STUDIES ON THE OPERATIONAL STABILITY OF THE EXTENDED AERATION PROCESS

By

PING-YI YANG

Bachelor of Science

National Taiwan University

Taipei, Taiwan

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Thesis Approved:

R. J. Stanley Jr.
Thesis Adviser

Don F Kincannon

M. Ramanathan

D. D. Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

The activated sludge process was developed in 1913 in England, and remained essentially unchanged during the next thirty years. During the past twenty-five years, many modifications of the process have been developed. The extended aeration process is one of the more recent modifications. It has been claimed to be simple in operation, low in cost, and stable to environmental changes. The increase in the number of extended aeration plants used in the United States is impressive. Because of the ever-increasing demand for water pollution control, many small communities and commercial establishments have found that the extended aeration activated sludge system is the desirable one for treatment of their organic wastes. However, some prominent researchers have concluded that the operation of an extended aeration system (without wasting sludge) is theoretically impossible. Regardless of this objection, the process has been used to an increasing extent.

The study herein reported was designed to determine how long a system in which all biological solids were returned to the aerator could be operated before the "inactive" fraction built up to such an extent that the biochemical efficiency was destroyed or greatly retarded. The work of previous investigators indicated that such systems should in time undergo biochemical failure. However, there

were no data which provided unequivocal proof that failure would actually occur, nor were there any data indicating how long it would take for such a system to lose its substrate removal capability.

CHAPTER II

LITERATURE REVIEW

Since the end of World War II, many modifications have been proposed to the activated sludge process. The process has been improved through years of research. Its use will be accelerated because of new pollution control laws. The extended aeration process (or total oxidation process) is one of the modifications of the activated sludge treatment process which is extremely attractive from an economic point of view. This kind of treatment process, if it could be successfully operated, could attain complete mineralization of organic wastes and obviate the need for separate sludge digestion facilities. It would be particularly useful for treatment of soluble industrial wastes. Although the extended aeration process would seem to have advantages, it has been the subject of much controversy during the past years. The major concern is over the accumulation of inert metabolic products and inactive biological solids. Regardless of these concerns, the increase in the number of extended aeration plants used in the United States is impressive; from three in 1950, to 1,224 in 1960, and to more than 2,600 in 1962. Were it not for the published conclusions of various research engineers warning against use of the process on the basis of its theoretical unsoundness, it might enjoy even wider use today.

The extended aeration process is designed to provide a detention

time in an aeration chamber of 16 to 24 hours, and a detention time in a final settling tank of four to eight hours. Long aeration periods are provided so that the organisms in the extended aeration process have sufficient time to assimilate the exogenous substrate into the cell components and then to oxidize these components. Many microorganisms can survive for a "considerable period" in the absence of nutrients (1). Reserve materials within the cell can be oxidized and provide the energy to make the cell survive for a "considerable period" of time. However, the extended aeration system is one in which low organic loadings are employed. The organism in this system must have the comptetence to take the food (organic wastes), but most of the organisms would be expected to be in a state of starvation because of the low substrate loading in the extended aeration system. Under such conditions, some cells might not survive very long but might die, thus releasing food materials for other cells. If extended aeration is to be a workable process, such autodigestion of the sludge must go on concurrently with metabolism of the carbon source in the incoming waste water.

Porges, et al. (2) reported that an equilibrium between the net autoxidation and net synthesis of new biological sludge had been established in the treatment of dairy waste. A portion of the soluble organic waste (skim milk) was converted to cell material and then autoxidized in the later phases of aeration. Porges, et al. concluded that the waste could be treated without any accumulation of sludge. This report stimulated a considerable amount of research on the process by workers in the water pollution control field.

Most of the findings led to the general conclusion that from a

theoretical standpoint total oxidation is not possible, since a portion of the soluble organic substrate is channelled into synthesis of so-called "permanently inert materials" (3)(4)(5)(6). Thus it was concluded that if no sludge was wasted, the extended aeration process could not perform successfully. It must be emphasized that in all of the studies (3)(4)(5)(6) from which the above conclusion was made, soluble organic substrates were used. Thus the inert materials referred to are inert biological materials produced by the microorganisms responsible for removal of the exogenous substrate.

Based on the pure culture study of Dawes and Ribbons (1), the endogenous substrates thus far recognized in bacteria include glycogen, lipid, poly-β-hydroxybutyric acid, protein, and RNA; inorganic polyphosphate (volutin) can serve as an endogenous store of phosphate. Most of these endogenous substrates can be utilized by various microorganisms. However, in addition to endogenous metabolism of individual species it must be remembered that the activated sludge system is a mixed population, i.e., a rather complicated ecosystem, and one species may cause death of another and may use the structural components of the other species as carbon source.

The report of McCarty and Broderson (7) is particularly interesting. These workers suggested that solids accumulation must be considered in the design of extended aeration systems. They felt that if no facilities for disposal of excess sludge were provided, the system will accumulate solids and discharge the excess suspended solids in the effluent. Thus, the purification efficiency of the extended aeration system could be expected to decrease as a result of the continual increase in solids. The sludge accumulated in the unit will include

the synthesized biological solids and the biologically nondegradable suspended solids which were originally present in the influent waste (e.g., small grit particles or certain biologically resistant organics such as lignin and cellulose). Therefore they suggested that industrial, soluble organic wastes and municipal wastes must be considered separately when designing extended aeration systems. In addition, they suggested that the efficiency of operation of extended aeration processes was closely related to the effectiveness of the settling tank in retaining the suspended solids. They also noted that nitrification will cause false values for BOD removal efficiency, the dropping of pH, and rising sludge in the settling tank. Nitrification is the result of excess aeration (long detention time) and low organic loading, which favor the growth of nitrifying bacteria. In wastes containing an abundance of nitrogen it would seem that nitrification could present a problem. They explained that the lowering of pH was caused by the formation of nitric acid. If pH dropped in the system, it would appear that filamentous organisms might come into predominance and a bulking sludge could develop as well as, or instead of, a rising sludge.

In a more recent study, Westrick, et al. (8) observed the operation of two extended aeration plants in Ohio. Both of these plants had no equipment to control the wasting sludge, i.e., all of the settled sludge was returned except the solids which escaped in the effluent. From their results they concluded that when the influent loading value was close to the design value and no facilities for the removal of sludge or some efficient means of solids separation were provided, the extended aeration plants could not produce the desired purification efficiency. Thus, their observation is much the same as that of McCarty and

Broderson (7), i.e., that an extended aeration plant must be designed with an oversized settling chamber to avoid the escape of solids in the effluent.

From the above review it can be seen that the results of other workers indicate that biologically inert organic solids will gradually accumulate, and that biological solids will escape in the settling chamber effluent. Both of these events can cause drastic reduction in purification efficiency. The buildup of biologically inert material is deemed to be the foremost consideration in assessing future possibilities for the process, since even if ways and means could be found to avoid loss of solids in the effluent, thus assuring retention of all biological solids, the increasing inert fraction could cause the system to fail biochemically. The complicated nature of the ecosystem which exists in an activated sludge, and the possibilities for predatory activity made it difficult to accept the concept of continual buildup of inert organic matter, and encouraged the initiation of the present investigational effort. Studies on the extended aeration process have been under way in the bioengineering laboratories of Oklahoma State University for nearly two years. Recently, studies on the ability of the process to accommodate quantitative shock loads have been reported (9). Also, some of the research included in this thesis has been recently reported (10).

CHAPTER III

MATERIALS AND METHODS

1. Experimental Apparatus

The bench scale extended aeration pilot plant employed in these studies was essentially the same as the one used in the shock loading studies reported previously (9). A flow diagram showing the aerator and settling chambers, the supernatant holding tank, and the Sharples centrifuge through which the holding tank liquor was processed is shown in Figure 1. The total volume of the system is 9.4 liters (6.2 liters, aeration chamber, and 3.2 liters, settling chamber). A sliding baffle was used to separate the aeration and settling chambers. Compressed air provided not only mixing and oxygen supply to the biological solids, but also provided suction to recycle settled solids from the settling chamber. Airflow rate was maintained at 2000 cc/min/l. This airflow rate provided for a dissolved oxygen concentration in the aeration chamber, which was always above 6 mg/l, and a DO concentration in the settling chamber which averaged slightly above 2 mg/l. Temperature was maintained at 23 ± 2°C.

Figure 2 shows the apparatus used in studies to determine the growth and substrate removal characteristics of cells from the extended aeration unit. For these studies a small inoculum of cells from the extended aeration unit was placed in the growth apparatus along with

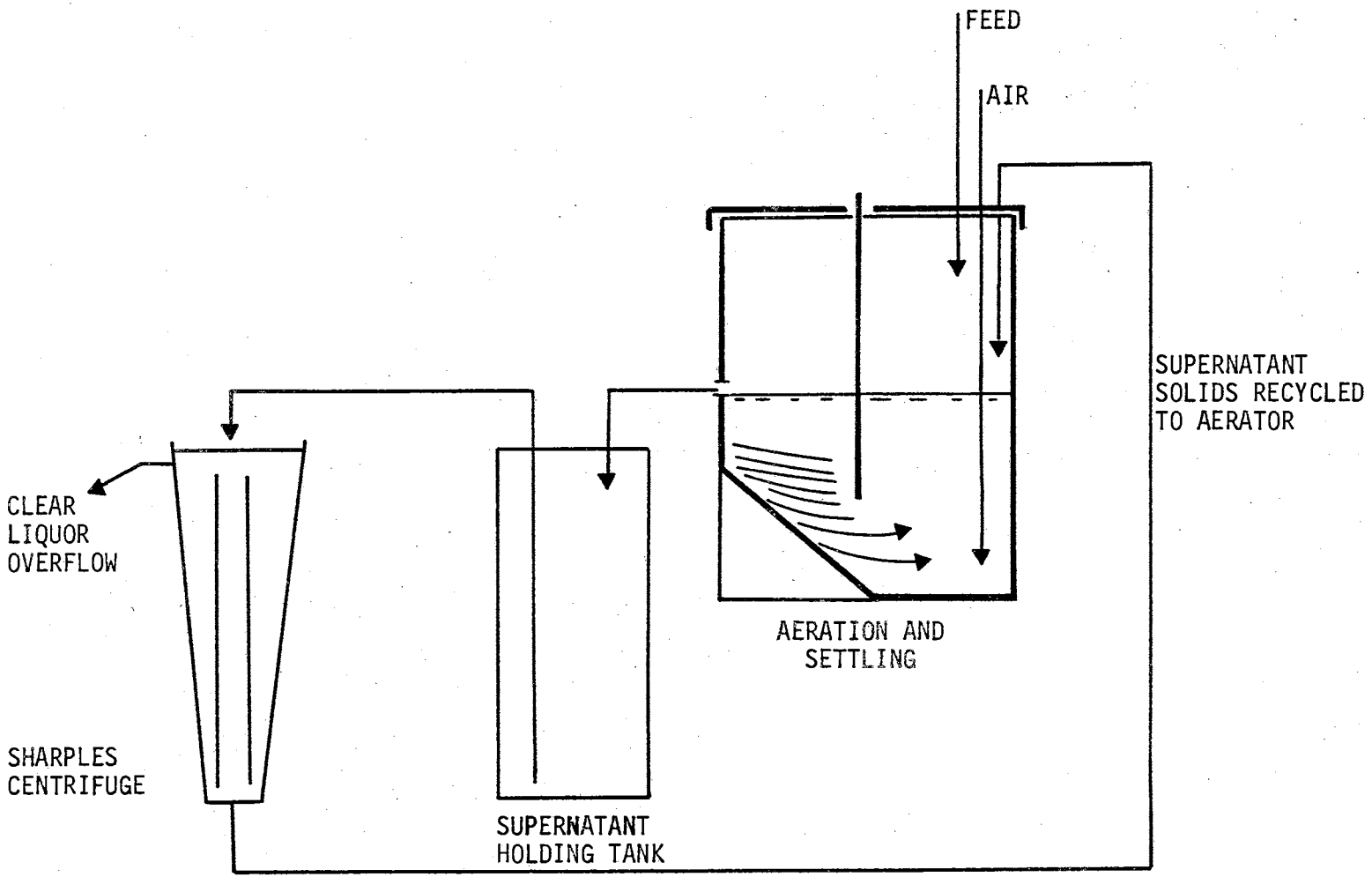


Figure 1 - Continuous flow extended aeration pilot plant.

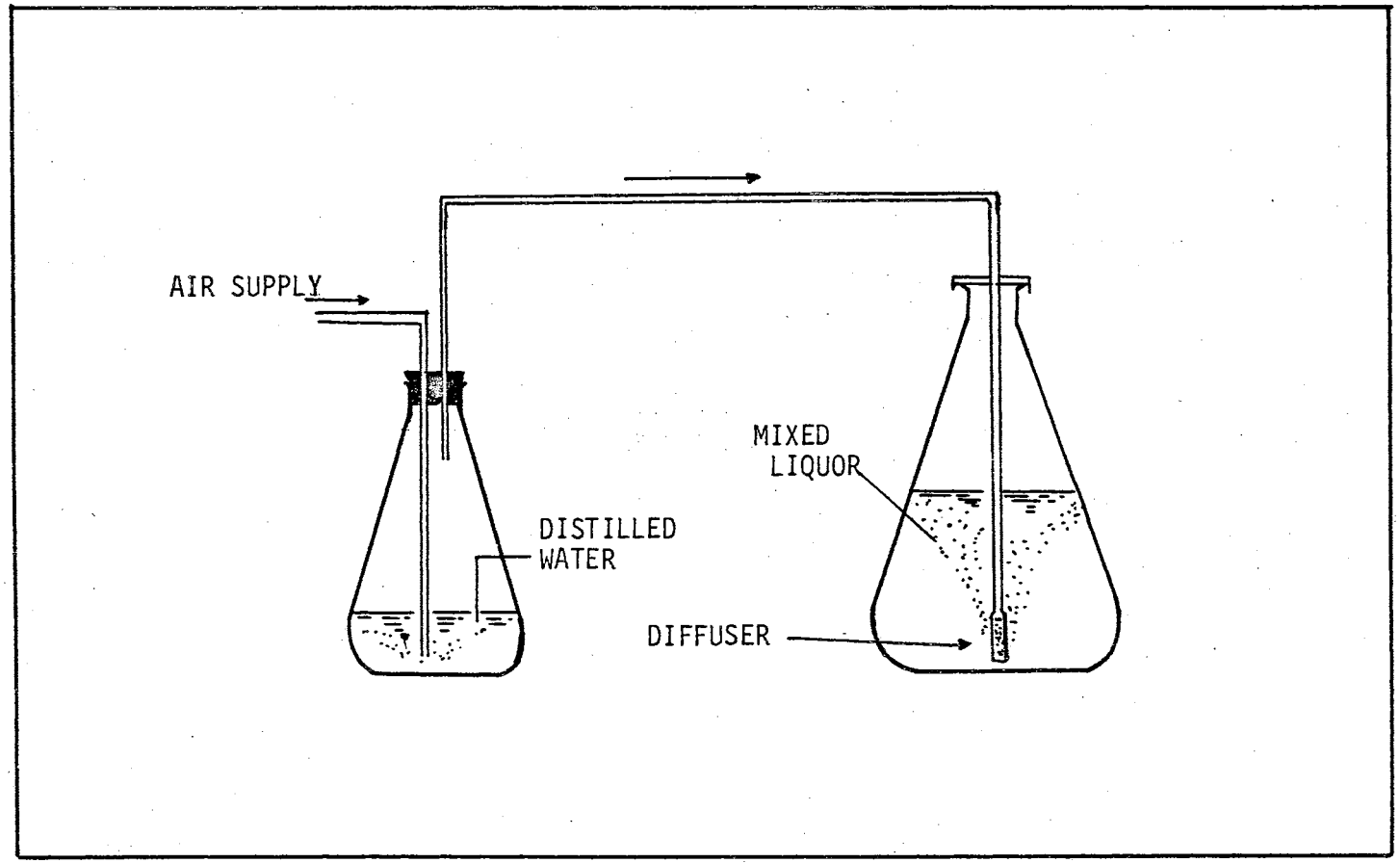


Figure 2 - Experimental setup for substrate utilization rate with low initial solids concentration.

fresh medium, and samples were withdrawn periodically for analysis.

2. Composition of the Synthetic Waste

Table I shows the composition of the synthetic waste during the continuous feeding operation. During periods of batch operation, the concentration of each constituent was increased 9.4-fold. The organic loading was approximately 50 lb COD/1000 cu ft aeration capacity (32 lb BOD_5/1000 cu ft) during continuous flow operations, and 32 lb COD/1000 cu ft (22 lb BOD_5/1000 cu ft) on the basis of total volume of the system (or aeration volume) during batch operation.

The composition of the synthetic waste used in the separate batch studies to assess rate of growth and substrate removal was the same as that shown in Table I.

TABLE I

COMPOSITION OF FEED FOR 500 mg/l GLUCOSE AS SUBSTRATE

Glucose	500	mg/l
$(NH_4)_2 \cdot SO_4$	250	mg/l
$MgSO_4 \cdot 7H_2O$	50	mg/l
$FeCl_3$	0.25	mg/l
$CaCl_2$	3.75	mg/l
$MnSO_4H_2O$	5	mg/l
Phosphate Buffer, 1.0 M (KH_2PO_4 + K_2HPO_4)	5	ml/l
Tap Water	50	ml/l

3. Procedure

During the operation under continuous flow conditions, the feed rate was set to provide an overall detention time of 24 hours (approximately 16 hours aeration and eight hours settling). During periods of batch operation, the baffle separating the two chambers was removed and the unit was fed once daily. During this period a 23-hour aeration period was employed. The sludge was permitted to settle for one hour after the daily sample (15 ml) was taken. After the one-hour settling period, one liter of supernatant was removed, centrifuged, and the biological solids were returned with one liter of feed solution to the reactor, thus the unit was again brought back to the operating level (9.4 liters). During continuous flow operation, the sterile feed solution was channelled to the aeration chamber through a dual unit positive displacement pump arrangement (minipump Model MM2-B-96R). The feed line was also cleaned (sterilized) regularly. There were never any indications of contamination of the feed solution. The effluent collected in the holding tank was periodically (once or twice daily) passed through the centrifuge (Sharples Superspeed), and any solids which had been carried over from the settling chamber were scraped from the bowl and returned to the aeration chamber. It is emphasized that no biological solids were either inadvertently or intentionally lost from the system throughout this study. The only solids "lost" from the system were those taken for samples to assess operational behavior.

Daily (or nearly so) 15 ml samples of mixed liquor were removed for analysis. At less frequent intervals (approximately twice per month) a total of 20 ml samples of mixed liquor were removed for measurement of endogenous O_2 uptake, sludge composition (carbohydrate

and protein) and periodic examination of substrate removal rate. The samples for the measurement of biological solids concentration were taken in such a way that the data represent those in the total system, not in the aeration chamber alone. The procedure for sampling was as follows: Just prior to taking a sample, the settling chamber outlet was stoppered, and the feed was momentarily shut off. The dividing baffle was then lifted and the contents of the settling chamber were allowed to mix completely. Also while the solids were mixing, the solids in the effluent which had been passed through the centrifuge were returned to the system. Then the 15 ml sample was pipetted from the unit and the dividing baffle was again inserted into place. The settling chamber effluent was reopened, and the feed restarted. This procedure allowed a direct assessment of the course changes in solids concentration in the system.

4. Analytical Methods

Biological solids concentration was determined by the membrane filter technique (Millipore Filter Co., Bedford, Mass., HA 0.45μ) as outlined in Standard Methods (11). Chemical oxygen demand (COD) was also run on the filtrate (11). At periodical intervals, COD's were also run on the effluent from the settling chamber. Protein and carbohydrate contents of the sludge were determined, respectively, by the biuret and anthrone (12) tests. At various times the $PO_4^{\equiv}$ (13), NH_3-N, NO_2-N, and NO_3-N (11) were determined on the filtrated effluent. In some batch experiments, the anthrone test (in addition to COD's) was run on the membrane filtrate. Endogenous O_2 uptake of the sludge was determined for a cell suspension obtained from a 10-15 ml sample of reactor mixed liquor (washed twice in 0.1 M phosphate buffer solution). The

rate of the endogenous O_2 uptake was measured in a Warburg respirometer using a reaction suspension of 40 ml, and 1.5 ml 20 per cent KOH in the center well. The system was maintained at 25°C and 90 osc/min. Periodically throughout the experimentation, dissolved oxygen in the aeration chamber mixed liquor and in the settling chamber effluent was measured by a galvanic cell oxygen analyzer, in accordance with the procedures given in the operating instructions supplied with the instrument (14).

CHAPTER IV

RESULTS

The effluent, from the primary clarifier of the municipal sewage treatment plant at Stillwater, Oklahoma, was used as initial seed for the development of the extended aeration sludge. After a few days of "batch" growth to allow acclimation and solids accumulation, the unit was put into operation on March 30, 1967, under continuous flow feeding with 1000 mg/l glucose as the substrate, and all biological solids contained in the effluent were returned to the aerator except a small portion (15 ml daily) taken for analysis. On October 12, 1967 (196 days after starting the unit), approximately half of the system was transferred to a second unit of the same type. Both systems were diluted to 9.4 liters with tap water. Since the biological solids concentration was now approximately halved, the feed concentration was reduced proportionately (500 mg/l glucose). One system was used for studies on the long-term behavior of the extended aeration process; the other was used for studies on the shock load behavior of the extended aeration process. Some of the shock load studies (quantitative shock) have recently been reported (9). The work reported herein pertains to the long-term behavior of the other unit which was operated under non-shock loading conditions. Portions of this work have also been reported at a recent industrial wastes conference (10). The early

phases of the experimental effort were conducted by Mr. T. V. DeGeare (spring and summer, 1967).

1. Daily Performance Characteristics of the Extended Aeration Pilot Plant

From the initial time forward the performance data are shown in Figures 3 to 17. A considerable number of parameters were assessed and are plotted on these graphs. Also, the days when the various batch studies were made are indicated on the graphs. The following identification key applies to Figures 3 to 17:

- ◻ = protein content of the biological solids
- ● = supernatant COD (unfiltered)
- ▵ = carbohydrate content of the biological solids
- ▲ = supernatant biological solids
- △ = biological solids in the system
- ○ = filtrate COD
- ●↓ = sample taken for endogenous O_2 uptake (Warburg)
- ▲↓ = sample taken for "low initial solids" batch experiments
- ■↓ = "high solids" batch experiment

At the time of initiating the experimental work, the feed consisted of 1000 mg/l glucose, and salt concentrations were proportionally increased (i.e., double those shown in Table I). During the first thirty days of operation, the biological solids concentration rose gradually from 2000 mg/l to slightly over 6000 mg/l, and then decreased to 4700 mg/l by the thirty-ninth day of operation. It must be emphasized that the decrease in solids concentration was due, not to the loss of solids in the effluent or purposely wasting sludge, since all

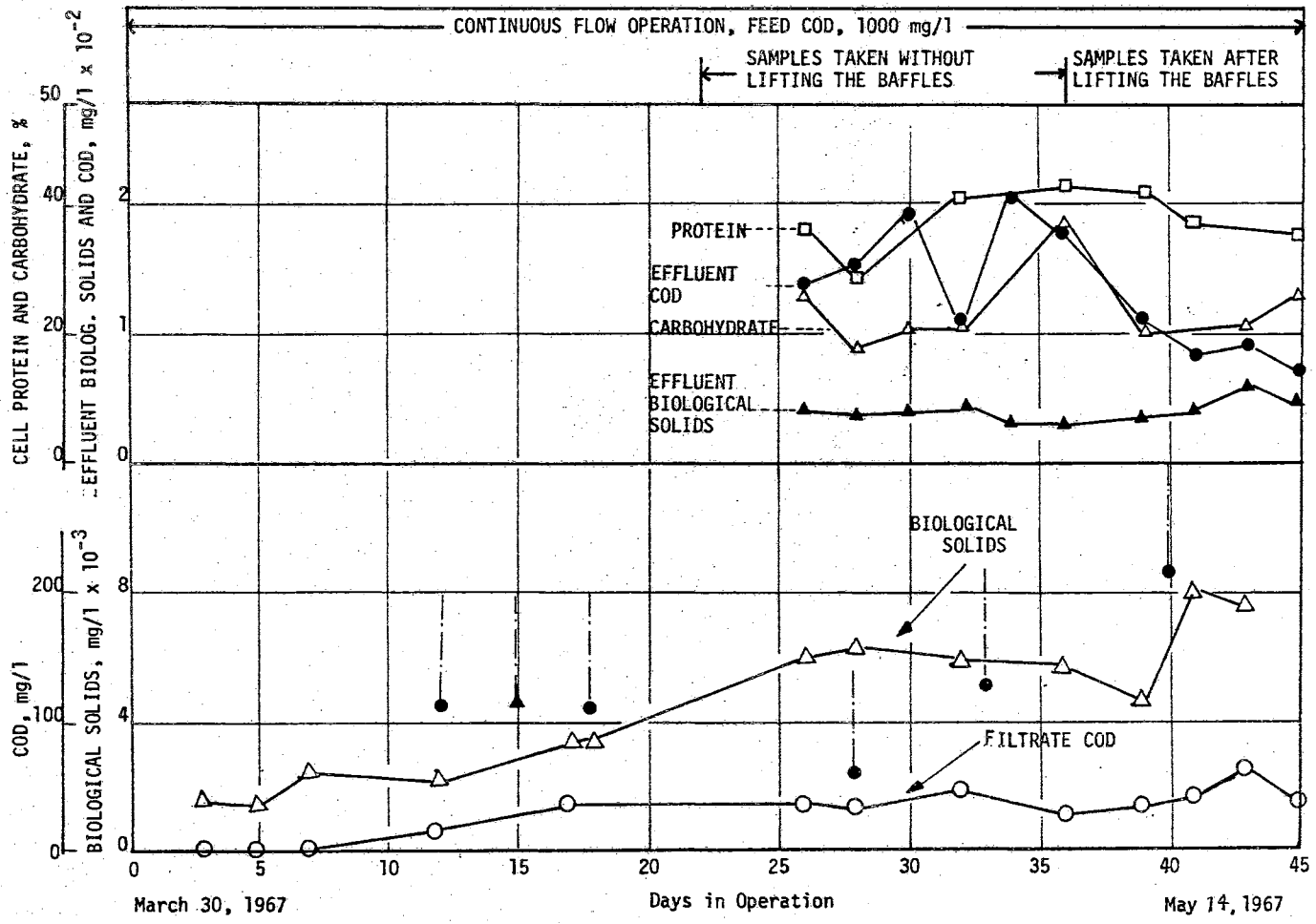


Figure 3 - Operational characteristics, March 30, 1967, to May 14, 1967.

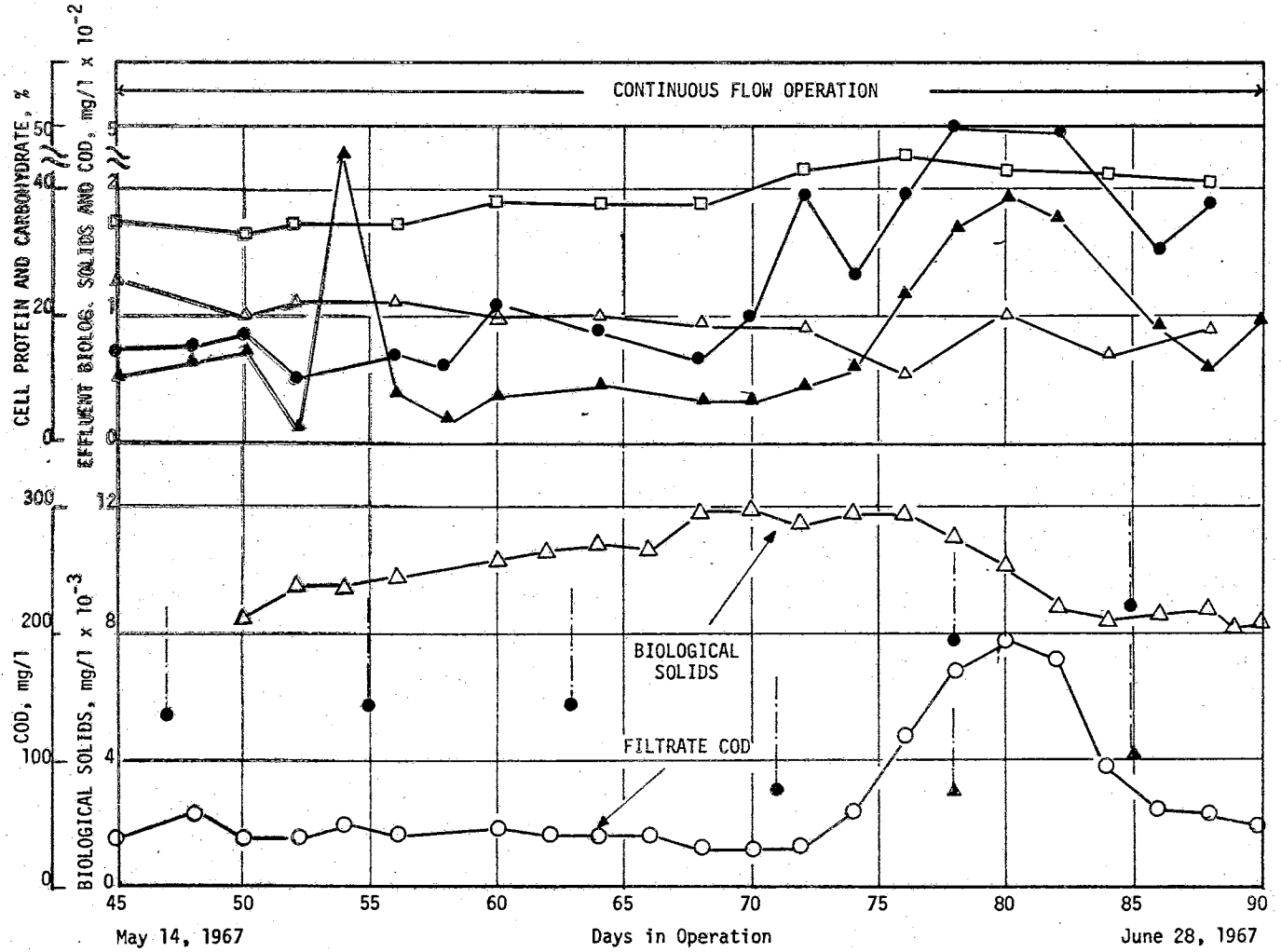


Figure 4 - Operational characteristics, May 14, 1967, to June 28, 1967.

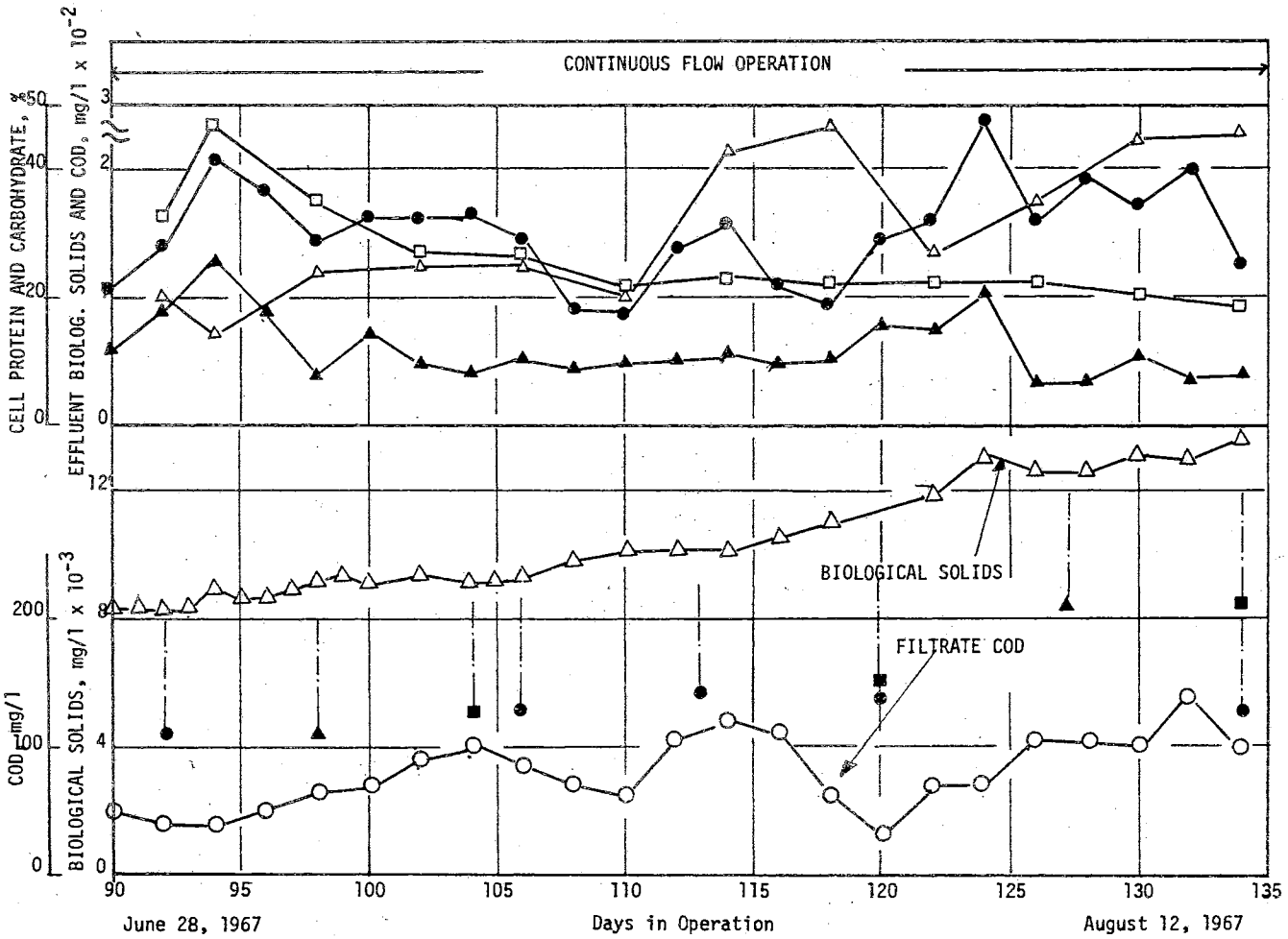


Figure 5 - Operational characteristics, June 28, 1967, to August 12, 1967.

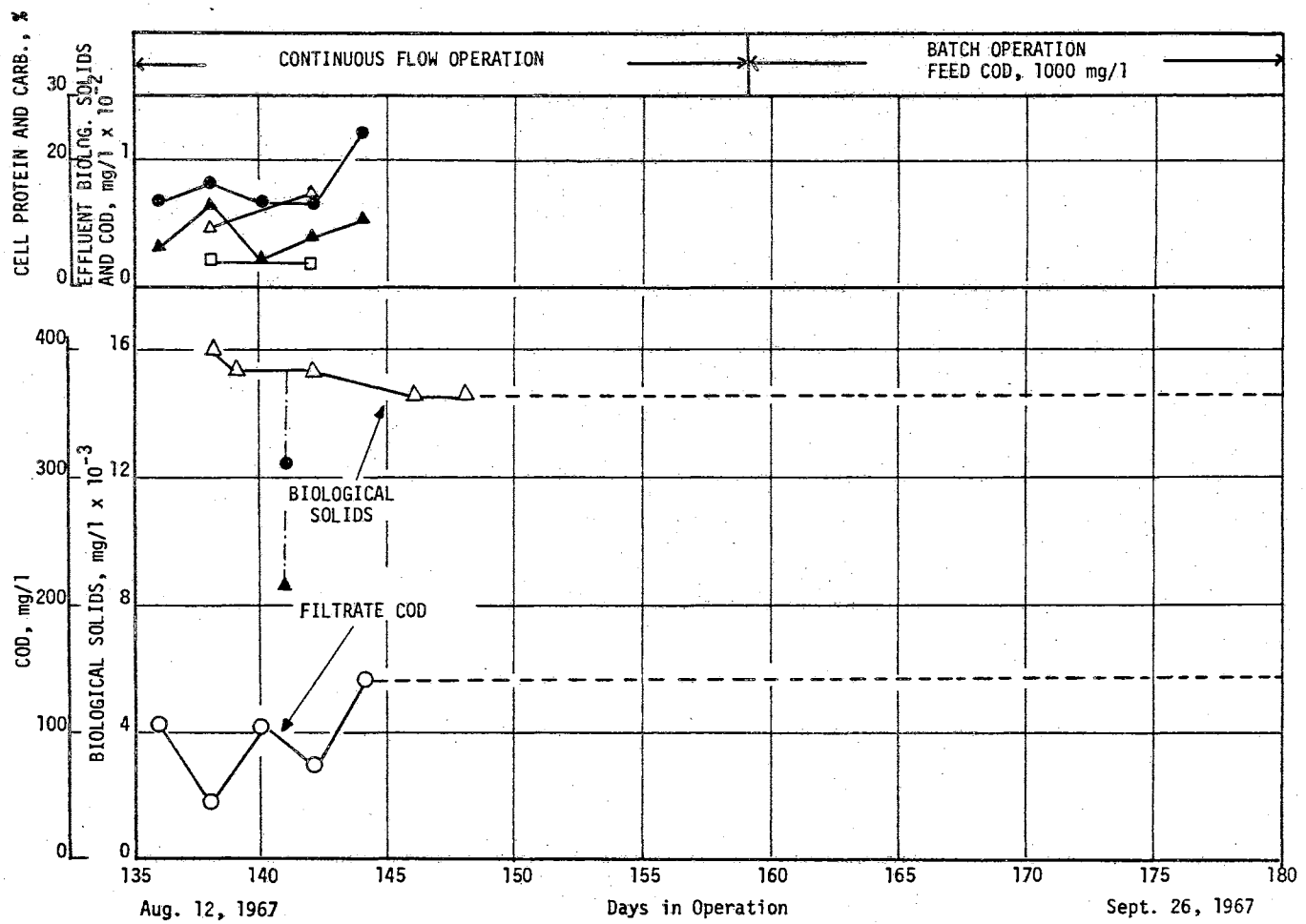
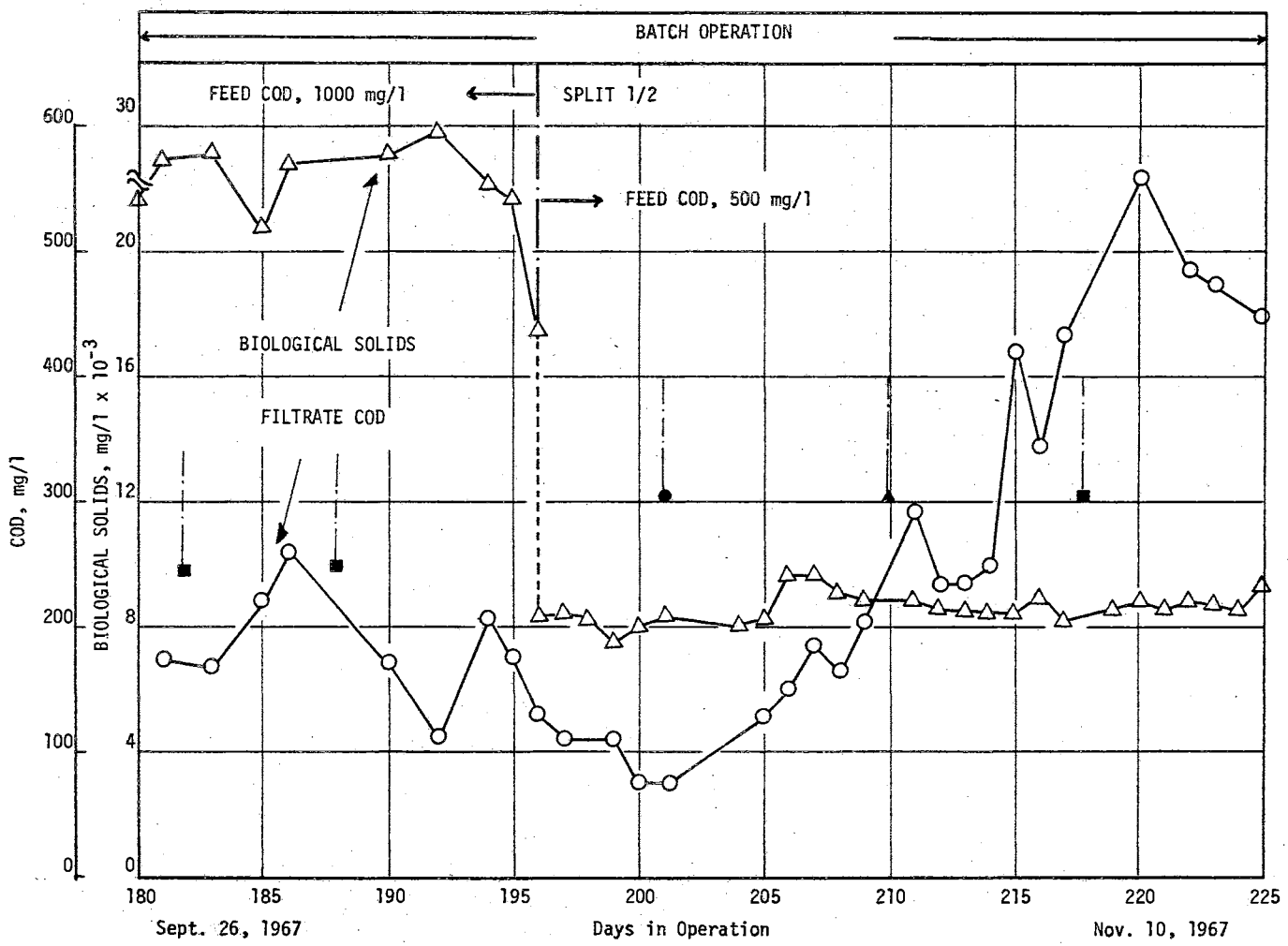


Figure 6 - Operational characteristics, August 12, 1967, to September 26, 1967.



Operational characteristics, September 26, 1967, to November 10, 1967.

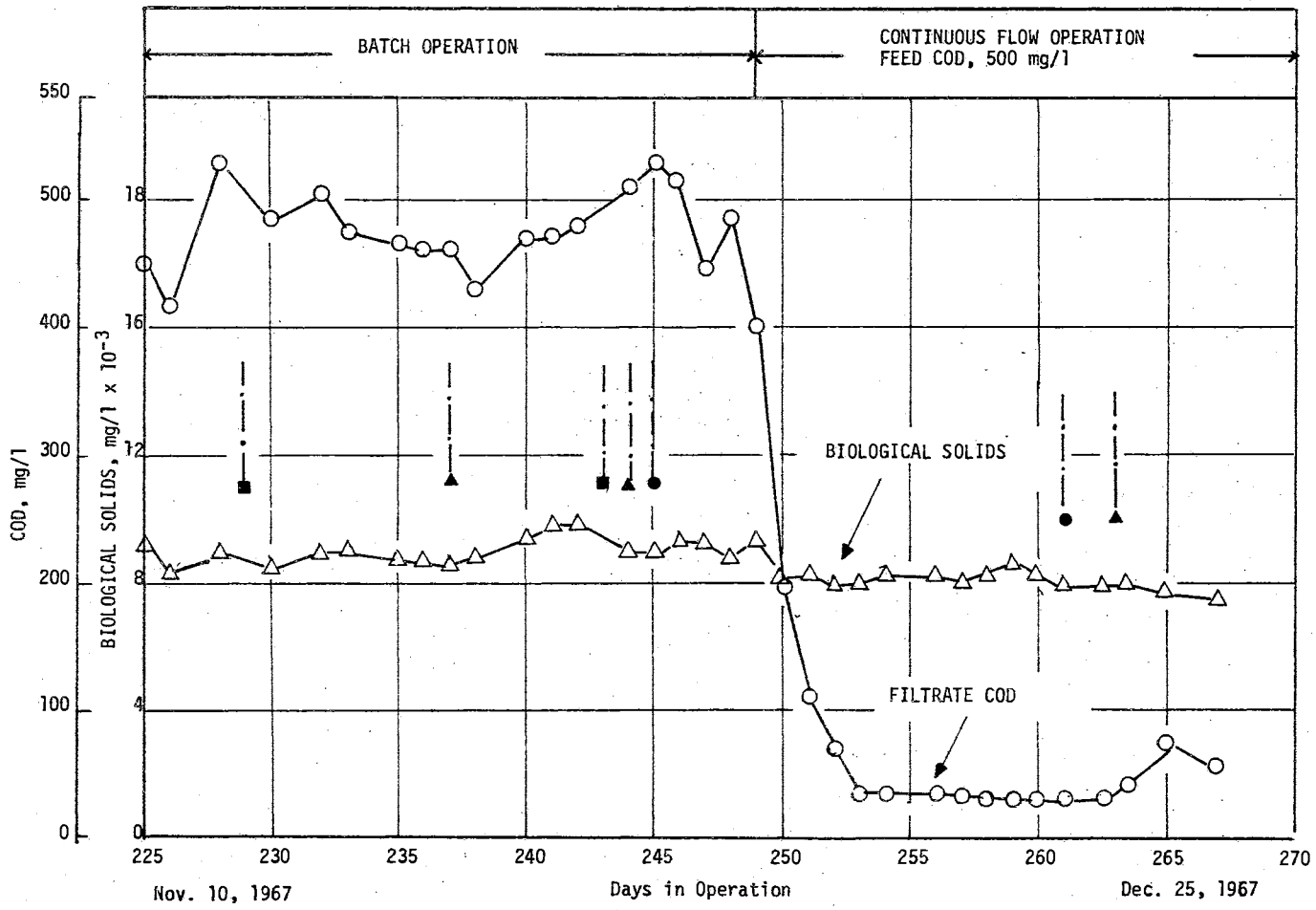


Figure 8 - Operational characteristics, November 10, 1967, to December 25, 1967.

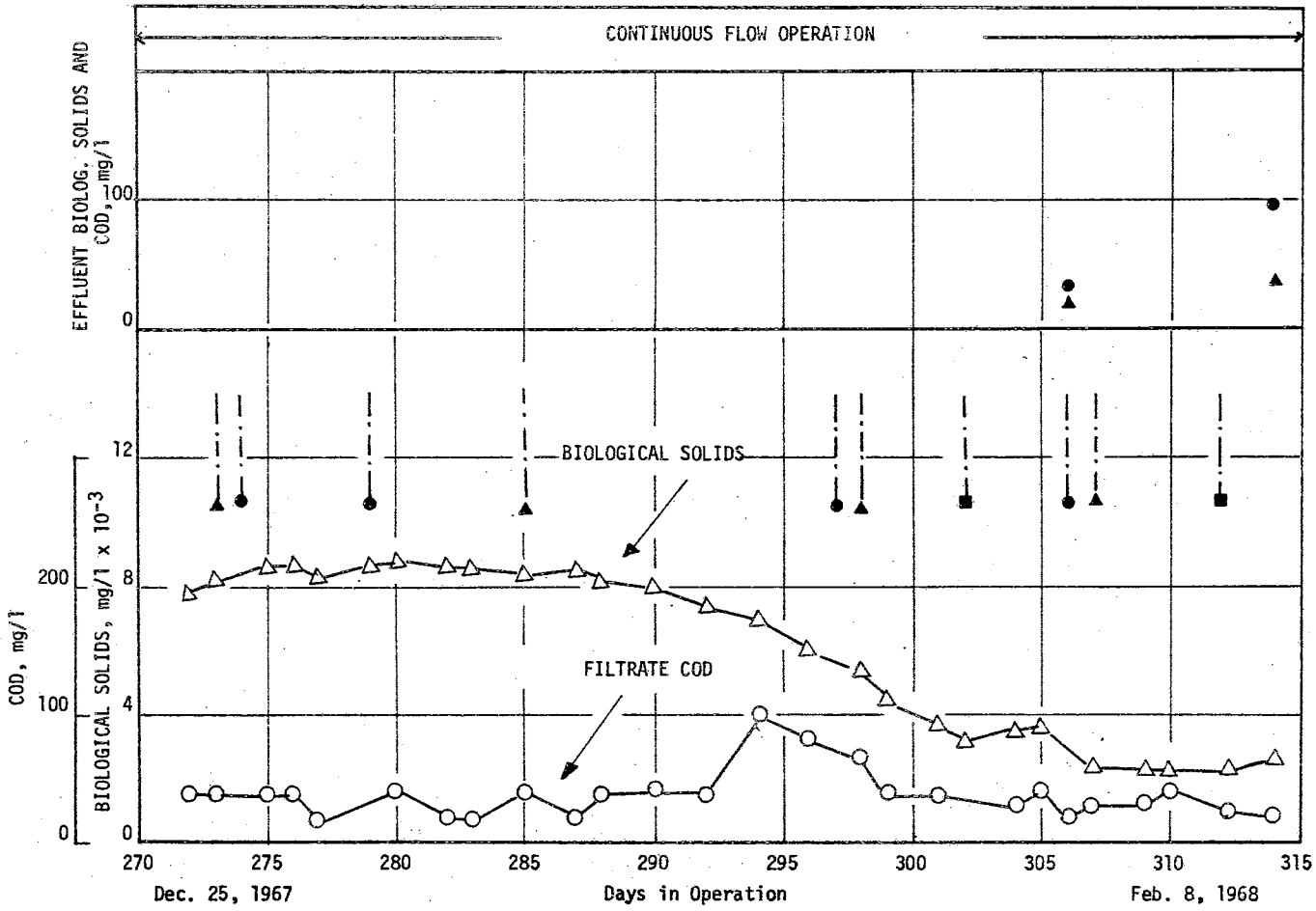


Figure 9 - Operational characteristics, December 25, 1967, to February 8, 1968.

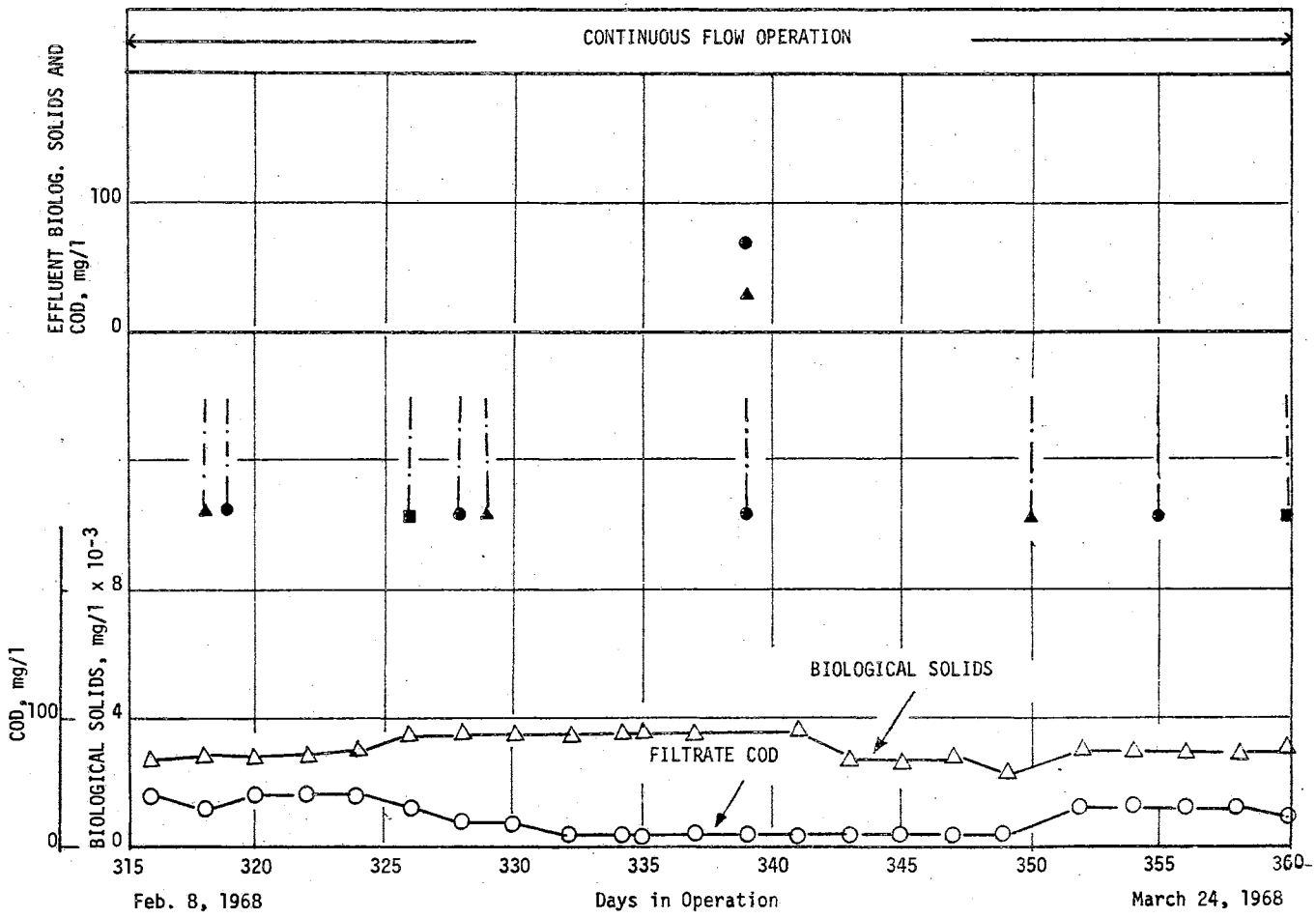


Figure 10 - Operational characteristics, February 8, 1968, to March 24, 1968.

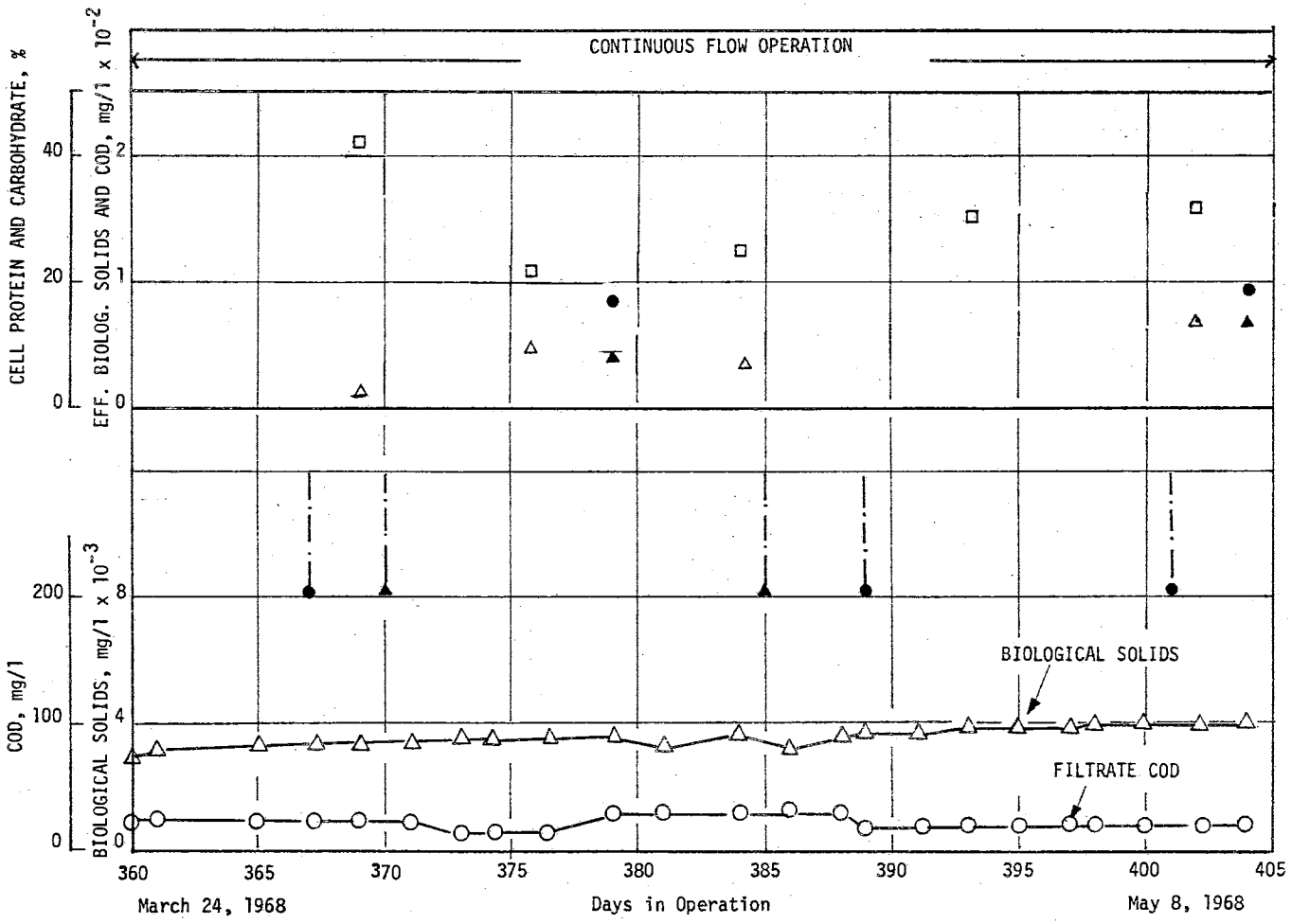


Figure 11 - Operational characteristics, March 24, 1968, to May 8, 1968.

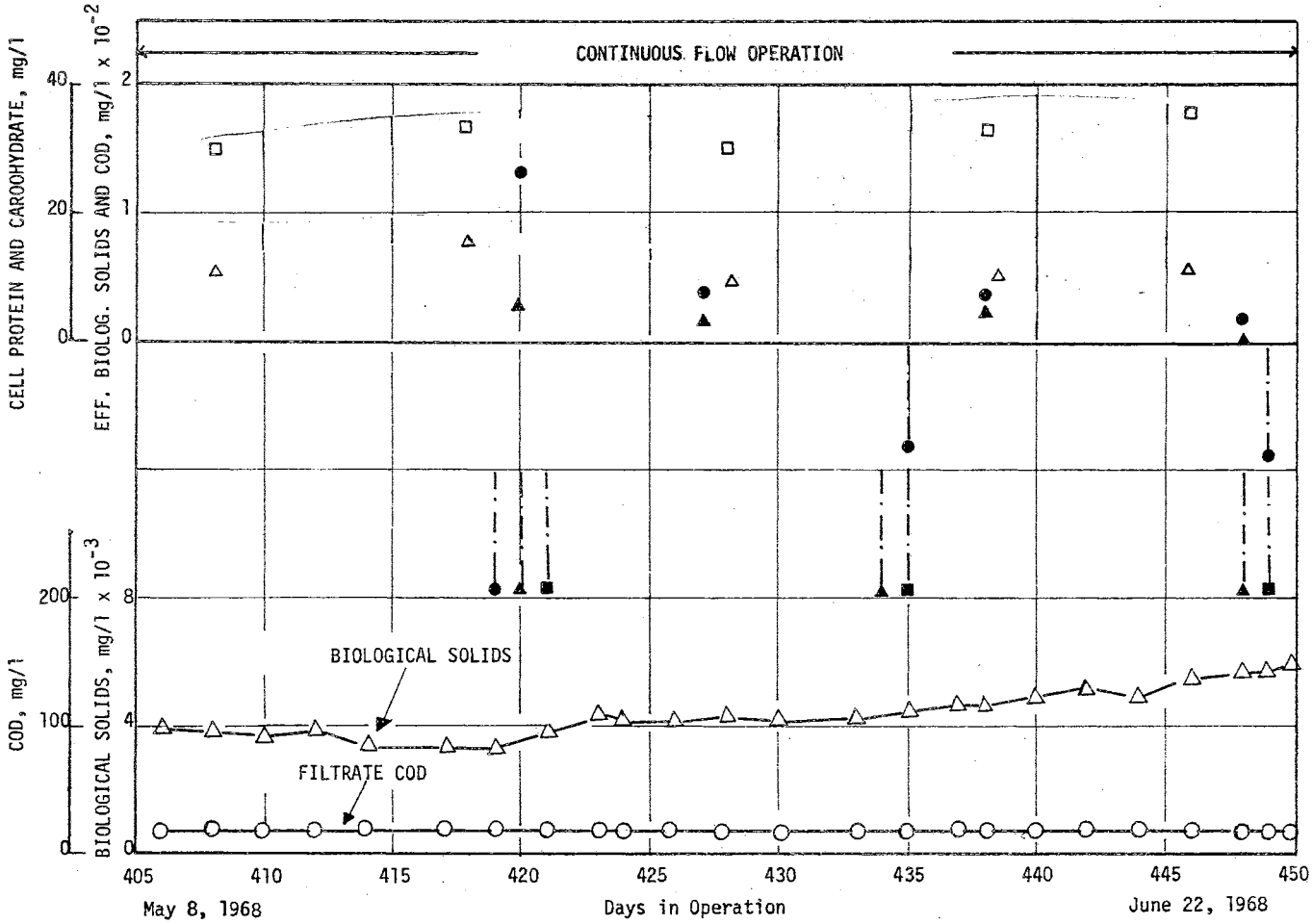


Figure 12 - Operational characteristics, May 8, 1968, to June 22, 1968.

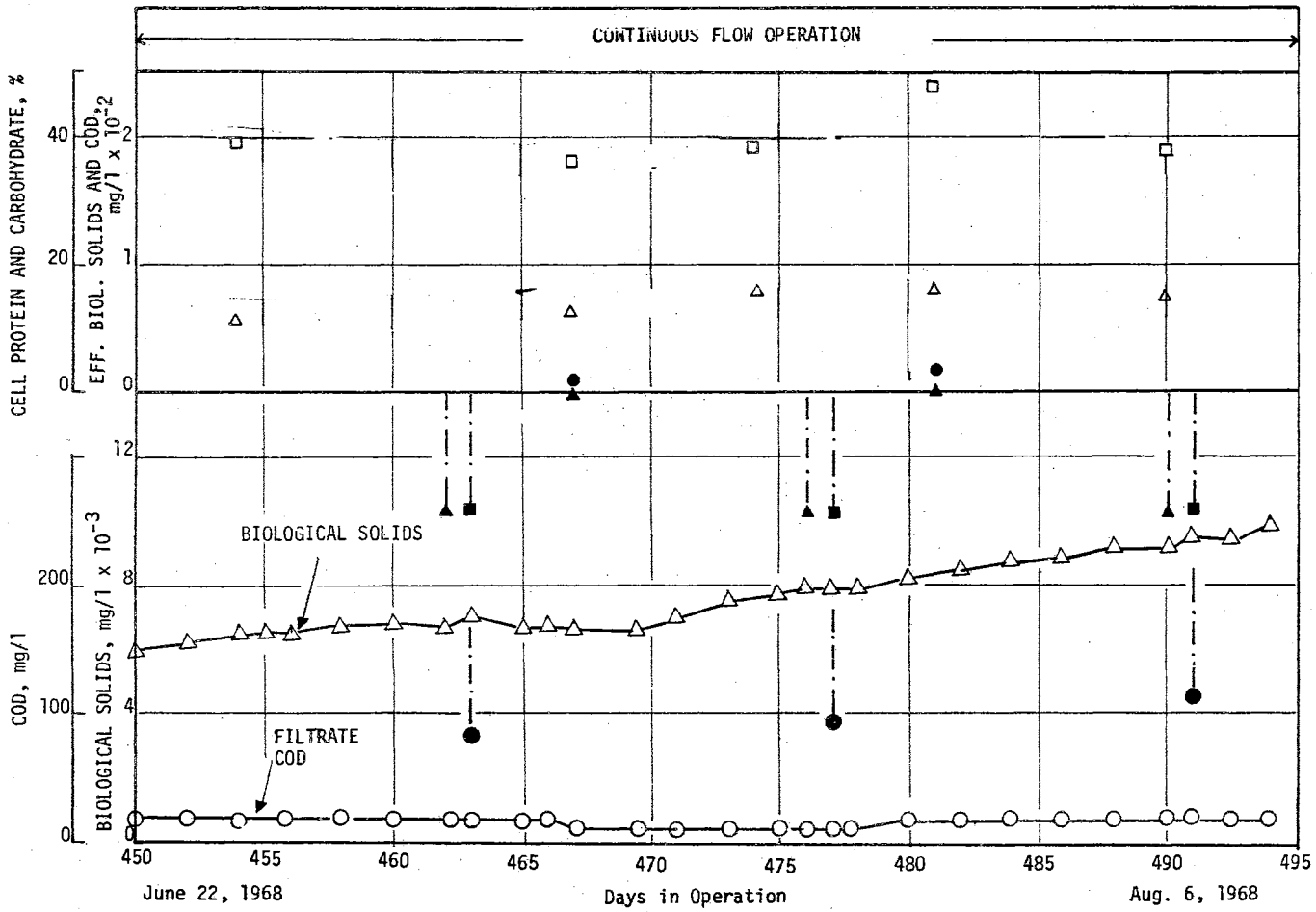


Figure 13 - Operational characteristics, June 22, 1968, to August 6, 1968.

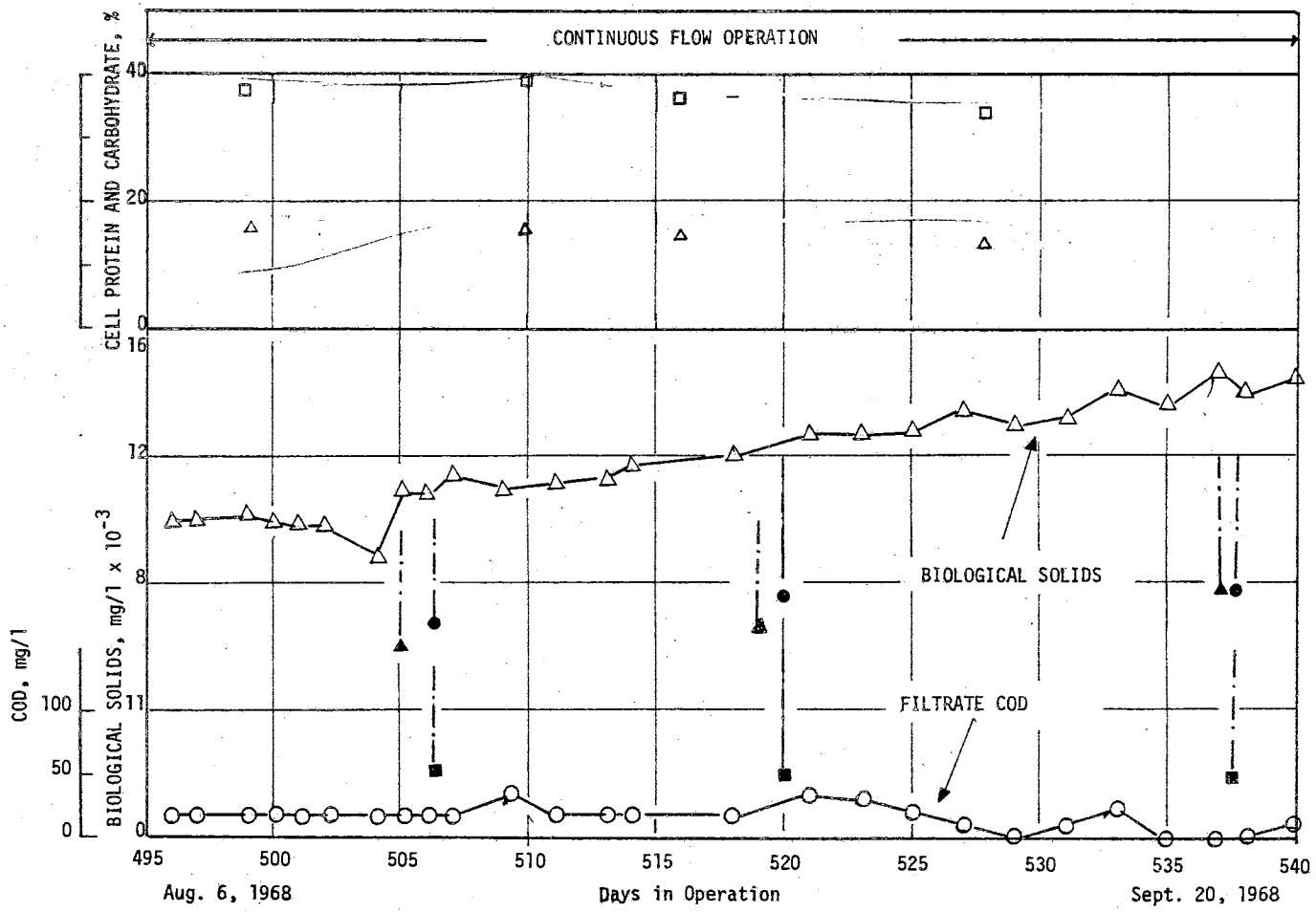


Figure 14 - Operational characteristics, August 6, 1968, to September 20, 1968.

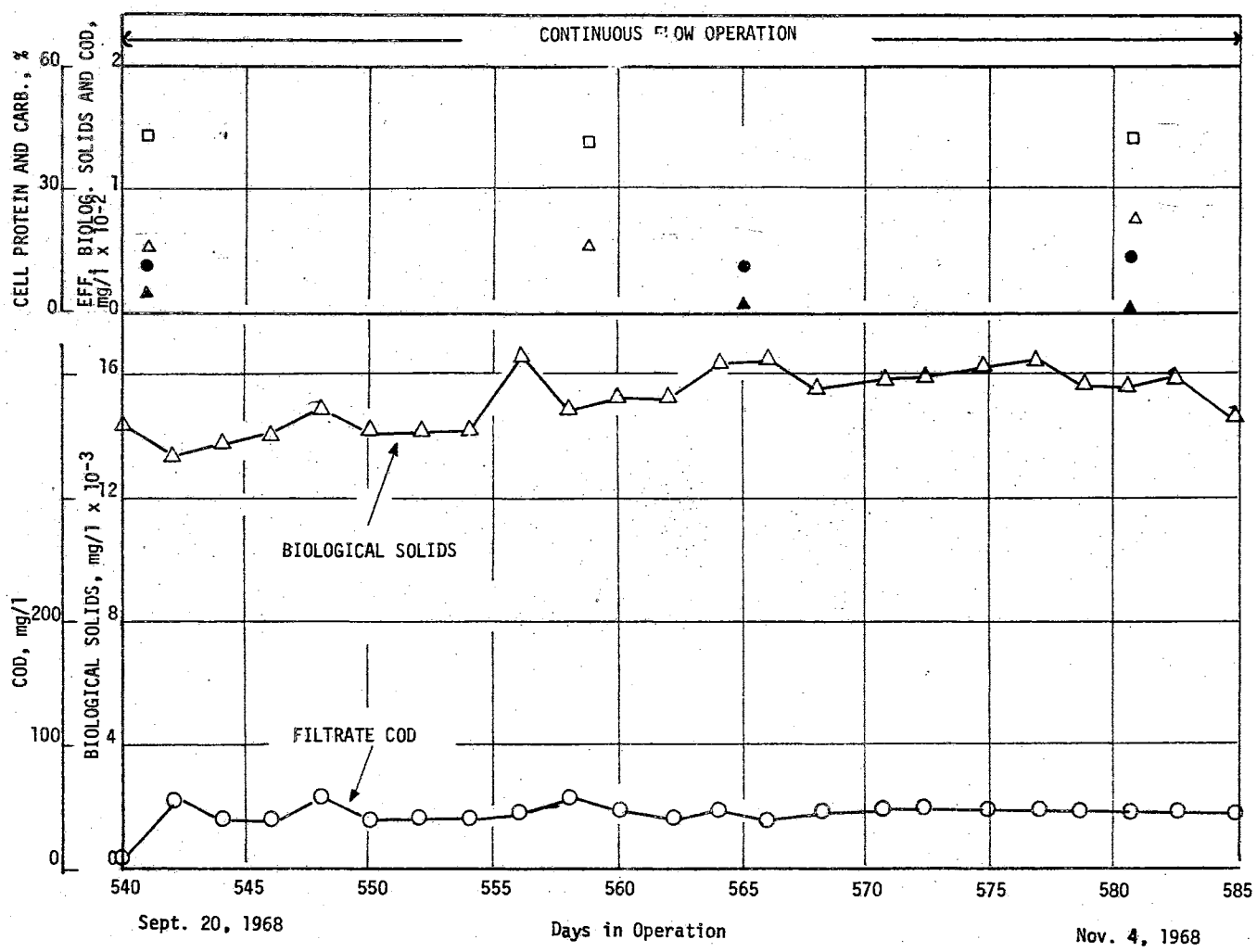


Figure 15 - Operational characteristics, September 20, 1968, to November 4, 1968.

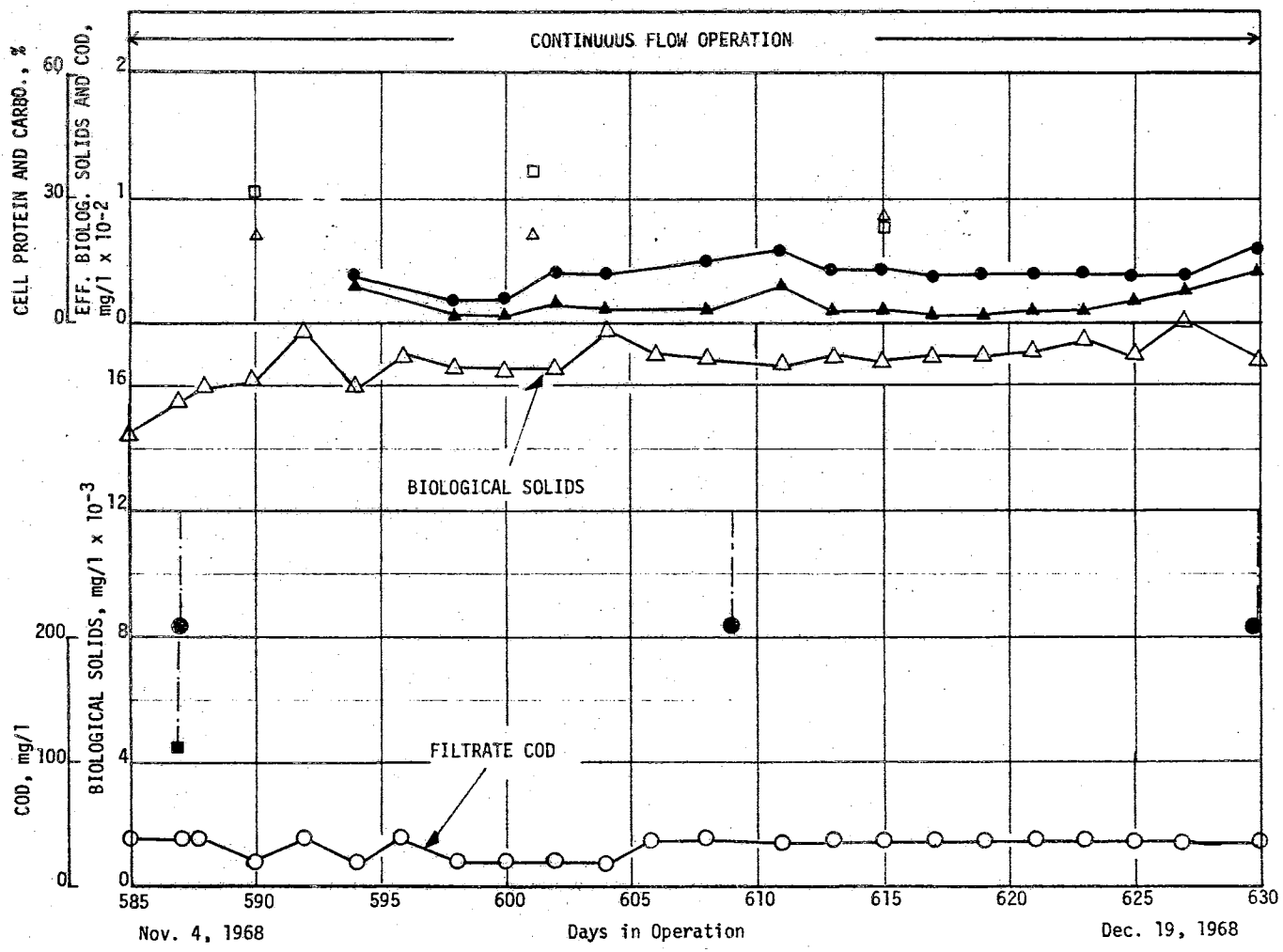


Figure 17 - Operational characteristics, November 4, 1968, to December 19, 1968.

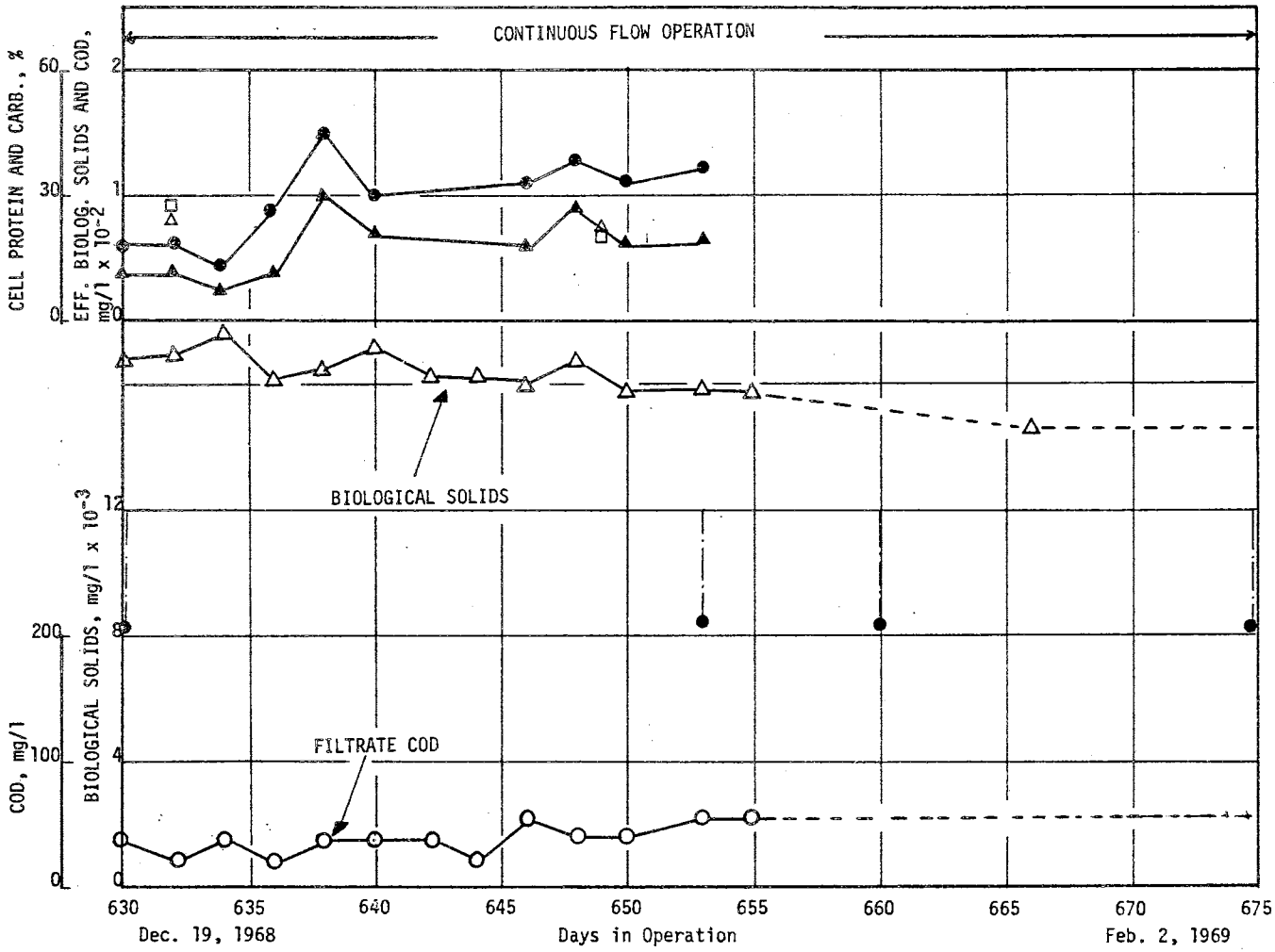


Figure 17 - Operational characteristics, December 19, 1968, to February 2, 1969.

of the biological solids in the effluent were passed through the Sharples centrifuge and returned to the aerator. The purification efficiency was 95 per cent during theis period. From day 40-70 (Figures 3 and 4), the biological solids concentration rose steadily to approximately 12,000 mg/l. During this period the purification efficiency was also approximately 95 per cent.

Between days 70 and 80, biological solids concentration decreased from 12,000 mg/l to 8500 mg/l. During this period the effluent solids concentration increased, and there was also a rise in filtrate COD. The COD removal efficiency dropped to between 80 and 85 per cent. Again it is emphasized that the decrease in solids concentration of the mixed liquor was due, not to the wasting of solids (either purposely or accidentally). However, during the decrease of solids concentration, some froth was formed on the surface of the liquor in the aeration chamber, and it appeared that a portion of the sludge had undergone a gradual lysis. The solids concentration levelled off at 8500 mg/l, and within five days (by day 85) the COD removal efficiency had returned to 95 per cent. During the next few months of operation the solids concentration gradually increased, and COD removal efficiency varied between 90 and 95 per cent (Figure 5).

Beginning on September 5, 1967 (day 159), the mode of operation was changed from continuous flow to batch (Figure 6). This was done partially as a convenience, and partially because it seemed desirable to observe the behavioral patterns under once daily rather than continuous feeding. By the 192nd day of operation (October 8, 1967)(see Figure 7), the biological solids concentration had built up to nearly 30,000 mg/l. At this solids concentration the sludge did not settle,

but the biochemical efficiency of the unit was not impaired. At this time plans were made to divide the unit in order to run another total oxidation unit, so that the shock load responses of such sludge could be studied (9). On day 193 there was a slight decrease in biological solids concentration in the unit. By day 196, the solids concentration had decreased to 17,600 mg/l. In a period of four days the system experienced a one-third decrease in biological solids concentration--a change equal in magnitude to that which had previously occurred; substrate efficiency remained high. A portion of the sludge appeared to be undergoing lysis, and the lysis products were metabolized by the remaining cells.

On October 12, 1967 (day 196), the sludge was parted into two portions (the original unit was used for the present study, while another similar unit was employed for the shock loading studies). The original unit was operated on a batch feeding cycle until December 5, 1967 (day 249), at which time continuous flow operation was resumed. In order to maintain a relatively constant organic loading (on the basis of COD per unit weight of sludge in the original unit), the feed concentration was halved; i.e., 500 mg/l rather than 1000 mg/l was fed.

During the period of batch operation, the residual COD in the unit rose gradually to approximately 500 mg/l (see Figures 7 and 8). This high residual COD does not necessarily represent a deterioration of COD removal efficiency. In a later portion of this chapter, experimental results in defense of the above statements will be presented. The buildup of residual COD is believed to be due to the mode of batch operation. Only a small portion of the daily residual soluble COD was taken from the unit, thus the residual COD in the unit gradually

accumulated. The fact that it did not continue to rise throughout the period of batch operation suggests that even this residual material was eventually subject to some degree of biological degradation.

In mid-January, 1968 (see Figure 9), the system began another cycle of decreasing solids concentration. From day 285 to 307, the biological solids concentration decreased from approximately 8500 to 2400 mg/l. The filtrate COD which had been averaging approximately 40 mg/l (i.e., approximately 95 per cent COD removal efficiency), rose to 100 mg/l during the early period of the decrease in solids concentration, but in less than a week returned to its previous level. This cyclic decrease in solids concentration was a more severe depression in solids concentration than those previously observed, but it was more gradual, requiring over 20 days. Again, it is emphasized that the solids were not lost or wasted; also there was no operational change (pH, temperature, etc.) which could have caused the decrease. This cyclic decrease in solids concentration can be attributed only to natural causation, and was brought about by the biological system itself. As before, there was some amount of froth on the surface of the aeration liquor. The general appearance was observed when microbial cells underwent lysis. It is apparent that if the lysis did occur, the organic products released upon cell disruption or dissolution were metabolized by the intact cells, since the COD removal efficiency was scarcely interrupted during this period.

The biological solids concentration remained at approximately 3000 mg/l through February and late March (see Figure 10) and then (see Figures 11, 12, 13, and 14) began a gradual rise during the following days, and values of approximately 16,000 were attained in October, 1968

(Figure 15). During this period both the biochemical and total purification efficiency were excellent. Spot checks on the biological solids concentration and COD concentration in the supernatant indicated that at times the overall efficiency was approximately 80 per cent or below (see days 379, 404, and 420), and at times the overall efficiency was close to or as good as biochemical efficiency (see days 427, 448, 467, 481, and 541). The protein content of the sludge was approximately 30-40 per cent, and carbohydrate content ranged between 10 and 20 per cent. When the solids concentration started to increase more constantly after 470 days of operation, the protein content of the sludge attained values of approximately 40 per cent (see Figures 13 and 18, days 481, 490, 499, 510, 516, and 528). The characteristic behavior of the process from November 4, 1968, through January, 1969, is shown in Figures 16 and 17. The biological solids concentration remained between 16,000 and 17,000 mg/l, and early in 1969 began a slight decline. Through the fall and winter months the biochemical efficiency remained at approximately 90 per cent, and sludge settleability and COD removal efficiency were excellent, as may be seen by the low supernatant COD and the biological solids concentration in the effluent. Late in 1968, the solids carried over in the settling tank supernatant COD rose. Again it is emphasized that the solids were not lost but were harvested by centrifugation and returned to the aerator. It is interesting to note that during the latter part of 1968 and into 1969 the protein content of the sludge decreased to between 20 and 25 per cent, whereas the carbohydrate content approached 20 per cent. The system is still in operation, and at the time of preparing this report (March, 1969), the biological solids concentration is

14,500 mg/l - 15,500 mg/l, and the COD removal efficiency is near 100 per cent.

2. Endogenous O_2 Uptake, Substrate Removal Rate (High and Low Initial Sludge Concentration)

In this section, various batch experiments made in order to gain further insights into the metabolic capability of the extended aeration sluge, as its age increased, are presented.

Periodically, samples of the sludge were taken from the unit, worked free of substrate, suspended in phosphate buffer, and O_2 uptake was determined (over a period of six hours) for a known concentration of sludge (gm/l). The unit O_2 uptake (mg/l accumulated O_2 utilization ÷ gm/l initial sludge concentration) per hour was calculated and recorded as the endogenous O_2 uptake, mg O_2/gm sludge/hr.

Small samples were also withdrawn from the aerator and used as seed in the apparatus (shown in Figure 2). In these experiments, the course of biological solids accumulation and COD removal were assessed. In some of these experiments, removal of the substrate (glucose) was also measured using the anthrone test. As a mean of facilitating comparison of the results of each experiment, the total amount of COD removal (mg/l) was divided by the average biological solids concentration (gm/l), i.e., initial + final ÷ 2. This value was then divided by the time period (hrs) of the experiment. The resultant value was recorded as "specific substrate removal rate, mg COD/gm sludge/hr. It is realized that this type of calculation provides only a rough comparative parameter, since substrate removal and sludge accumulation in these "low incident solids" systems could not often be approximated with kinetics of zero order.

At various times, experiments of the type described above were conducted in the extended aeration unit itself. Such experiments were easily facilitated during a routine daily feeding period when the unit was being batch fed and during periods of normally continuous flow operation, and the system was batch fed on the day a substrate removal rate was run. For these "high initial solids" experiments, the specific substrate removal rate was determined as for the "low initial solids" experiments.

The values for endogenous O_2 uptake and specific substrate removal rate (both low and high initial solids) are shown in Figure 18. The endogenous O_2 uptake rate fluctuated rather widely during the first 250 days of operation. From day 30 to day 60 it dropped sharply as biological solids continued to accumulate, and it rose sharply when the biological solids concentration in the system experienced a decrease. Unfortunately, during the rapid decrease in solids concentration which took place just prior to 200 days of operation, no O_2 uptake data was taken. The most significant trend took place after day 270. Just prior to and during the gradual decrease in solids concentration (see Figures 9 and 18), the O_2 uptake rate followed a rising trend. It remained rather high, and as biological solids gradually built up in the system, the O_2 uptake rate followed a gradual decreasing trend and appeared to level off between one and two mg O_2/gm sludge/hr. After attainment of this low endogenous rate it was of interest to determine the endogenous rate of new or young cells grown up from a small inoculum of cells taken from the unit. Endogenous rates between 10 and 18 mg O_2/hr/gm sludge were observed. Thus, the endogenous activity of the extended aeration sludge is approximately 5 to 10 per cent of

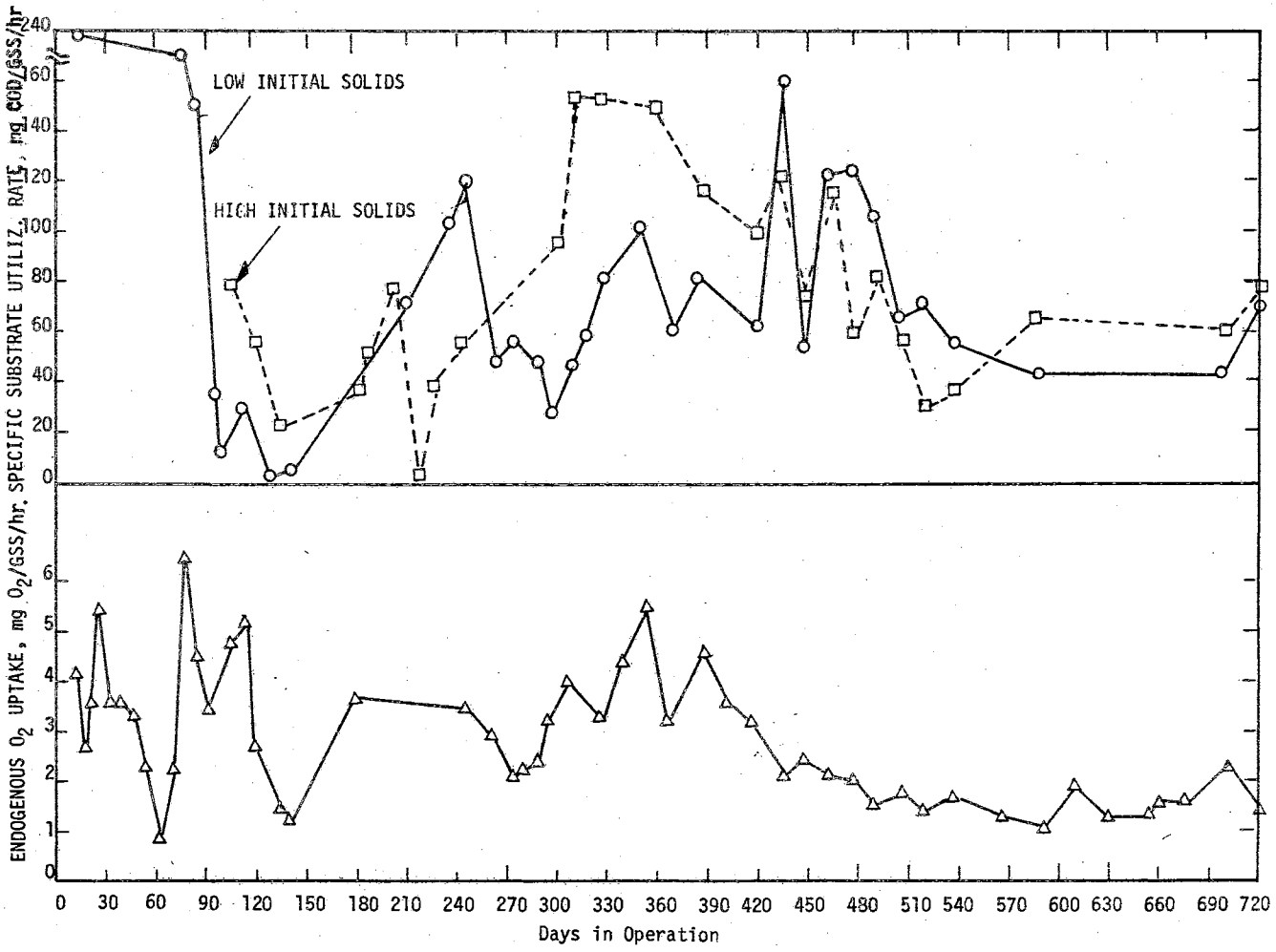


Figure 18 - Specific substrate utilization rate and endogenous O_2 uptake of extended aeration.

that for young cells of the same origin.

From Figure 18 it is seen that the specific substrate utilization rate for high initial solids and low initial solids systems tended to follow similar patterns. However, the high initial solids substrate utilization rate dropped to 8 mg COD/gm solids/hr on day 218, then gradually rose. The low removal rate value was obtained a few weeks after the sludge had been parted in order to run the shock load unit. Also, the unit had been recently switched from continuous flow to batch operation. During the later period of operation the values for substrate removal rate at both high and low initial solids concentration appear to have levelled off at values in the range 40-60 mg COD/gm sludge/hr.

The course of substrate removal and biological solids accumulation for the batch experiments at both high and low initial biological solids concentrations are presented in Figures 19 through 53. Since the significance of the specific substrate removal rate may be subject to debate, these figures are presented in order that a reader may scrutinize the actual experimental result rather than have only the calculated parameter upon which to base a judgement. These figures can be used in conjunction with Figures 3 through 17, as well as with Figure 18.

The low value for the specific substrate utilization rate shown in Figure 18 for day 218 (8 mg COD/gm sludge/hr) was calculated from the results shown in Figure 32. From Figure 7 it is seen that this run was made approximately three weeks after the unit had been switched from continuous flow to batch operation. During this period the residual COD in the unit after twenty-three hours of aeration was

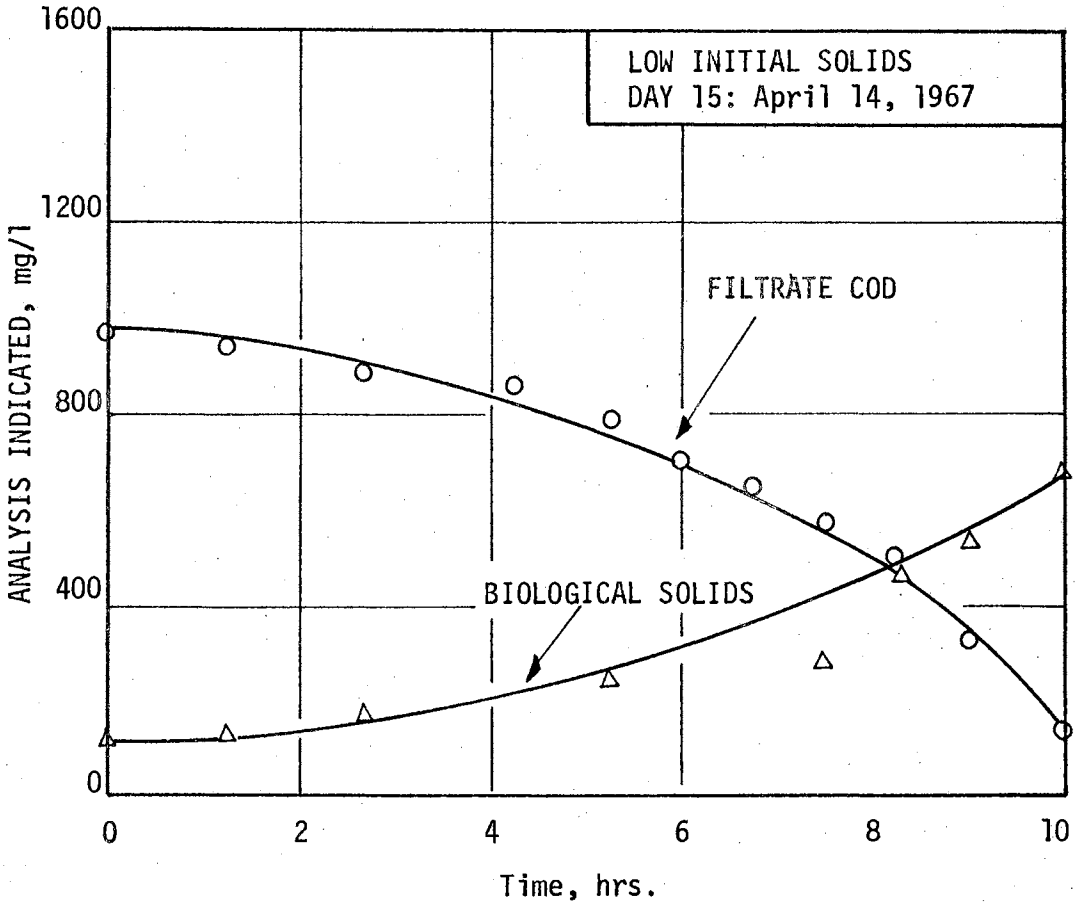


Figure 19 - Response of the extended aeration activated sludge to slug dosage of glucose after 15 days of operation.

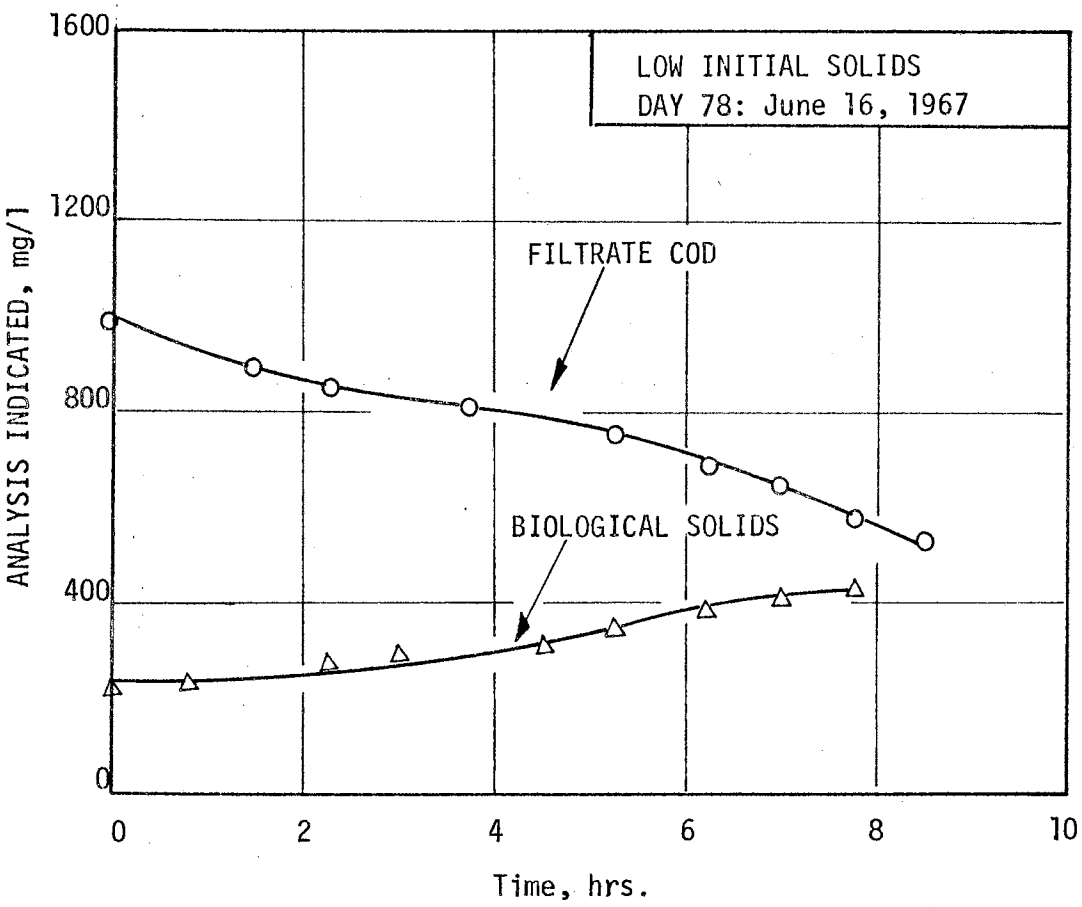


Figure 20 - Response of the extended aeration activated sludge to slug dosage of glucose after 78 days of operation.

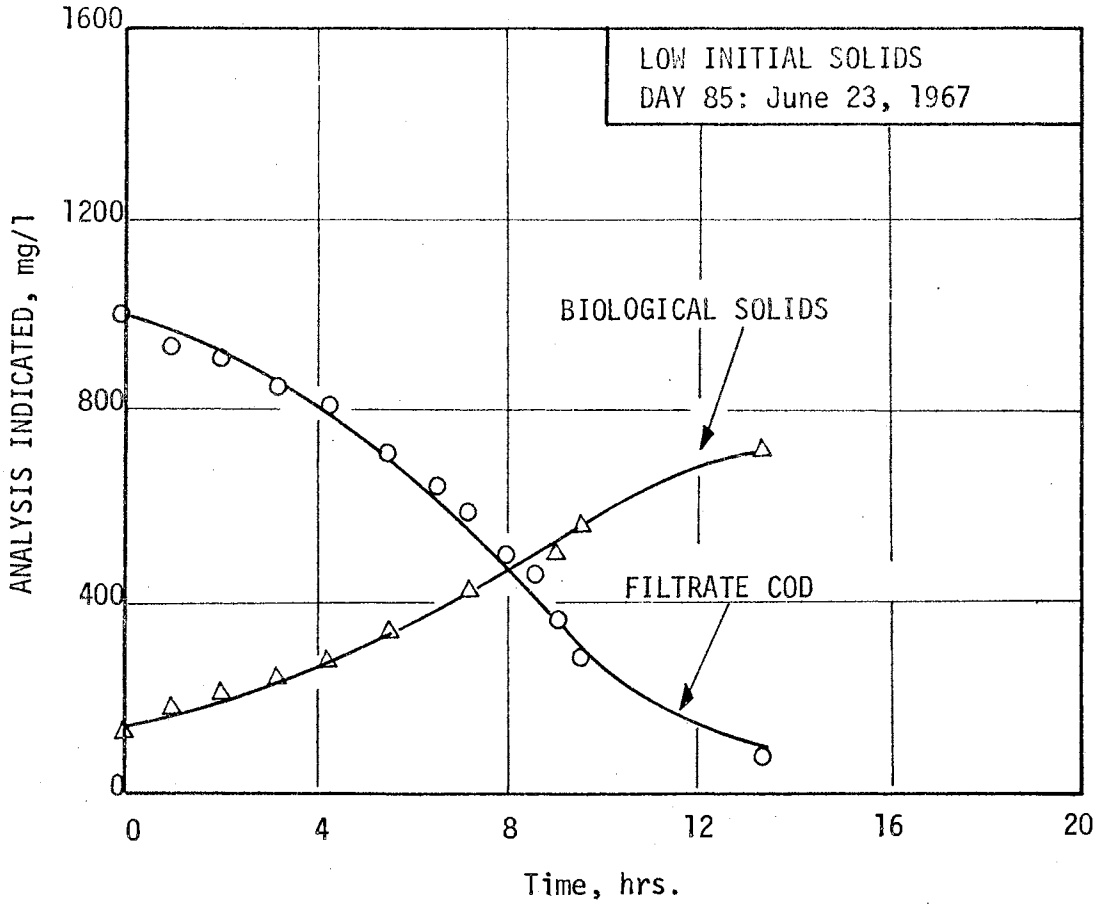


Figure 21 - Response of the extended aeration activated sludge to slug dosage of glucose after 85 days of operation.

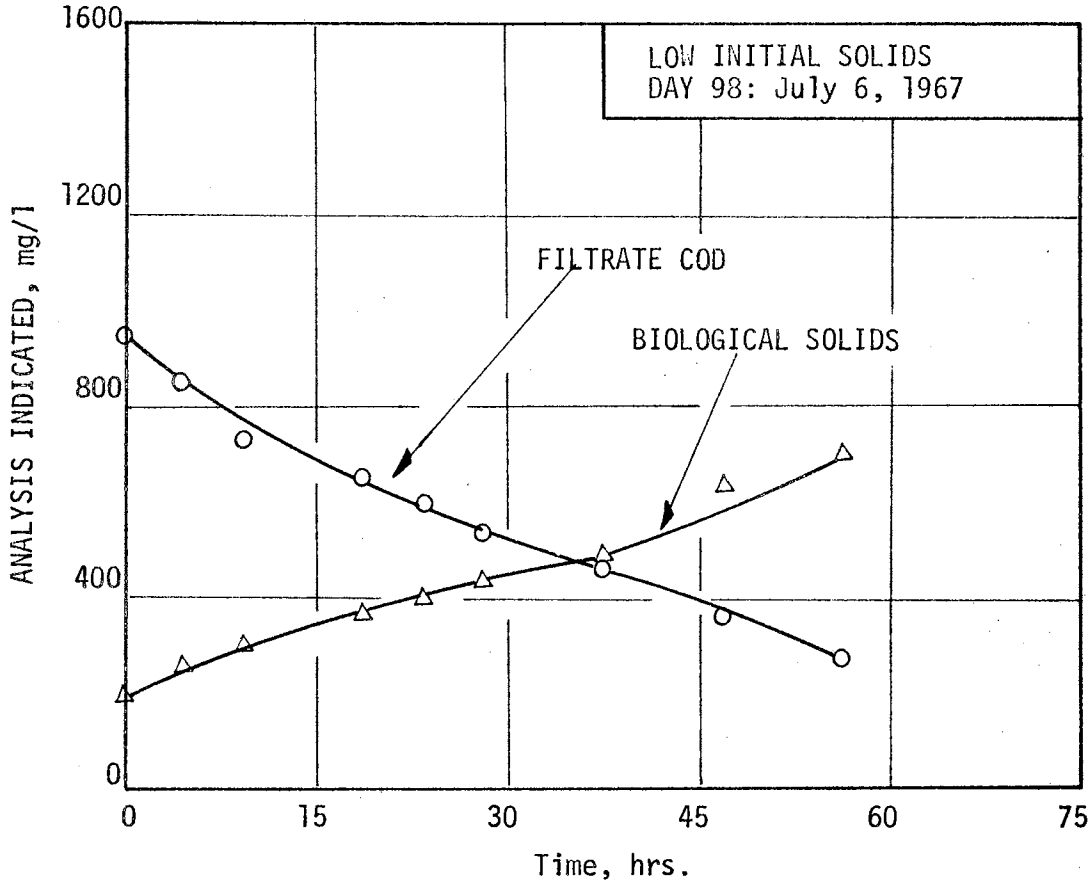


Figure 22 - Response of the extended aeration activated sludge to slug dosage of glucose after 98 days of operation.

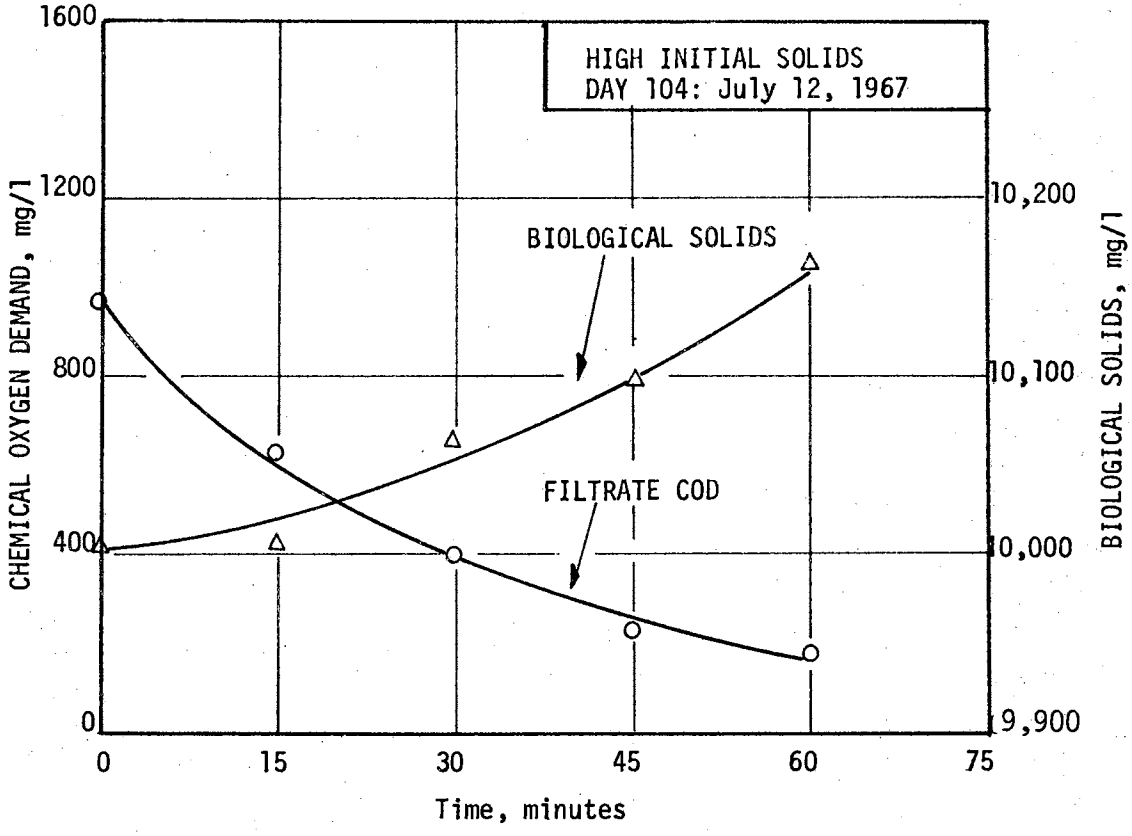


Figure 23: Response of the extended aeration activated sludge to slug dosage of glucose after 104 days of operation.

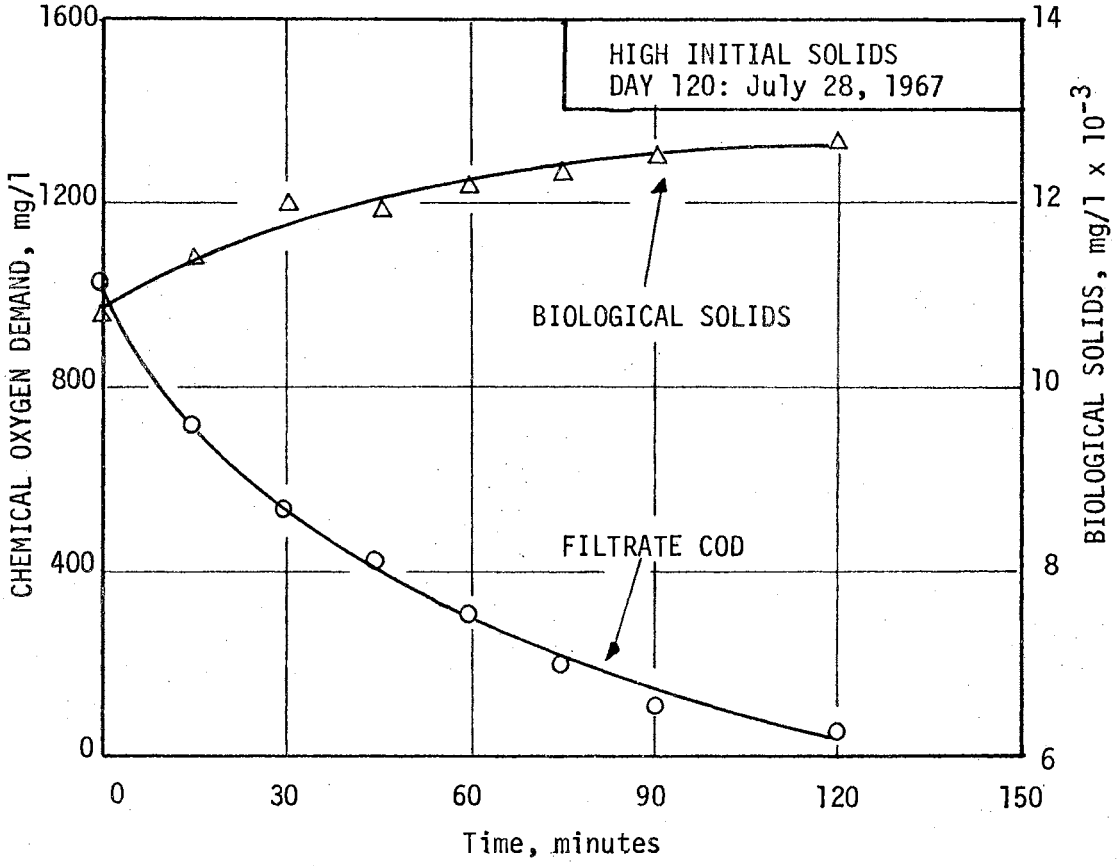


Figure 24 - Response of the extended aeration activated sludge to slug dosage of glucose after 120 days of operation.

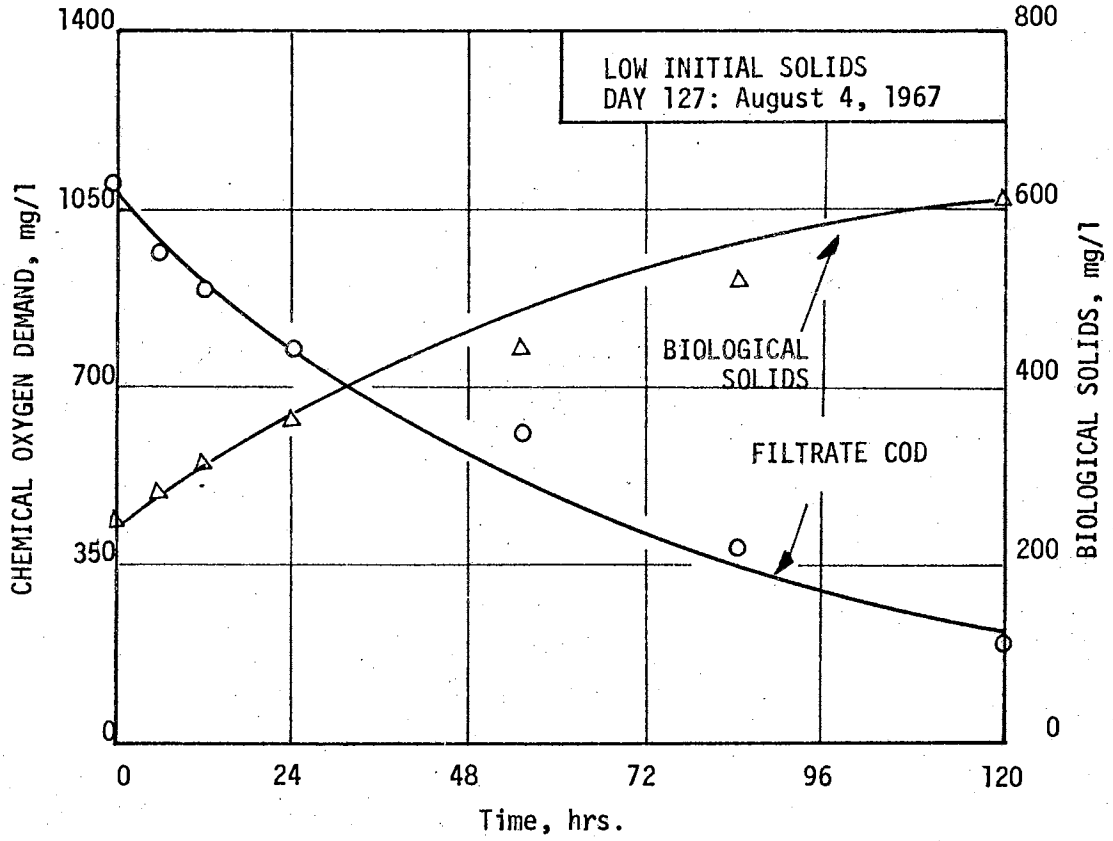


Figure 25 - Response of the extended aeration activated sludge to slug dosage of glucose after 127 days of operation.

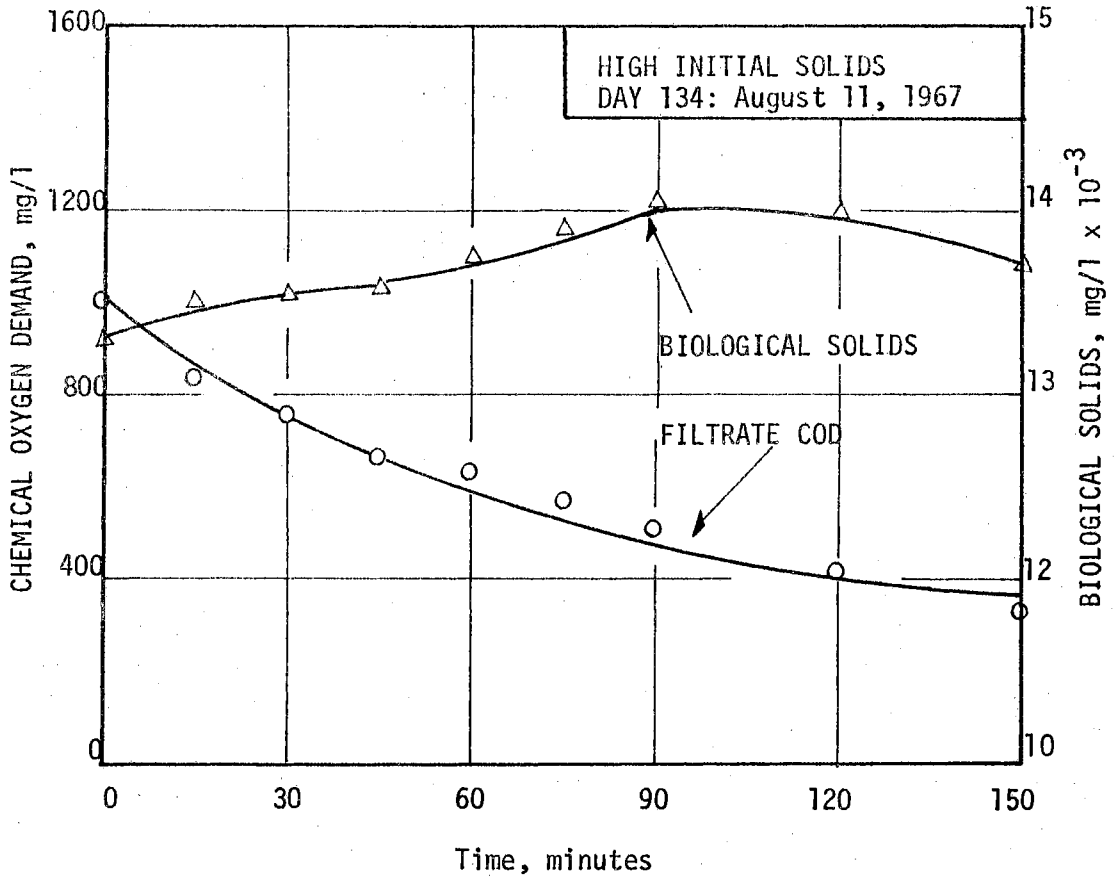


Figure 26 - Response of the extended aeration activated sludge to slug dosage of glucose after 134 days of operation.

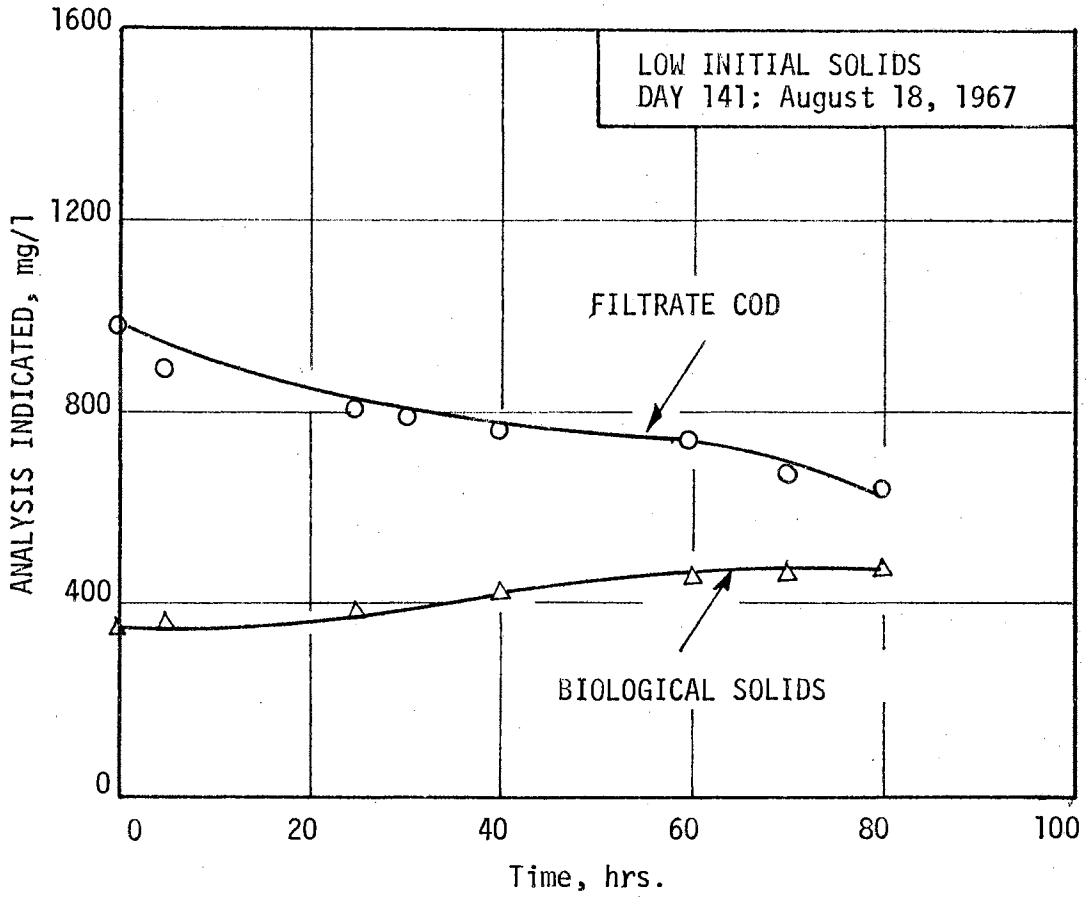


Figure 27 - Response of the extended aeration activated sludge to slug dosage of glucose after 141 days of operation.

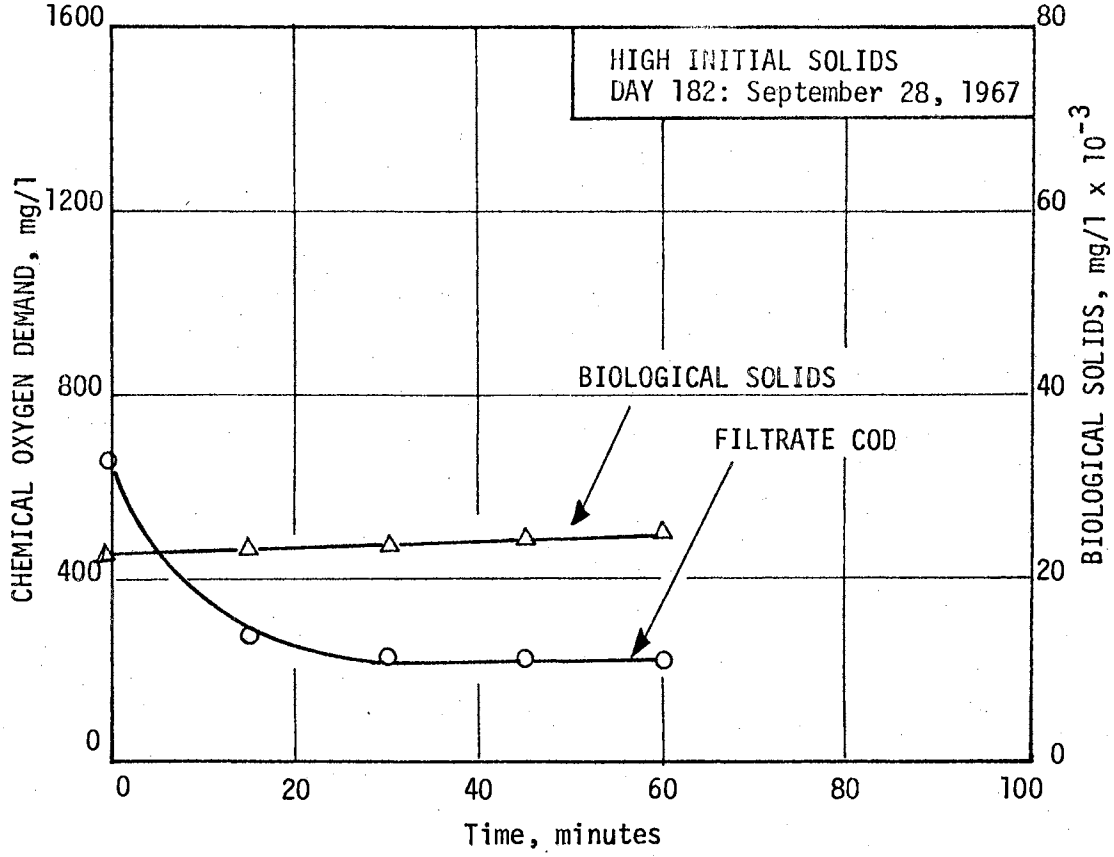


Figure 28 - Response of the extended aeration activated sluge to slug dosage of glucose after 182 days of operation.

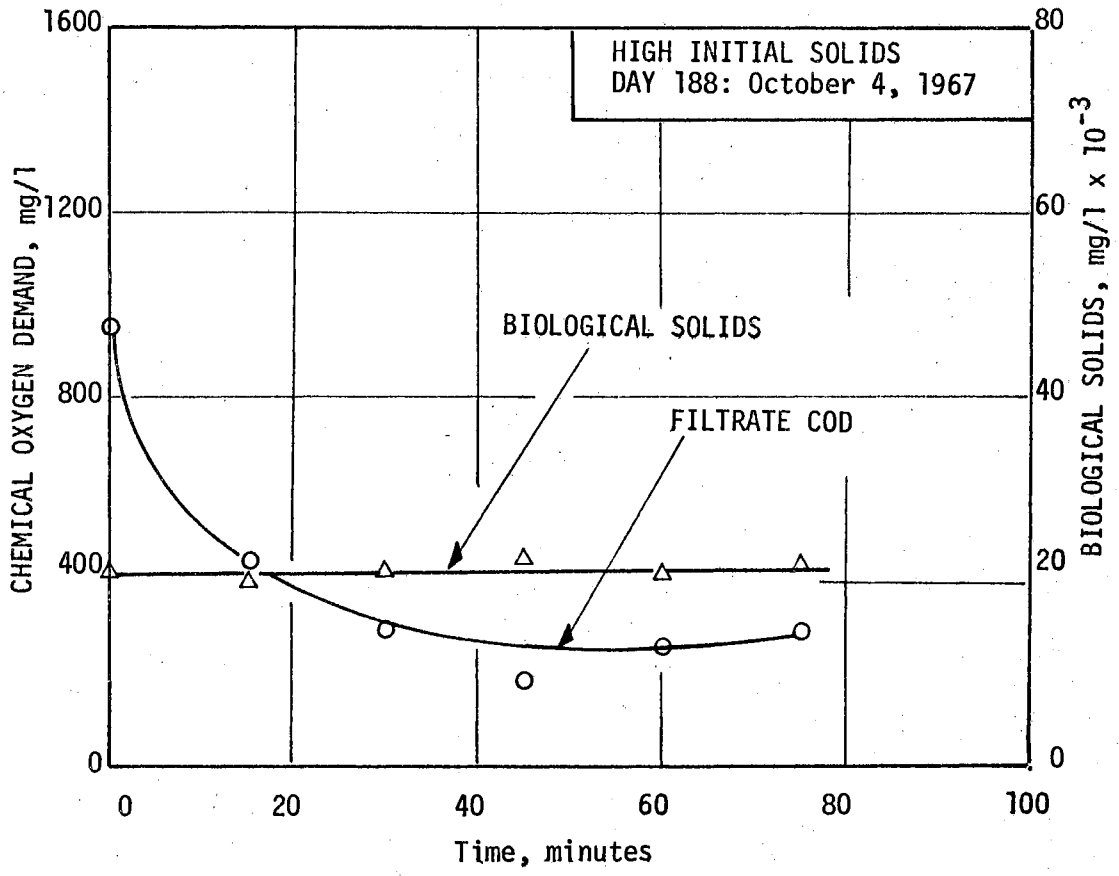


Figure 29 - Response of the extended aeration activated sludge to slug dosage of glucose after 188 days of operation.

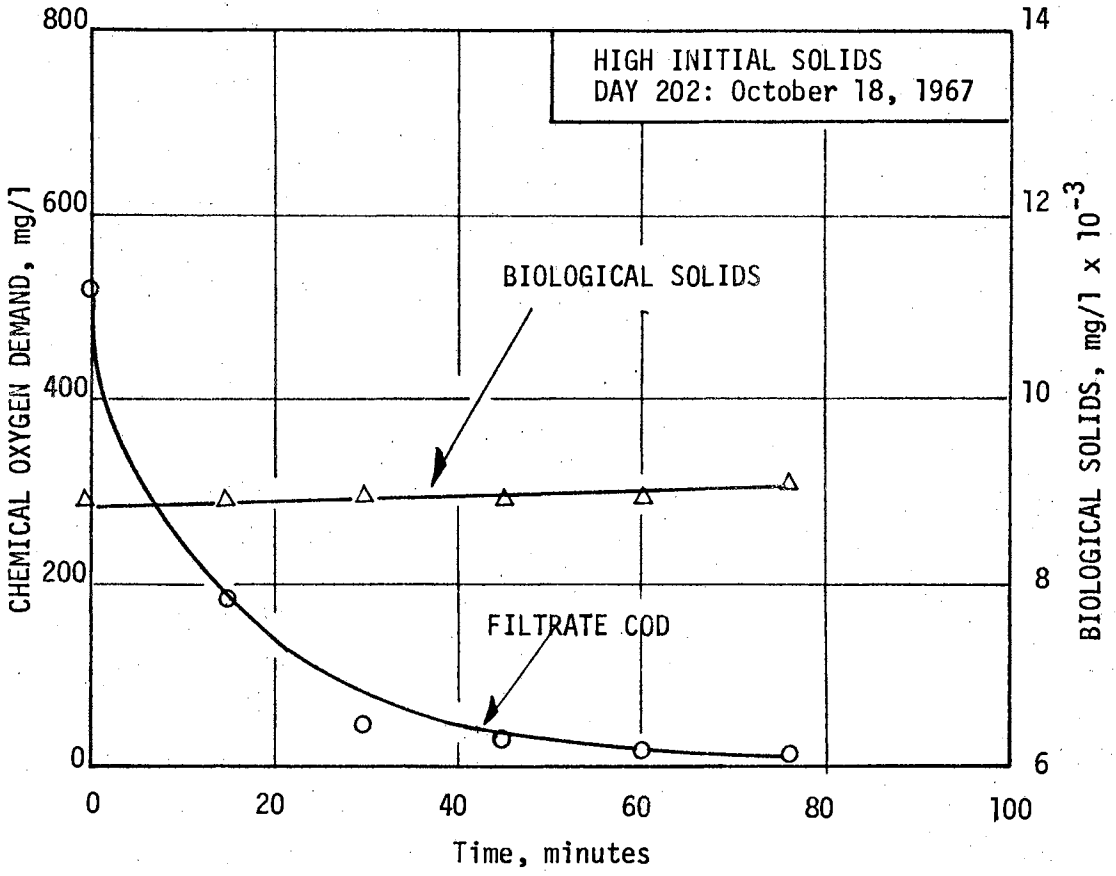


Figure 30 - Response of the extended aeration activated sludge to slug dosage of glucose after 202 days of operation.

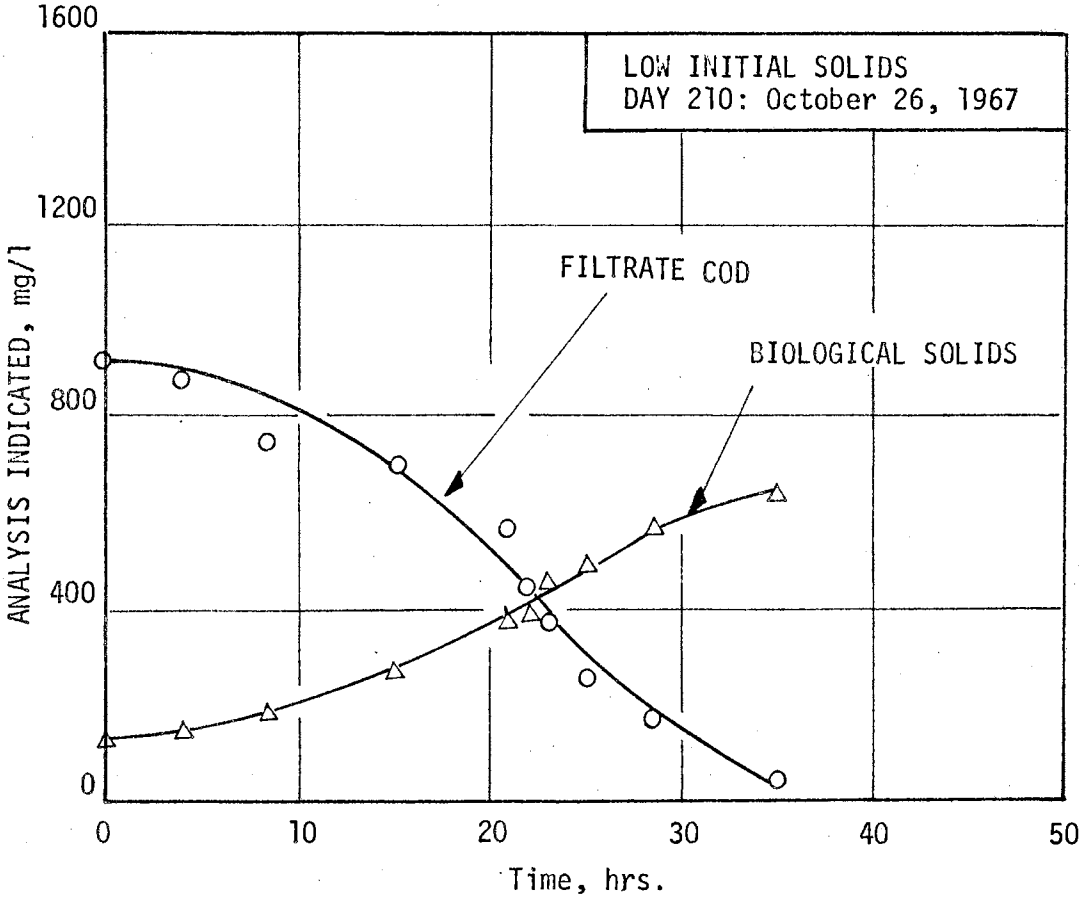


Figure 31 - Response of the extended aeration activated sludge to slug dosage of glucose after 210 days of operation.

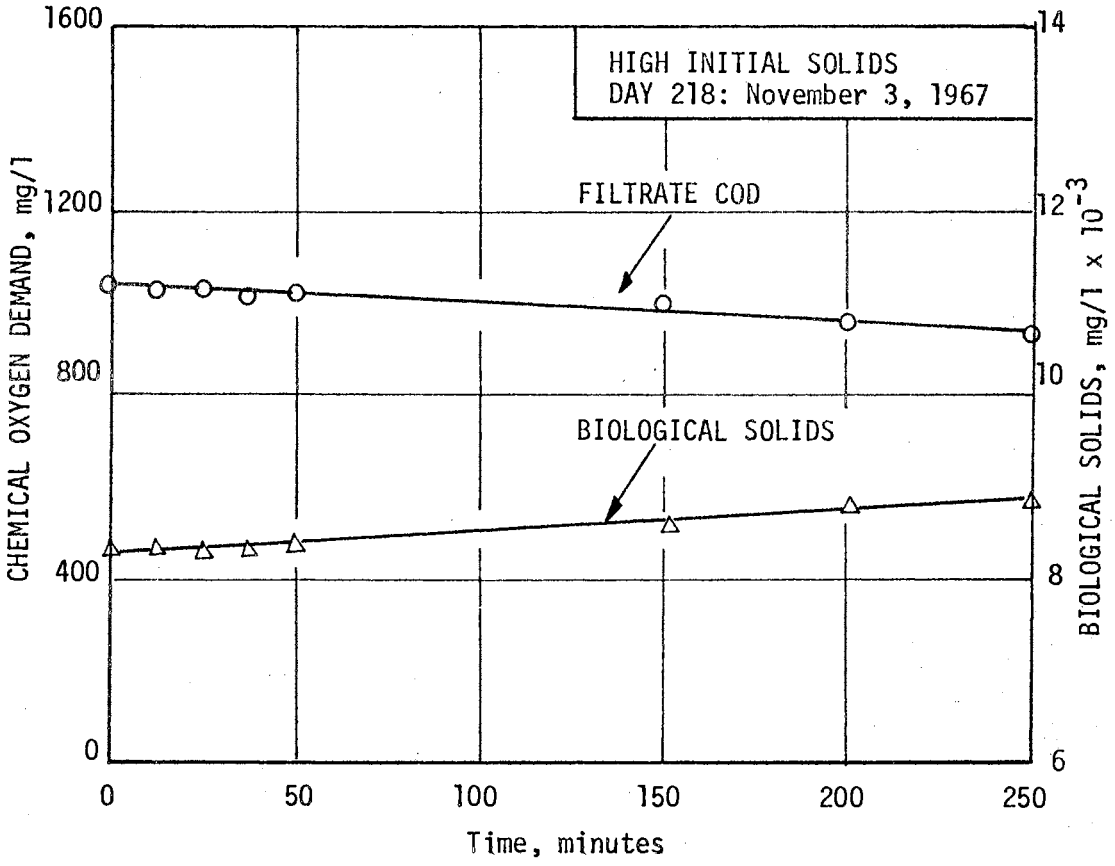


Figure 32 - Response of the extended aeration activated sludge to slug dosage of glucose after 218 days of operation

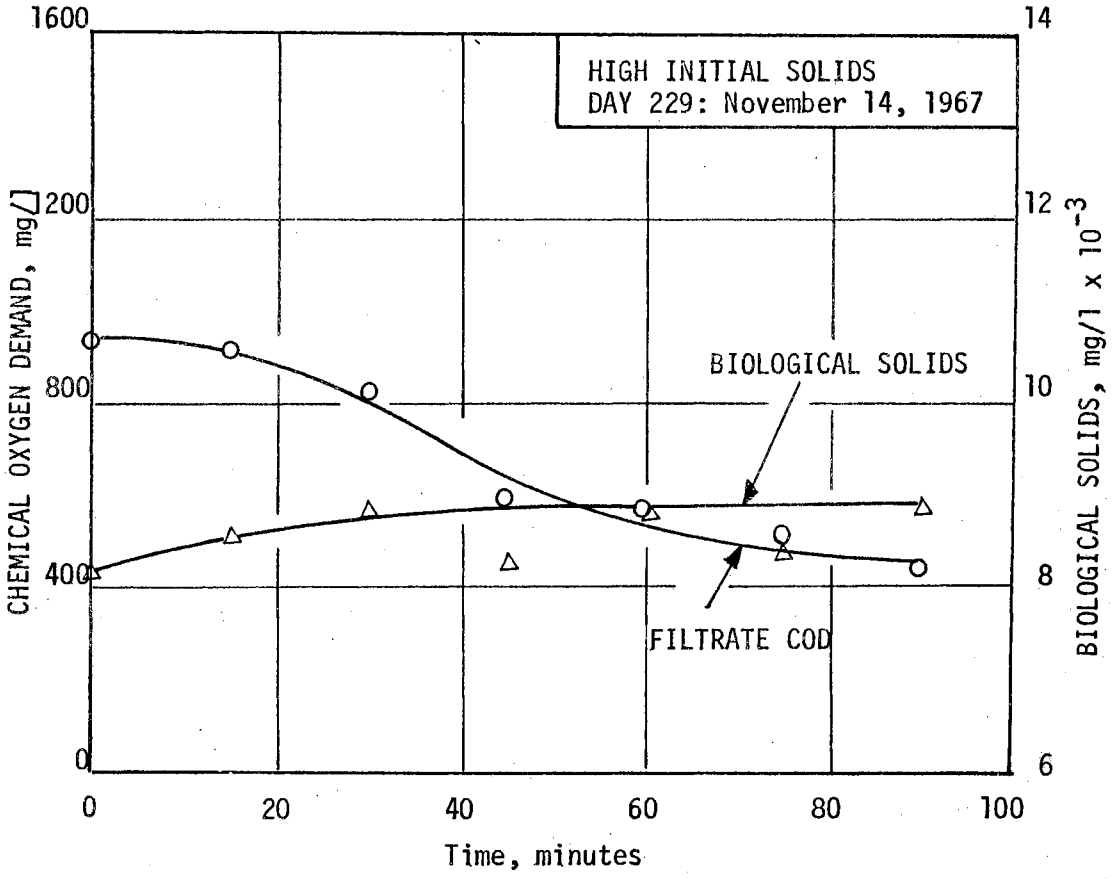


Figure 33 - Response of the extended aeration activated sludge to slug dosage of glucose after 229 days of operation.

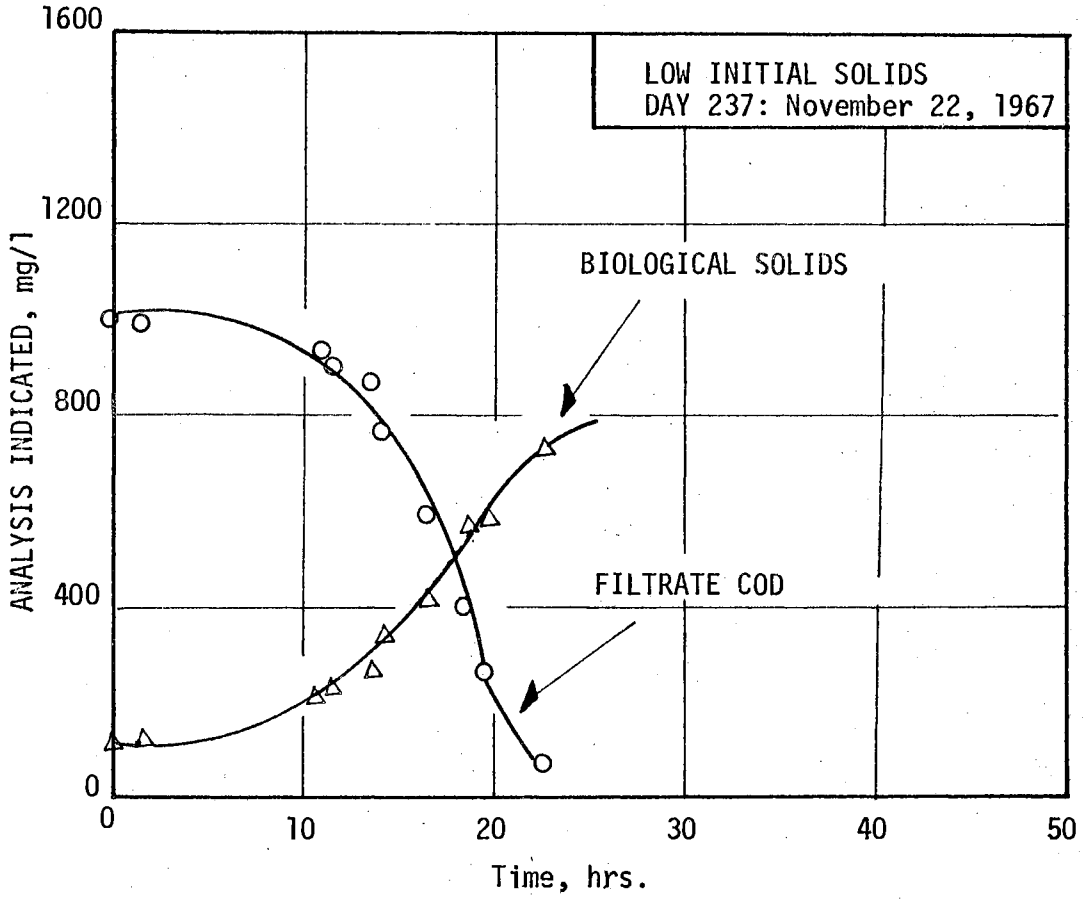


Figure 34 - Response of the extended aeration activated sludge to slug dosage of glucose after 237 days of operation.

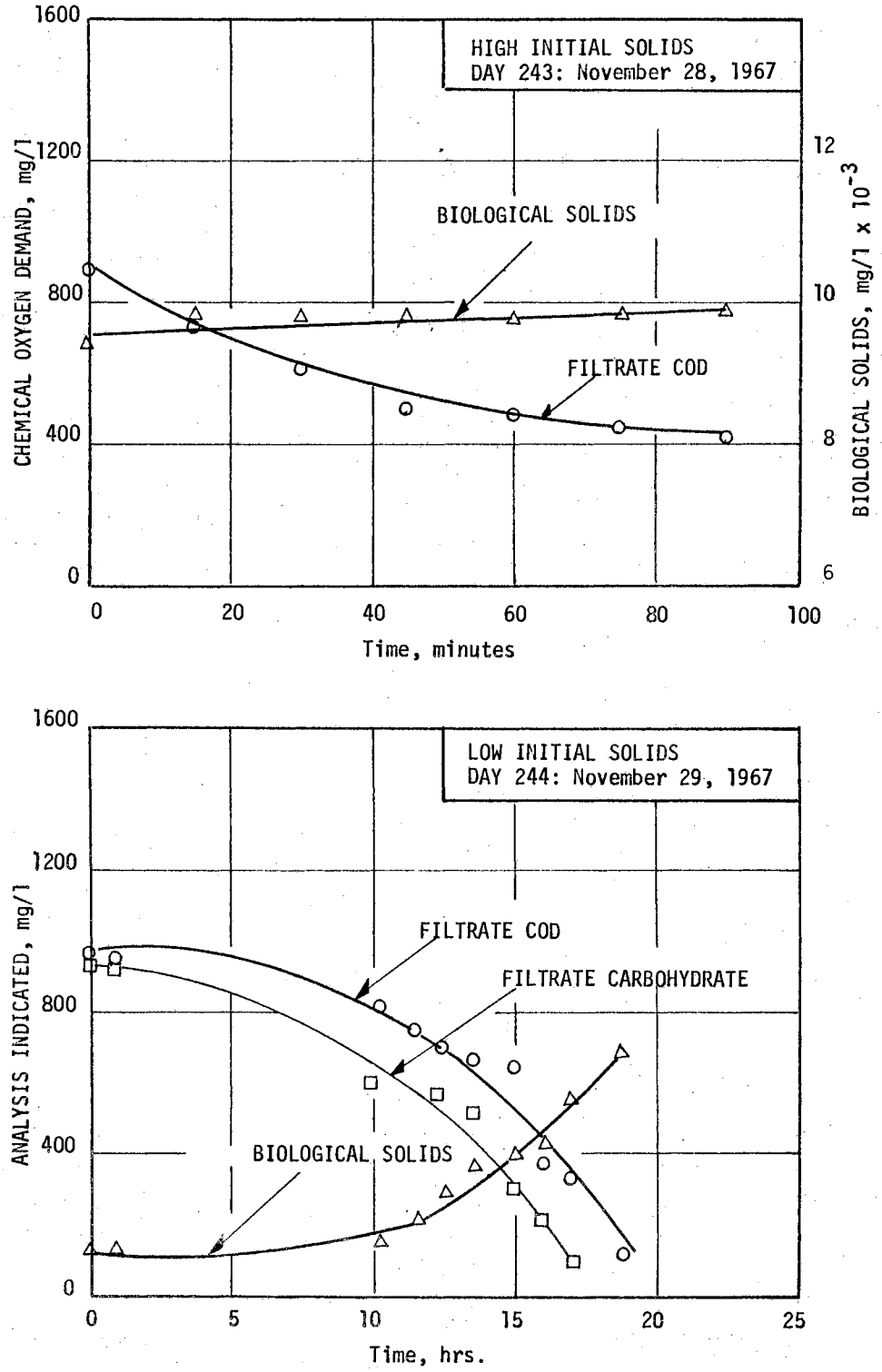


Figure 35 - Response of the extended aeration activated sludge to slug dosage of glucose after 243 days.

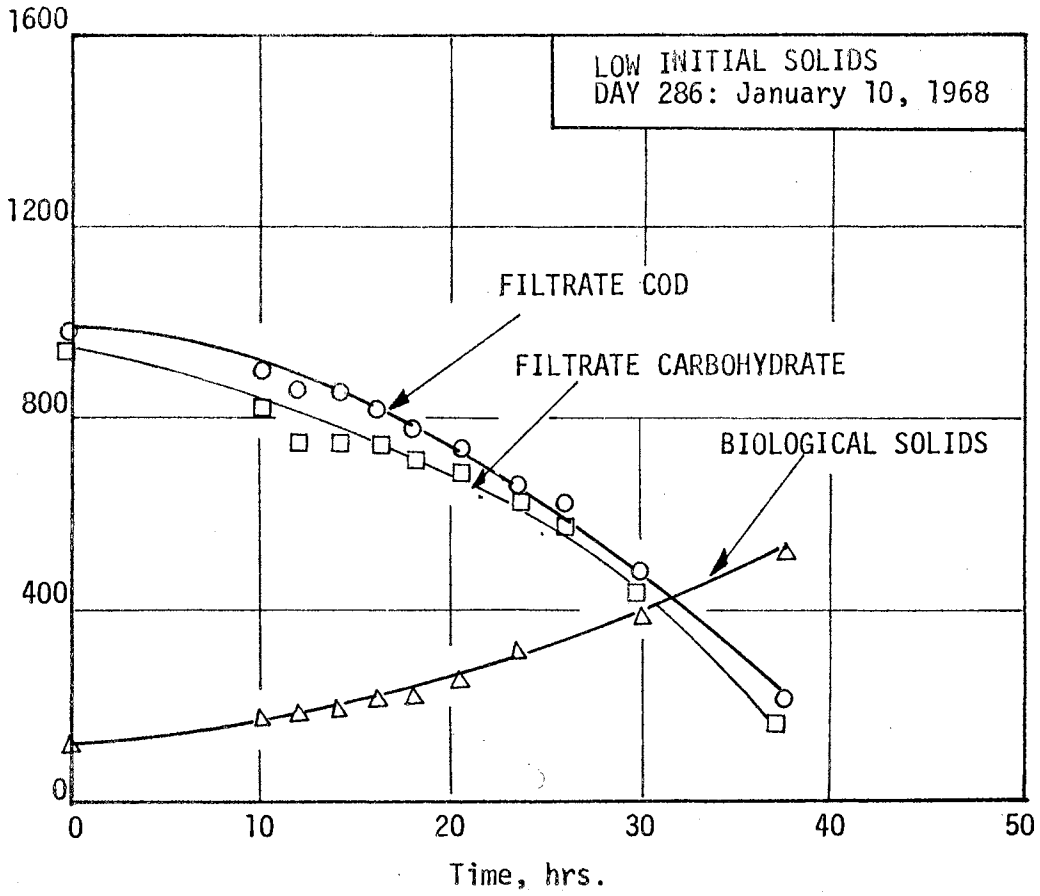
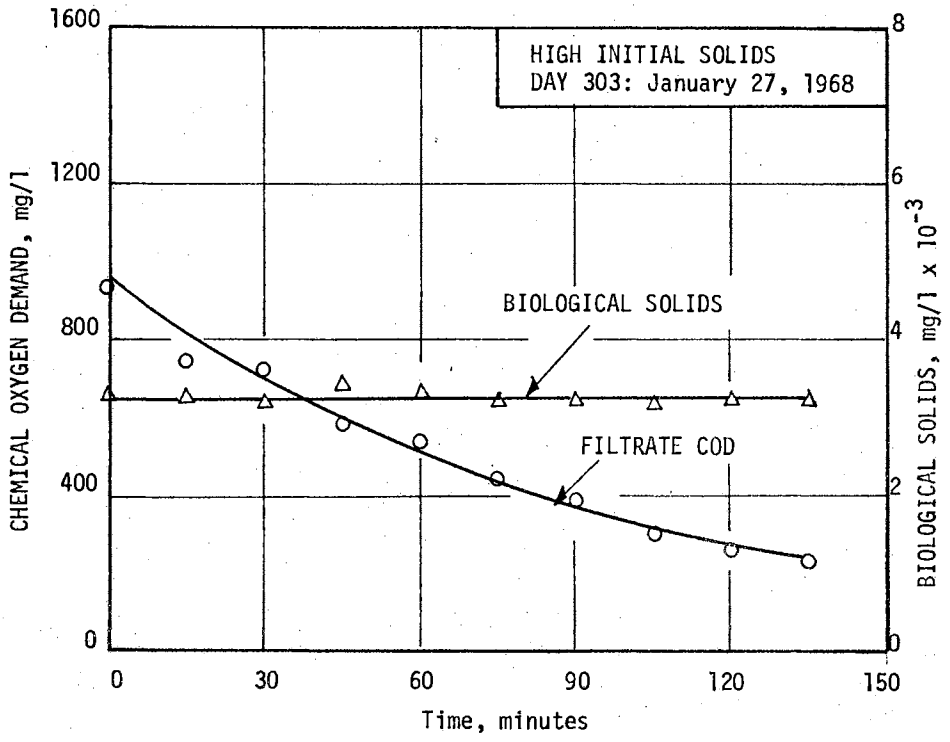


Figure 36 - Response of the extended aeration activated sludge to slug dosage of glucose after 286 days of operation.



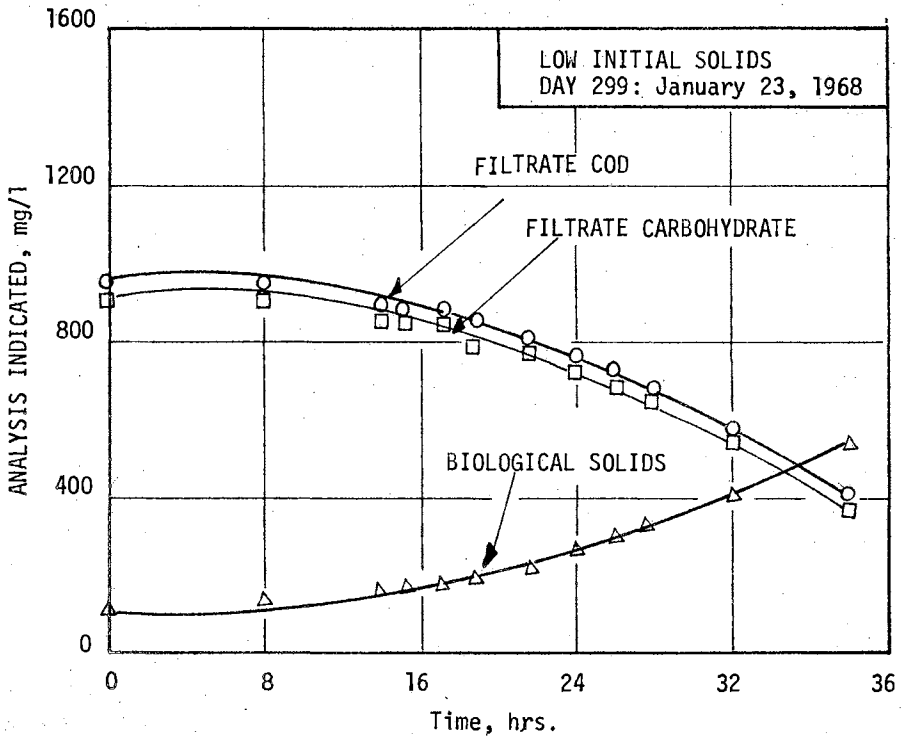


Figure 37 - Response of the extended aeration activated sludge to slug dosage of glucose after 299 days of operation.

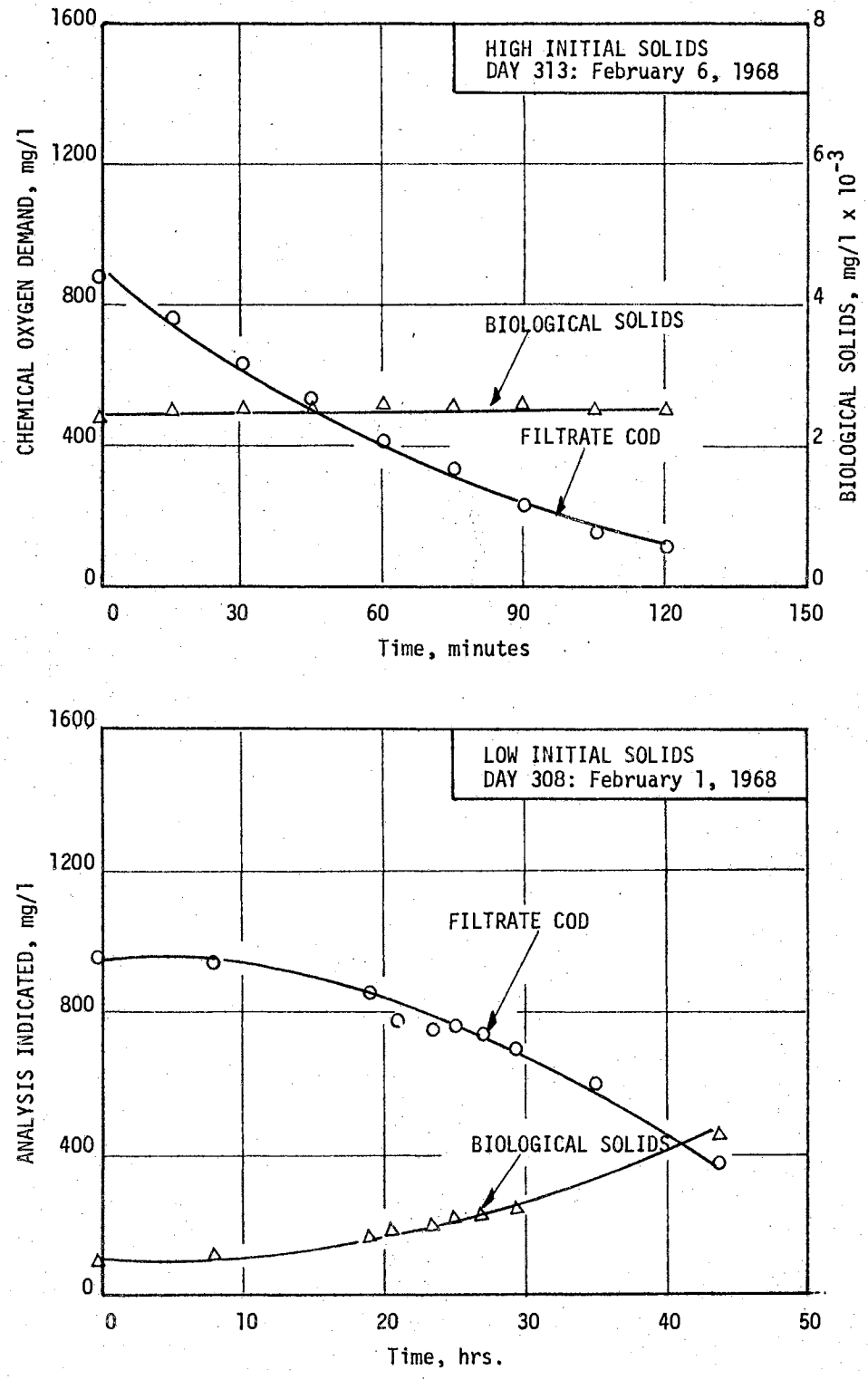


Figure 38 - Response of the extended aeration activated sludge to slug dosage of glucose after 308 days of operation.

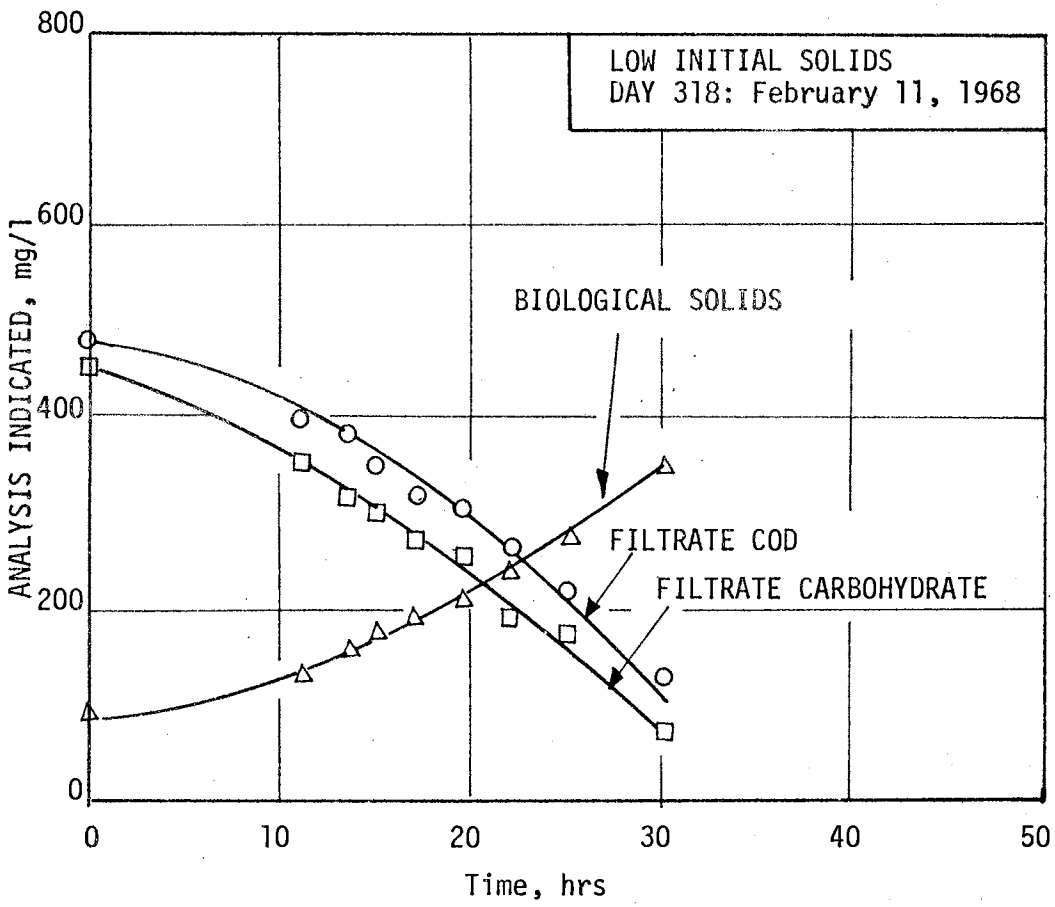
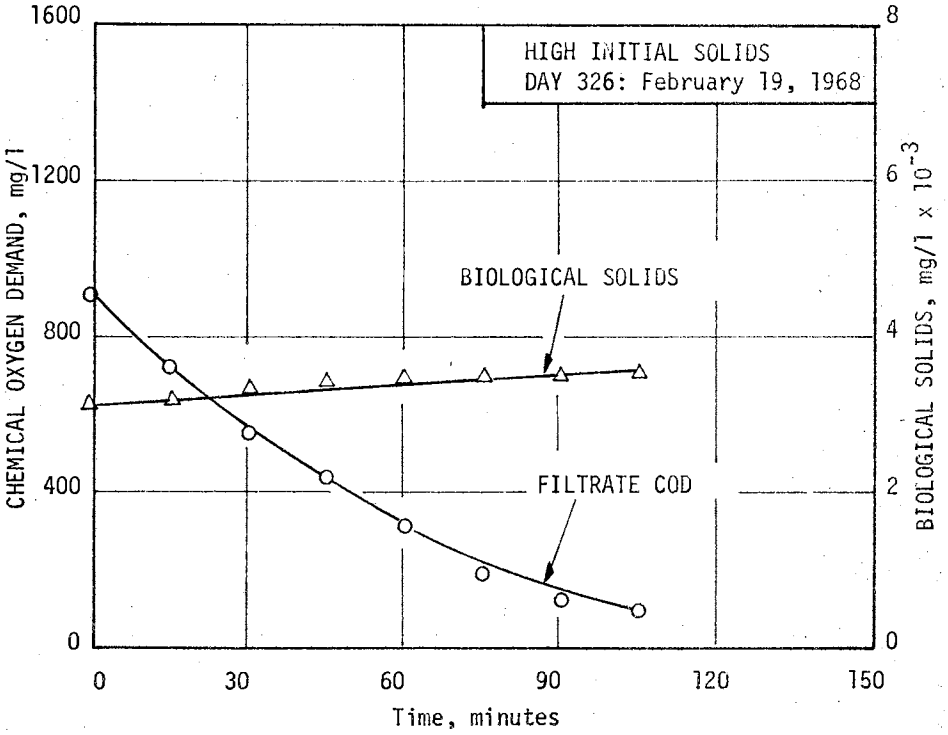


Figure 39 - Response of the extended aeration activated sludge to slug dosage of glucose after 318 days of operation.



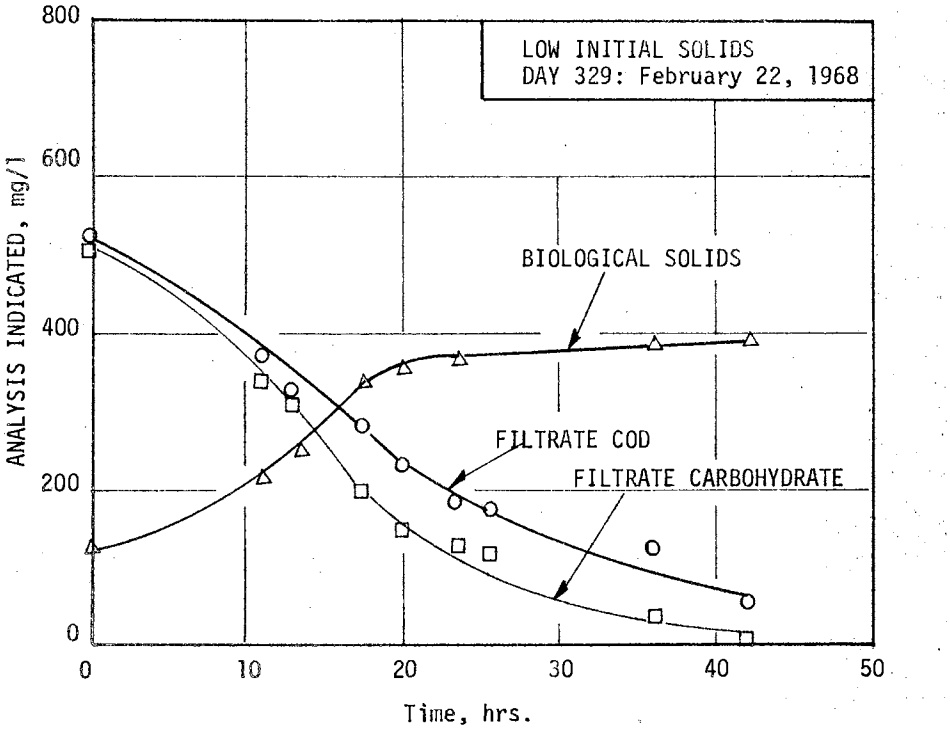


Figure 40 - Response of the extended aeration activated sludge to slug dosage of glucose after 326 days of operation.

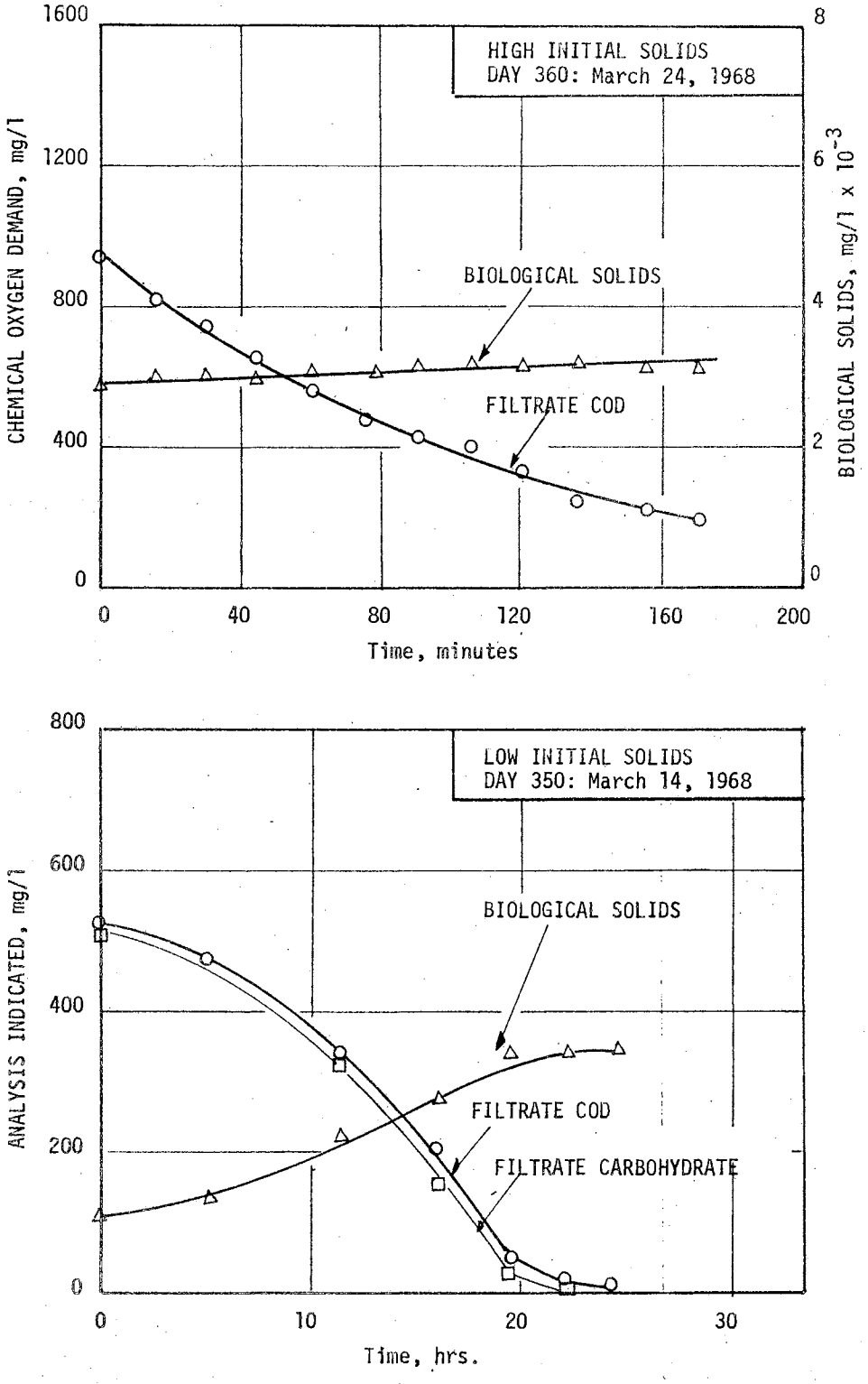


Figure 41 - Response of the extended aeration activated sludge to slug dosage of glucose after 350 days of operation.

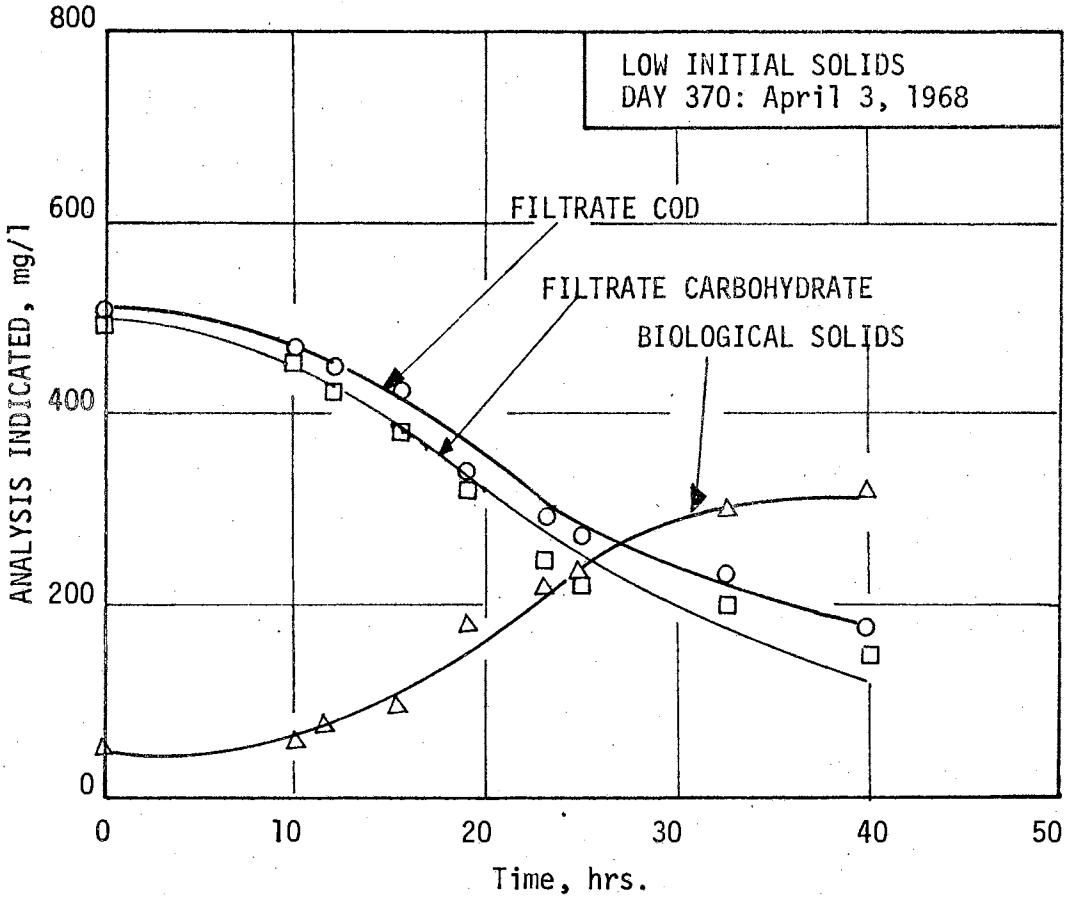


Figure 42. Response of the extended aeration activated sludge to slug dosage of glucose after 370 days of operation.

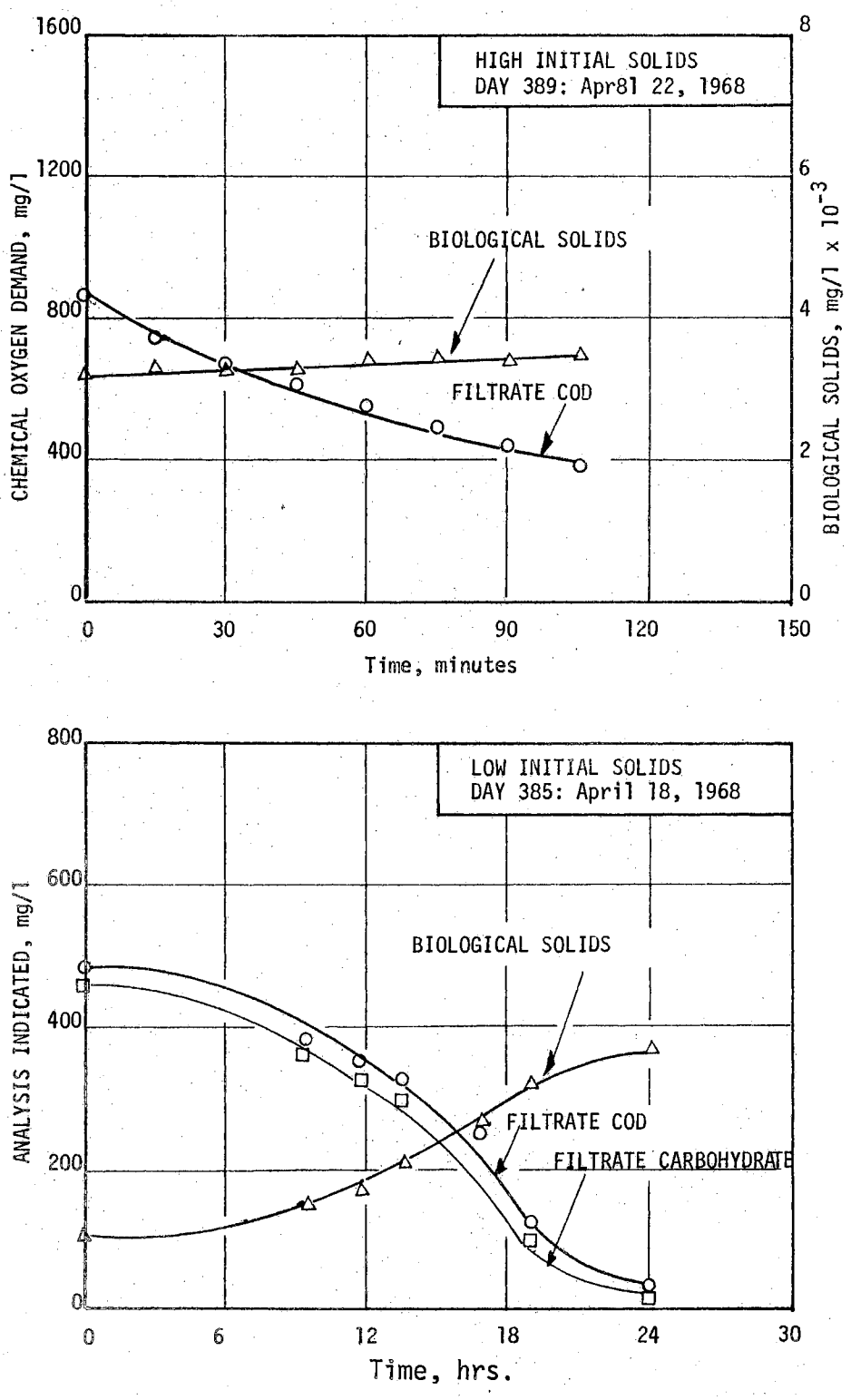
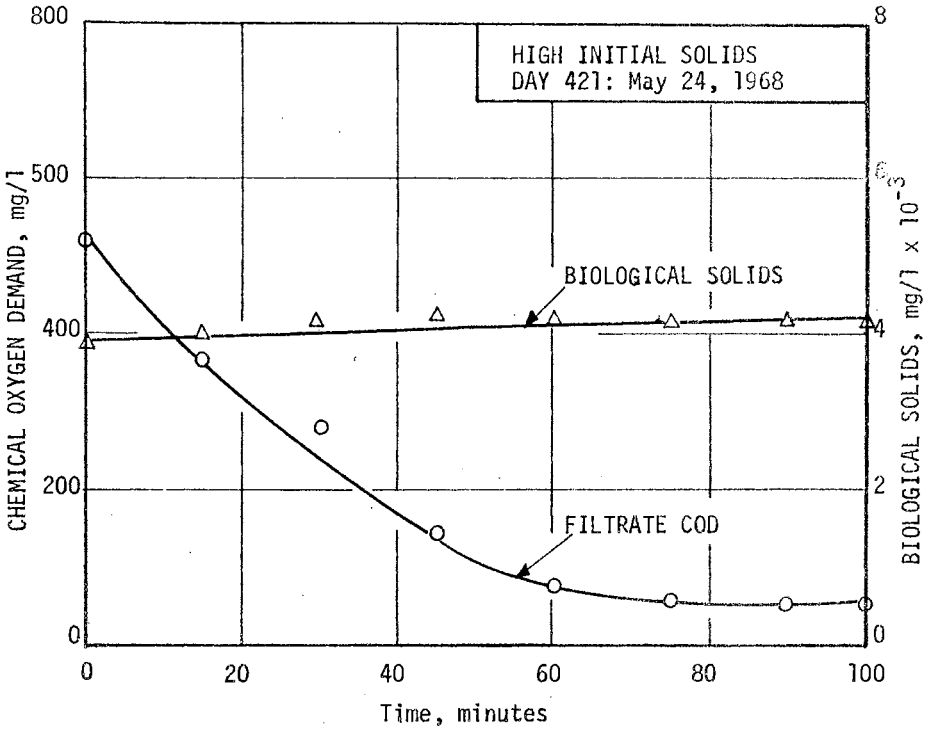


Figure 43 - Response of the extended aeration activated sludge to slug dosage of glucose after 385 days of operation.



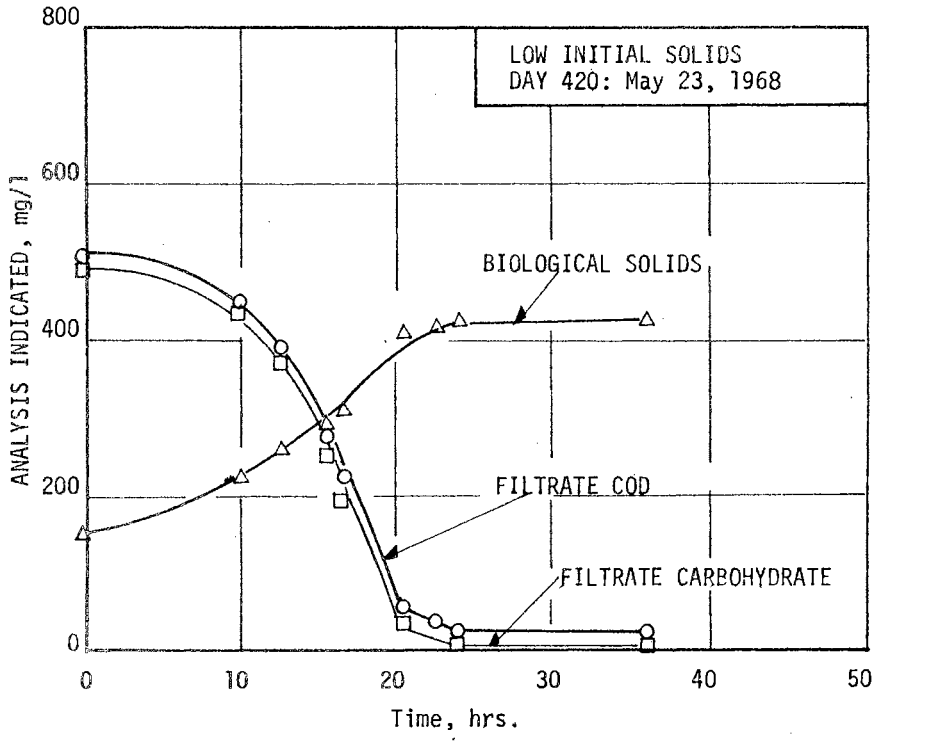


Figure 44 - Response of the extended aeration activated sludge to slug dosage of glucose after 420 days of operation.

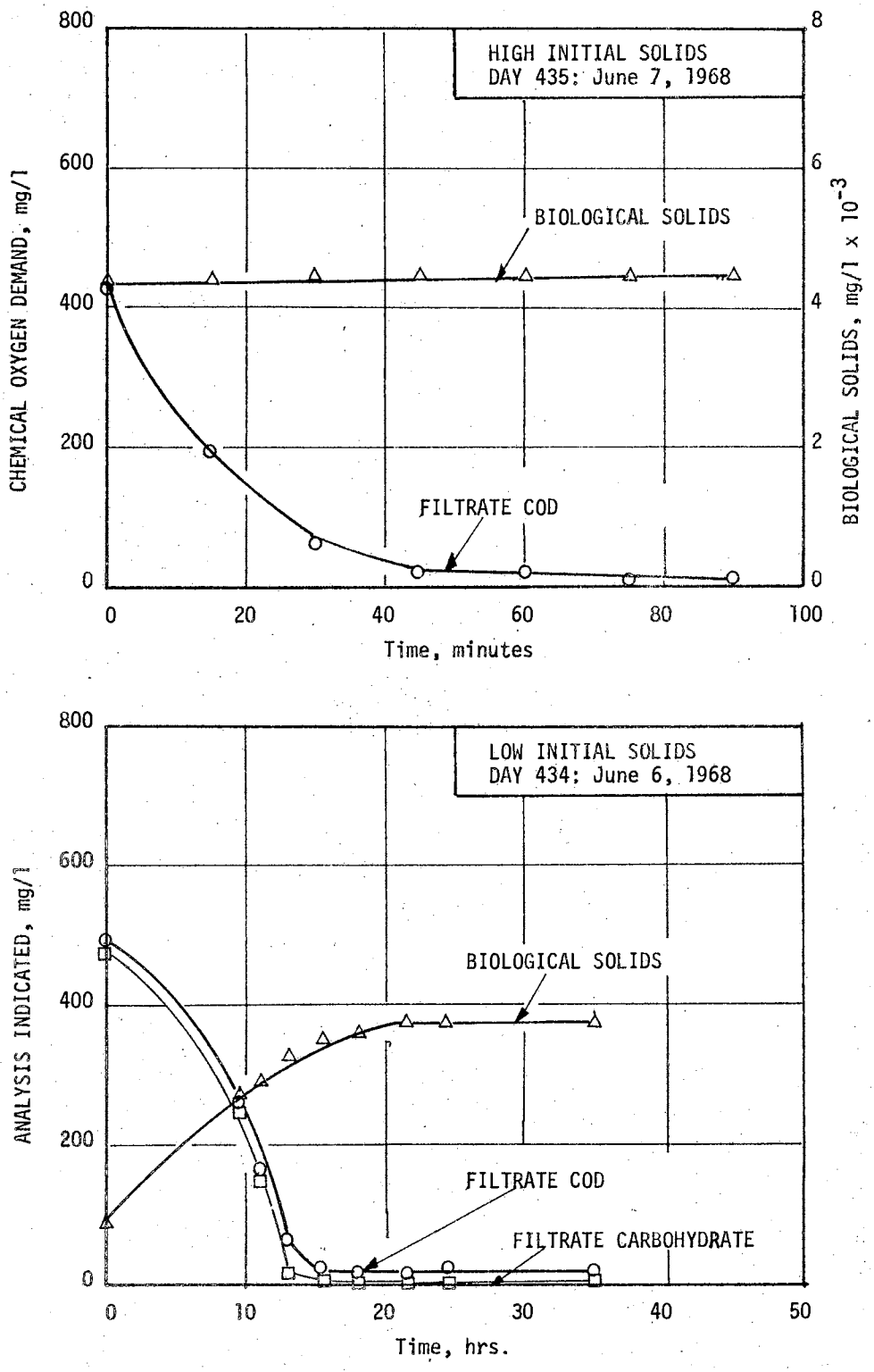
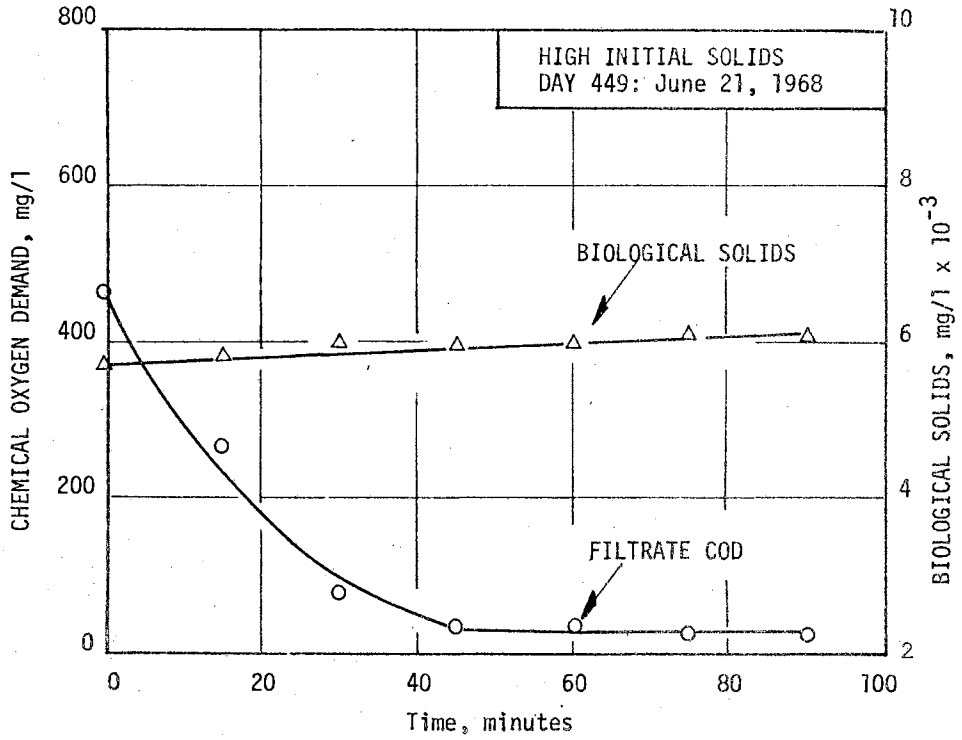


Figure 45 - Response of the extended aeration activated sludge to slug dosage of glucose after 434 days of operation.



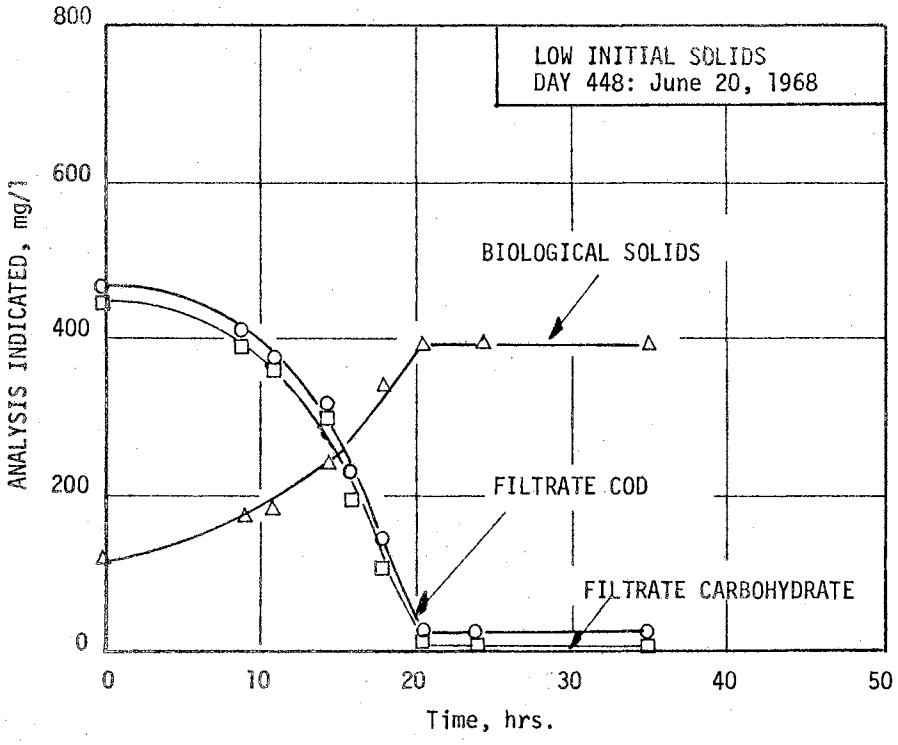


Figure 46 - Response of the extended aeration activated sludge to slug dosage of glucose after 448 days of operation.

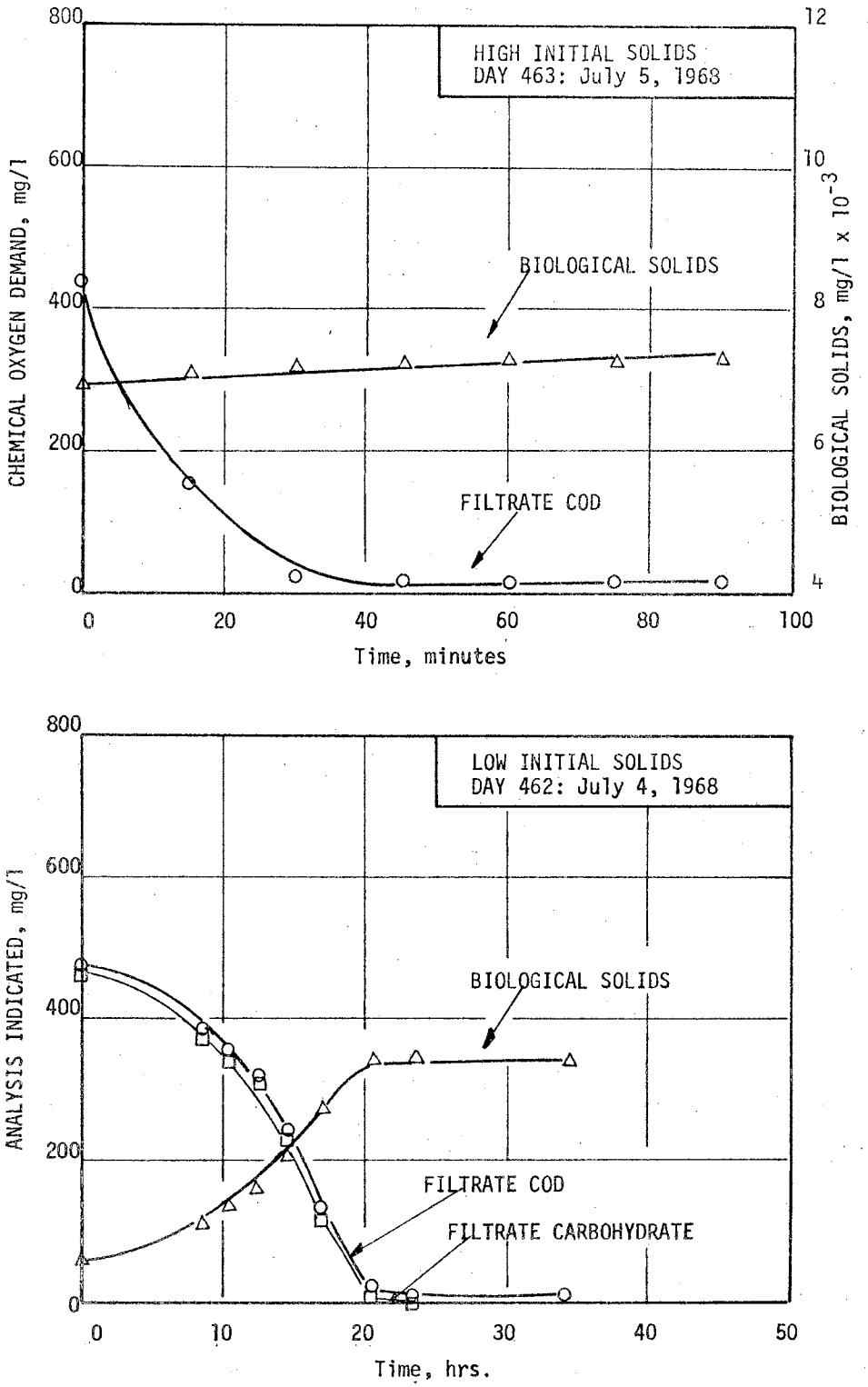
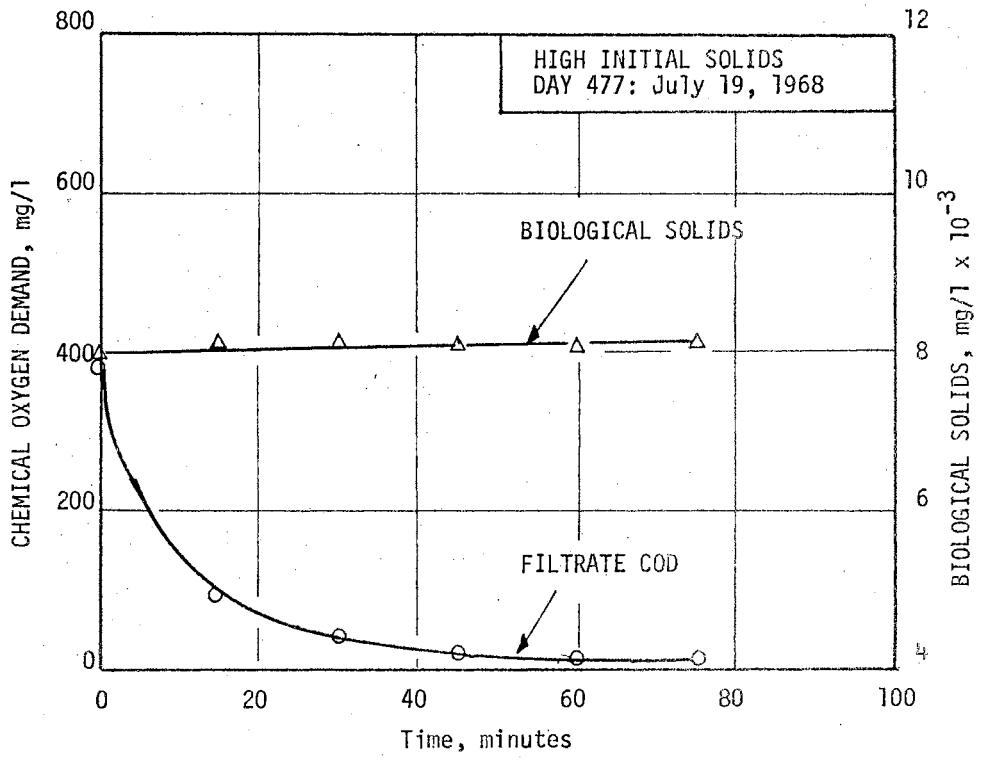


Figure 47 - Response of the extended aeration activated sludge to slug dosage of glucose after 462 days of operation.



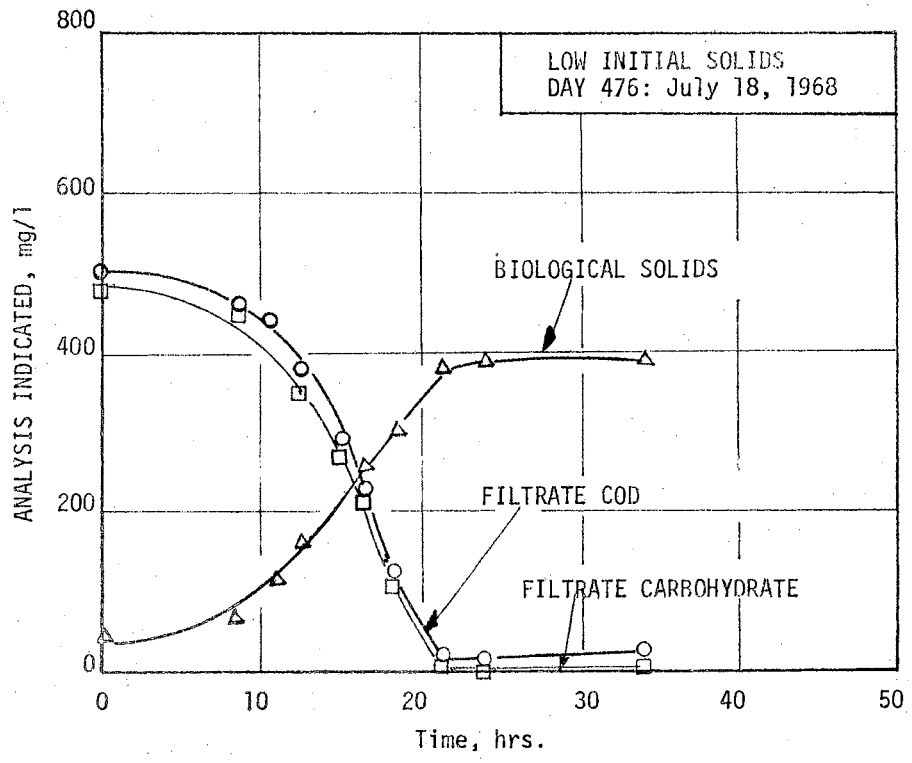
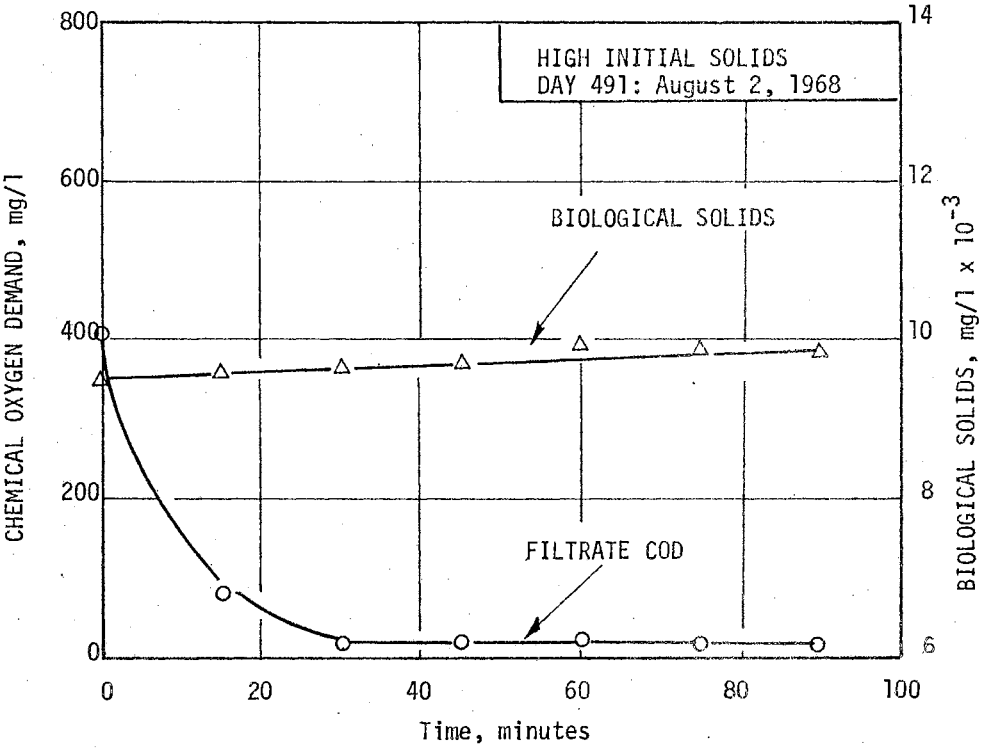


Figure 48 - Response of the extended aeration activated sludge to slug dosage of glucose after 476 days of operation.



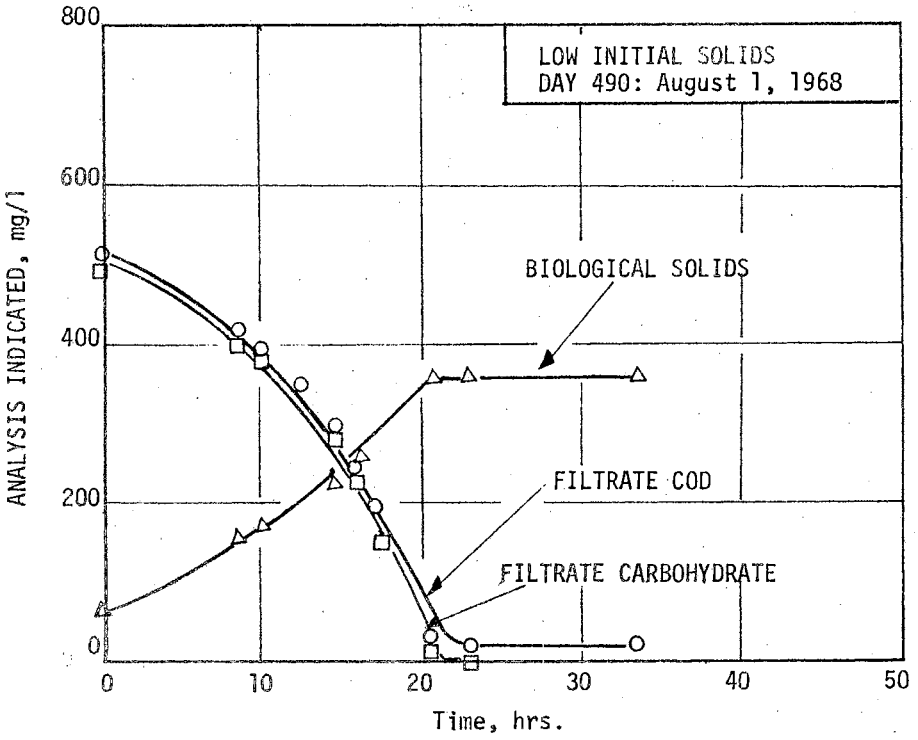


Figure 49 - Response of the extended aeration activated sludge to slug dosage of glucose after 490 days of operation.

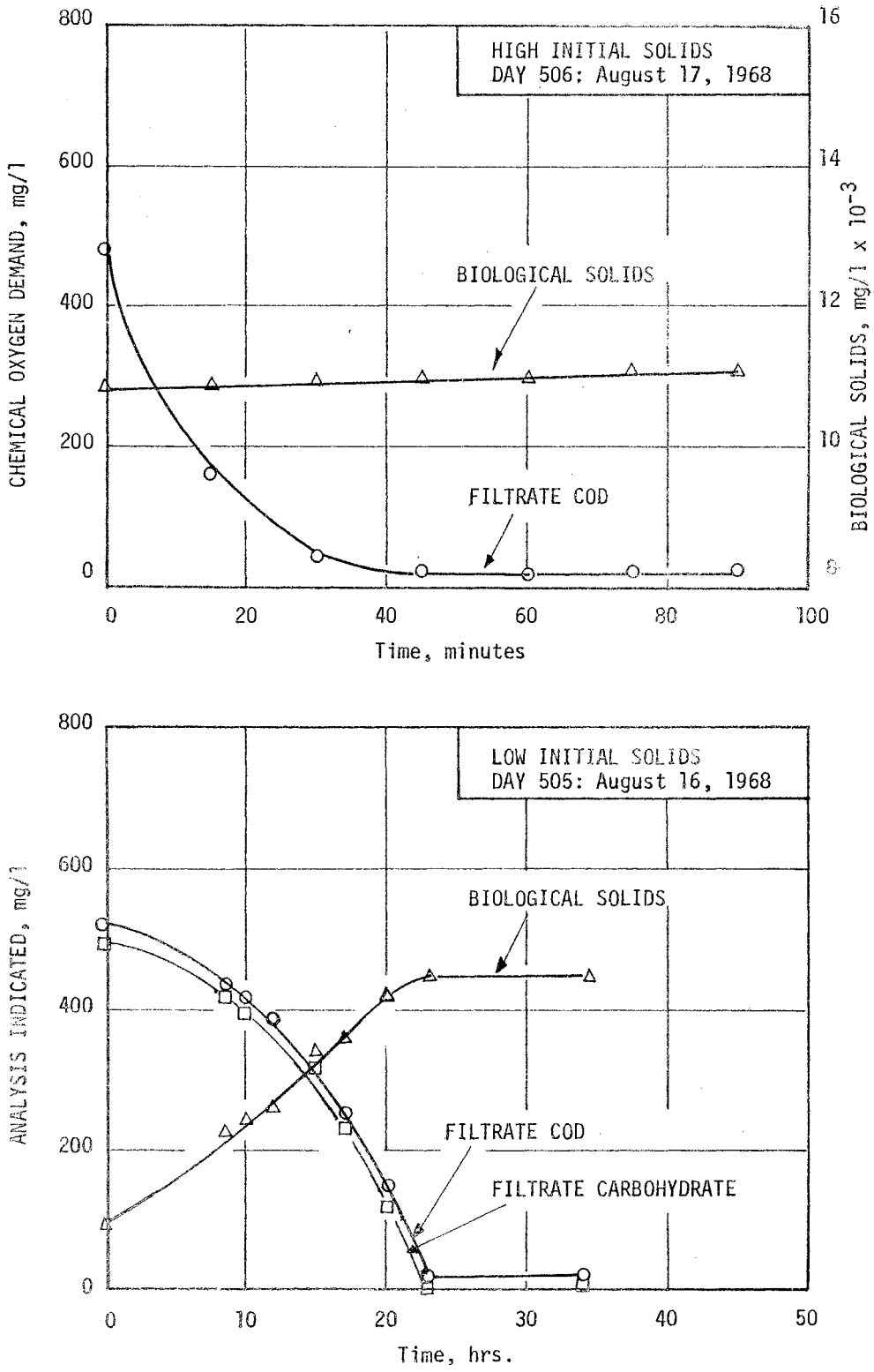
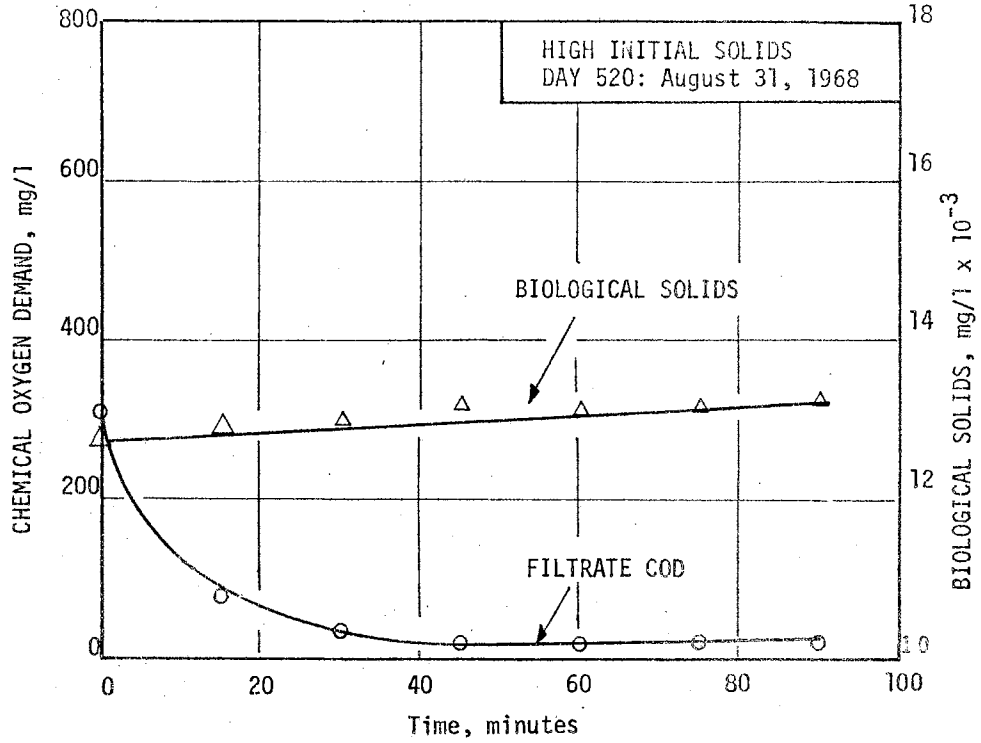


Figure 50 - Response of the extended aeration activated sludge to slug dosage of glucose after 505 days of operation.



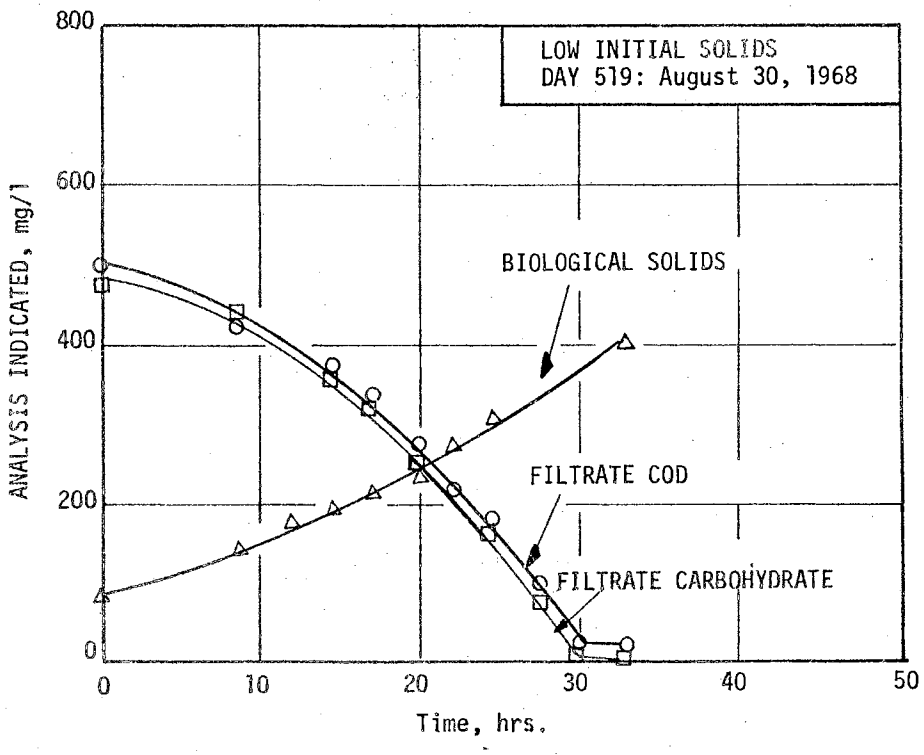


Figure 51 - Response of the extended aeration activated sludge to slug dosage of glucose after 519 days of operation.

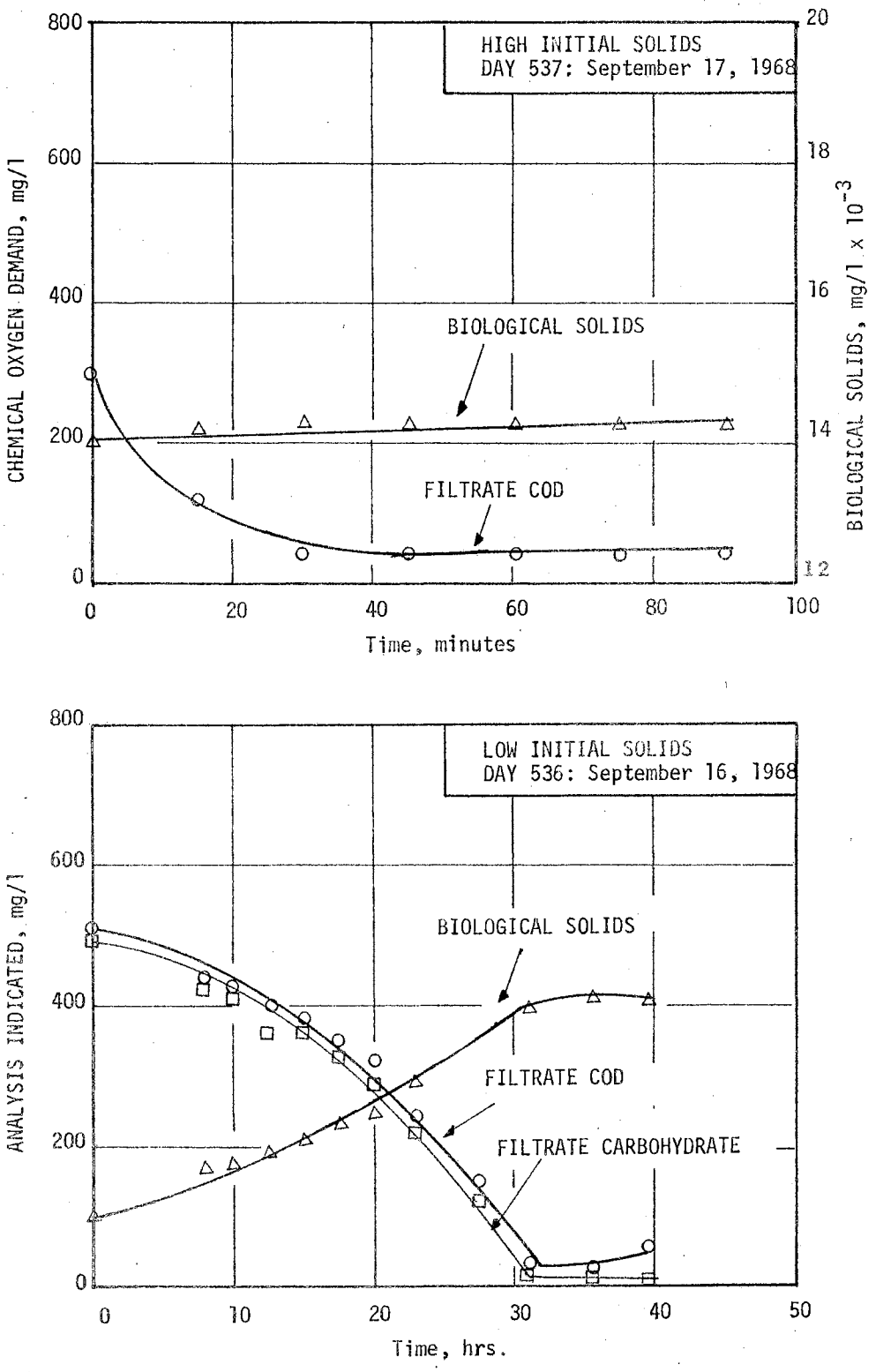


Figure 52 - Response of the extended aeration activated sludge to slug dosage of glucose after 536 days of operation.

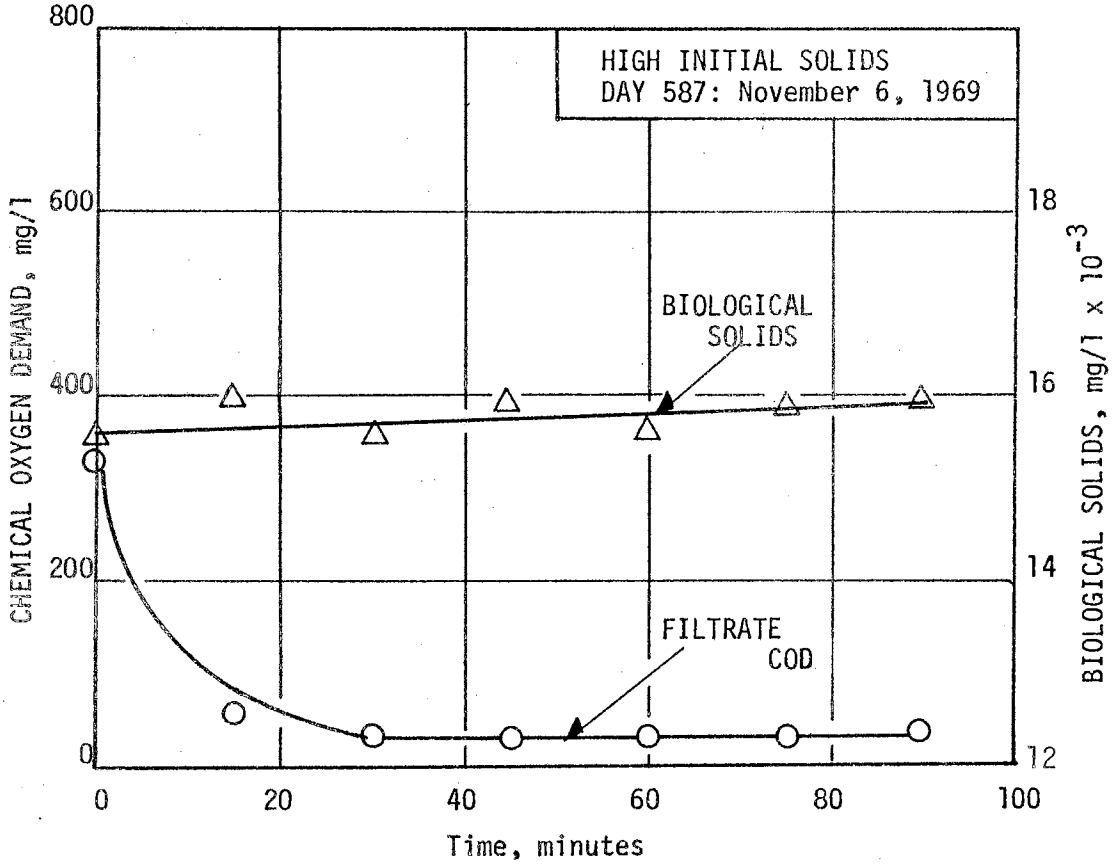


Figure 53 - Response of the extended aeration activated sludge to slug dosage of glucose after 587 days of operation.

rising. As mentioned previously, the mode of batch operation was such that the normally low residual COD observed during continuous flow operation could not escape from the unit during batch periods of operation. However, the results shown in Figure 32 would appear to indicate that at the time the run was made, some of the buildup in residual COD was caused by decreased ability of the cells to metabolize the substrate. Unfortunately, anthrone analyses were not made at this time and there was no way of estimating the nature of the residual COD. In other work (9) the residual COD was also high during batch operation of an extended aeration unit, and carbohydrate analyses run in conjunction with COD's showed that the residual COD was not due to the original substrate. Two additional high initial solids runs were made during the period of batch operation, one on day 229 (Figure 33), and one on day 243 (Figure 35). At the time these runs were made, the residual COD had levelled off at approximately 500 mg/l. It is seen in both Figures 33 and 35 that the amount of COD (500 mg/l glucose) which was fed was removed in less than 1.5 hours. On this basis it was concluded that the high residual COD in the unit was not an indication of loss of COD removal capability of the sludge, but was a result of accumulation of the small residual COD which normally would have been in the effluent during continuous flow operation but was prevented from escaping during batch operation. The same effect was noted in other studies (9).

In all runs made directly in the extended aeration unit (high initial solids) with the exception of the run on day 218, the COD was removed very rapidly, usually in less than two hours, and often in approximately thirty minutes. During periods of continuous flow

operation, the detention time in the aerator was 16 hours, and it was 23 hours during periods of batch operation. Thus the detention time was much in excess of that absolutely required. The low initial solids experiments indicate that the cells do not go into a log phase rapidly, and that the population is a rather slow-growing one. For many of the experiments at low initial solids concentration the course of substrate removal was determined by the anthrone test as well as COD analyses (see Figures 37 through 39, and Figures 39 through 52). It is seen that in general, both analyses give similar values, thus for these slower-growing cells there was no evidence for the accumulation of metabolic intermediates and/or endproducts.

3. $PO_4^{\equiv}$, NH_3-N, NO_2-N, and NO_3-N in the Effluent (Filtrate)

The removal of phosphate and nitrogen by extended aeration plants or, on the other hand, the emission of these materials by such plants, is of increasing interest. It was therefore appropriate to gain some insights into this aspect. Such analyses were not run on a routine basis, but betweeen days 351 and 664, thirty-one samples were examined. The results are shown in Table II. In the present study the PO_4-P and NH_3-N concentrations in the feed were 169 mg/l and 53 mg/l, respectively. It is interesting to note that at times the effluent PO_4-P concentration was higher than the influent concentration. This result may be attributed to release of phosphate by the cells. In general, small quantities of NO_3-N were noted. It would appear that the lengthy aeration period (16 hours) did not enhance excessive nitrification. Organic nitrogen was not run on the filtrate.

TABLE II

INORGANIC PHOSPHATE, PHOSPHORUS, AND NITROGEN CONTENTS IN THE EFFLUENT (FILTRATE), mg/l

	Date	Age of Sludge* Days	$PO_4^{\equiv}$	P	NH_3-N	NO_3-N	NO_2-N	Total Inorg. N
1968	3-15	351	384	125	25	10	<0.1	35.0
	22	358	399	130	31.5	7.5	"	39.0
	4- 4	371	395	129	26	9.5	"	35.5
	10	377	425	138	25.5	6.3	"	31.8
	20	387	390	127	23	6.3	"	29.3
	29	396	565	184	26	4.3	"	30.3
	5- 8	405	555	180	26	2.8	"	28.8
	14	411	445	145	22	3.2	"	25.2
	23	420	445	145	26	3.2	"	29.2
	6- 3	431	445	145	30.5	3.2	"	33.7
	13	441	465	153	27.5	3.2	"	30.7
	21	449	-	-	25	3.2	"	28.2
	29	457	380	124	25	3.2	"	28.2
	7-12	470	540	176	25	3.2	"	28.2
	19	477	510	166	49	2.1	"	51.1
	26	484	420	137	25.5	3.2	"	28.7
	8- 4	493	395	129	25.5	3.1	"	28.6
	13	502	435	142	25.5	3.2	"	28.7
	24	513	460	150	25.6	2.2	"	27.8
	9- 1	521	465	153	25	3.2	"	28.2
	11	531	465	153	26.2	3.7	"	29.9
	24	544	800	260	37	8	"	45
	10- 9	559	400	130	28.8	1.9	"	51.2
	12	562	465	153	28.2	2.3	"	51.2
	11- 3	584	800	260	33	3.4	"	36.4
	12	593	680	222	41	1.4	"	42.4
	23	604	600	195	40	2.5	"	42.5
	12- 7	618	620	202	36	3.4	"	39.4
	24	635	520	170	42.8	8.3	"	51.1
1969	1-10	652	655	214	40	7.2	"	47.2
	22	664	265	90	16.5	4	"	20.5

*Time in days since startup of the extended aeration unit.

Note: Influent $PO_4^{\equiv}$ concentration = 518 mg/l
Influent PO_4 - P concentration = 169 mg/l
Influent NH_3-N concentration = 53 mg/l.

CHAPTER V

DISCUSSION

The extended aeration process for the treatment of organic waste has received considerable attention by researchers during the past two decades. The majority of workers have concluded that biological solids concentration will continue to build up and cause the ultimate failure of such systems. Therefore, it has been generally concluded that sludge wasting is necessary to avoid the final failure (i.e., prevent loss of ability to metabolize substrate). The present study was originally designed to determine the time required to produce such failure in a system in which no sludge was wasted. The results after nearly two years of operation of an extended aeration system with no sludge wasting indicate that the system has not yet lost its biochemical efficiency. The effluent quality compares favorably with that of the more conventional (sludge wasting) activated sludge plants. The results also show that sludge does not accumulate steadily, but there are periodic cycles of decreasing solids concentration followed by succeeding periods of solids accumulation. Furthermore, during the periods of decreasing solids concentration, no gross leakage of COD in the effluent has been observed. Since biological solids were neither intentionally nor accidentally wasted and there were no external stresses, such as changes in pH, temperature, etc., to which the

decreasing cycles can be ascribed, it seems reasonable to conclude that the periodic relief of solids accumulation is brought about due to natural phenomena, and for causation of this effect it is necessary to examine the nature of the ecosystem in an extended aeration activated sludge.

Activated sludge consists of bacteria, protozoa, rotifers and, sometimes, nematodes. The bacteria are generally considered to be the most important group of microorganisms, for they are the ones which metabolize most of the soluble organic matter in the waste water. The use of an extended aeration was first suggested on the surmise that during endogenous metabolism of the bacteria they would autodigest their biomass. It is well known that endogenous respiration can cause the reduction of cell mass, but this does not indicate that any species of microorganism can totally oxidize itself. However, it is known that species of microorganisms undergo complete or nearly complete autolysis after attaining a maximum growth level (15)(16), thus the cellular materials can become available as food for the other species. If no other species were present, the system would fail. Fortunately, activated sludge represents a mixed population system, and other species are present. Also, the various microorganisms can produce enzymes which can cause the partial lysis or complete dissolution of other cells; thus, it is not necessary to rely on autolysis for relief of solids accumulation (16)(17)(18)(19). Another way a decrease in biological solids concentration can be brought about is through bacteriophage-induced lysis. Fortunately, this kind of infection, if it occurred in the activated sludge system, would not affect all species in the ecosystem, since specific bacteriophage infect specific species,

thus relief of sludge accumulation but not total killing can be expected. All of the above mechanisms can convert cell material into exogenous substrate. In order for it to be used, it is necessary that species which possess the metabolic capability to utilize it as a substrate be present, or else the quality of the effluent will deteriorate. In the present study such species were apparently present, since the effluent COD did not rise appreciably during cyclic decrease in biological solids concentration. It cannot be expected that cell disruption or dissolution will stay in balance with cell synthesis thus allowing the system to operate at some equilibrium solids concentration. Attainment of constant biological solids concentration would require a precise balance between the specific natural lytic agents and species which could metabolize the various cell components which are made available as substrate. Such a situation might exist at times, but it cannot be expected to be the normal state of the system. One must expect an ever-changing population to exist in an activated sludge. In addition, an extended aeration system is a low organic loading system, and the cells exist under starvation conditions. Ability to compete for the limited supply of substrate is a principal factor in determining the prominence of microbial species in environments in which the demand for the substrate greatly exceeds the supply. Since the nature of the cell constituents can be expected to change, so, too, can the predominant bacterial species. In addition to bacterial interactions, predatory and parasitic relationships are operative in natural ecosystems. The action of protozoa feeding upon bacteria, the action of myxobacteria and myxomycetes upon bacteria, and the parasitism of one fungal species by another can be expected to be operative in activated sludge systems

(especially in the highly competitive environment of the extended aeration activated sludge system). All of these factors militate against development of stable or equilibric conditions with respect to biological solids concentration in an extended aeration system. The time required to complete a cycle of net accumulation and net decrease of sludge cannot be predicted, nor can the periodicity of such cycles, but the results of this study to date attest to the fact that such cycles do exist. It is worthy of note that the data of Washington, et al. (20) also suggests that in the total oxidation system cyclic reduction in biological solids accumulation can occur.

Results of recent experiments with heterogeneous populations have indicated that the soluble cell fraction, released after mechanical breakage of cell walls, provides an excellent substrate for microbial growth (21). In other recent work employing heterogeneous populations, systems have been observed wherein essentially total oxidation of sludge synthesized in the log and declining growth phase has occurred in a subsequent prolonged endogenous phase (22)(23).

During the present study there were times when the sludge did not settle very well. However, the settling problem was no greater than that often observed in normal activated sludge processes (sludge wasting systems). When solids built up to very high levels, settling problems can be anticipated. There are various engineering expedients which might be employed to alleviate the sludge settleability problem during periods of extremely high solids concentration (10). Thus there is reason to believe that the settling problem is not an insurmountable one, and can eventually be solved.

The results of this experimentation do not contribute much to

remove the stigma of theoretical or mechanistic "unsoundness" which has surrounded the process. However, the results should not be construed as a guarantee that the process will not or cannot fail. The results may be interpreted as a definite indication that the process is not theoretically unsound. Its successful operation depends upon developing in the population (either naturally or possibly through bioengineering procedures) the unique combination of agents to disrupt or dissolve an excess portion of the population, and those agents (microbes) which can metabolize the substrates which have been made available. There may be long periods when the required combination of organisms is not present. During such times, sludge can be expected to accumulate. If the period is long enough and cells which can in essence feed on other members of the population do not develop, the various cell components may indeed be considered "biologically inert." They are inert until cells develop which can use them. The results to date indicate that such species will develop. Even if the systems failed now, after two years of successful operation, it would still have to be adjudged a successful one. In the field, if extended aeration systems had to be restarted after two years, it would still provide a satisfactory and economical engineering expedient in which secondary treatment was accomplished without the expense of separate sludge digestion.

CHAPTER VI

CONCLUSIONS

On the basis of this work, the following conclusions seem warranted:

1. In an extended aeration activated sludge process, with all solids returned to the aeration tank, the biological solids concentrations will not necessarily keep building up. The biological solids concentration decreased periodically, and causation for this effect can be attributed only to natural phenomena characteristic of the heterogeneous population comprising the activated sludge.

2. After nearly two years of operation, the system has not lost its ability to remove a reasonably high organic loading (500 mg/l glucose, retention time 16 hours). Furthermore the substrate removal studies indicate the sludge capability for removing the substrate exceeds the loading which is being applied.

3. In accordance with conclusions one and two, it seems apparent that it can no longer be considered that total oxidation is theoretically impossible. On the basis of the present results, it seems reasonable to make a tentative recommendation for wider application of the extended aeration process. It should prove a useful method for treatment of soluble organic industrial wastes.

CHAPTER VII

FUTURE WORK

The present results warrant a re-examination of the extended aeration process, since they have done much to remove the stigma of theoretical unsoundness which has been associated with this process since it was first proposed. The major work which should be undertaken next is the investigation of the natural causes by which periodic relief of solids accumulation is brought about. Work designed to assess the operation of these ecological mechanisms may not lead to engineering predictions of the extent and periodicity of the decreasing solids cycles, but may provide further proof of the theoretical soundness of the process. Work should also be undertaken to determine if various bioengineering expedients, i.e., external controls designed to enhance lysis, changes in predominance, etc., can be employed to control the solids level in the system. Work on ways and means to enhance settling, or work on other possible means of separating the solids from the effluent is also warranted.

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VITA

Ping-Yi Yang

Candidate for the Degree of

Master of Science

Thesis: STUDIES ON THE OPERATIONAL STABILITY OF THE EXTENDED AERATION PROCESS

Major Field: Bioenvironmental Engineering

Biographical:

Personal Data: Born in Hu-Wei, Taiwan, China, January 12, 1938, the son of Chai-Fong Yang and Wun-Foung Yang.

Education: Graduated from Provincial Hu-Wei High School, Yun-Lin, Taiwan, in June, 1957; completed requirements for the degree of Bachelor of Science from National Taiwan University, Taipei, Taiwan, in June, 1961. Completed requirements for the degree of Master of Science at Oklahoma State University in August, 1969.

Professional Experience: Food Officer, Chinese Army (1961-1962); research worker in the Wei-Hsin Food Company, Taipei, Taiwan (1962-1967); Bioenvironmental Engineering Research Assistant while a graduate student at Oklahoma State University, Stillwater, Oklahoma.

Membership in Professional Societies: Chinese Agricultural Chemical Society; American Water Works Association.