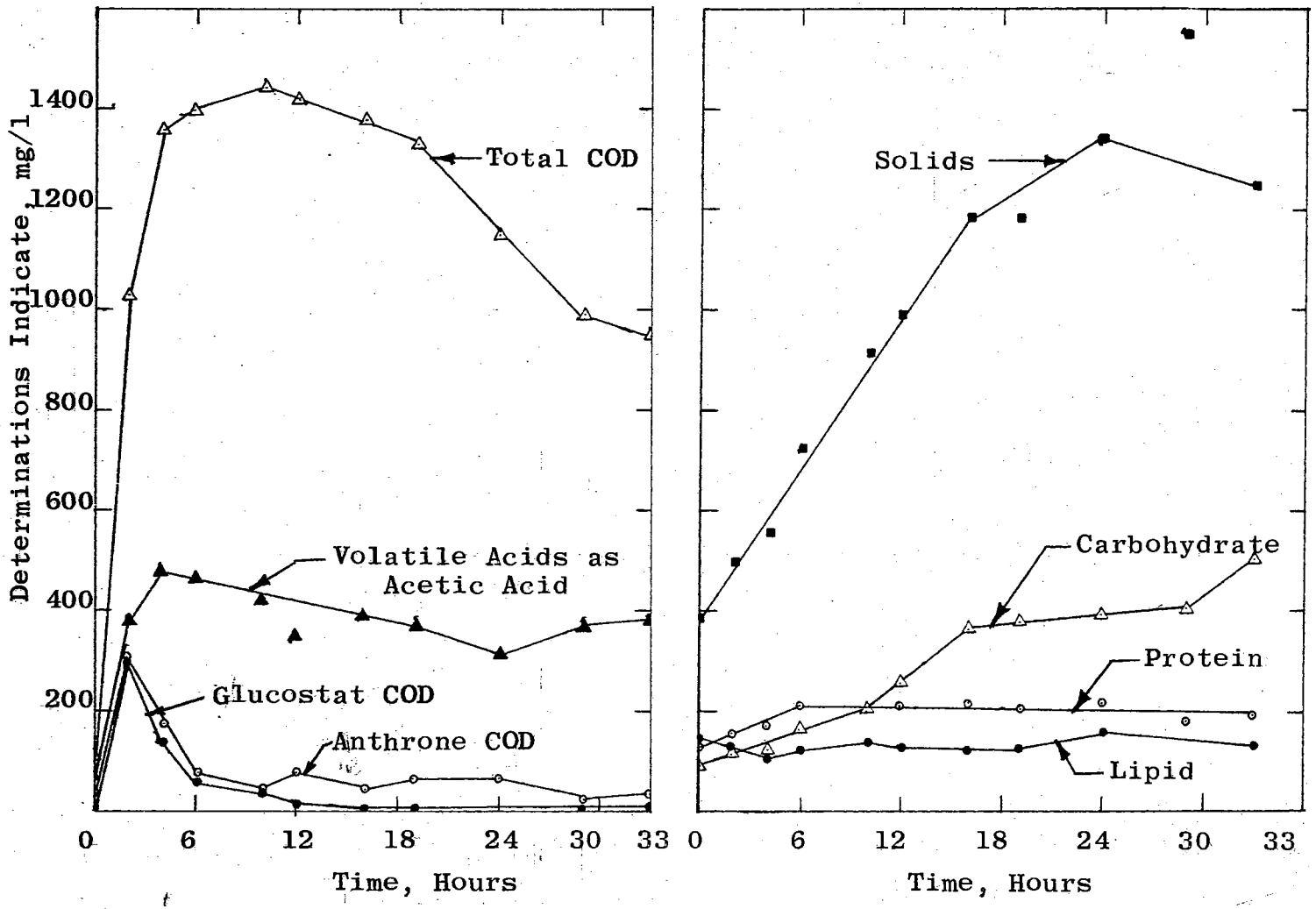

Fig. 74 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE INFLUENT FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 TO 3000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

maximum of 480 mg/l and was then reduced slowly to 380 mg/l at thirty-three hours. It can be seen from Figures 71 and 74 that volatile acids in the system remain relatively high when the shock load is not accompanied by an adequate nitrogen source. The gas chromatographic analyses of the samples are shown in Table VI. It can be seen that acetic acid is the predominant acid present in the sample, and that a considerably higher concentration of acids is detected by the volatile acid test than by gas chromatography. It can be observed from Figure 74 that there was a very little increase in protein and lipid content of the sludge while the carbohydrate content showed a considerable increase. Elemental analyses of the sludge samples are shown in Table VII. It can be seen that percent nitrogen content decreased considerably while the percent carbon and hydrogen remained fairly constant.

The response to a gradual shock load of 3000 mg/l glucose with a BOD/N ratio of 40 is shown in Figure 75. The shock loading condition employed here is the same as that for Figure 74. The total COD increased rapidly to 1530 mg/l and reached a steady state value of 1450 mg/l; however, there was very little increase in anthrone and glucostat COD values. It can also be seen that there was very little increase in solids concentration. Comparison of Figures 74 and 75 indicates that there is considerable difference in the response of the system to the same shock loading condition. It can also be observed that less volatile acids were produced by the cells in the latter experiment. The gas chromotographic analyses of the samples are shown in Table VIII. The acetic acid was again the major volatile acid present although small amounts of isobutyric and hexanoic acid were observed.

The dissolved oxygen concentrations in the aerator during shock loading experiments are shown in Tables IX, X, and XI. The dissolved oxygen concentrations in the aerator when

TABLE VI

ANALYSIS OF INDIVIDUAL VOLATILE ACIDS BY GAS CHROMATOGRAPHY DURING SHOCK LOADING

Time Hrs	Acetic mg/l	Propionic mg/l	Iso Butyric mg/l	Butyric mg/l	Iso Val eric mg/l	Val eric mg/l	Hexa noic mg/l	Total Vol. Acids As Acetic Acid, mg/l Gas Chro.	Distil.
0	15	5	-	6	-	10	-	32.0	75.0
2	152.5	-	7.5	-	-	10	11.0	169	383.0
4	125	12.5	-	-	-	10	35	159	480.0
6	182.5	20	-	10	-	20	45	241	465.0
10	195	17.5	-	-	-	20	35	239	420.0
12	207	20	-	-	-	12.5	32.5	247	353.0
16	182.5	12.5	-	-	-	12.5	32.5	216	398.0
19	208	30	-	-	-	8	25.0	250	375.0
24	185	17.5	-	10	-	15	30.0	227	315.0
29	264	22.5	-	13	-	17.5	25.0	314	375.0
33	265	22.5	-	-	-	17.5	22.0	304	382.0

TABLE VII

CHANGES IN ELEMENTAL COMPOSITION OF SLUDGE DURING GRADUAL SHOCK LOADING OF 3000 mg/l GLUCOSE WITH BOD/N = 40

Time Hrs.	% Carbon	% Nitrogen	% Hydrogen
0	38.3	8.08	6.60
2	37.8	7.25	6.27
4	39.5	7.82	6.20
6	39.3	8.05	6.30
10	38.7	6.90	6.60
12	38.0	5.30	6.34
16	39.0	5.98	6.50
19	36.8	4.60	5.93
24	38.2	4.60	6.34
29	31.6	3.35	5.05
33	37.5	4.84	6.18

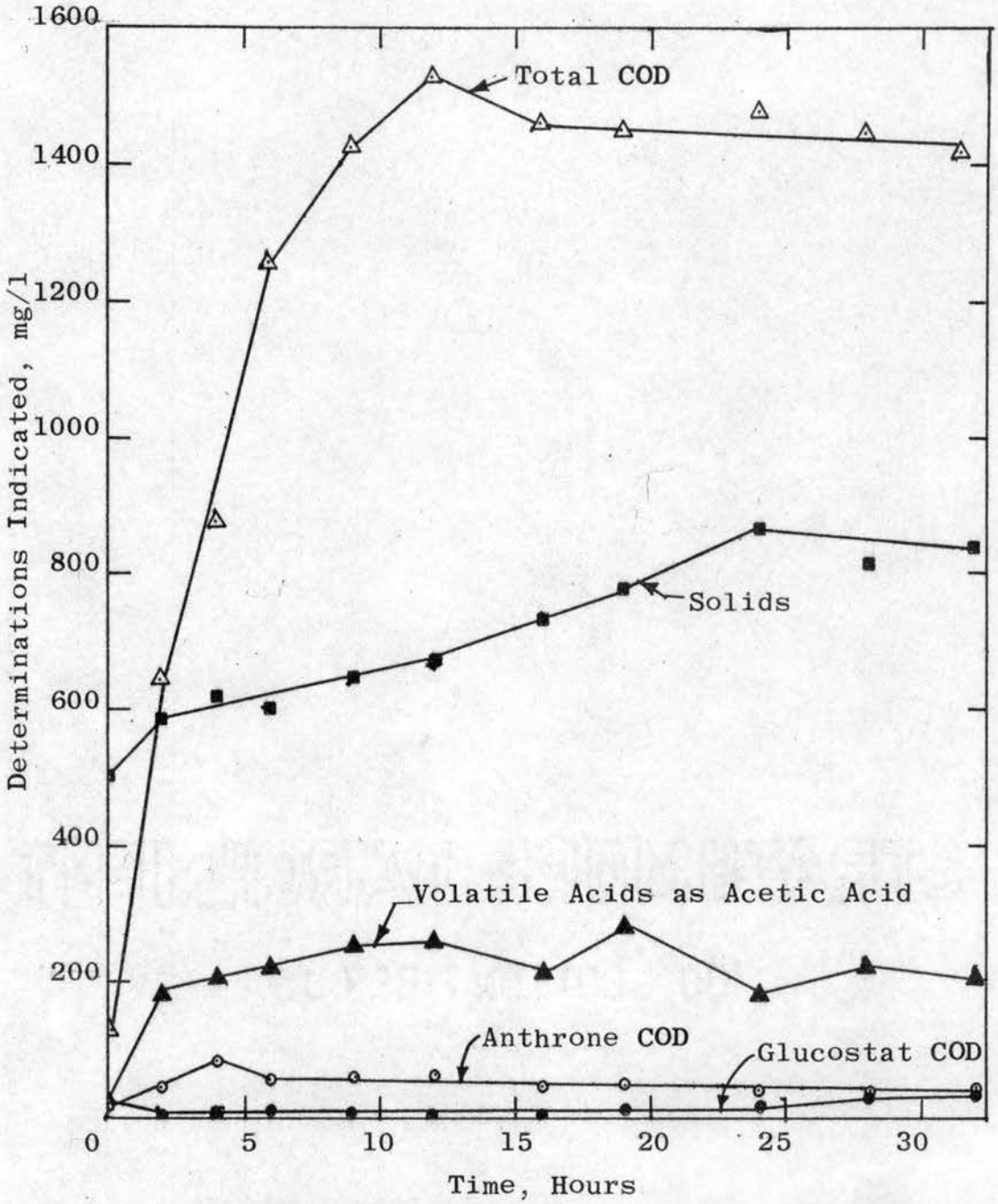

Fig. 75 - SHOCK LOAD RESPONSE OF THE STEADY STATE CONTINUOUS FLOW UNIT AT 4-HOUR DETENTION TIME AFTER CHANGING THE FEED FROM 1000 mg/l GLUCOSE WITH BOD/N = 7 to 3000 mg/l GLUCOSE WITH BOD/N = 40 (NO RECIRCULATION)

TABLE VIII

ANALYSIS OF INDIVIDUAL VOLATILE ACIDS BY GAS CHROMATOGRAPHY DURING SHOCK LOADING

Time Hrs	Acetic mg/l	Propionic mg/l	Iso Butyric mg/l	Butyric mg/l	Iso Val eric mg/l	Val eric mg/l	Hexa noic mg/l	Total Vol. Acids As Acetic Acid, mg/l Gas Chro.	Distil.
0	12.5	2.0	-	-	-	5.0	-	17	36.0
2	157	-	12.5	-	-	-	6	168	186.0
4	160	-	16	-	-	-	10	176	210.0
6	232	-	12	-	-	-	28	255	228.0
9	225	-	6	-	-	-	35	247	252.0
12	250	-	8	-	-	-	30	271	258.0
16	158	-	10	-	-	-	23	177	216.0
19	178	-	6	-	-	-	32	199	282.0
24	144	-	5	-	-	-	33	165	180.0
28	163	-	4	-	-	-	25	178	220.0
32	125	-	-	-	-	-	37	144	204.0

TABLE IX

OXYGEN CONCENTRATION IN AERATOR DURING GRADUAL SHOCK LOADING EXPRESSED AS mg/l AT 25°C.

4-hour detention time						8-hour detention time						12-hour detention time					
time hrs	3000 mg/l glucose	time hrs	5000 mg/l glucose	time hrs	3000 mg/l glucose (recir)	time hrs	3000 mg/l glucose	5000 mg/l glucose	time hrs	3000 mg/l glucose (recir)	5000 mg/l glucose (recir)	time hrs	2000 mg/l glucose	time hrs	3000 mg/l glucose	time hrs	5000 mg/l glucose
0	7.35	0	8.35	0	8.05	0	7.80	7.75	0	8.35	8.35	0	8.30	0	7.90	0	8.25
2	6.75	2	7.05	2	6.85	2	7.70	7.60	2	8.30	8.45	2	7.70	2	7.32	2	7.30
4	6.70	4	6.72	4	7.00	4	7.40	6.80	4	8.35	8.35	4	7.45	4	7.22	4	7.05
6	7.10	6	6.15	6	7.33	6	7.20	6.85	6	8.15	8.15	6	7.80	6	7.05	6	6.20
9	6.87	10	6.80	10	7.20	8	7.20	6.85	9	8.05	7.80	8	7.55	8	7.22	8	6.80
12	6.70	12	6.82	12	7.33	10	7.50	6.95	12	8.15	7.95	10	7.70	10	6.94	10	7.30
16	6.42	16	6.15	18	7.60	12	7.68	7.22	16	7.95	8.05	12	7.70	12	6.96	12	7.12
19	6.90	20	6.15	27	7.33	14	7.92	7.78	20	7.95	7.70	14	7.80	14	7.12	14	7.12
24	6.35	25	6.15	29	7.33	16	8.40		25	8.30	8.45	18	7.70	18	7.12	18	7.45
28	6.35	29	6.15						29	8.15	8.25	21	7.70	24.5	6.96	21	7.05
32	6.42	33	6.15						33	8.40		26	7.70	28	7.32	26	7.22
												30	7.80			30	7.22
												34	7.90			34	7.12
	Fig. 71		Fig. 73		Fig. 12		Fig. 17	Fig. 19		Fig. 18	Fig. 20		Fig. 22		Fig. 23		Fig. 25

TABLE X

OXYGEN CONCENTRATION IN AERATOR DURING GRADUAL AND SLUG SHOCK LOADING EXPRESSED AS mg/l AT 25°C.

4-hour detention time							8-hour detention time			12-hour detention time			
time hrs	2000 mg/l + 2000 mg/l glucose slug	time hrs	3000 mg/l + 3000 mg/l glucose slug	time hrs	2000 mg/l + 2000 mg/l glucose slug (recir)	3000 mg/l + 3000 mg/l glucose slug (recir)	time hrs	2000 mg/l + 2000 mg/l glucose slug (recir)	3000 mg/l + 3000 mg/l glucose slug (recir)	time hrs	2000 mg/l + 2000 mg/l glucose slug	time hrs	3000 mg/l + 3000 mg/l glucose slug
0	8.10	0	7.75	0	8.55	8.55	0	8.25	8.15	0	8.30	0	8.25
2	7.85	2	7.32	2	7.60	7.32	2	8.25	8.20	2	7.35	2	8.30
4	7.50	4	6.70	4	7.25	6.55	4	8.25	8.15	4	7.95	4	7.95
6	7.85	6	6.45	6	7.70	5.95	6	8.50	8.50	6	8.25	6	7.60
10	6.50	10	6.00	10	7.85	7.10	9	8.15	7.95	14	8.40	10	7.70
12	6.75	12	5.60	12	7.80	7.10	12	8.42	8.20	28	8.32	14	7.10
16	6.95	16	6.00	16	7.95	7.10	16	8.32	8.15	32	8.15	18	7.45
18	6.62	19	6.28	19	7.95	7.05	20	8.32	8.32			25	7.60
24.5	6.95	24	5.80	24	7.80	7.10	24	8.50	8.50			28	7.80
28	6.95	28	5.40	28	7.95	6.90	27	8.50	8.50			34	7.85
				33	7.95	7.15	30	8.50	8.50				
	Fig. 30		Fig. 32		Fig. 31	Fig. 33		Fig. 38	Fig. 40		Fig. 44		Fig. 46

TABLE XI

OXYGEN CONCENTRATION IN THE AERATOR DURING GRADUAL SHOCK LOADING UNDER NITROGEN DEFICIENT CONDITIONS EXPRESSED AS mg/l AT 25°C.

4-hour detention time							8-hour detention time				12-hour detention time				
time hrs	3000 mg/l glucose BOD/N=30	time hrs	3000 mg/l glucose BOD/N=40	time hrs	3000 mg/l glucose (recir) BOD/N=30	3000 mg/l glucose (recir) BOD/N=40	time hrs	3000 mg/l glucose BOD/N=30	time hrs	3000 mg/l glucose (recir) BOD/N=30	3000 mg/l glucose (recir) BOD/N=40	time hrs	3000 mg/l glucose BOD/N=21	time hrs	3000 mg/l glucose BOD/N=30	time hrs	3000 mg/l glucose BOD/N=40
0	8.35	0	8.15	0	8.50	8.50	0	7.75	0	8.50	8.50	0	8.12	0	8.35	0	8.30
2	8.65	2	7.15	2	8.40	8.40	2	7.30	2	8.50	8.50	2	7.05	2	8.16	2	8.22
4	8.75	4	7.40	4	8.32	8.33	4	6.90	4	8.42	8.50	4	7.15	4	8.00	4	8.00
6	8.35	6	7.30	6	8.40	8.33	6	7.12	6	8.50	8.42	6	7.50	10	7.30	6	7.64
10	7.60	10	6.80	9	8.32	8.33	12	7.05	9	8.42	8.50	8	7.50	14	7.22	10	7.70
12	7.50	12	6.45	12	8.40	8.33	16	7.12	12	8.50	8.50	12	7.30	18	7.40	14	7.45
16	6.65	16	6.35	15	8.25	8.25	20	7.05	16	8.50	8.50	16	7.20	28	6.87	18	7.32
20	5.15	20	6.22	24	8.50	8.48	24	7.20	19	8.50	8.50	20	7.30	31	7.65	28	7.70
28	6.70	25	5.93	27	8.32	8.33	28	7.15	24	8.70	8.70	25	7.40			31	7.70
		28	5.75	30	8.50	8.48	34	7.15	27	8.60	8.60	28	7.30			35	7.90
		33	6.05	33	8.50	8.48	48	7.40				31	7.50			38	8.00
							52	7.15				35	7.05				
	Fig. 50		Fig. 53		Fig. 51	Fig. 54		Fig. 56		Fig. 57	Fig. 60		Fig. 62		Fig. 64		Fig. 67

it was operated at 1000 mg/l glucose are not included in the tables, as they did not vary to any appreciable extent. It can be seen from the tables that there was only a slight drop in oxygen concentration during the shock loads, and in no case did the oxygen concentration drop to values which would interfere with the response of the continuous flow unit undergoing a shock load. It can be inferred that the oxygen content did not restrict the performance of the continuous flow unit.

CHAPTER VI

DISCUSSION

Before the discussion of results, it is pertinent to present some of the observations made during the operation of the continuous flow systems for a period of approximately a year. The most common problems encountered were side growth on the walls of the aerator, and clogging of diffusers. These problems were especially acute when solids recirculation was practiced. To overcome this difficulty, the diffusers and aerators were cleaned daily. The solids in the aerator sometimes showed a tendency to flocculate, although most of the time they were in a dispersed state. Whenever solids flocculated, the solids were discarded and fresh units were started. Many times, although the solids were initially in a dispersed state, they showed a considerable tendency to flocculate in response to a shock loading. A total of seven experiments were discontinued due to cell flocculations which caused solids accumulation in the aerator. With cell feedback, the solids in the system were always flocculent and their accumulation in the aerator was prevented by increasing the air supply and providing two diffusers, as mentioned under Materials and Methods. Another common problem encountered was foaming. This was especially acute when the units were shock loaded with 3000 and 5000 mg/l glucose. During the experiments the sides of the aerator were frequently cleaned to prevent accumulation of foam. In two experiments the foaming was too excessive to be controlled by frequent cleaning, hence these experiments were discontinued. However, no foaming was encountered when

solids recirculation was adopted. Although anti-foamer sprays could have been used, they were not employed because they could conceivably interfere with the purification process. Considerable variation in microbiological population was also observed, although no attempts were made to identify the organisms. Normally, the mixed liquor was light grey or light yellow in color. In three experiments the units took on a distinctly red color when shock loaded. Of special interest was the system which became red after being shock loaded with 5000 mg/l glucose, since it returned to its normal color when the unit was fed again with 1000 mg/l glucose. Sludge from the aerators which were operated without cell feedback exhibited no settling ability; as a result considerable difficulty was encountered in separating the solids from mixed liquor during the experiments. Sludge in systems in which cell feedback was practiced exhibited excellent settling ability at all times, except in one instance. When the system was shock loaded with 5000 mg/l glucose, the sludge gradually lost its settleability and became very bulky. Ten days were required before it exhibited its previous settling characteristics. Considerable variation was also observed in the "steady state" biological solids concentration in the aerator. Cell yields obtained for all experiments are shown in Table XII. It can be seen that the yield in a continuous flow unit is not constant, and exhibits considerable variation. This observation is also clearly indicated in Figures 9 and 15, in which solids show considerable variation with time when the feed was maintained constant at 1000 mg/l glucose. It is important to point out that this finding is in agreement with the observation of Gaudy and Rao (95) in batch studies; i.e., cell yields can vary for a single substrate.

TABLE XII

CELL YIELD IN THE "STEADY STATE" CONTINUOUS FLOW UNIT OPERATED AT 1000 mg/l GLUCOSE

Detention time (hrs)	Solids mg/l	Total COD remaining mg/l	Yield (mg of solids/mg of total COD used
4.0	500	70	0.505
"	450	56	0.445
"	340	98	0.353
"	520	73	0.530
"	368	150	0.405
"	452	164	0.505
"	650	20	0.625
"	396	110	0.417
"	500	130	0.538
"	240*	90	0.510
8.0	496	96	0.512
"	472	105	0.495
"	436	101	0.455
"	500	118	0.530
"	412	80	0.420
"	472	80	0.483
12.0	400	80	0.410
"	476	112	0.50
"	400	80	0.41
"	340	124	0.365
"	320	98	0.334
"	320	145	0.350
"	384	90	0.386
"	368	120	0.392

* operated at 500 mg/l glucose

1. Response to Gradual Shock Loading

From the results shown in Figures 10, 16, and 22, it is apparent that the system possessed the capability of accepting a shock load concentration of twice the previous influent concentrations. However, at the 4-hour detention time even 2000 mg/l glucose had some effect, as shown by the increase in total COD for a period of four hours (Figure 10). The effect of a gradual shock load of 2000 mg/l seems to decrease with increasing detention time, as can be seen from Figures 10, 16, and 22. However, the amount of glucose present in the system is considerably higher at 12-hour detention time as compared with detention times of 4 and 8-hour. The release of metabolic intermediates appears to decrease with increasing detention time. The biochemical efficiency of all of the systems is approximately 90%, based on total COD removal, and considerably higher if efficiency is based on glucose removal. Since all of the systems were able to handle a gradual shock loading of 2000 mg/l, there was no particular value in studying this level of shock loading with sludge recycle, since it might be expected such systems would definitely handle this shock load.

When the system was subjected to a greater shock loading, such as tripling of the previous influent concentration, the response appeared to be dependent upon the detention time and the solids concentration maintained in the aerator. It is very clear from Figures 11, 17, and 23 that the severity of disruption of the system with a 3000 mg/l glucose gradual shock load decreases with increasing detention time. It should be noted that this statement is true only if the comparison is made on the basis of total COD removal. It can be seen that the total COD in the effluent was very high at the 4-hour detention time, and that there was very little increase in effluent COD at 8 and 12-hour detention times. However, the system operated at the 12-hour detention time showed a considerable degree of

fluctuation in total COD, as can be seen from Figure 23. Although COD was quite high at the 4-hour detention time, there was very little increase in glucose concentration (Figure 11). In contrast to systems operated at the 4 and 8-hour detention time, the unit operated at the 12-hour detention time exhibited a fairly high residual glucose COD. It is apparent from Figures 17 and 23 that the 3000 mg/l glucose shock load could be successfully handled at detention times of 8 and 12 hours. If the response to the 3000 mg/l glucose shock load is considered on the basis of glucose concentration in the effluent, all three systems are capable of handling this shock load. It is apparent from Figures 12, 18, and 24 that when solids recirculation was used, the systems were not affected at all due to the increased glucose concentrations in the influent. These results demonstrate the importance of solids concentration in the aerator as a factor which determines the response to quantitative shock loadings. Systems with solids recirculation are quite stable and do not show any variation in their response to the 3000 mg/l glucose gradual shock load. This is clearly indicated at the 4-hour detention time (Figures 11 and 12).

When the systems were subjected to a five-fold increase in the steady state concentration of glucose, they could not readily respond to such a shock load (Figures 13, 19, and 25). In contrast to the response to the 3000 mg/l glucose shock load, the maintenance of higher solids concentrations in the aerator does not offer any protection against 5000 mg/l shock load, as shown in Figures 14, 20, and 26. It can also be seen that the system which was operated at the 4-hour detention time was the most severely affected at 5000 mg/l glucose, and the severity of disruption of the steady state decreased with increasing detention time (Figures 13, 14, 19, 20, 25, and 26). It is interesting to note that the response at any detention time to 5000 mg/l glucose was almost identical with respect to total COD removal, whether solids were

recirculated or not. The major difference in the response was the presence of a higher glucose concentration in the systems with solids recirculation. The residual COD remaining in the system after it had attained a new steady state was considerably less for systems employing sludge recirculation than for systems without cell feedback. It can also be noted that the systems operated at the 4-hour detention time were severely upset and took a considerably longer time to reach the new steady state. The main difference between the two systems (with and without solids recirculation) was that the systems without feedback exhibited the release of metabolic intermediates and/or end products which were not apparent in the recycle systems. This was the case with all gradual shock loading experiments. From the gradual shock loading experiments it was observed that the release of metabolic intermediates was related to the glucose concentration in the influent and the detention time of the system; i.e., the higher the glucose concentration and the shorter the detention time, the greater was the production of intermediates. This is true only for systems without cell feedback.

The response to the gradual shock loading can be predicted based upon the principles of operation of a completely mixed continuous flow system. In such a system the rate of growth of biological solids is determined by the dilution rate, and the steady state solids level is a function of influent substrate concentration and the cell yield for the particular substrate and bacterial species present. This is true only if the growth rate of the system is less than the maximum growth rate. In all the experiments conducted the growth rate was below the maximum, and was controlled only by the dilution rate. Hence, the growth rate of each system would be 0.25 hr^{-1}, 0.125 hr^{-1}, and 0.083 hr^{-1} for a 4, 8, and 12-hour detention time, respectively. Upon disruption of the steady state by increasing

the supply of influent glucose, the system could respond quite readily by a rapid increase in the growth rate. Under this condition the system may act somewhat like a batch-operated system with respect to substrate removal rate, as well as biological sludge growth, but after a period of time the applied organic concentration in the system levelled off and once again glucose became the limiting nutrient and the growth rate was controlled by dilution rate. In all of the experiments under gradual shock loading it was apparent that the response to shock load was accompanied by an increase in the biological solids concentration until it reached a new steady state level. During the transition stage the growth response to a gradual shock load is controlled primarily by the rate of increase of glucose concentration in the aerator. If the rate of increase of substrate concentration (minus the amount of substrate oxidized) cannot be paralleled by the rate of solids production, substrate will continue to be lost in the effluent until the biological solids reach a level at which the substrate removal rate becomes approximately equal to its rate of inflow. This was very apparent at the 4-hour detention time when the systems were shock loaded with 3000 and 5000 mg/l glucose (Figures 11 and 13). Other factors which control the response to gradual shock loadings are detention time and solids concentration in the aerator. The higher solids concentrations (approximately 800 mg/l in the present study) give protection against gradual shock loading up to a certain glucose concentration beyond which solids do not afford any protection; for example, up to 3000 mg/l glucose at 4-hour detention time in the present study (Figure 12). It is also evident that the ability of a system to accept gradual shock loads will increase as its detention time increases. This is apparent because the rate of increase of glucose concentration in the aerator is greater at the 4-hour detention time as compared with the 8 and 12-hour detention time for the same influent

glucose concentration. For example, the concentration of glucose in the aerator would reach 50% of its influent concentration within three hours at the 4-hour detention time, but would require six hours and nine hours at 8 and 12-hour detention times, respectively. Hence it would appear to be obvious that the effect due to gradual shock loading will be greater for the system with lower detention time. However, it should be emphasized that the response time at the higher detention time may not be as fast as with the shorter detention time on account of its lower growth rate. In the present study it was found that the system operating at the 4-hour detention time could successfully respond to twice the previous influent concentration, whereas systems at 8 and 12-hour detention times could successfully respond to triple the previous steady state concentration. With solids recirculation, systems at all three detention times could respond to triple the previous steady state concentration. Komolrit (46) in studying the effect of qualitative shock loadings in similar continuous flow units has indicated that a system operated at a 4-hour detention time could successfully respond to twice the previous influent concentration, whereas at a detention time of sixteen hours a system could respond to more than triple the previous substrate concentration. It is interesting to note that the sludges responded somewhat similarly in respect to COD removal whether subjected to quantitative or qualitative shock loads.

Another factor that is not apparent from the figures presented for the gradual shock loads is the effect of loading (lbs of glucose/1000 cft aerator volume/day) on the response in continuous flow unit to shock loading at various detention times. In all of the experiments the shock load concentration of glucose was maintained constant at all detention times. Although the influent had the same concentration of glucose, the rate at which it was applied to the systems was quite different. Indeed, it was for this

reason that the systems operated at longer detention times showed a better response to the gradual shock load as compared with the 4-hour detention time. The steady state influent feed of 1000 mg/l glucose at a 4-hour detention time is equivalent to 380 lbs glucose/1000 cft aerator vol/day. Hence, when the system was shock loaded with 2000, 3000, and 5000 mg/l glucose, the loading equivalents were 760, 1140, and 1900 lbs/1000 cft aerator vol/day, respectively. The same shock load concentration at the 8-hour detention time would represent only one-half the loading at the 4-hour detention time, and one-third at the 12-hour detention time. When recirculation was used, the loading would be less, due to the reduced amount of glucose applied to the system. It was found that at the 4-hour detention time the system could respond to 2000 mg/l glucose, representing a loading of 760 lbs/1000 cft aerator vol/day. At the 8 and 12-hour detention times the system could handle a shock loading of 3000 mg/l; i.e., a loading of only 570 and 340 lbs/1000 cft aerator vol/day, respectively. A loading of 760 lbs/1000 cft. aerator vol/day would represent a glucose concentration of 4000 mg/l and 6000 mg/l at the 8 and 12-hour detention times, respectively. It may be inferred from the results shown in Figures 19 and 25 that the response to the above mentioned glucose concentrations at the 8 and 12-hour detention times might be more severely disruptive than the response to 2000 mg/l glucose at the 4-hour detention time (Figure 10). It has been shown that when solids recirculation was employed, a successful response was evidenced at glucose concentrations up to 3000 mg/l for all three detention times. The corresponding loading would be 760, 380, and 254 lbs. of glucose/1000 cft aerator vol/day at the 4, 8, and 12-hour detention times. The results seem to indicate that the loading capacity of the system decreases with increasing detention time. It is the author's opinion that this aspect warrants further study before a definite

conclusion can be drawn. It is also apparent that the continuous flow systems are capable of handling higher organic loading than the accepted optimum loading of 35 lbs/1000 cft aerator vol/day with the conventional activated sludge process (7); however, it should be emphasized that the substrate removal efficiency in the present study was measured as biochemical efficiency; i.e., it did not include sludge settleability.

2. Responses to Slug Loading

The response of the continuous flow units to slug shock loadings was quite unexpected. It was reasoned that when the concentration of glucose was brought to a specific value in the aerator, the cells would behave somewhat like acclimated batch grown cells; i.e., they were expected to remove substrate rapidly with a concomitant buildup of biological solids. However, from the results obtained in this study it appears that this was not the case. From the results shown in Figures 27, 34, and 41, it is apparent that the continuous flow units did not exhibit much flexibility in accommodating slug doses. In these experiments the units were shocked with a slug dose of 2000 mg/l glucose while maintaining the influent feed at 1000 mg/l, which was the previous steady state feed concentration. It can be seen that the time taken to reduce the total COD varies with detention time; i.e., the longer the detention time, the greater was the time the system needed to reduce the applied glucose slug load. This is probably due to the fact that it takes a longer time to dilute out the glucose slug dose as the detention time is increased. It can also be seen from the theoretical washout curve that at a 4-hour detention time the system did not have any ability to respond to a slug dose (based on total COD in the effluent), and the response seemed to improve with increasing detention time. Although the total COD curve followed the theoretical wash-

out curve, there was considerable utilization of glucose as shown by the difference between total COD and anthrone COD curves (Figures 27 and 41). In three experiments (Figures 36, 41, and 44), although there was considerable utilization of the applied glucose slug, there was very little increase in the solids concentration. This was due to the release of considerable amounts of intermediates. The lack of solids increase is due to the fact that conversion of glucose to intermediates does not involve much energy change needed for the cell growth (i.e., incomplete oxidation of glucose), and further, the release of intermediates might change a quantitative shock to a qualitative shock. With solids recirculation, the system response was only slightly better, as can be seen from Figures 28, 35, and 42. Even in these systems the time for COD removal increases with detention time; however, with solids recirculation there was an increase in solids concentration, indicating the utilization of the applied glucose. These results indicate that maintenance of higher concentrations of solids in the aerator would improve the response to slug shock loadings. When shock loaded with a 3000 mg/l slug of glucose, systems operated at 4 and 8-hour detention times do not respond well (Figures 29 and 36). However, at the 12-hour detention time an improved response to this slug shock load was evident (Figure 43). The responses to a 2000 mg/l glucose slug dose coupled with a 2000 mg/l glucose gradual shock load were shown in Figures 30, 37, and 44. The response pattern was nearly the same as that to a 2000 mg/l glucose slug shock load without an accompanying gradual shock. The solids concentration increased considerably in all of the systems; this was due mostly to the gradual shock load. It can also be seen that there was not a great deal of "excess" solids produced, which strongly points to the failure of the system to use the glucose slug effectively. It was shown under conditions of gradual shock loading that systems operated at 8

and 12-hour detention times could handle 2000 mg/l glucose as a gradual shock load, which further supports the view that the glucose slug dose is not used to any great extent. This statement applies only if the response of the system is considered in terms of total COD removal. It can be seen that considerable amounts of intermediates were produced (Figures 30 and 44). When the same shock load was studied with solids recirculation, the systems showed a slight improvement in response as compared with the systems without feedback (Figures 31, 38, and 45). With solids recirculation, the response was better at the longer detention times (as compared with 4-hour detention time). When the system was shock loaded with a 3000 mg/l glucose slug dose and 3000 mg/l glucose gradual shock load, the response was relatively unsuccessful at any detention time (Figures 32, 39, and 46). Since systems operated at 8 and 12-hour detention times were capable of taking a gradual shock loading of 3000 mg/l glucose, it can be inferred that the system could not successfully respond to a 3000 mg/l glucose slug dose. Even with solids recirculation there was not much improvement in the response (Figures 33, 40, and 47). However, it can be seen that the response to this shock load showed improvement at the 12-hour detention time. All three systems were able to handle a 3000 mg/l glucose gradual shock load. The results indicate that the response is entirely different if a 3000 mg/l glucose shock is applied in the form of a slug instead of a gradual shock load.

It was apparent from all of the experiments with the slug shock load that completely mixed systems do not have enough flexibility of response to handle this type of shock load. The maintenance of higher solids concentrations did not have much effect, although slight improvement in the response was noted. It should be emphasized that this statement applies only for the range of solids con-

centrations maintained in the present study; however, when the solids concentration was in excess of 3000 mg/l, a successful response to glucose slug shock loading was indicated (Figure 48). This indicates that successful response to slug shock loading is a function of solids concentration in the aerator. Higher solids concentration in the aerator can be maintained by employing higher recirculation ratios. It was found also from this study that in most of the experiments the total COD curve followed closely the theoretical washout curve; however, there was considerable difference between anthrone COD and total COD. This seems to indicate that glucose applied as slug dose is converted to metabolic intermediates which are not immediately utilized. The diluting out of the total COD is also indicated by the lack of increase in solids concentration in the system when subjected to only slug doses of glucose. However, when the system was subjected to gradual shock loading in addition to slug doses, there was a considerable buildup of biological solids, and this was primarily attributable to the introduction of the gradual shock loading. It is not implied that the slug dose is merely washed out of the system since, in that case, the glucose COD curve should also approximate the theoretical washout curve. The results do indicate that utilization of glucose applied as a slug dose is rather limited in completely mixed continuous flow systems. It was also found that the adverse effect of slug doses seems to decrease with increasing detention time. This is due to the fact that greater opportunity exists for glucose utilization at higher detention times, as the glucose is not diluted out as fast as with the lower detention time. A possible reason for the lack of buildup of solids in systems subjected to slug doses is that solids production is controlled by the influent substrate concentrations. When the unit was subjected to only slug doses, the growth rate must increase very rapidly if it is

to accommodate the glucose slug. If the growth rate does not increase rapidly enough, the dilution rate exceeds the capacity of the system, resulting in the dilution of the applied slug. However, when the system is subjected to only a gradual shock load, the growth rate need not change rapidly, since the change in glucose concentration in the aerator is not abrupt, resulting in a successful response to the gradual shock load. This would indicate that the growth rate is controlled hydraulically rather than by the substrate concentration in the aerator. The result seems to support this view, and it is further substantiated by the fact that when the slug dose was also accompanied by a gradual shock load, there was a rapid increase in solids concentration. George (96) in his study of the effect of qualitative slug doses in continuous flow units, has indicated that a system operated at 1000 mg/l sorbitol at an 8-hour detention time can handle successfully a slug dose of only 250 mg/l glucose without much loss in the efficiency of the system. He also indicated that slug doses above 250 mg/l and up to 2000 mg/l glucose severely affect the efficiency of the system. The results obtained in this study support his finding that the ability to respond to slug doses lies well below 2000 mg/l glucose concentration under the operational conditions herein employed. However, it should be remembered that there may be inherent differences in the biochemical mechanism involved in response to quantitative and qualitative shock loads. Barth, et al. (97), studying the effect of metal slug doses in activated sludge systems, reported that acclimation of the system to low concentrations of metal did not offer protection from slug doses. Although this type of slug doses is not similar to the glucose slug, it seems to indicate that slug doses for the most part are not readily metabolized in the activated sludge system.

Another aspect that was noted with most of the slug load experiments was the increased protein synthesis in the system (for example, Figures 27 and 28). This is probably an indication that the response to the slug shock loading is accompanied by a multiplication of cells (i.e., increase in numbers) without much storage of carbohydrate material.

3. Responses to Shock Load under Nitrogen Deficient Conditions.

It is apparent in Figures 49, 52, 55, and 58 that the biochemical efficiency of these systems was seriously retarded. In these experiments the only change was the reduction in nitrogen content in the influent feed; however, at the 12-hour detention time when the BOD/N ratio was changed from 7 to 21, the system response was not at all affected (Figure 61). Even when the nitrogen content in the influent was changed from a BOD/N ratio of 20 to 30 and to 40, the biochemical efficiency of the system remained fairly high (Figures 63 and 66), although at a ratio of 40 the system efficiency was slightly impaired (Figure 66). When lesser amounts of nitrogen accompanied the feed, there was a decrease in solids concentration and protein content of the sludge, and an increase in carbohydrate content. These experiments clearly indicated that the responses of the systems were seriously affected, especially at the 4 and 8-hour detention times, if the influent feed was not accompanied by an adequate amount of nitrogen. These experiments also show clearly that completely mixed continuous flow systems are very sensitive to changes in nitrogen concentrations in the influent feed. The effect of gradual organic shock loadings not accompanied by an adequate nitrogen source were also investigated. In all systems examined the BOD/N ratio was maintained at 7 prior to shock loading, and under shock loading conditions the BOD/N ratio was maintained at 30 and 40, at 4

and 8-hour detention. At the 12-hour detention time an experiment was conducted with 3000 mg/l glucose at a BOD/N ratio of 21 (Figure 62). It is clear from this figure that the system could respond to the 3000 mg/l glucose shock load successfully at BOD/N ratio of 21. This result is in accordance with the optimum BOD/N ratio recommended by other investigators (56) (57). Having determined that a BOD/N ratio of 21 was adequate for the shock loading condition at the 12-hour detention time, subsequent experiments were conducted by operating a steady state system at a BOD/N ratio of 20 prior to administering a shock. During the shock experiment BOD/N ratios were maintained at either 30 or 40. It is apparent from Figures 50, 56, and 64 that when the systems were subjected to 3000 mg/l glucose at a BOD/N ratio of 30, the biochemical efficiency of the system was considerably reduced especially at the 4 and 8-hour detention times; however, the system which was operated at the 12-hour detention time responded more successfully. Although total COD was very high, anthrone COD was fairly low, indicating the release of metabolic intermediates. These experiments also indicate that the released intermediates are not subsequently utilized. It is also seen that nitrogen deficiency is characterized by marked decrease in protein content and increase of carbohydrate content of the sludge. When employing solids recirculation, the response was only slightly better (Figures 51, 57, and 65) at the 4 and 8-hour detention times. However, the system which was operated at the 12-hour detention time responded successfully. It is also observed that when higher solids concentrations were maintained in the aerator through recirculation, the system response is better compared with the system without cell feedback (for example, Figures 50 and 51). This possibly indicates that maintenance of solids concentration higher than that employed in the present study would be likely to lessen the severity of shock loads under nitrogen deficiency.

The major difference between the two systems (with and without solids recirculation) was that metabolic intermediates were not detected when recirculation was employed. Another important difference appeared to be the sludge composition. With solids recirculation there was not much increase in carbohydrate synthesis. The response of the systems to shock loading with 3000 mg/l glucose at a BOD/N ratio of 40 was very similar to that at 30. Also, in this series of experiments at the 12-hour detention time the system showed remarkable ability to withstand the shock load. The system operated at the 8-hour detention time showed improved performance at a a BOD/N of 40 compared with BOD/N of 30 (Figures 59 and 56). In this particular experiment (Figure 59) when shock loaded the unit became distinctively reddish in color, indicating a change of predominance in the system. It was felt that the improved response could be due to a shift in predominating organisms in the aerator. Having observed that the system operated at the 12-hour detention time could respond to 3000 mg/l glucose at BOD/N ratios of 30 and 40, it was of interest to find out whether the same response could be obtained with an 8-hour detention time. The results were shown in Figures 69 and 70, and it is obvious that the system could not successfully respond to the shock load.

It is apparent from all of the experiments that nitrogen deficiency seriously affects the biochemical efficiency of the system. Komolrit (46), studying the qualitative shock loading under nitrogen deficiency in continuous flow systems, indicated a similar loss in biochemical efficiency. From the results of this study it appears that the efficiency of the continuous flow systems is related to the amount of nitrogen rather than the nature of substrate. These studies have also indicated certain basic differences in the performance of continuous flow units with and without cell feedback. The systems without feedback were characterized by the release of considerable amounts of metabolic

intermediates which were totally absent in systems employing feedback. The biochemical composition of the sludge also differed. The system without feedback was characterized by reduction in protein content and increase of carbohydrate, whereas with feedback there was very little increase in carbohydrate content. Since these changes are not immediately apparent in the figures, the value of percent protein and carbohydrate for each experiment are shown in Table XIII. In this table only the parallel experiments which were conducted in both systems (with and without recirculation) are shown in order to bring out the essential difference in cell composition for the two systems. It can be clearly seen from Table XIII that the systems without feedback show a marked decrease in protein content which is accompanied by an increase in carbohydrate content, whereas in the systems with feedback percent carbohydrate does not exhibit a considerable increase although the percent protein slightly decreases. The results obtained without feedback are in agreement with the findings of Gaudy and Engelbrecht (59), and Van Gils (60). From the results shown in Figures 59 and 64, it appears that successful response to shock load under nitrogen deficiency can occur if the cells are capable of synthesizing sufficient carbohydrate. The reason for this apparent difference between the two systems could be due to the nitrogen in the recycled sludge which helps to maintain the composition of sludge fairly constant. The percent protein and carbohydrate content of the sludge at the 12-hour detention time also indicates a possible reason why this system responded better to shock load under nitrogen deficient conditions. It can be seen that there is very little decrease in protein content of the sludge at the 12-hour detention time as compared with the 4 and 8-hour detention times when solids recirculation was used. This may be the reason for its better performance, i.e., the nitrogen deficiency of the system was not reflected in the sludge com-

TABLE XIII

CHANGES IN PERCENT PROTEIN AND CARBOHYDRATE DURING SHOCK LOAD UNDER NITROGEN DEFICIENT CONDITION

4-hour detention time										
No recirculation						With recirculation				
	3000 mg/l glucose BOD/N = 30			3000 mg/l glucose BOD/N = 40			3000 mg/l glucose BOD/N = 30		3000 mg/l glucose BOD/N = 40	
Time (hrs)	%P	%c	Time (hrs)	%P	%c	Time (hrs)	%P	%c	%P	%c
0	47.5	10.8	0	54.5	18.3	0	36	31.0	36	31
2	41.0	9.6	2	49.0	18.5	2	32.3	28.5	30.5	30.5
6	38.0	17.6	4	44.2	24.3	4	33.6	33.6	32.5	36.5
10	39.5	26.6	6	33.4	24.1	6	29.2	29.5	33.3	34.7
12	39.5	25.0	10	23.6	22.5	9	29.4	28.4	31.2	31.2
16	36.3	28.2	12	24.8	28.0	12	26.0	26.6	29.6	30.4
20	33.5	29.0	16	23.2	31.5	15	26.7	27.2	29	28
24	28.7	32.5	20	20.7	27.6	19	27.2	26.0	25	27
28	27.5	34.5	25	19.7	22.7	24	28.5	26.5	27	27.2
32	25.3	34.0	28	19.9	27.3	27	26.6	25.3	28	31.2
			33	16.4	27.0	30	27.2	27.4	26.8	20.5
						33	26.6	27.0	26.2	30.4
	Fig. 50			Fig. 53			Fig. 51		Fig. 54	

%P = percent protein = $\frac{\text{mg/l protein}}{\text{mg/l solids}}$ %c = percent carbohydrate = $\frac{\text{mg/l carbohydrate}}{\text{mg/l solids}}$

TABLE XIII (Cont)

8-hour detention time

No recirculation						With recirculation				
	3000 mg/l glucose BOD/N = 30			3000 mg/l glucose BOD/N = 40			3000 mg/l glucose BOD/N = 30		3000 mg/l glucose BOD/N = 40	
Time (hrs)	%P	%c	Time (hrs)	%P	%c	Time (hrs)	%P	%c	%P	%c
0	42.5	10.3	0	49	9.6	0	48	26	48	26
2	34.7	9.1	2	42.7	9.4	2	46.5	24.4	44.8	24.8
4	38.4	8.1	4	45.0	9.9	4	48.6	25.6	41.7	24.7
6	33.4	11.6	6	43.8	13.7	6	48.2	28.0	48	28.6
10	25.4	13.6	10	32.0	20.2	9	45.6	27.3	46.2	29.2
16	23.8	20.3	12	25.8	18.6	12	41.5	28.4	38.5	29.3
20	23.5	21.6	16	18.4	19.8	16	39.0	30.4	40.5	30.4
24	23.6	22.6	19	23.3	29.7	19	37.3	31	38.0	29.6
28	23.8	22.5	24	20.7	28.0	24	36.4	29.8	36.4	28.5
34	23.8	21.5	28	18.8	39.7	27	35	29.8	35.5	30.3
48	23.8	21.1	33	16.8	45.6	30	34.8	29.4	34.2	29.4
						33	32.2	28.7	34.5	28.0
	Fig. 56			Fig. 59			Fig. 57		Fig. 60	

TABLE XIII (Cont)

12-hour detention time

No recirculation						With recirculation				
	3000 mg/l glucose BOD/N = 30			3000 mg/l glucose BOD/N = 40			3000 mg/l glucose BOD/N = 30		3000 mg/l glucose BOD/N = 40	
Time (hrs)	%P	%c	Time (hrs)	%P	%c	Time (hrs)	%P	%c	%P	%c
0	35.6	19.4	0	50.2	12.5	0	34.3	14.2	34.3	14.2
2	38.0	18.4	2	50.4	14.7	2	31.8	16.7	-	-
4	33.4	19.2	4	44.5	14.2	4	34.4	16.2	33	16.1
6	31.0	24.0	6	46.8	16.3	6	34.6	17.2	32	16.7
10	20.6	32.0	10	46.4	17.8	9	34.0	16.6	32.6	16.0
14	17.7	43.0	18	47.6	28.5	12	34.0	16.2	31.9	16.2
18	16.6	44.2	26	40.4	28.7	16	33.8	16.9	33.6	20
24.5	17.6	45.8	28	37.6	28.8	19	37.0	19.5	35	21
28	17.6	40.5	31	33.4	28.0	24	32.4	19.2	33.2	17.9
21	16.4	39.6	35	25.2	29.5	28	35.6	19.6	32	18.7
			39	22.4	29.3	31	30.8	15.6	32.3	18.5
						35	28.7	14.6	33.0	17.8
	Fig. 64			Fig. 67			Fig. 65		Fig. 68	

position. It is also possible that nitrogen is being diluted out very slowly at 12-hour detention time compared with 4 and 8-hour detention times, which might explain the results obtained with 12-hour detention time; however, it cannot be unequivocally stated since the effluents were not analyzed for their nitrogen content.

Helmers, et al. (58) have concluded that a value of less than 7.5 percent organic nitrogen in the volatile matter of activated sludge is indicative of nitrogen deficiency. From the results shown in Table XIII (with solids recirculation) it is doubtful whether organic nitrogen is a reliable index in assessing the nitrogen deficiency of the system. Although organic nitrogen (Kjeldahl method) was not measured in these experiments, from the value of the recorded protein content it can be surmised that there would not be much reduction in organic nitrogen content of the sludge. These results tend to indicate that the composition of sludge is not a good index for assessing the performance of the system under shock loading conditions when solids recirculation is practiced. Another observation worthy of note is that the solids level does not increase as much under nitrogen deficient conditions as it does for systems supplied with excess nitrogen. In only one experiment was there excess solids buildup (Figure 64). However, McKinney and Symons (61) and Symons and Bechir (62) have indicated that nitrogen deficient systems were characterized by excess solids synthesis based on their studies over an extended period of time. From the results obtained from this study it is clear that excess solids buildup does not occur under short term nitrogen deficient conditions.

Gaudy and Engelbrecht (59) have indicated that substrate removal efficiency was not affected due to lack of nitrogen in batch operated activated sludge processes. The results of the present study bring out the basic difference between batch and continuous flow units regarding response

to nitrogen deficiency. In regard to substrate removal, the continuous flow units are very sensitive to nitrogen deficiency compared with batch systems. These differences are due primarily to the basic differences in the operation of the two systems. The batch process is not subjected to any hydraulic flow which is characteristic of the continuous flow systems. In the continuous flow systems cells are diluted out, and unless cells are replaced by replication, aeration solids are lost from the system. This does not occur for batch systems. It can also be seen from Table XIII that the nitrogen deficiency is accompanied by a marked decrease in the protein content of the cells, especially when recirculation is not practiced. This would tend to indicate that the nitrogen deficiency is reflected in this process relatively rapidly compared with the batch process. Even in the recycle system due to the low recirculation ratio adopted, not all of the cells leaving the system are replaced. Possibly higher recirculation ratio might improve the performance of the continuous flow system under nitrogen deficient conditions.

It is also of interest to note that modifications proposed by Rama Rao et al. (65) and Gaudy, et al. (66) may not be applicable to continuous flow systems. Their modifications were based on the fact that substrate removal was not affected due to nitrogen deficiency. However, it is to be emphasized that their modifications were not necessarily proposed for completely mixed reactors.

4. Release of Intermediates during Shock Loading.

It was observed that during gradual shock loads the amount of released intermediates decreased with increasing detention times. The amount of intermediates also depended on the concentration of glucose in the influent. The results suggest that the production of intermediates is related to growth rate; i.e., the higher the growth rate,

the greater is the production of intermediates. This observation is in agreement with that of Pirt (81). The present experiments employing solids recirculation indicated very little release of intermediates under gradual shock loads and complete absence of intermediates under nitrogen deficient conditions. In the study designed to examine the nature of the intermediates, solids recirculation was not practiced. It is apparent from Figures 71 through 75 that a considerable amount of volatile acids was present in the medium when the system was shock loaded. When the unit was subjected to shock loading under nitrogen deficient conditions, the volatile acids were not subsequently utilized, whereas in the system supplied with excess nitrogen they were utilized. The results indicate that the enzymes required for utilization of volatile acids are inducible, and explain why the volatile acids were not utilized under nitrogen deficiency, since an adequate source of nitrogen is necessary to induce the necessary enzyme(s). The result is in general agreement with that of Krishnan and Gaudy (75), who showed that intermediates produced during glucose metabolism by glycerol-acclimated cells were not utilized under nonproliferating conditions. In the present study it was also observed that intermediates consisted largely of volatile acids, and the major acid produced was acetic acid although small amounts of other acids were present. The volatile acids production was not due to the lack of oxygen in the system; in all of the experiments the oxygen measurement indicated the presence of excess oxygen at all times. Maxon and Johnson (98) showed that yeast in the presence of excess dissolved oxygen converted glucose to ethanol when a certain critical dilution rate was reached. To account for this they suggested that when a certain rate of glucose metabolism/gm of organism is reached, the oxidative enzymes of the yeast are saturated and glycolytic enzymes which are present in greater abundance operate to supply additional

energy for growth. Strickland (99) also showed that excess sugar concentration results in its fermentative utilization by yeast. It is also known that E. coli can convert pyruvic acid to acetic and formic acid (100). It is possible that these mechanisms may be involved in the production of intermediates. It was also observed that considerable amounts of other materials were present in addition to volatile acids, as can be observed from the total COD curve. It is possible that intermediates of the TCA (Tricarboxylic Acid) cycle and fermentation products may be present in addition to volatile acids. It is quite likely that α-keto glutaric acid may be present, especially under nitrogen deficient conditions, since lack of nitrogen would prevent its conversion to glutamic acid. Bechir and Symons (62) have also suggested the possibility of release of glutarate in nitrogen deficient continuous flow systems. Since the analyses for intermediates were chiefly concerned with volatile acids, no definite statements can be made pertaining to the presence of other intermediates or end products. It is likely that the materials listed above may be present; however, this must be confirmed through future research. Regardless of the mechanism(s) of intermediate production, the present study has revealed that considerable amounts of intermediates are produced under shock loading conditions and an adequate source of nitrogen is necessary for their subsequent utilization. These studies also bring out the importance of the COD test as a parameter for assessing the response of biological treatment units, since it provides a measure of the total amount of oxidizable organic matter present in the system. However, because of the known presence of intermediate products it cannot be directly correlated to the original carbon source.

Considerable variations in response of systems subjected to identical shock loads were observed. When the units were shock loaded with 5000 mg/l glucose, it can be seen

from Figures 13 and 73 that the response was not exactly the same. In Figure 13 glucose increased to a maximum of 900 mg/l, whereas in Figure 73 there was very little increase. Also, there was considerable difference in the residual total COD. The difference between these two experiments could very well be due to the difference in the initial and final solids concentration between the two systems. When the two systems were shock loaded with 3000 mg/l glucose under nitrogen deficient conditions, the response was also dissimilar (Figures 74 and 75). It can be seen from Figures 74 and 75 that the solids concentrations and total COD levels showed considerable difference. As mentioned earlier in this chapter, the yield in the steady state continuous flow systems exhibited considerable variation. The steady state yield varied from a maximum of 0.625 to a minimum of 0.353 at 4-hour detention time. However, there is not much variation in the steady state yield at 8 and 12-hour detention time (Table XII). It is felt that these variations are due to the heterogeneous populations of the system. The heterogeneous population is likely to consist of both slow and fast growing organisms. Depending on the type of organism predominating in the system, the yield will also vary, since the measured yield is the overall yield of all the organisms, it is to be expected that considerable variation in the cell yield will occur.

It was also observed that lipid was not synthesized to any great extent in the continuous flow systems (Figures 73 and 74). This result is in agreement with that of Van Gils (60). The elemental composition of sludge seems to reflect the characteristics of sludge with respect to its protein content (Tables V and VII). When the system was shock loaded with 3000 mg/l glucose at a BOD/N ratio of 40 (Figure 74), the protein content decreased from 36% to 16%. The reduction in protein content is reflected in the nitrogen content of the sludge, as can be seen from Table VII; how-

ever, the elemental composition of sludge did not reflect the changes in carbohydrate content of the sludge. In this particular experiment the carbohydrate content of the sludge increased from 25 to 40%, which is not at all reflected in the percent carbon of the sludge. It can be concluded that the elemental composition of the sludge with respect to nitrogen as measured by the CHN analyzer follows the changes in protein content of the sludge.

The results of this study have revealed several interesting facts regarding the ability of completely mixed activated sludge systems to handle shock loads. When the system was subjected to a gradual shock load, a successful response depended on the detention time employed and the solids concentration maintained in the aerator prior to the shock. The severity of a deleterious response to a gradual shock load decreased when a longer detention time was employed, and also when higher solids concentrations were maintained through sludge recycling. The successful response at the longer detention time was due mainly to the fact that the concentration of shock substrate (glucose) was maintained constant at all detention times, and as a result of this the shock substrate was applied more slowly as the detention time increased. It was also observed that the release of intermediates depended upon glucose concentration, detention time, and whether or not sludge recycle was employed. The release of detectible intermediates decreased with increased detention time when sludge was not recycled, and was considerably lower when sludge was recycled.

The continuous flow system has limited ability to cope with a slug shock loading. The response, however, was successful when the solids concentration was in excess of 3000 mg/l. Considerable reduction in biochemical efficiency was observed when the shock load was administered with inadequate amounts of nitrogen. However, when the sludge recycling was practiced, the system responded success-

fully to 3000 mg/l glucose at a BOD/N ratio of 30 and 40 at the 12-hour detention time. Considerable amounts of volatile acids were released into the medium when the system was subjected to gradual and nitrogen deficient shock loads without sludge recycling. Acetic acid was found to be the major volatile acid produced. The subsequent utilization of volatile acids was indicated when adequate amounts of nitrogen accompanied the shock load.

The results of the present study have clearly shown that completely mixed systems are not free from the deleterious effects of quantitative shock loading. One of the possible ways this can be minimized is through the maintenance of higher solids concentration in the aerator. This can be easily achieved by employing a higher recirculation ratio.

In recent years a considerable number of studies have been made regarding the kinetics and mathematical formulations governing the various parameters in steady state systems. However, there is very little information available regarding the mathematical model in continuous flow systems subjected to transient (i.e., shock) loading. Recently, Eckhoff and Jenkins (101) have proposed a mathematical model for continuous flow systems subjected to transient loading. Although their formulation does have some merit, their model is based on certain assumptions which, in the author's opinion, are not correct. Eckhoff and Jenkins have proposed an equation for calculating the effluent COD due to transient loading. In their formulation they assumed that solids concentration remains constant. This does not appear to be valid, since transient loading is always accompanied by an increase in solids concentration. Further, in their equation they assumed that U and $\mathcal{L}$ are constants. U, which is equal to $\mu/s.Y_s$ is not a constant, but is actually a variable. μ (growth rate) is a function of substrate concentration, and since s also varies due to transient load-

ing, it is doubtful that U is a constant. Having observed that the experimental data did not fit their theoretical equation, they modified their equation by introducing a coefficient for adsorption. A coefficient of adsorption does not appear to have any significance when the waste is soluble. It is the author's opinion that extensive data is required before any realistic mathematical model can be developed. And, further, all of the variables that change due to transient loading should be thoroughly investigated in order to arrive at a reasonable mathematical model. Luedking and Piret (102) have also proposed mathematical equations for transient conditions. Like Eckhoff and Jenkins, they also made certain assumptions which are not correct. They assumed that bacterial density continues at steady state, but only substrate or product becomes transient. This assumption is not valid. It is highly improbable that a system can be at steady state with respect to bacterial density and yet remain transient with respect to substrate or product concentration. The assumption that solids concentration remains constant during transient loading is not supported by the results of the present study. Since the object of the present study was to observe the response of continuous flow systems to shock loads, no attempt was made to formulate any mathematical model regarding transient loading. As mentioned earlier, the key to any mathematical formulation depends on the study of interaction of various factors that undergo changes due to transient loading.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The response of continuous flow activated sludge systems to shock loads was investigated at detention times of 4, 8, and 12 hours with and without solids recirculation. In addition to the response of the continuous flow systems to shock loads, the release of intermediates which may accompany shock loads was also investigated. The results of the study support the following conclusions:

1. The sludge yield in a "steady state" continuous flow system employing heterogeneous populations is not a constant, but is subject to variations.

2. Dissolved oxygen concentration in the aerator does not undergo considerable reduction due to the introduction of shock loads imposed upon the system, and hence the response to shock loads herein observed was not limited by the dissolved oxygen concentration in the aerator.

3. The response of the continuous flow system to gradual shock loading is dependent upon the detention time and solids concentration in the aerator. At a detention time of four hours without cell feedback the units responded successfully to a change in inflow feed concentrations from 1000 to 2000 mg/l glucose, whereas at 8 and 12-hour detention times the units responded successfully to 3000 mg/l glucose. A successful response to 3000 mg/l glucose was indicated at all three detention times when cell feedback was employed. Based on this conclusion, it can be calculated that the loading capacity (lbs of glucose/1000 cft aerator volume/day) of the continuous flow systems decreases with

increasing detention time.

4. Under gradual shock loading, systems without cell feedback were characterized by the release of metabolic intermediates or end products. These were not released in significant amounts by systems employing cell feedback.

5. The accumulation of intermediates was related to the detention time, glucose concentration, and whether solids are recirculated; i.e., the higher the glucose concentrations and lower the detention time, the greater is the detectible production of intermediates, provided cells are not recirculated.

6. The ability of completely mixed continuous flow systems to respond successfully to slug shock loads is limited.

7. The response to slug shock loads is improved by increasing the detention time and also by maintaining higher solids concentrations in the aerator.

8. The biochemical efficiency of these continuous flow systems is considerably reduced when subjected to shock loads under nitrogen deficient conditions.

9. Under nitrogen deficient conditions, the system without cell feedback is characterized by the release of intermediates which are not subsequently rapidly utilized. Systems employing cell feedback exhibit very little release of intermediates.

10. Under nitrogen deficient conditions, systems without solids recirculation show a marked decrease in protein content with an accompanying increase in carbohydrate content. Using solids recirculation, the biochemical composition of the cells did not vary much.

11. Lipids were not synthesized to any great extent in the continuous flow system under either nitrogen limiting or excess nitrogen conditions.

12. During shock loading, volatile acids are released into the medium. The released volatile acids are subse-

quently utilized when the shock load is accompanied by adequate amounts of nitrogen. Under nitrogen deficient conditions, the volatile acids are not utilized. Acetic acid is found to be the main volatile acid produced during a shock load.

13. The elemental composition of the sludge does not truly reflect the changes in the biochemical composition of the cells.

CHAPTER VIII

SUGGESTIONS FOR FUTURE WORK

Based on the results of the present study, it is felt that the following research aspects would be worthwhile for future investigations:

1) The present study has indicated that the loading capacity (lbs glucose/1000 cft aerator volume/day) of the continuous flow system decreases with increasing time. This aspect should be investigated in detail by operating the system at constant loading at various detention times and shocking the system to different loading rates.

2) Further, shock loading experiments should be conducted at different solids levels (i.e., using different recirculation ratios) so as to devise an operational table indicating successful response to various concentrations of shock substrate at different solids levels. This aspect would be extremely useful in predicting the performance of continuous flow systems subjected to gradual as well as slug shock loading.

3) The present study has indicated a successful response to nitrogen-deficient gradual shock loadings at a detention time of 12 hours when solids recirculation was used. It would be interesting to analyze the effluent for all forms of nitrogen in order to ascertain whether nitrogen is lost to the effluent at higher detention times, (i.e., 4 and 8-hour detention times).

4) The release of intermediates or end products during shock loadings should be investigated in detail with respect to identity as well as quantity of intermediates.

Furthermore, the generality of the production of intermediates with other substrates should be investigated. The mechanism of intermediate production and its possible control should be investigated in detail.

5) Past studies in the Oklahoma State University Bioengineering laboratories have indicated that concurrent removal of substrate occurs with "old cell" sludge subjected to qualitative shock load. This aspect should be studied in the continuous flow system using recirculation of sludge. These studies will be extremely useful from the practical standpoint, since all field units operate with sludge recirculation.

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