CONTINUOUS ROTATING BIOLOGICAL CONTACTOR FOR DENITRIFICATION

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By

SELCUK SOYUPAK, M.Sc.

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AUTHOR : Selcuk Soyupak, M.Sc.
(Middle East Technical University)

SUPERVISOR: Dr. K.L. Murphy

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ABSTRACT :

This work presents the results of a pilot plant study where a completely submerged rotating biological contactor was used for denitrification of domestic wastewater.

The literature review emphasizes the existing knowledge on RBC operation and design fundamentals. A brief summary of the theory of denitrification has been presented as this subject already has been presented in detail by various authors.

Dye studies were performed for 4 stage series operation and single stage operation. A two CSTR with interchange flow model seemed to fit the hydraulic model for single stage operation. The dye response was observed

to be function of biological growth which in turn varied with temperature.

"Zero order" kinetics were shown to represent the data obtained for denitrification rates at hydraulic loadings of 2.5 l/min and 4.0 l/min best for the range of NO_3+NO_2-N concentrations studied.

An energy of activation of 16,500 kcal/mole was calculated for hydraulic loading range of 2.5-4.0 l/min.

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ABBREVIATIONS AND SYMBOLS

A_o : frequency factor
BOD : biochemical oxygen demand
BOD_5 : 5 day biochemical oxygen demand
BST : batch stirred tank

°C : degrees Centigrade
cal/mole: calories per mole
cm : centimeter
COD : chemical oxygen demand
CSTR : continuous stirred tank reactor

DO : dissolved oxygen

E : activation energy
Et : dimensionless residence time distribution

F : area under RTD curve
°F : degrees Fahrenheit
ft : feet
ft^2 : square feet

g : gram
gpd : gallons per day

hr : hour
hrs : hours

K : reaction rate or reaction rate constant for $n=0$ or $n=1$ respectively
^{o}K : degrees Kelvin
l : liter
l/min : litre/minute

MLSS : mixed liquor suspended solids
MLVSS: : mixed liquor volatile suspended solids
m : meter
m^2 : meter square
mg : miligram
min : minute
mg/l : miligram per litre
mm : milimeter

NO_2-N : nitrite nitrogen
NO_3-N : nitrate nitrogen
NH_3-N : ammonia nitrogen

pH : logarithm of hydrogen ion concentration
ppb : parts per billion

R : gas constant
RTD : residence time distribution
rpm : revolution per minute

SS : suspended solids
SRT : sludge retention time

T : temperature
TKN : total Kjeldahl nitrogen
TOC : total organic carbon
t : time

Θ : dimensionless time

α : confidence level

$\int$: integral

% : percent

$>$: greater than

$>>$: considerably greater than

1. INTRODUCTION

The Rotating Biological Contactor (RBC) has in the past been used for removal of carbonaceous BOD extensively. In addition, some investigators have proposed its use for nitrification and algae nutrient removal. Only one reported attempt, Pretorious (1971) has been located that uses the Rotating Biological Contactor (RBC) system for denitrification.

Although the Rotating Biological Contactor treatment system is basically a biological treatment system and the basic principles of biological treatment have been thoroughly studied, the exact mechanisms of removal by the RBC is not known. Different design techniques have been proposed by different authors.

The aim of this study is to review existing knowledge about RBC operation and design formulation, and to study the effects of various operating variables (temperature, hydraulic loading, and mode of operation) on denitrification by the completely submerged RBC.

2. REVIEW OF EXISTING LITERATURE

Since basic principles of biological treatment for carbonaceous BOD removal and nitrification have been well documented by various investigators and authors, they will not be repeated. Rather emphasis will be placed on the Rotating Biological Contactor.

2.1 Rotating Biological Contactors

2.1.1 The Definition and Physical Description of RBC

Partially Submerged RBC Systems

The RBC unit is a series of discs closely spaced on a shaft which is rotated just above the surface of waste liquid to be treated. The discs are believed to perform five specific functions (Antonie, 1974):

a) provide a large amount of available surface area for the development of a fixed biological growth,

b) provide contact of this growth with the wastewater,

c) efficiently aerate the wastewater by carrying a thin film of liquid from the tank,

d) provide a controlled, mechanical means of stripping excess biomass from the surfaces, and

e) provide thorough mixing of each stage of treatment.

Various disc diameters are being used in practice; Antonie (1974) employed a unit of 3.7 m, Steels (1974) used diameter of 3.0 m, while Bruce (1973) described a package plant developed for small communities with 1.0 m disc diameter. McAliley (1974) used a diameter of 3.7 m while Summer (1973) and Antonie (1970) indicated that discs up to 3.0 m diameter are available. Chittenden (1971) described his system consisting of 3.3 m discs. It is apparent that the diameter varies with the company producing the RBC although 3.0 m diameter is normal except for specific package plants.

The typical disc spacings used in practice have been reported by Chittenden (1971) who indicated that typical center to center distance of discs to be 2.5 to 3.8 cm. Bruce (1973) indicated that a 10.0 mm gap between adjacent surfaces for a package plant was used while Antonie (1970) employed 2.5 cm center to center spacing for a package plant of 1.8 m diameter discs. Normally the disc spacings are fixed by the manufacturers of the RBC.

The third property fixed by the manufacturer is the rotational speed; Beak (1973) gave 1 rpm as typical for a 3.0 m diameter disc. One rpm for a 3.0 m diameter disc was also quoted by Steels (1974), and Bruce (1973) for a package plant.

It must be concluded that various combinations of different disc diameters, speeds (rpm's) and disc spacings are possible depending upon the specific field of applications.

Totally Submerged RBC Systems

This type of system is employed when aeration is not essential and/or desirable. The current literature does not give any application of this type of RBC.

2.1.2 Historical Development and Various Applications

A rotating disc was first used by Doman (1929). Maximum BOD_5 removal achieved was 27%. The apparatus that he used was a series of partially submerged discs rotated at 0.5 rpm. The detention time was 2.4 hrs and maximum microbial film thickness was less than 0.8 mm.

Thirty years passed before the RBC was again used to treat wastewater. Grieves (1972) in his literature survey stated that, Hartmann had experimented extensively with a rotating disc plant in 1958. The following conclusions were reported:

a) the optimal rpm was 5 to 7 for a 1.0 m diameter disc,
b) the optimum disc spacing was at 15.0 mm,
c) the discs should be submerged as deeply as possible,

d) best performance occurred when the disc rotation was in the direction of the wastewater flow,

e) staging was advisable from a "construction view point", but did not affect efficiency,

f) the system was especially suited to small plants, because of its low maintenance costs and insensitivity to fluctuations in load, and

g) the operational cost was "considerably less" than those for activated sludge or trickling filter processes.

Grieves (1972) cited further contributions by Hartmann and Popel in Europe around the mid-sixties. Most of the existing literature in the English language appeared after 1968.

2.1.3 Mechanism of Removal by RBC

After commencement of operation with any substrate, a layer of microbial film develops on the surfaces of the discs. The film is submerged in the substrate to absorb food and emerges into the air to absorb oxygen. During submersion of the disc, oxygen is transferred from the liquid film to substrate and substrate removal by the film continues. Hartmann (Steel, 1974) believed that the organisms which are suspended in the liquid also aid in substrate removal.

2.1.4 Factors Affecting the Performance of RBC

To describe mechanistically the performance of any RBC system would be cumbersome. The success of any such description is doubtful, since there are many independent and interdependent operational variables which affect the ultimate performance of system.

The main factors that effect the performance of an RBC system under steady state conditions are:

1) PHYSICAL FACTORS:

a) the temperature,
b) the physical dimensions of discs (disc diameter, disc spacings),
c) the rotational speed of discs,
d) the physical dimensions of the tank,
e) the physical configuration of the tank,
f) the inlet and outlet arrangements,
g) the oxygen content of surrounding atmosphere, etc.,
h) the hydraulic loading
i) the existence of staging, and
j) the temperature of substrate.

II) CHEMICAL AND BIOLOGICAL FACTORS:

a) the type of substrate, and
b) the concentration of substrate.

The following variables should be added to the above list when non-steady state performance is being evaluated:

a) the pattern of change in the hydraulic loading with time,

b) the pattern of change of the organic loading to the system, and

c) the change of temperature of air and temperature of incoming waste.

As one can visualize, there are many factors affecting the performance of any RBC system. That is why many authors resort to an experimental evaluation by changing some of the important operating variables and observing the response in the RBC performance. Few authors have attempted to develop an overall formula for RBC systems under steady or non-steady operation.

PHYSICAL FACTORS

Temperature

Since the RBC treatment system is basically a biological treatment system, it is not surprising that it is temperature dependent.

Many investigators have studied the effects of temperature on the performance of the RBC. Antonie (1970) as a result of his pilot plant study, reported that for any specified operating conditions, as the wastewater temperature was reduced, the performance also was reduced. This reduction was not significant between 10° and 21°C but was drastic below 10°C. Similar trends have been observed for Kjeldahl and NH_3-N removal and the author suggest the use of higher residence times to achieve the desired performance levels.

Antonie (1974) in his introduction of the "Bio-Surf" process as an NH_3-N removal device reported that the process efficiency was reduced drastically below 55°F. For 95% removal, Q_{10} (between 55-45°F) is given as 1.70.

Pretorius (1974) reported that the energy of activation was equivalent to 3658 cal/mole giving Q_{10} (between 10°C-20°C) equal to 1.25. This was based upon a laboratory study of nitrification by RBC system.

Davies and Pretorius (1975) studied denitrification by RBC systems. Their anaerobic unit was only partially submerged. They reported 3 different temperature sensitivity zones for denitrification:

$$Q_{10} = 13.06 \text{ for } T<10 \text{ C}$$

$$Q_{10} = 1.38 \text{ for } 10^\circ\text{C}-30^\circ\text{C}$$

$$Q_{10} = -2.65 \text{ for } T>30^\circ\text{C}$$

In another pilot plant nitrification study, Wilson (1974) reported a Q_{10} of 2.36 between 10°C and 20°C, and an energy of activation equal to 14,200 kcal/mole.

Oxygen Availability

Authors have different thoughts as to whether or not oxygen enrichment of the atmosphere surrounding the discs helps the performance of the RBC.

The first attempt to enrich the atmosphere to which the discs are exposed, was made by Torpey and his co-workers (1972). Using a 10 stage laboratory unit, they observed the detention time needed for 90% removal of BOD_5 was reduced to 18 minutes, when oxygen enrichment was applied to the first stage of their system. When the first and third stages of the 3 operating stages were enriched, they observed that substantial reduction in NOD was achieved.

No attempts have been made in practice to enrich the atmosphere around the discs to increase the performance. Hartmann (Beak, 1973) believed that oxygen transfer to the biomass is not a limiting factor, and claimed that oxygen enrichment would not be advantageous.

A second study was made by Pretorius (1974) with an enriched surrounding atmosphere to observe its effects on nitrification. For fixed operational conditions, the following results were obtained:

a) enrichment to 40% oxygen increased the reaction rate 1.75 times,

b) at 60% oxygen, the reaction rate was 2 times higher, and

c) at higher values, increases in the reaction rate levelled off.

There does not appear to be sufficient evidence concerning the relative effect of oxygen enrichment in comparison to the other factors affecting the RBC's performance to justify a conclusion. In addition, no attempts have been reported .. whether or not it is feasible to enrich the atmosphere.

Rotational Speed

The important effects of rotational speed will be on:

a) the oxygen transfer from the atmosphere to the disc,

b) the oxygen transfer from the atmosphere to the liquid,

c) the oxygen transfer from the disc to the liquid,

d) the substrate transfer from and to the disc, from and to the bulk liquid, and

e) the organisms.

Many authors have investigated the effects of rotational velocity for their RBC systems performance.

Antonie (1970) as a result of a prototype application showed that, an increase in rpm from 2 to 3.2 increased the percentage of BOD, and NH_3-N removal. A change from 3.2 to 4.6 rpm did not increase the removal efficiency for either NH_3-N or BOD. The COD and SS removal percentages did not show any particular change with increased rpm but increases in rpm resulted in a drastic power consumption increase.

Antonie's observation indicated that there is a certain optimum level of rpm as far as BOD_5 and NH_3-N removal rates concern. His data indicated that it is approximately 3 rpm. This would be specific for only the particular system employed and could be different for other systems or other operating conditions.

In the literature, another optimum value of 5-7 rpm was given by Hartmann (Grieves, 1972) for his 0.90 m diameter disc.

Weng and Molof (1974) studied the effects of rpm values on nitrification with a laboratory scale disc unit. They obtained no nitrification at 10 and 20.5 rpm but at 30 rpm, the NH_3-N concentration was reduced from 26.6 to 22.7 mg/l. When the rpm was increased from 30 to 42, NH_3-N decreased to 17.1 mg/l in the last stage. The authors attributed the cause for the lack of nitrification at 10 and 20 rpm to the presence of excess COD which they claimed had a toxic effect on nitrification.

Another study on the effect of rpm on performance was presented by Welch (1968). The author employed a pilot scale RBC unit on a synthetic sewage. He claimed there was a definite improvement if the rpm were increased for a given fixed hydraulic and organic loading. The author failed to explain whether this increase was due to an increase in D.O. level or due to increased mass transfer.

These studies indicate that there is a definite relationship between rpm and performance values. Any laboratory or pilot plant procedure which is to be used for generation of information for actual full size plant should be operated at optimum rpm values.

Hydraulic Loading

The hydraulic loading is one of the variables which has been most thoroughly studied and is one of the most important design parameters for RBC systems.

Welch (1968) in his pilot-scale study of a synthetic sewage prepared from dairy waste, found that the hydraulic loading affected the plant performance under fixed rpm and influent COD concentrations. Antonie (1970) observed a similar trend for BOD removal, Kjeldahl and NH_3-N removal, and COD removal for domestic sewage. The data examined from both of these references indicated that, to increase the detention time above a certain value does not lead to further improvement.

Similar observations were made by Summer and Bennett (1973) as a result of their pilot plant study on pulp, paper and fireboard effluents, Gillespie et al (1974) from a pilot-scale RBC study on pulp and paper wastes, and McAliley (1974) from a pilot study on unbleached kraft mill waste.

Staging of RBC Units

One of the first comments on the effects of staging was by Hartmann (Grieves, 1972). It was indicated that staging was advisable from "a construction viewpoint", but did not affect efficiency.

In a translation of Hartmann's paper by Steels (1976), the author explained how to design a two stage treatment plant for domestic sewage and pointed out that if the stage number is more than 2, a correction factor should be applied to reduce the required area needed.

Antonie (1970) in his description of the "Bio-Disc" process, claimed that increasing the number of stages, increased the efficiency. Since, in his belief, BOD reduction by the RBC process is concentration dependent, staging should help the system to operate as plug flow reactor.

Joost (1969) claimed that biochemical reaction is concentration dependent following a "first order" equation, therefore, staging would lead to increased economy.

NCASI (1974) reported, that for certain types of wastes at fixed hydraulic loadings, as the number of stages was increased, the cumulative removal increased. Beyond a certain number of stages, it was observed that the removal curve levels off. An interesting observation is that 6 stages at 2 gpd/ft^2 and 4 stages at 3 gpd/ft^2 gave the same performance. Therefore a reduction in the hydraulic loading to a fixed number of stages may do the same job, as increasing number of stages at a fixed hydraulic loading.

Aacken and Antonie (1971) claimed that the most effective use of disc surface area was achieved in successive rows or stages of discs. They stated that this kind of operation resulted in an improved residence time distribution which yielded a greater BOD removal rate. Further it allowed the development of a mixed culture in each stage that is especially suited to treating the wastewater present in that stage.

Torpey _et al_ (1972) claimed that another advantage of staging was that it separated the carbon oxidation phase and nitrification phase thus giving the most efficient results.

Hydraulic Surging and Organic Shock Loading

This is another parameter which has been examined by different authors for their particular systems.

Antonie (1970) simulated the flow pattern of the influent to a pilot plant, from an industrial plant operating 8 hrs and giving an intermittent flow, with constant concentration. During the early hours of the operating period, the quality of the pilot plant effluent was poor. It took several hours to reach a steady performance level. When a small recycle was maintained during the 24 hour period, the removal results were improved.

Popel according to Steels (1974) reported that for a peak load which was 4 times the average load and with a continued duration of 2.5 hrs, the BOD removal rate was higher than it would have been for an uniform load, and that if the loading was extended to 5 hrs instead of 2.5 hrs, the results were worse but still better than the uniform load efficiency.

Popel's observations can be explained if at uniform conditions, the bacteria were not working at their maximum capacity, so it would be possible to remove more substrate in the same system when the peak loading was applied. It would be useful if a parameter which could show the optimum substrate removal capacities of the RBC system could be developed.

A hydraulic surge study conducted by Marki and Antonie (1970) indicated that a RBC system subjected to a ten-fold increase in hydraulic loading for 8 hrs each week still gave significant BOD removals during the shock loading periods. A rapid recovery to steady state condition was observed.

In another study reported by NCASI (1974) on pulp and paper wastes, it was observed that when a hydraulic loading which was 4 times the original loading and of 4 hrs duration was applied, the effect was much less than when influent BOD concentration was raised 4 times the original. Recovery occurred over a shorter period and there was continuing BOD removal activity. Again, the total BOD removal rates were higher than the steady state removal rates. This last observation by NCASI (1974) and Popel's observation are in agreement.

2.1.5 Substrate Removal Kinetics

Joost (1969) claimed that "a first order" reaction is applicable and thus staging should prove beneficial and economical. He gave the following general formula for the RBC system performance:

$$\%\ BOD_5\ \text{Reduction/Stage} = K \times C^a \times R^b \times T^c \times S^d \quad (1)$$

where: K is the treatability constant,
C is the concentration of waste material,
R is the physical configuration of system
T is the temperature of waste,
S is the reactor residence time, and
a, b, c, and d are exponents.

The practical range of applicability was not discussed in detail.

A design method, applicable to a particular domestic sewage, has been developed by Hartmann (Steels 1974). The author has presented design graphs. By knowing only the inlet BOD and using these graphs, the disc area/flow rate required for desired BOD removal efficiencies can be found. The above solution is applicable only for RBCs with two stages. The author also gives factors if more than 2 stages are to be used, and if variations in either hydraulic or organic loadings are anticipated.

It should be emphasized that this method is applicable only, to Germany conditions. Similar methods or charts could be developed for any local conditions.

Another attempt to develop a design method based on pilot-plant data was made by McAliley(1974). He presented the following formula for the specific removal rate:

$$\frac{F(S_i - S_o)}{A} = P \frac{S_o}{K + S_o} \qquad (2)$$

where: F is the flow rate,

S_i is the influent substrate concentration,

S_o is the effluent substrate concentration,

A is the area respectively, and

P and K are the constants to be developed from pilot-plant work.

The above equation indicates the existence of two different rate dependency regions where $K \gg S_o$ the expression is first order and where $S_o \gg K$ it is zero order. The above method seems to be applicable for design of RBC systems, but more work in this direction is needed to show its validity. Further, one can anticipate scale up problems resulting from the applicability of P obtained from pilot plant work to predict the actual full scale removal rate.

McAliley introduced another useful concept in RBC design, that is the oxygen limiting point of operation where oxygen transfer rate is less than the reaction rate.

Grieves (1972) attempted to develop a steady state and dynamic model to represent the RBC performance. He tried to demonstrate the validity of his model by concurrent laboratory studies. He found that the experimental results and results predicted by the model gave good conformance. NCASI used Grieves' model without success but they indicated that the failure could have been caused by scale up difficulties.

3. A SHORT REVIEW OF ESSENTIALS OF DENITRIFICATION

Biological denitrification is the last step of biological nitrogen removal from wastewaters following the nitrification step.

Biological denitrification is basically an anaerobic process employing heterotrophic micro-organisms. These organisms utilize the NO_3 as a hydrogen acceptor to derive energy for their activities, in the presence of an acceptable organic energy source.

The various mechanisms involved in the biological denitrification process has been reviewed by various authors and these reviews will not be repeated as excellent literature reviews are already available. Rather the theory and the important results of the basic denitrification processes will be presented.

3.1 Basic Reactions Involved in Denitrification

3.1.1 Reactions:

Denitrification can be defined as a two step process. Methanol is generally used as a carbon or energy source.

The denitrification reactions can be written in the following manner:

Step 1: NO_2^- formation:

$$NO_3^- + 1/3\ CH_3OH \rightarrow NO_2^- + 1/3\ CO_2 + 2/3\ H_2O \qquad (3)$$

Step 2: N_2 gas formation:

$$NO_2^- + \tfrac{1}{2}\ CH_3OH \rightarrow \tfrac{1}{2}N_2 + \tfrac{1}{2}CO_2 + \tfrac{1}{2}H_2 + OH^- \qquad (4)$$

The above equations represent only the nitrate dissimilation part of denitrification. McCarty (1973) presented the following resultant equation for both nitrate dissimilation and bacterial production:

$$CH_3OH + 0.92\ NO_3^- + 0.92\ H^+ \rightarrow 0.06\ C_5H_7O_2N$$
$$+ 0.43\ N_2 + 0.7\ CO_2 + 2.25\ H_2O \qquad (5)$$

Therefore theoretically it is natural to expect, 0.95 g CH_3OH-C (methanol carbon) utilization for denitrification of each g of NO_3-N, with the production of 0.53 g of micro-organism.

McCarty, Bech, and St. Amant (1969) gave the following formulas for calculating actual micro-organism production and methanol requirement based upon their denitrification studies.

For biomass production:

$$C_b = 0.53\ N_o + 0.32\ N_1 + 0.19\ DO \qquad (6)$$

where: C_b is the biomass produced in mg/l,

N_o is the initial NO_3-N concentration in mg/l,

N_1 is the initial NO_2-N concentration in mg/l, and

Do is the dissolved oxygen concentration of influents in mg/l.

Dissolved oxygen is another consumer of CH_3-OH, as in the presence of oxygen and a carbon source growth of aerobic bacteria will occur.

For methanol consumption:

$$C_m = 0.53\ NO + 0.32\ N_1 + 0.19\ Do$$

where: C_m is the required methanol (mg/l)

The experimental results obtained by Sutton, Murphy and Dawson (1974) confirmed the estimates from the above formulas.

3.1.2 Kinetics of Denitrification

Various authors have indicated the denitrification rate to be zero order with respect to NO_3-N concentration for suspended growth systems if CH_3-OH is supplied in sufficient quantities and the NO_3-N concentration is above 1.0 mg/l.

These authors include Moore and Schroeder (1970), and Murphy and Sutton (1974).

In addition, Sutton, Murphy and Dawson (1975) and Requa and Schroeder (1973) indicated the denitrification rate to be zero order with respect to NO_3-N concentration for supported growth systems. Harremoes (1975) reported that the denitrification rate was half order with respect to NO_3-N, owing to diffusion limitations in supported growth systems.

3.1.3 Temperature Dependency

The temperature dependency of denitrification processes is one of the most thoroughly studied aspect of denitrification since it is essential factor for process design and volumetric determination.

Table 1 gives the type of processes and the corresponding temperature dependency relationship presented by various authors. The authors listed in Table 1. presented the temperature dependency of denitrification as an empirical expression

$$K = A_o \, e^{-E/RT} \tag{8}$$

where: K is the zero order reaction rate,
A_o is the constant
E is the activation energy,
R is the gas reaction constant, and
T is the temperature in ^oK.

TABLE 1

TEMPERATURE DEPENDENCY OF VARIOUS DENITRIFICATION UNITS

Type of Systems	Frequency Factor A_o	Activation Energy E	Author
BST SRT = 3 days	6.78×10^{14}	20,400	Sutton and Jank (1976)
BST SRT = 6 days	4.78×10^{9}	13,900	"
CSTR SRT = 3 days	8.76×10^{8}	12,900	"
CSTR SRT = 6 days	1.08×10^{11}	15,900	"
CSTR SRT = 9 days	8.76×10^{10}	15,650	"
BST + CSTR SRT = 3 days	5.42×10^{10}	15,300	"
BST + CSTR SRT = 6 days	1.11×10^{11}	15,900	"
Pall Rings	2.89×10^{6}	7,025	"
Intalox Saddle	2.97×10^{9}	11,090	"
Batch Laboratory	3.195×10^{11}	+16,800	Dawson and Murphy (1972)

Pretorious and Davies (1974) define 3 different temperature dependency regions for denitrification rates achieved by RBCs namely:

$$Q_{10} = 13.06 \text{ for } T<10^{\circ}C$$

$$Q_{10} = 1.38 \text{ for } 30^{\circ}C>T>10^{\circ}$$

$$Q_{10} = -2.65 \text{ for } T>20^{\circ}C$$

where: Q_{10} is the rate increase for 10°C temperature increase, and

T is the temperature in °C.

One of the main purposes of this study is to determine the temperature dependency relationships for denitrification by the RBC under different hydraulic loadings.

4. EQUIPMENT AND PROCEDURES

4.1 Pilot Plant and Reactor Descriptions

The RBC unit used in this study comprises part of a pilot plant facility located at the Wastewater Technology Centre at CCIW, Burlington, Ontario. The pilot plant was installed expressly for nitrification and denitrification research. Figure 1 indicates a simplified flow diagram of the pilot plant. The screened raw sewage is obtained continuously from Burlington Skyway Sewage Treatment Plant. The nitrified effluent passes through a temperature control unit. A NO_3^--N spike is applied when necessary. The nitrified effluent then enters the denitrification units.

The RBC used for denitrification in this study was an Autotrol Bio-Surf, Serial No. 7415. The unit was originally manufactured as a 4 stage reactor (Figure 2). There are a total of 44 discs (11 in each stage) with a total surface area of 306 ft^2 (28.4 m^2). Rotation was at 13 rpm. The diameter of discs was 47.3 cm (18-5/8 inch). The total volume of the total unit was 408 ℓ for 4 stage operation. This measurement was done when biological growth existed on the discs. The volume for single stage operation was measured as 100ℓ.

FIGURE NO. 1 SIMPLIFIED FLOW DIAGRAM OF NITRIFICATION/ DENITRIFICATION PILOT PLANT

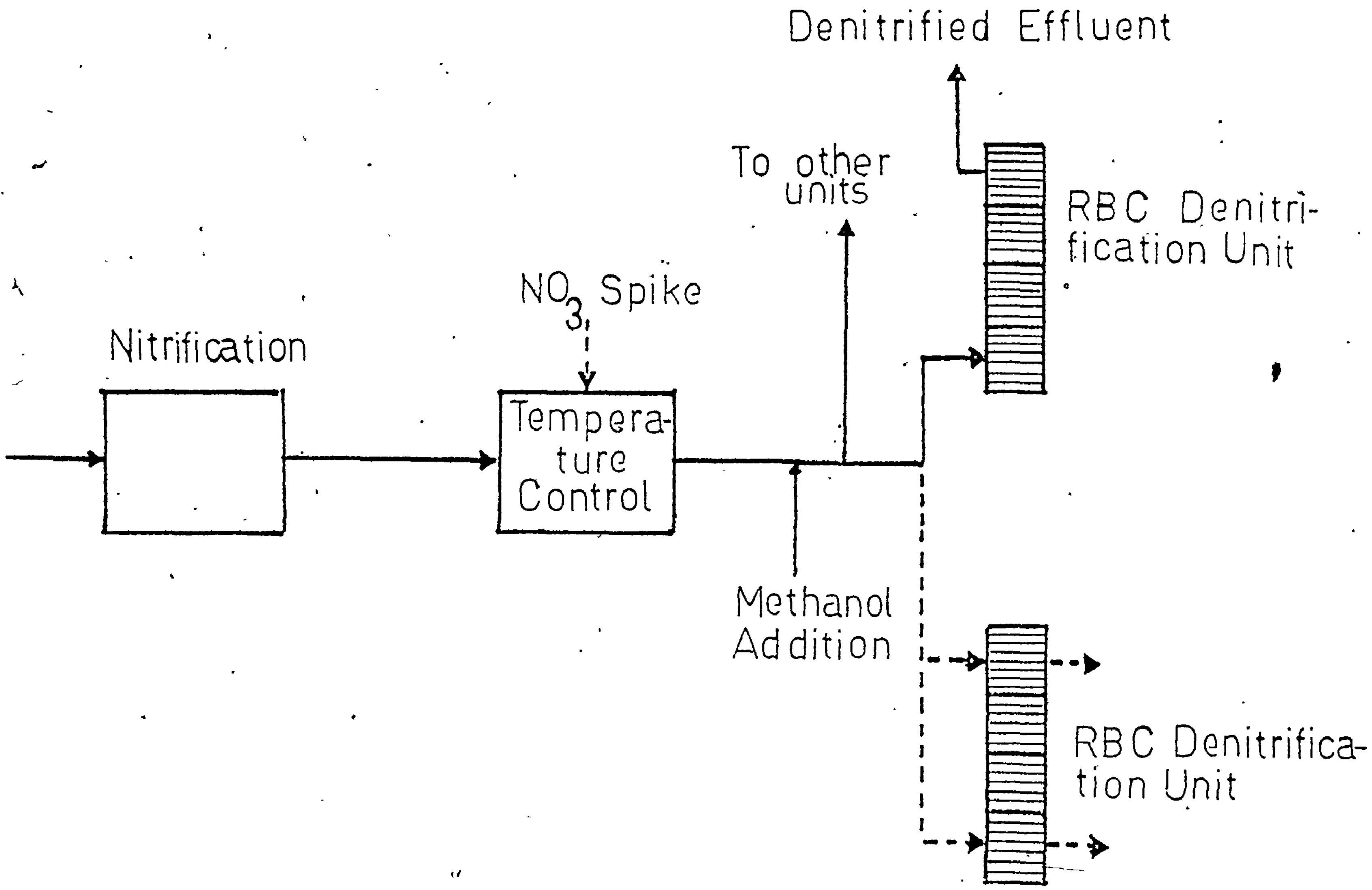
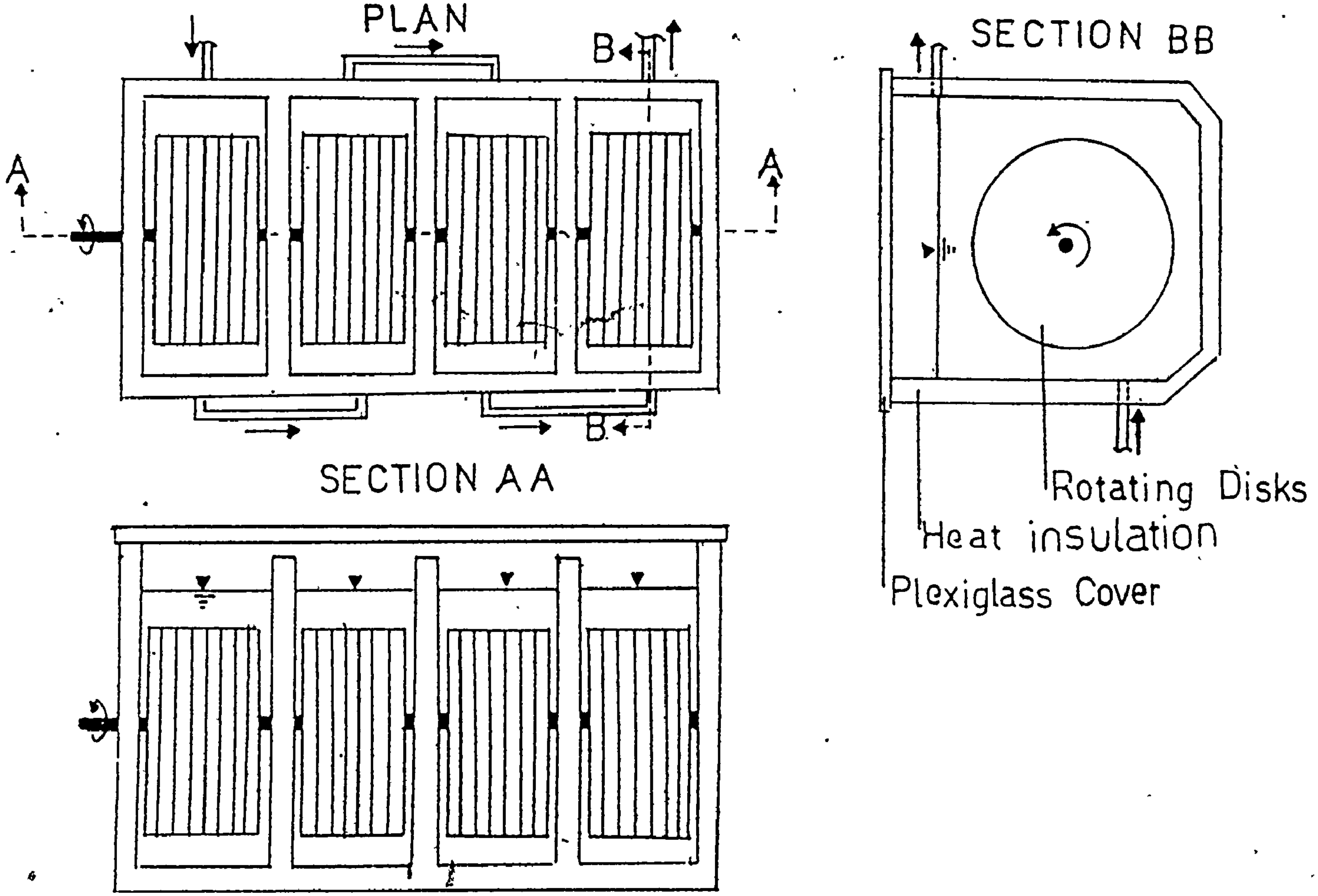


FIGURE NO. 2 COMPLETELY SUBMERGED RBC



Variable speed positive displacement pumps delivered nitrified secondary effluent to the submerged RBC unit.

4.2 Start Up

The RBC had been operated two months before the initiation of the experimental program. No attempt was made to evaluate the minimum start up time required. The original unit provided by Autotrol was covered with one half inch (1. 3 cm) styrofoam on the sides to reduce the heat transfer and to obtain a relatively constant temperature in all stages of RBC.

4.3 Experimental Program and Work

Since the purpose was mainly to investigate the basic design criteria of RBC as a denitrification unit, the effects of the following design variables or controlled factors were investigated - temperature, hydraulic loading and mode of operation (single stage or 4 stage in series).

It was planned to run the RBC under temperature levels of 5°C, 10°C, 15°C, 20°C, and 25°C (two runs for each temperature level) for 4 stage in series operation. This original program was altered later, since unreasonable and impractical amounts of NO_3-N spike were needed to have measurable quantities of NO_3-N in the effluent to determine removal rates. Only single runs were employed with the 4 stage in series operation.

Similarly, two runs were planned for temperature levels of 5°, 10°, 15°, 20°, and 25°C, at hydraulic loadings of 2.5 l/min and 4.0 l/min of single stage operation.

As it was expected that the dye response would be a function of the biological growth which existed on the discs, dye studies at 4 different temperature levels with biological growths specific to that temperature level were carried out. A separate dye study was made after all growth on the discs was stripped off.

Detailed experimental designs for single stage operation and 4 stage series operation are included in the appendix. The plant was operated at least 5 days before taking samples for the determination of denitrification rates at any specified operating condition.

4.4 Feed Characteristics

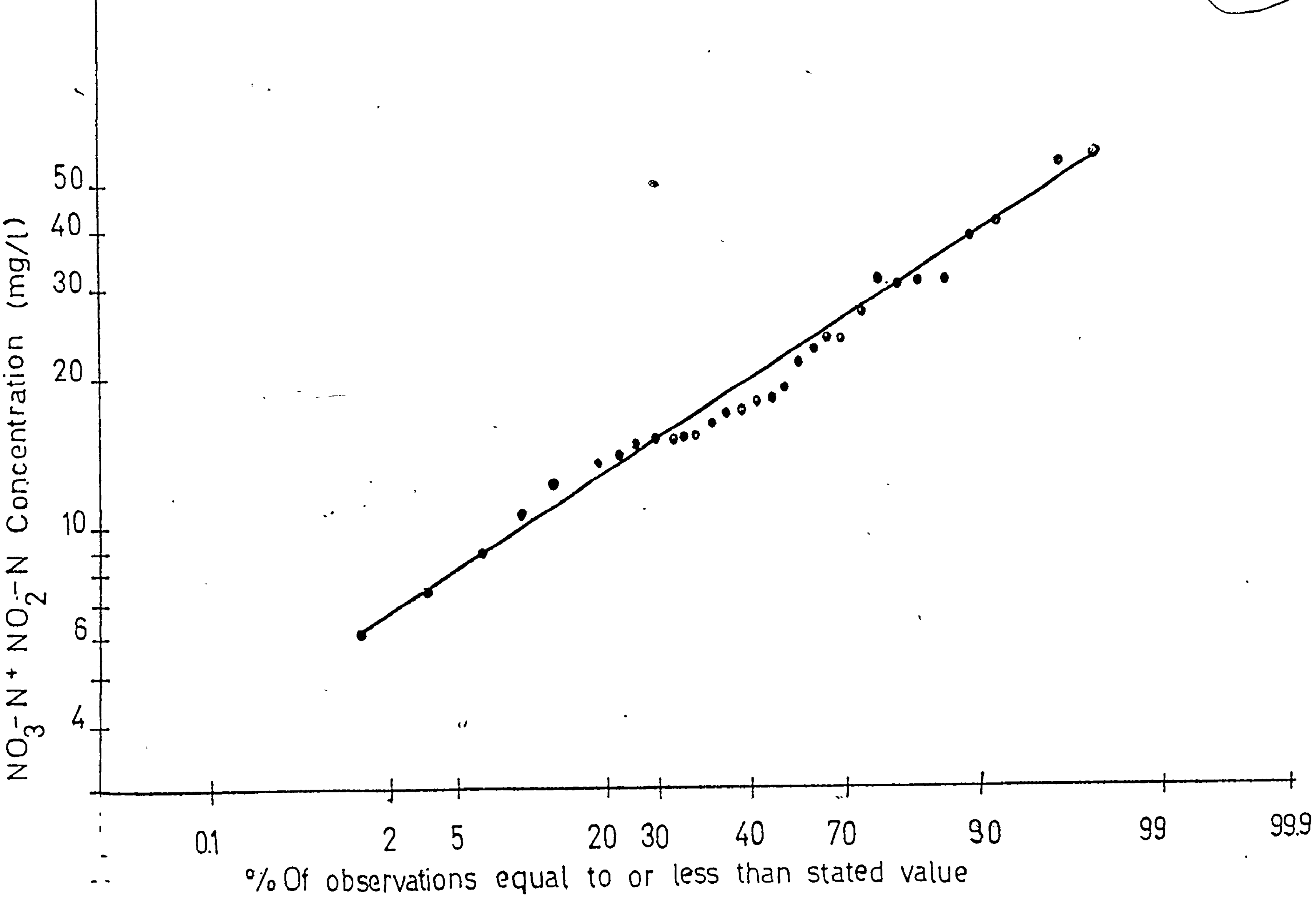
The NO_3-N concentration of the feed fluctuated and was dependent upon the efficiency of the nitrification step, the strength of raw sewage and the spike addition if any.

NO_3-N spikes in the form of KNO_3 were necessary especially at high temperature levels to obtain NO_3-N residual in the effluent in order to measure the denitrification rate.

Carbon was added in the form of methanol. The C:N ratio in the feed was kept about 1.5:1.0 so that microbiological activity was not limited by carbon limitations.

Figure 3 shows the probability distributions of NO_3+NO_2-N concentration in the feed throughout the study. The resulting carbon nitrogen ratio from the addition of

FIGURE NO. 3 PROBABILITY DISTRIBUTION FOR $NO_3^-N + NO_2^-N$ FEED TO DENITRIFICATION UNIT



methanol is given in Figure 4.

4.5 RBC Operation and Sampling

The operation of the RBC was controlled closely. The operation of the unit was easy and generally trouble free. The following operating problems were noted.

a) Continuous running of the disc shaft was essential as a considerable amount of bio-mass was lost after each power failure which effected the performance capacity of the unit.

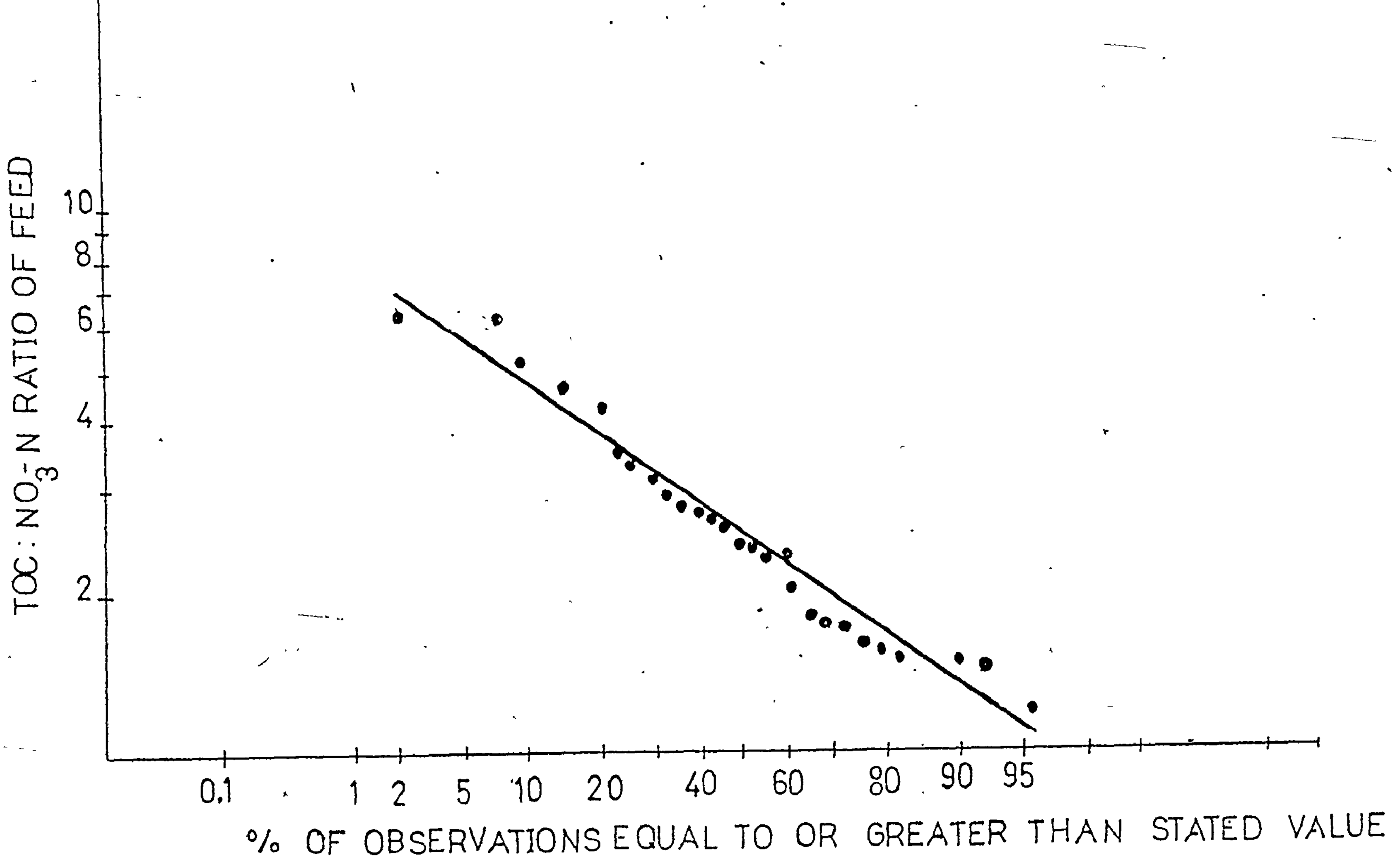
b) The biomass activity stopped when raw water which contained chlorine was used as make up water due to possible chlorine toxicity. After this fact was observed, dechlorinated water was used as make up water.

c) Occasional bubbling within the reactor due to air entrainment was observed. This caused some of the biomass on the rotating discs to be stripped off.

d) With the hydraulic loading employed, and with the reduced microbial activity at low temperature, a measurable concentration of DO was monitored in the first compartment of four stage in series operation. This reduced the rate of denitrification in this compartment.

Sampling was done after 5 days of continuous operation for each run. The total duration of sampling for each run was 2 hours, with one sample for every half an hour.

FIGURE NO. 4 PROBABILITY DISTRIBUTION FOR TOC:NO_3^-N OF FEED



The samples were analyzed directly or kept refrigerated and analyzed later.

The dye samples were collected with 1 min and 2 min intervals for hydraulic loadings of 4.0 l/min and 2.5 l/min respectively, after pulse dye injection.

5. RESULTS AND DISCUSSION

5.1 Hydraulic Characterization

5.1.1 Simulation of Single Stage Operation

Three separate dye studies were conducted to simulate the flow through a single stage RBC. Dye studies were made on a single stage with the unit operating at 15°C and hydraulic loadings of 4 l/min, 2.5 l/min with biomass specific to the operating conditions. An additional dye study was performed at 15°C with all the biomass removed from the discs.

Rhodamine WT dye was injected as a pulse input and the effluent response was measured. The measured dye concentration for the above operating conditions are listed in Appendix 2.

The dye concentrations obtained from all tracer response studies (Figures 5,6, and 7) indicate that the responses for the single stage operation is intermediate to that of a single CSTR with 40 ℓ volume, i.e., the volume not occupied by rotating discs and that of a single CSTR with 100 ℓ volume, i.e., the total volume of the single stage.

A computer program (Appendix 2) calculated the dye recovery, mean dye residence time, residence time distribution (E), dimensionless residence time distribution (Et), and F curves.

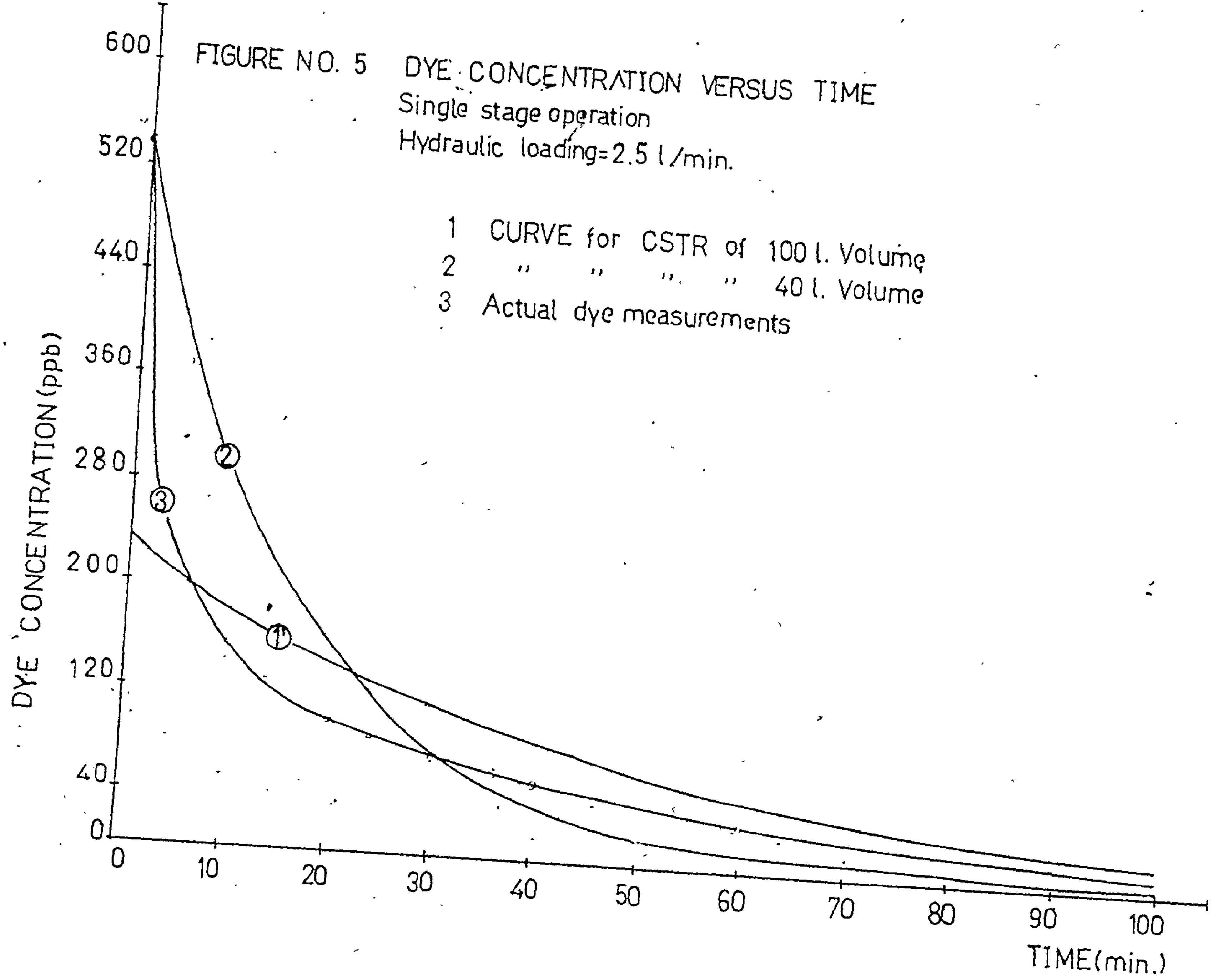


FIGURE NO. 5 DYE CONCENTRATION VERSUS TIME
Single stage operation
Hydraulic loading=2.5 l/min.

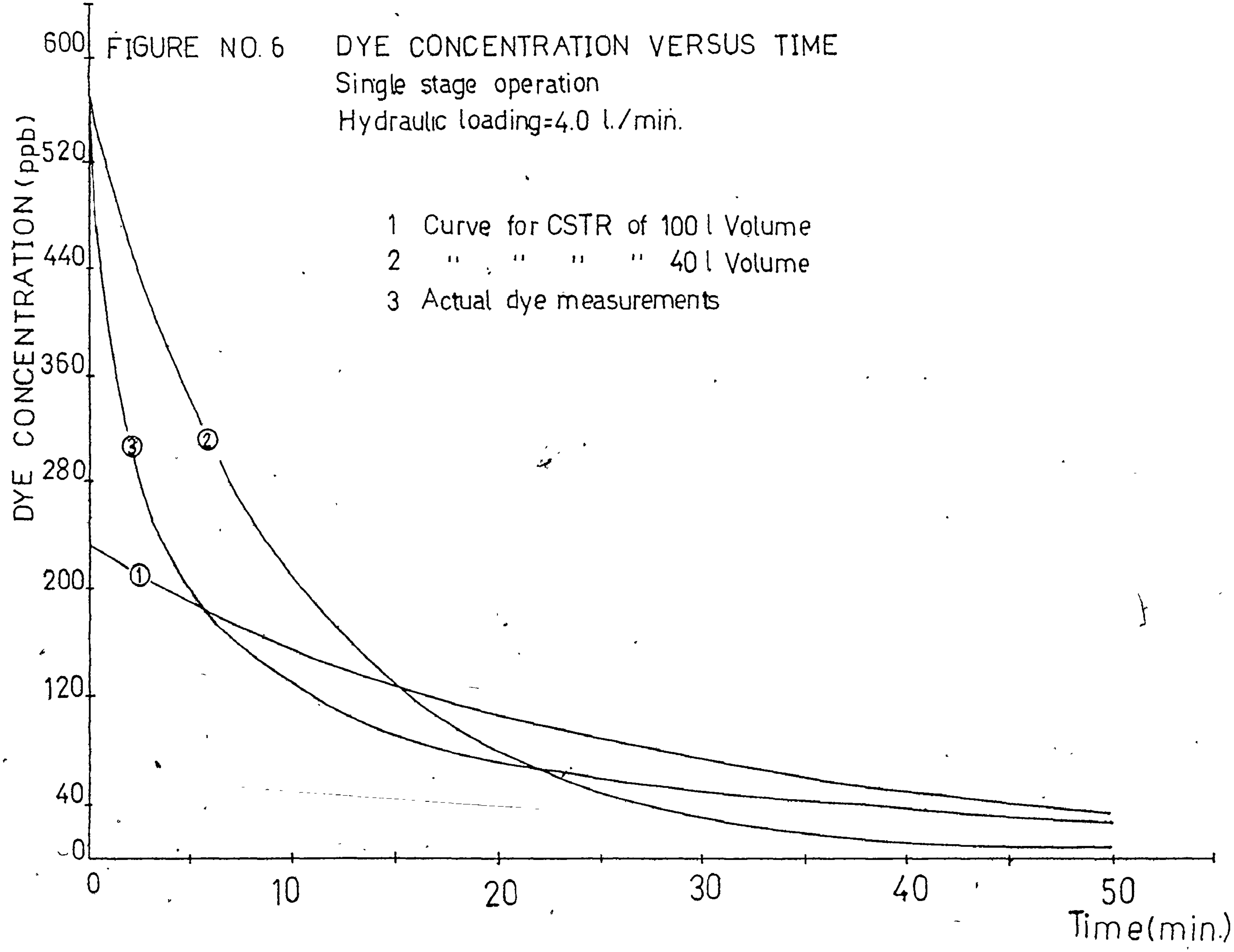


FIGURE NO. 6 DYE CONCENTRATION VERSUS TIME

Single stage operation

Hydraulic loading=4.0 l./min.

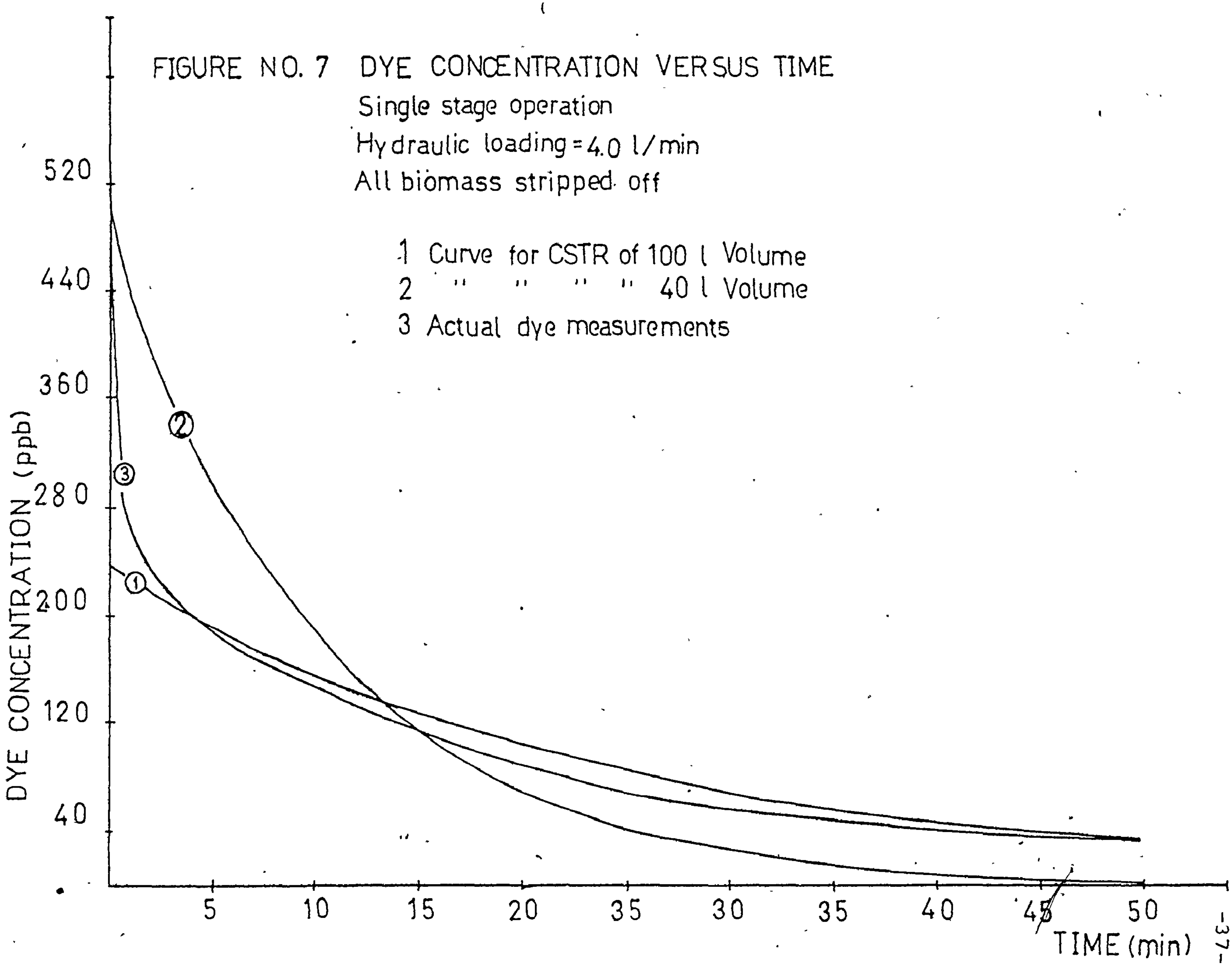


FIGURE NO. 7 DYE CONCENTRATION VERSUS TIME

Single stage operation

Hydraulic loading = 4.0 l/min

All biomass stripped off

The effect of the accumulated biomass in modifying the tracer response curve is illustrated by dimensionless residence time distribution curves (Et) (Figure 8) for the single stage tracer studies.

Both RTD (residence time distribution) and concentration curves implied that the actual flow pattern differed from that of a single CSTR. A model employing two CSTRS with interchange flow was proposed (Fig. 9). The volume not occupied by disc drum was considered to be 100% active and basically a CSTR of 40 ℓ volume, and the liquid volume within the disc drum was considered to be a CSTR of 60 ℓ volume with no dead space. An interchange flow between the two CSTR's (v_B) was postulated. No shortcircutating was considered to exist.

The method uses a material balance of the dye to determine the flow rate between 2 CSTR's.

At any time t, after a pulse dye injection:

$$CA_t\ VA = CA_o\ VA - \int_{t=0}^{t} CAvdt - \int_{t=0}^{t} CA\ v_B\ dt + \int_{t=0}^{t} CB\,v_B dt \tag{9}$$

and

$$CB_t VB = \int_{t=0}^{t} CA\ v_B\ dt - \int_{t=0}^{t} CB\ v_B\ dt \tag{10}$$

FIGURE NO 8 DIMENSIONLESS RESIDENCE TIME

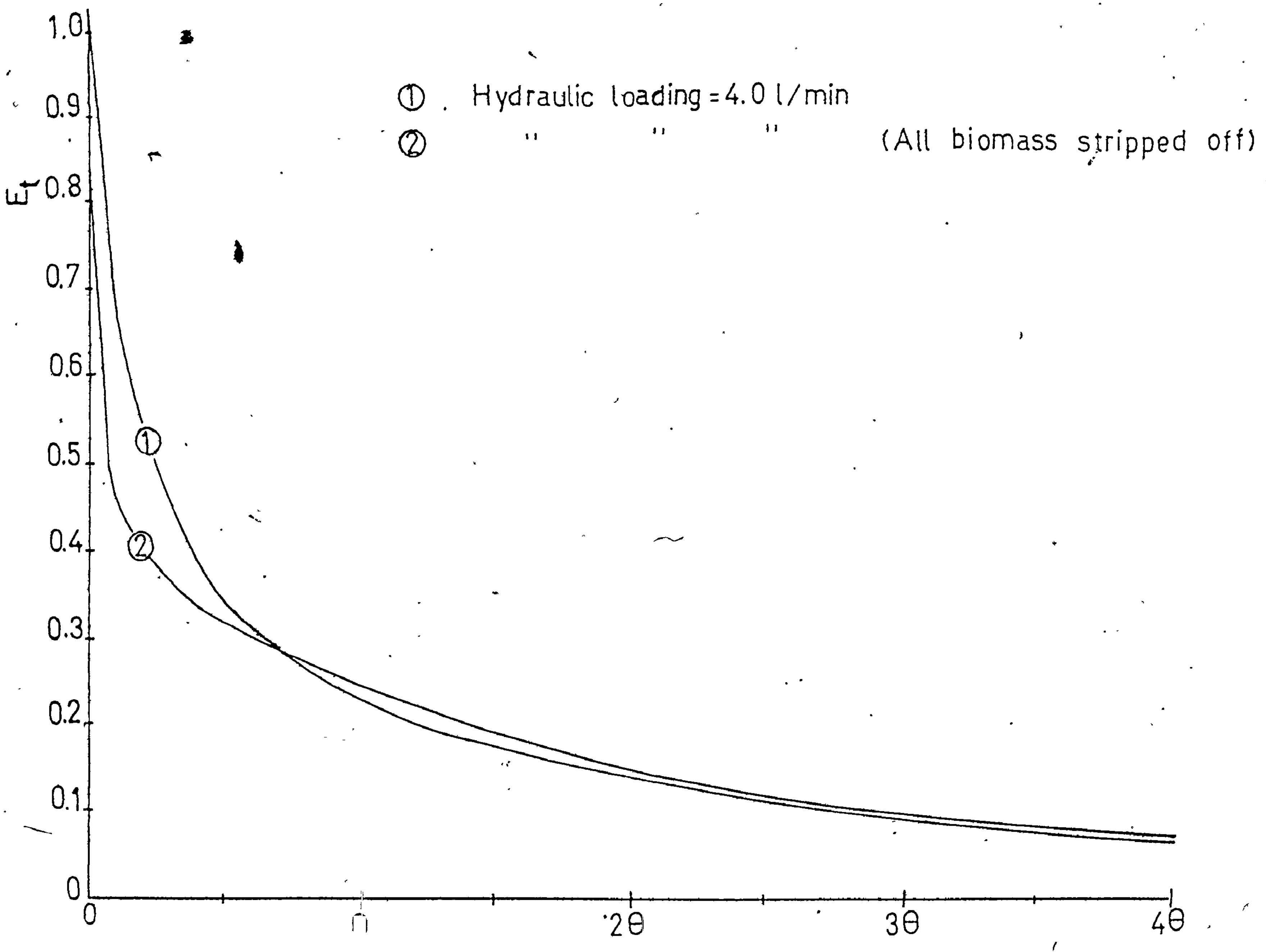
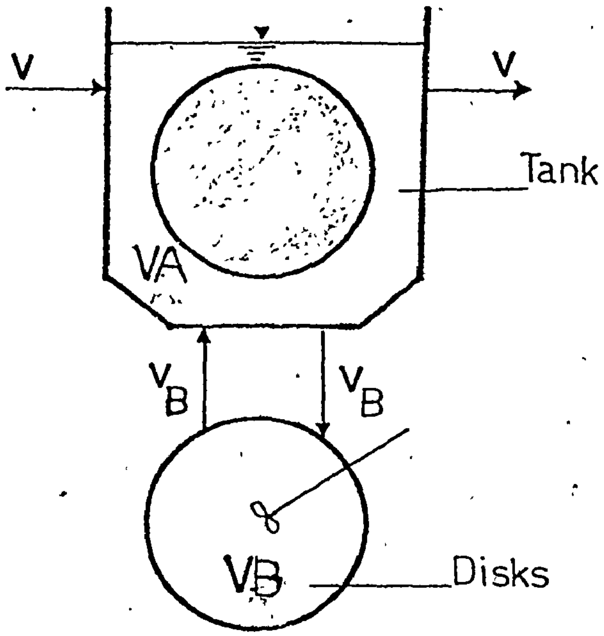


FIGURE NO. 9 PROPOSED FLOW PATTERN FOR SINGLE STAGE OPERATION



where:

CA_o = concentration of dye at time t = 0 in outer CSTR, ppb

CA_t = concentration of dye at time t after pulse injection in outer CSTR, in ppb

CA = concentration of dye in outer CSTR, ppb

CB_t = concentration of dye at time t after pulse injection in inner CSTR, in ppb

CB = concentration of dye in inner CSTR, ppb

v = hydraulic flow rate, l/min

v_B = the flow exchange rate between inner and outer CSTR, l/min

VA = volume of outer CSTR, ℓ

VB = volume of inner CSTR, ℓ

From equations 9 and 10:

$$CA_t\ VA = CA_o\ VA - \int_{t=0}^{t} CAvdt - CB_t\ VB \tag{11}$$

and

$$CB_t\ VB = CA_o\ VA - \int_{t=0}^{t} CAvdt - CA_t\ VA \tag{12}$$

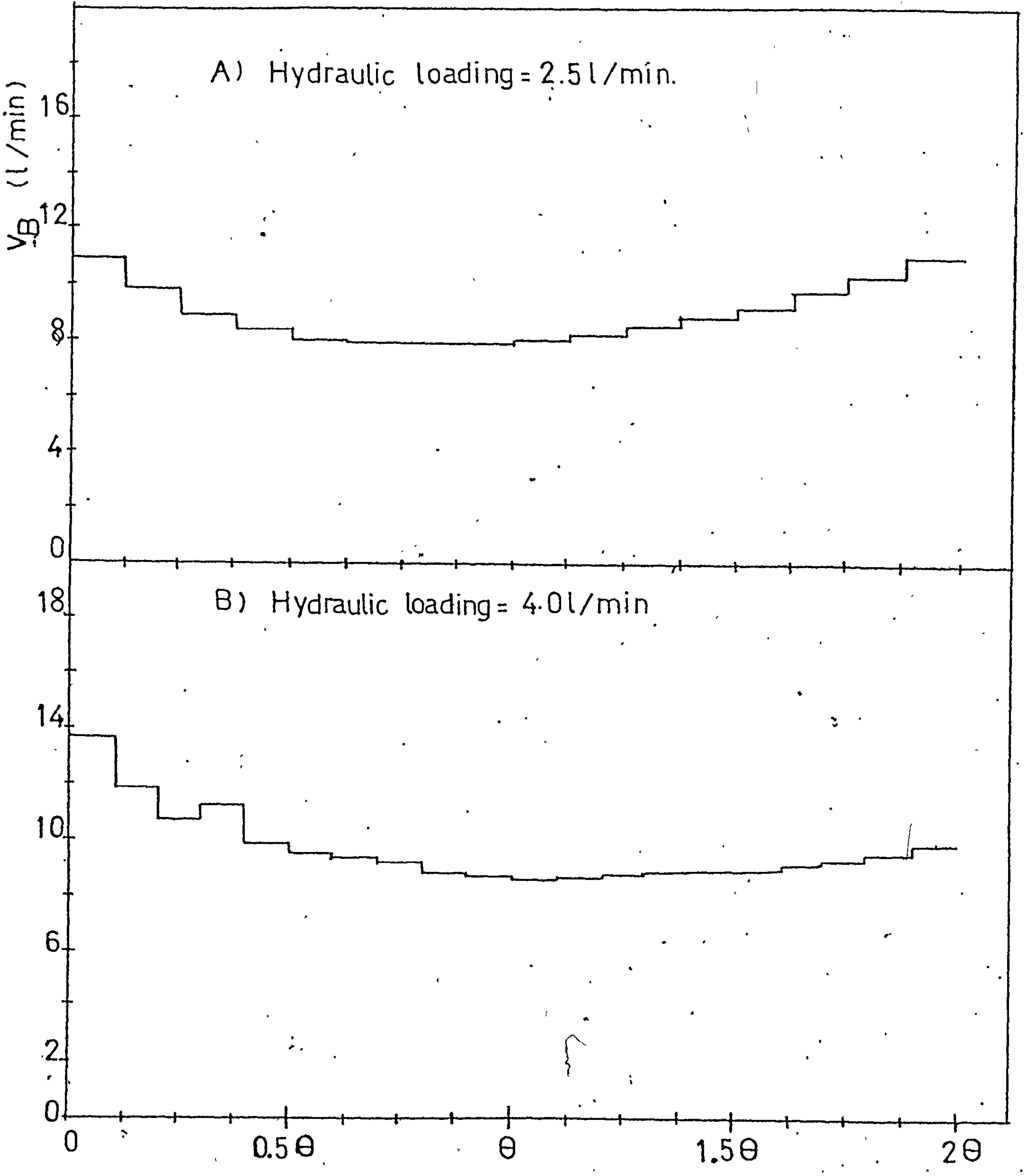
The only unknown of equation (12) is CB_t, since CA and CAt are known as a result of the dye study. VA is known due to the geometry of unit, and v, the hydraulic load is selected. Therefore, CB_t, the dye concentration in the disc drum, can be calculated using equation (12).

Once CB_t, at any time, is calculated, the determination of flow exchange rate between inner and outer CSTR's is possible by using the modified form of equation (10):

$$v_B = \frac{CB_t \ VB}{\int_{t=0}^{t} CA \, dt - \int_{t=0}^{t} CB \, dt} \qquad (13)$$

This method was applied to the data obtained from the pulse dye study on the single stage mode using the computer program presented in Appendix 2. The results are presented in Figure 10. Figure 10 indicates that there is relatively a constant flow exchange rate between the inner and outer CSTR's for 2 detention times of the outer CSTR at a hydraulic loading of 2.5 l/min. Figure 10 indicates that the flow exchange rate between inner and outer CSTR's is relatively constant except in the early period at a hydraulic loading of 4.0 l/min. If the proposed model of 2 CSTR's with interchange flow fitted perfectly, the v_B values calculated would be constant over the entire duration. Figure 10 indicates that there are only slight deviations from the proposed model.

FIGURE NO. 10 INTERCHANCE FLOW RATES(CALCULATED USING MATERIAL BALANCE ON PULSE DYE INJECTION)



Figures 11 and 12 give the dye concentrations of both inner and outer CSTR's. CB values are calculated by using the above numerical method and flow exchange rate as presented in Figure 10.

While this method is a powerful tool to determine if there is a relatively constant interflow rate between the inner and outer CSTR, its sensitivity depends upon the consistency of pumping rate and accuracy of concentration measurement. It is natural to expect high propogation of errors after a prolonged integration period.

The validity and degree of deviation of the proposed model can be checked by comparing the actual data to calculated curves using the formula given by Dedrick and Bischoff (1968). Their formula calculates the dye concentration in the outer CSTR for pulse input for the postulated flow model.

Dedrich and Bischoff's Formula for the concentration in the outer CSTR of a compartment model is:

$$\frac{CA_t}{CA_o} = \frac{\left(r_2 + \frac{v_B}{VB}\right) e^{r_2 t} - \left(r_1 + \frac{v_B}{VB}\right) e^{r_1 t}}{2R} \qquad (14)$$

where:

$$r_1, r_2 = -\tfrac{1}{2}\left[\frac{v}{VA} + \frac{v_B}{VA}\left(1 + \frac{VA}{VB}\right)\right] \mp R \qquad (15)$$

FIGURE. NO 11 DYE CONCENTRATION OF INNER AND OUTER CSTRS

Hydraulic loading=2.5 l/min

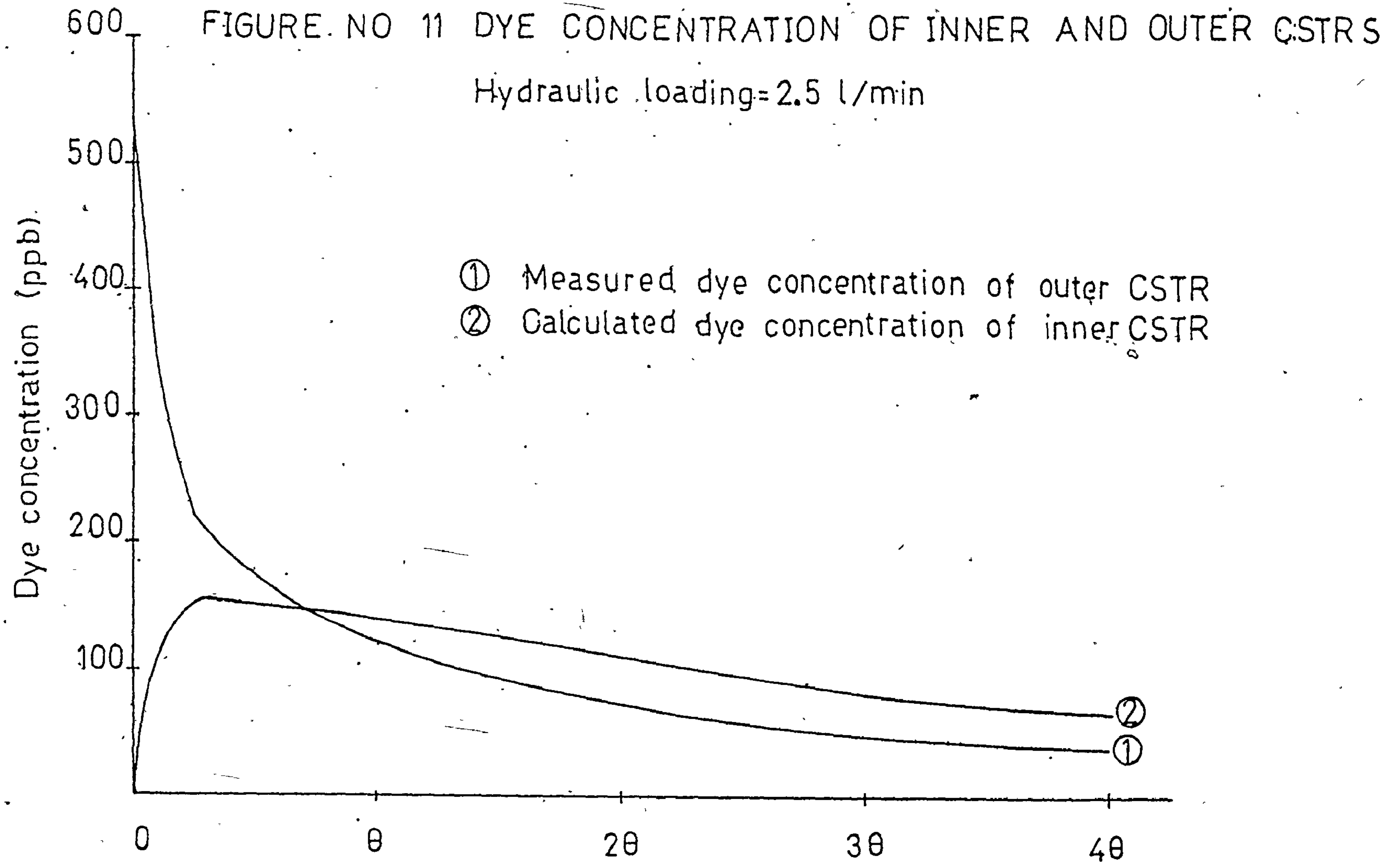
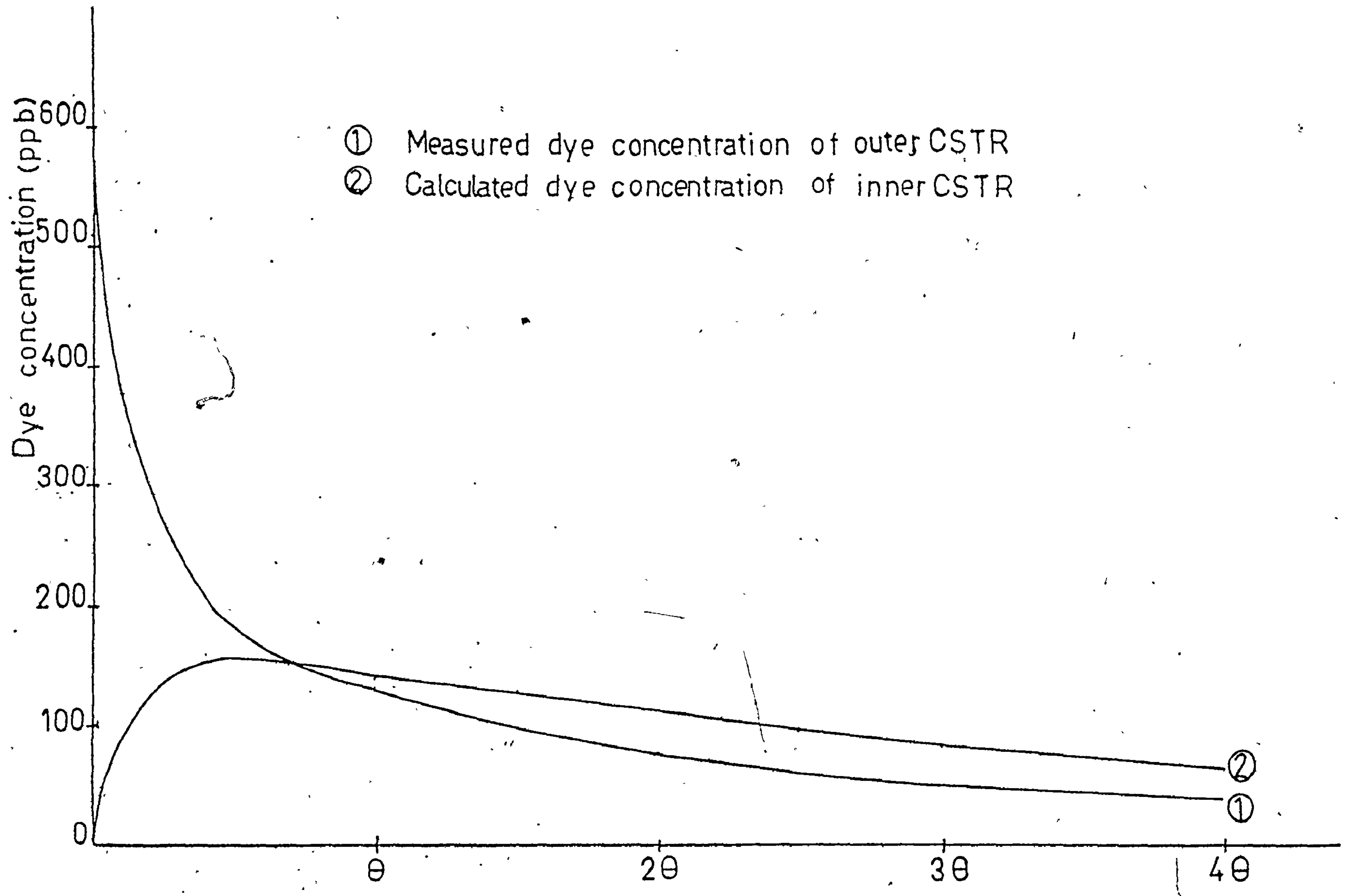


FIGURE NO 12 DYE CONCENTRATION OF INNER AND OUTER CSTR'S

Hydraulic loading = 4.0 l/min



and

$$R = \sqrt{\tfrac{1}{4}\left[\frac{v}{VA} + \frac{v_B}{VA}\left(1 + \frac{VA}{VB}\right)\right]^2 - \frac{v\ v_B}{VAVB}} \qquad (16)$$

Figures 13 and 14 give the comparison of the curves for the predicted responses using Equations 14, 15, and 16 (Appendix 2, Program DEDBIS), and the measured dye concentrations, for hydraulic loadings of 2.5 l/min and 4.0 l/min.

5.1.2 Simulation of 4 Stage Operation

Pulse dye injection was applied at a flow different operating conditions, namely, rate of 4 l/min and at temperatures of 10, 15, 20, and 25°C. For all the above operating conditions, there was biological growth on the discs.

A corresponding dye injection at 4 l/min flow rate and temperature of 15°C was made and all the biomass stripped from the discs.

The tracer concentrations are given in Appendix 2. Also E_t versus θ curves were calculated for different operating conditions, using the computer program of

FIGURE NO 13 COMPARISION OF ACTUAL DYE MEASUREMENTS WITH THE FITTED CURVE (NONLINEAR CURVE FITTING TECHNIQUE IS APPLIED TO DEDRICK AND BISCHOFFS FORMULA)

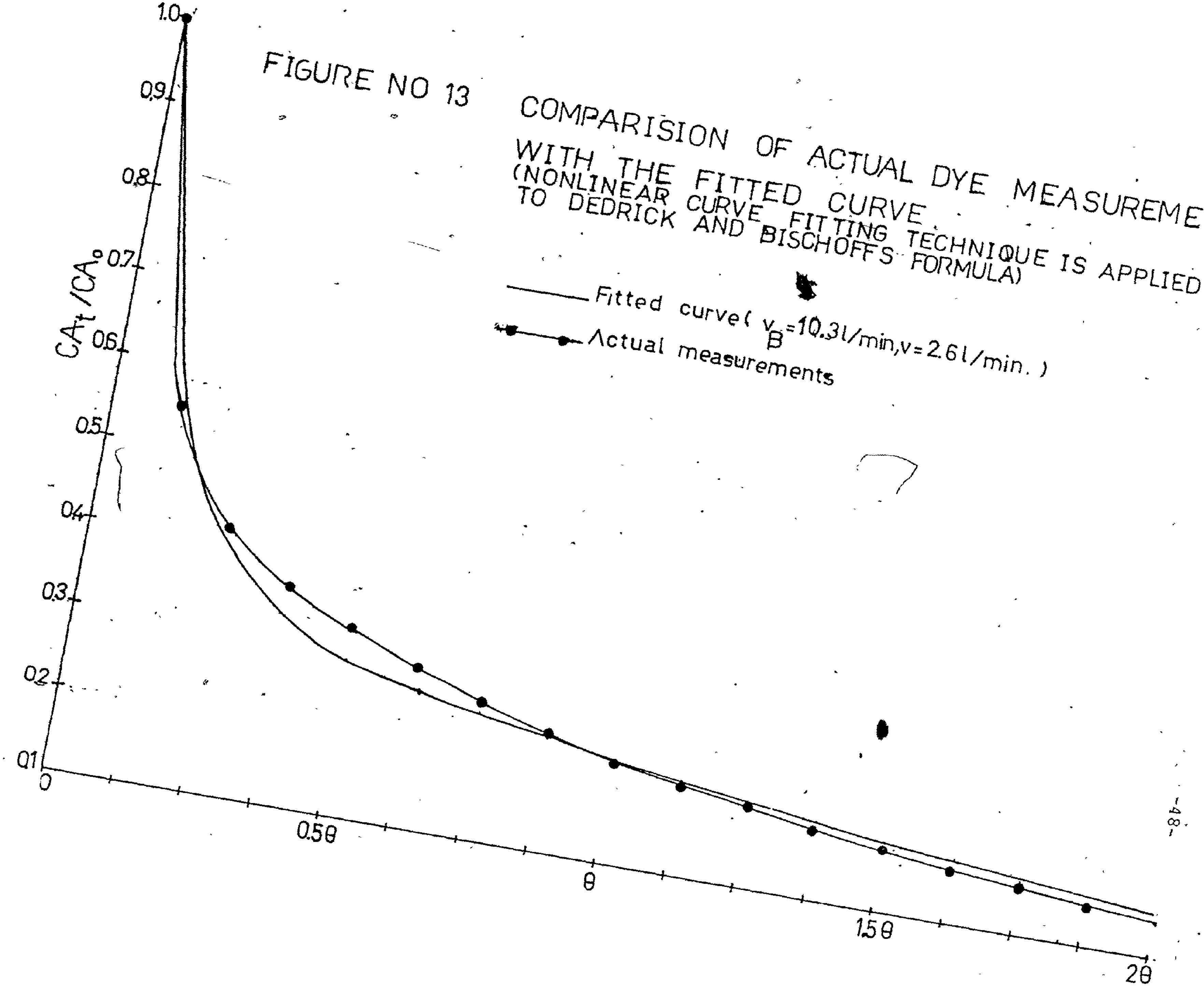
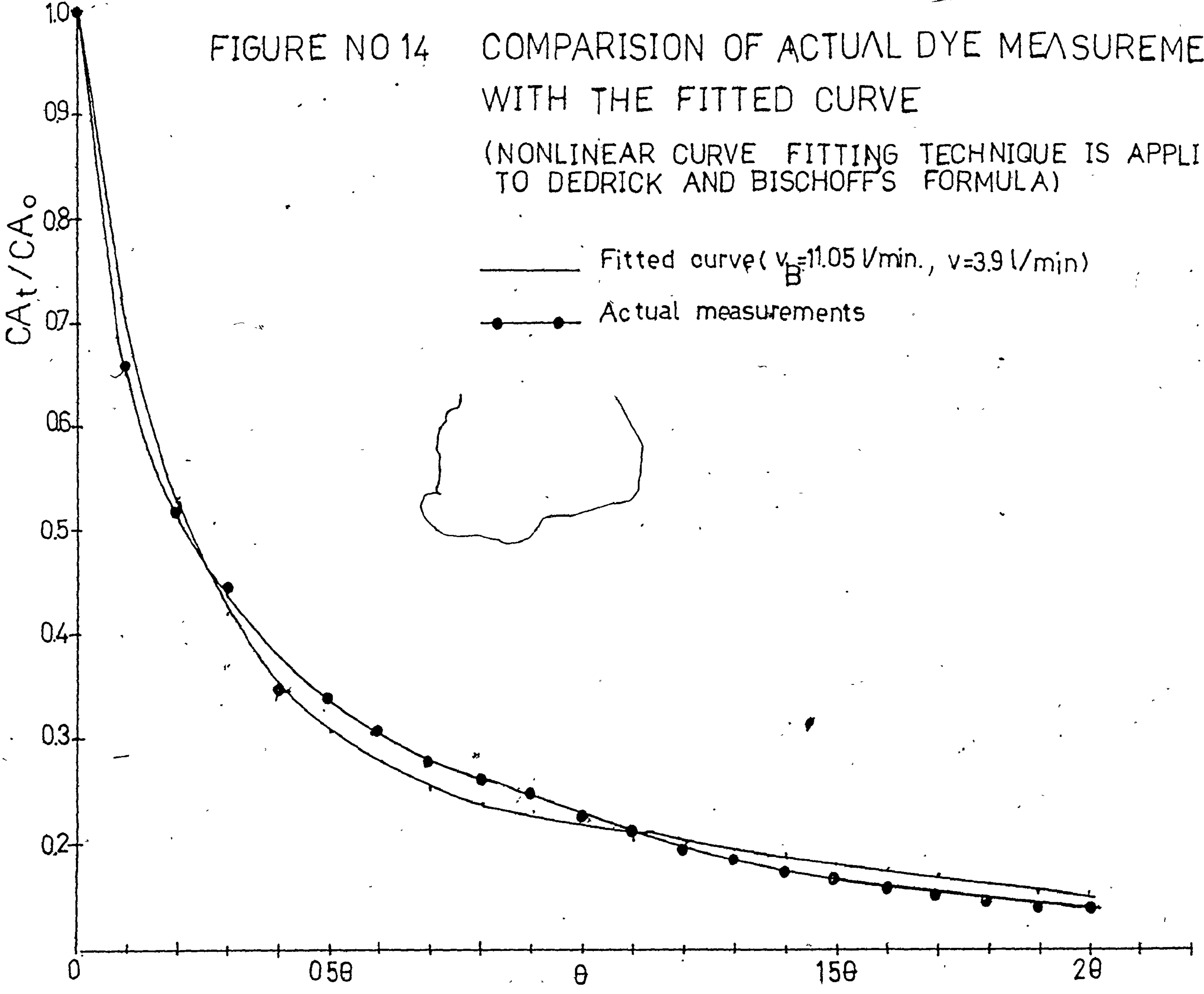


FIGURE NO 14 COMPARISION OF ACTUAL DYE MEASUREMENTS WITH THE FITTED CURVE

(NONLINEAR CURVE FITTING TECHNIQUE IS APPLIED TO DEDRICK AND BISCHOFF'S FORMULA)



Appendix 2. These curves are plotted on Figure 15 (see Table 2).

Figure 15 shows that the tracer response curve is a function of the biomass that exists at a given operating temperature. This conclusion is supported by comparison of Figures 4, 5, and 6.

5.2 EVALUATION OF A TOTALLY SUBMERGED RBC FOR DENITRIFICATION

It has been demonstrated that each compartment of an RBC can be simulated as two CSTR's with interchange flow. Geometric properties of reactors dictates that the outer surface area (1.40 m^2) of a total surface area of discs (7.10 m^2) would be available to the outer CSTR, while the remainder 5.70 m^2 is available to the inner CSTR. The reactor walls which are equivalent to 0.5 m^2 should also be included as an active area as they attached heavy biomass throughout the study. Therefore, the effective surface area of the outer CSTR would be 1.90 m^2.

Using a model similar to Figure 9, a material balance for the substrate in the outer CSTR gives:

$$vS_o - K A_A S_A^n - v_B S_A + v_B S_B - v S_A = 0 \tag{17}$$

where: S_o = the substrate concentration in influent, mg/l

v = hydraulic loading, l/min

K = substrate removal rate, $mg/m^2.min$

A_A = available area of outer CSTR, m^2

FIGURE NO. 15 DIMENSIONLESS RESIDENCE TIME DISTRIBUTION FOR FOUR STAGE IN SERIES

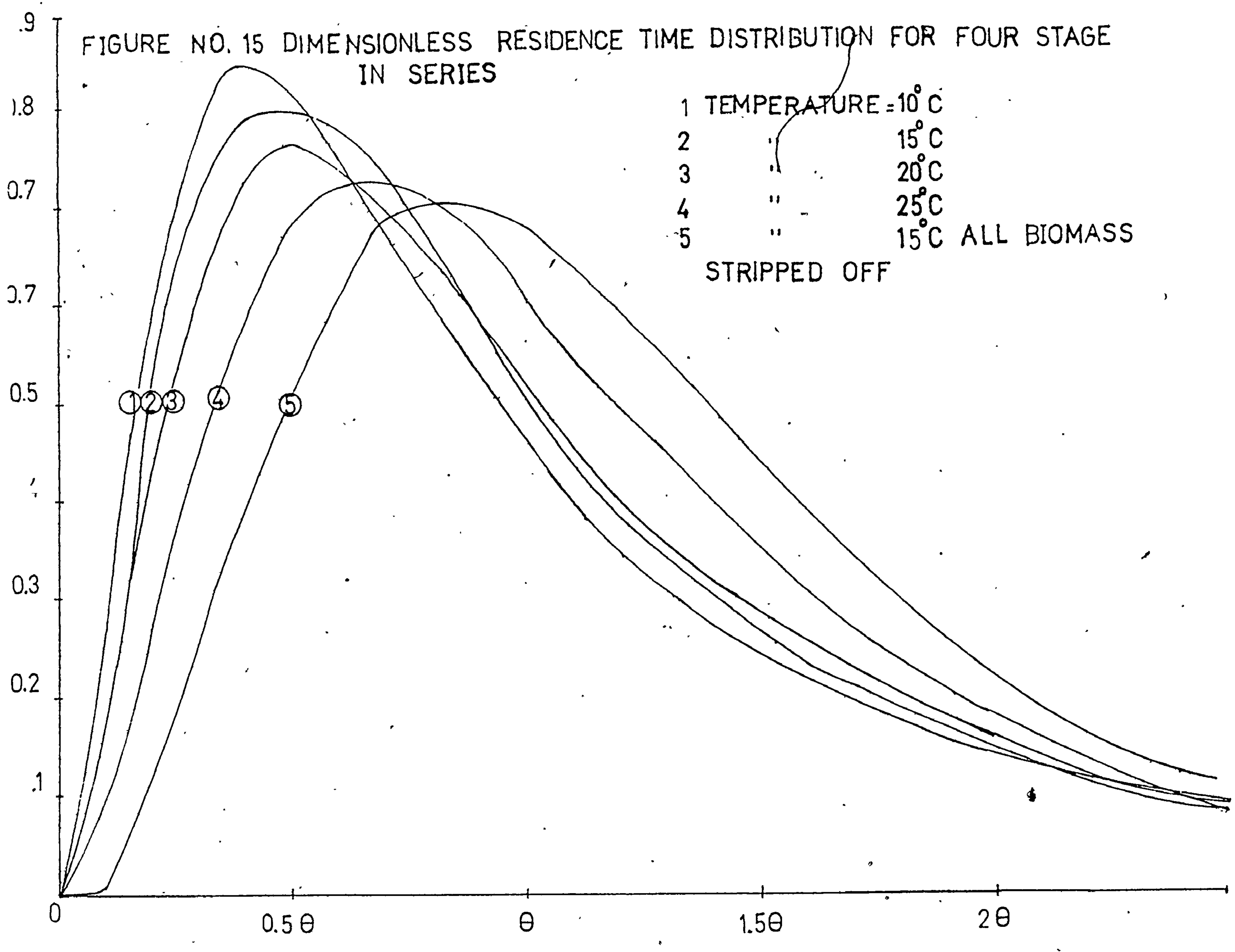


TABLE 2

THE OBSERVED BIOMASS UNDER DIFFERENT OPERATING TEMPERATURE FOR 4 STAGE IN SERIES MODEL OF OPERATION

Temperature under which dye study performed	Stages containing heavy biomass
25°C	Only first stage
20°C	First two stages
15°C	First three stages
10°C	All stages
15°C (stripped)	None

v_B = flow exchange rates between inner and outer CSTR, 1/min

S_A = substrate concentration in outer CSTR, mg/l

S_B = substrate concentration in inner CSTR, mg/l, and

n = order of denitrification rate, dimensionless.

A material balance on the inner CSTR gives:

$$v_B S_A - K A_B S_B^n - v_B S_B = 0 \qquad (18)$$

where:

A_B = the area available in inner CSTR, m^2

For a zero order reaction rate, n=0, was inserted and S_B and K values were calculated using equations 17, and 18. Table 3 gives the calculated K, S_A, and S_B values for different operating temperatures and hydraulic loadings, using the data tabulated in Appendix 1. These calculations are summarized in Appendix 3.

Similarly for the first order reaction rate, n=1 was inserted, and S_A, S_B, and K values were calculated using equations 17 and 18 (Table 4 and Appendix 3).

The empirical Arrhenius temperature dependency describing the denitrification for the totally submerged RBC may be calculated using the K values from Tables 3 and 4.

TABLE 3

THE CALCULATED DENITRIFICATION RATES AND SUBSTRATE CONCENTRATIONS OF INNER AND OUTER CSTR's ASSUMING ZERO ORDER KINETIC MODEL(K's are in mg/m^2-hr)

ydraulic oading 1/min	K at Temperature (^oC)	S_o mg/1	S_A mg/1	S_B mg/1	K at Temperature (^oC)	S_o mg/1	S_A mg/1	S_B mg/1
2.5	$K_{5^oC}=66.1$	13.6	10.3	9.7	$K_{20^oC}=455.4$	30.0	6.9	3.3
	$K_{5^oC}=159.6$	25.2	17.1	15.8	$K_{20^oC}=315.6$	29.0	13.0	10.5
	$K_{10^oC}=92.4$	17.0	12.3	11.6	$K_{25^oC}=528.8$	32.0	6.2	2.2
	$K_{10^oC}=100.2$	18.0	12.9	12.1	$K_{25^oC}=375.6$	22.9	3.9	0.9
	$K_{15^oC}=177.6$	13.8	4.7	3.5	$K_{25^oC}=1007.4$	29.0	2.8	0.0
	$K_{15^oC}=169.2$	13.3	4.7	3.4				
4.0	$K_{5^oC}=30.0$	13.6	12.7	12.5	$K_{10^oC}=240.0$	17.0	9.4	7.7
	$K_{5^oC}=82.1$	26.2	23.6	23.1	$K_{15^oC}=145.3$	19.0	14.4	13.4
	$K_{5^oC}=123.7$	15.4	11.5	10.6	$K_{20^oC}=631.6$	30.0	10.0	5.7
	$K_{5^oC}=53.7$	17.0	15.3	14.9	$K_{25^oC}=705.9$	30.0	7.7	2.9
	$K_{5^oC}=116.8$	14.1	10.4	9.6	$K_{25^oC}=735.8$	40.0	16.7	11.7
	$K_{10^oC}=66.3$	17.0	14.9	14.5	$K_{25^oC}=378.9$	54.0	42.0	39.4
	$K_{10^oC}=94.7$	18.0	15.0	14.4				

TABLE 6

THE CALCULATED DENITRIFICATION RATES AND SUBSTRATE CONCENTRATIONS OF INNER AND OUTER CSTR's ASSUMING FIRST ORDER KINETIC MODEL (K'$_a$s are in $1/m^2$-min)

Hydraulic Loading 1/min	K at Temperature (°C)	S_o (mg/l)	S_A (mg/l)	S_B (mg/l)	K at Temperature (°C)	S_o (mg/l)	S_A (mg/l)	S_B (mg/l)
2.5	0.11	13.6	10.3	9.7	1.68	30.1	6.9	3.8
	0.16	25.2	17.1	15.8	0.47	29.0	13.0	10.6
	0.12	17.0	12.3	11.6	2.23	32.0	6.2	3.0
	0.13	18.0	12.9	12.1	2.89	22.9	3.8	1.6
	0.79	13.8	4.7	3.4	7.53	29.0	2.8	0.6
	0.76	13.3	4.7	3.4				
4.0	0.04	13.6	12.6	12.4	0.46	17.0	9.4	7.8
	0.05	26.2	23.6	23.0	0.17	19.0	14.4	13.4
	0.19	15.4	11.4	10.6	1.46	30.0	10.0	6.2
	0.07	17.0	14.9	14.4	2.47	30.0	7.6	3.8
	0.19	14.1	10.4	9.6	0.43	40.0	23.3	19.8
	0.06	17.0	15.3	14.9	0.15	54.0	42.0	39.4
	0.10	18.0	15.0	14.3				

The Arrhenius temperature dependency was calculated by using reparameterized equation, Sutton (1971):

$$K = K^*(e^{-E/RT_o} A_o) \tag{19}$$

where:

$$K^* = e^{-\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)} \tag{20}$$

A computer program (Appendix 2) calculates K* and E values, once K values and corresponding temperatures are inserted. This program utilizes a least square fitting technique using linear regression.

Another program (Appendix 2), calculates the 95% confidence limits for predicting of actual reaction rate values, utilizing the output of previous program. Computational examples are illustrated in Appendix 4 and the results are given in Table 5.

As there did not appear to be much difference in the models for 2.5 l/min and 4.0 l/min hydraulic loadings, assuming zero order reaction rates, the results for both flow rates were combined and analyzed together. The ANOVA results (Table 5) indicated no lack of fit for the combined data at the 95% significance level. The fitted curve for the combined data is presented in Figure 20. Similar data for a "first order" rate is also presented in Table 5. Using a first order model, the analysis of variance indicated the two flow rates could not be pooled as with the zero order model.

TABLE 5

RESULTS OF LINEAR REGRESSION FOR ARRHENIUS TEMPERATURE DEPENDENCY

Operating Condition	-E/R	Activation Energy cal/mole	$\ln A_o e^{\frac{-E}{RT_o}}$	A_o	ANOVA RESULTS	
					$\frac{\text{Mean Square Lack of Fit}}{\text{Mean Square Pure Error}}$	Critical F value $\alpha=0.95$
ZERO ORDER						
Hydraulic loading = 2.5 l/min	-7800	15400	5.35	1.21×10^{14}	1.04	4.75
Hydraulic loading = 4.0 l/min	-8800	17300	5.36	3.35×10^{15}	0.52	4.06
Combined Data	-8400	16500	5.34	8.42×10^{14}	2.52	2.70
FIRST ORDER						
Hydraulic loading = 2.5 l/min	-13800	27000	-0.57	3.65×10^{20}	2.01	4.75
Hydraulic loading = 4.0 l/min	-8000	15800	-1.34	3.03×10^{20}	0.64	4.06
Combined Data	-11200	22000	-0.92	3.08×10^{16}	4.23	2.70

5.3 Discussion of Concentration Dependency of Denitrification by RBC

Figures 16, 17, 18, and 19 show that denitrification rates achieved for hydraulic loadings of 2.5 l/min and 4.0 l/min can be represented by narrower 95% confidence levels for zero order kinetics.

In order to statistically evaluate the models, the ratios of residual mean squares to variances of observations were calculated.

$$\lambda = \frac{\Sigma S^2/n}{\sigma^2}$$

where:

σ^2 = variance of observations,
ΣS^2 = sum of squares of residuals,
λ = ratio, and
n = degrees of freedom.

While there is no rigorous statistical test for the null hypothesis, larger deviations from unity indicate a real lack of fit ~~for the model~~. ~~On this~~ is basis, the smaller values of λ with zero order model for 2.5 l/min hydraulic loading and combined data tend to indicate superiority for the zero order model (Table 6).

TABLE 6

EVALUATION OF MODELS FOR ZERO ORDER AND FIRST ORDER ASSUMPTIONS

Hydraulic Loading	Zero Order			First Order			
	$\Sigma S^2/n$	σ	λ	$\frac{\Sigma S^2}{n}$	σ^2	λ	F
2.5 l/min	0.16	0.16	1.00	0.37	0.27	1.33	4.09
4.0 l/min	0.27	0.31	0.87	0.90	0.99	0.90	3.34
Combined Data	0.20	0.13	1.54	0.82	0.37	2.17	2.34

FIGURE NO 16 TEMPERATURE DEPENDENCY OF DENITRIFICATION RATE
First order kinetics
Hydraulic loading=2.5 l/min

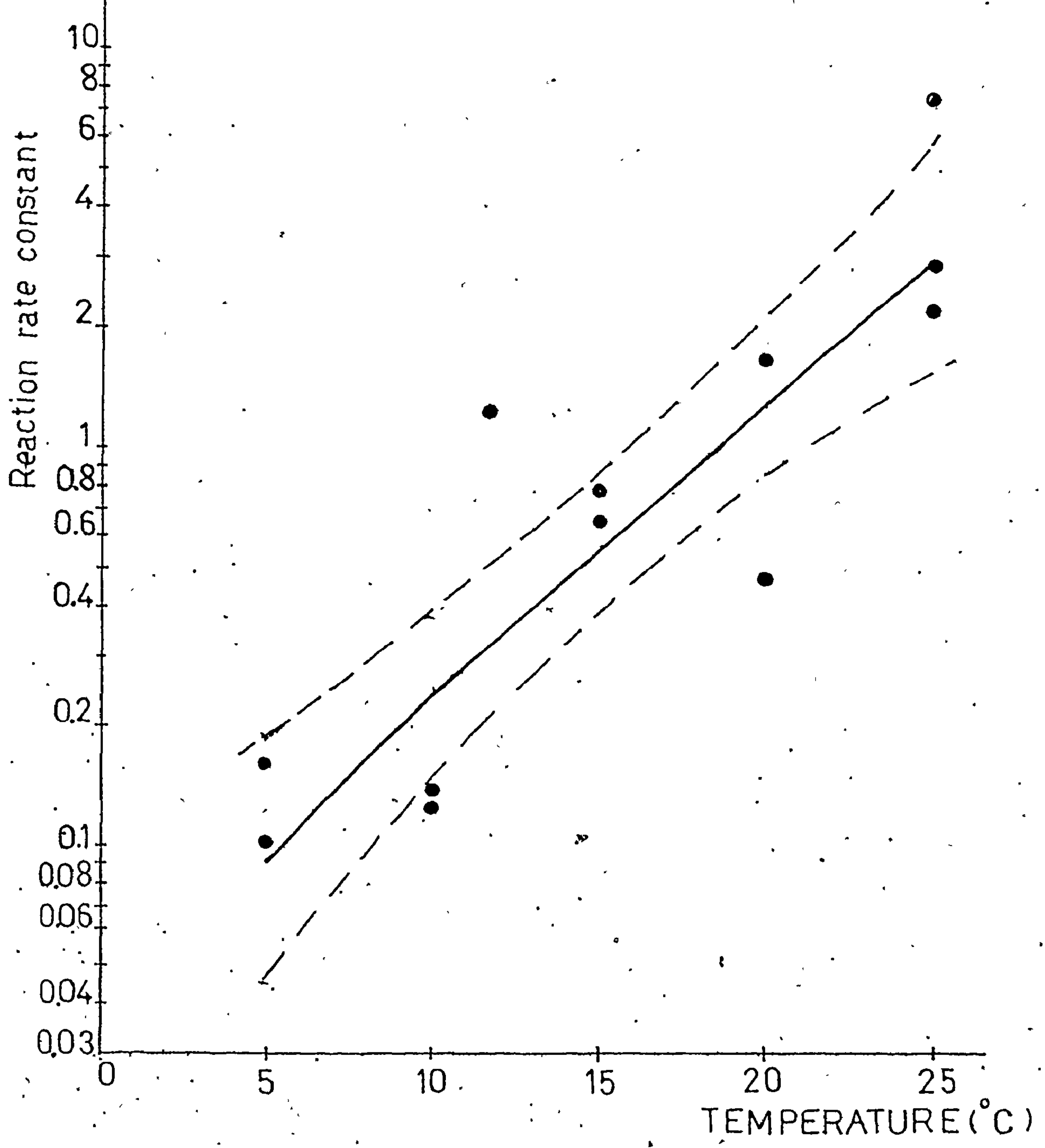


FIGURE NO 17 TEMPERATURE DEPENDENCY OF DENITRIFICATION RATE

First order kinetics

Hydraulic loading = 4.00 l/min

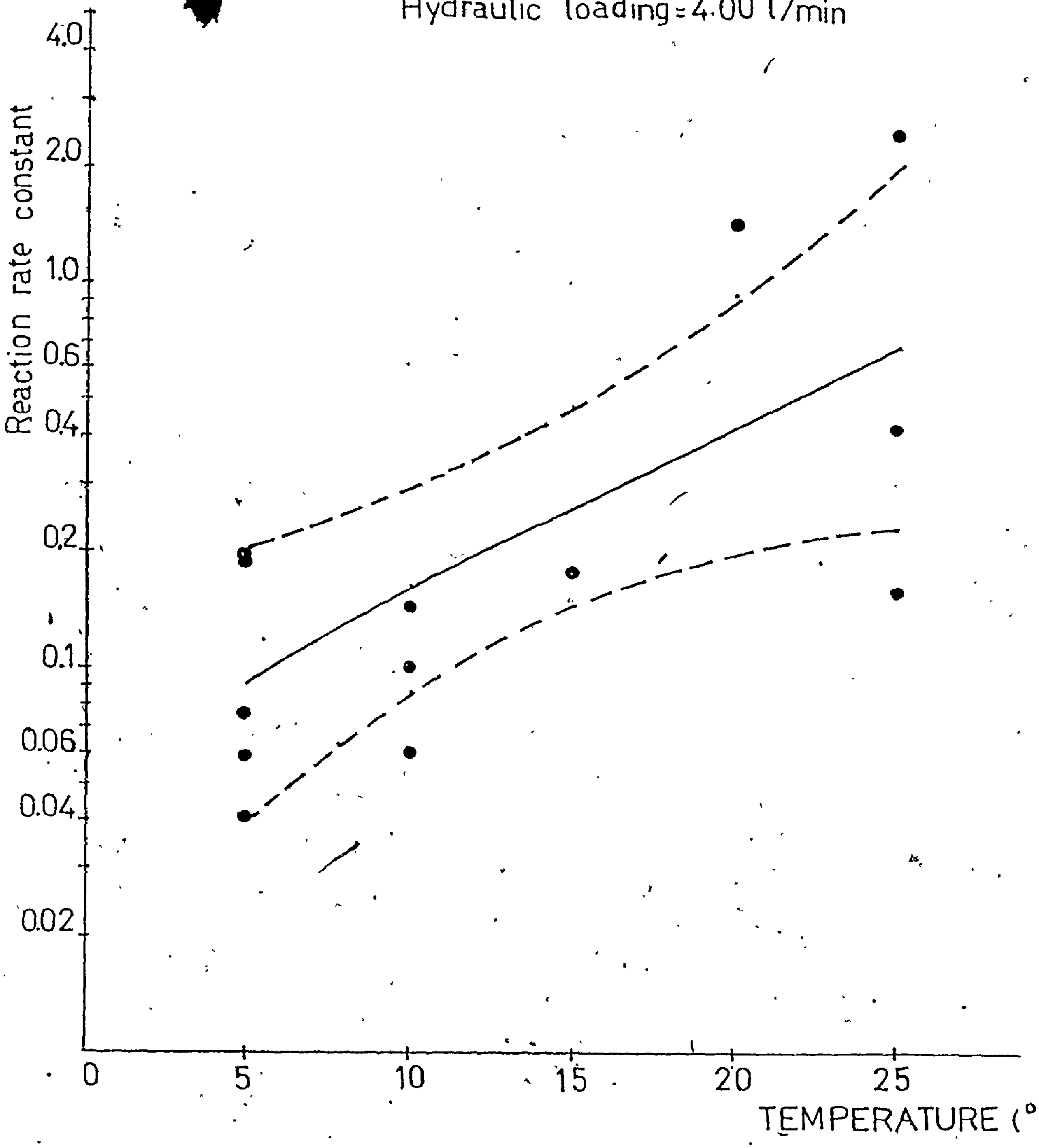


FIGURE NO. 18 TEMPERATURE DEPENDENCY OF DENITRIFICATION RATE

Zero order kinetics

Hydraulic loading=2.5 l/min

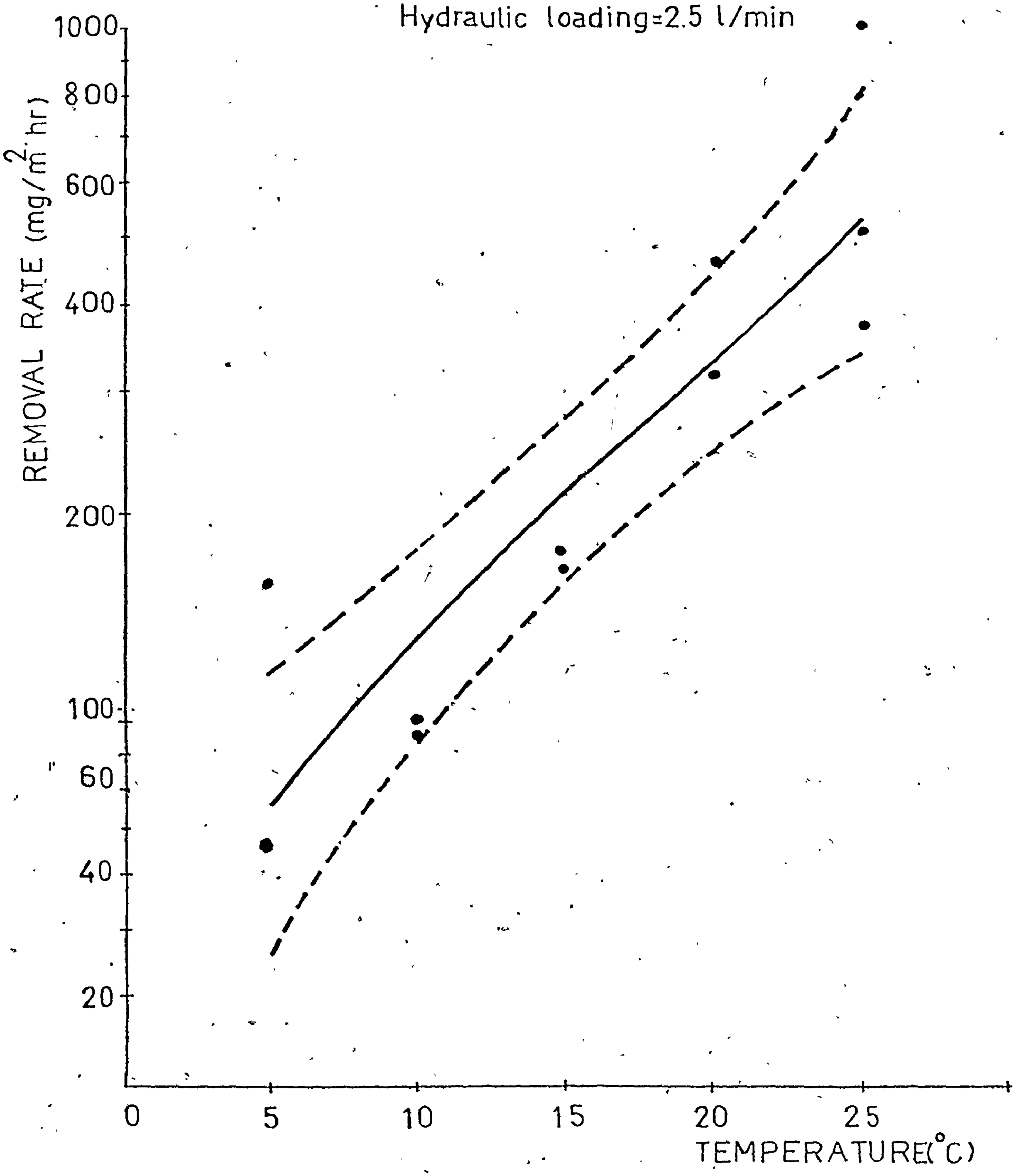


FIGURE NO 19 TEMPERATURE DEPENDENCY OF DENITRIFICATION RATE

Zero order kinetics

Hydraulic loading = 4.0 l/min

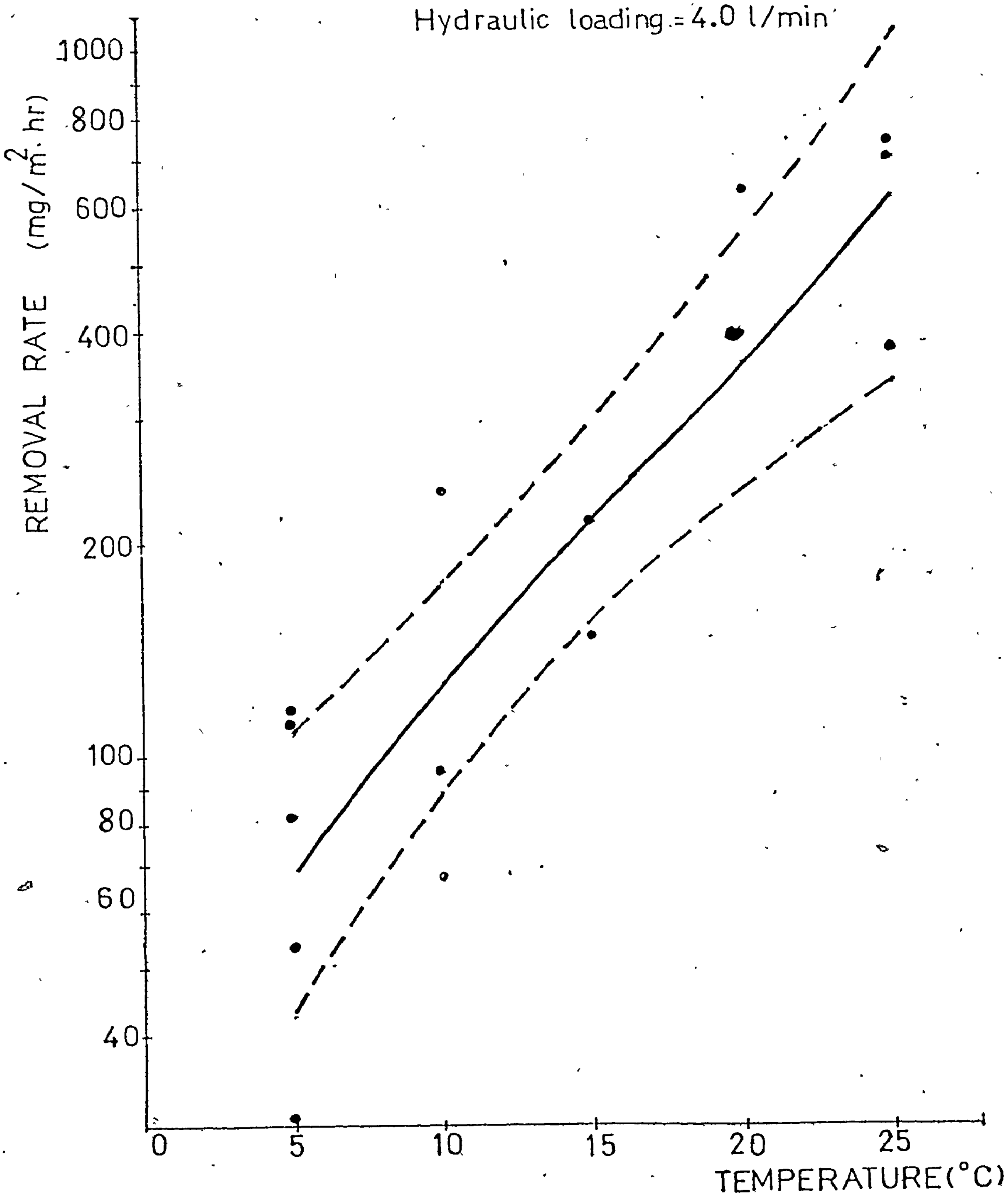


FIGURE NO. 20 TEMPERATURE DEPENDENCY OF DENITRIFICATION BY RBC

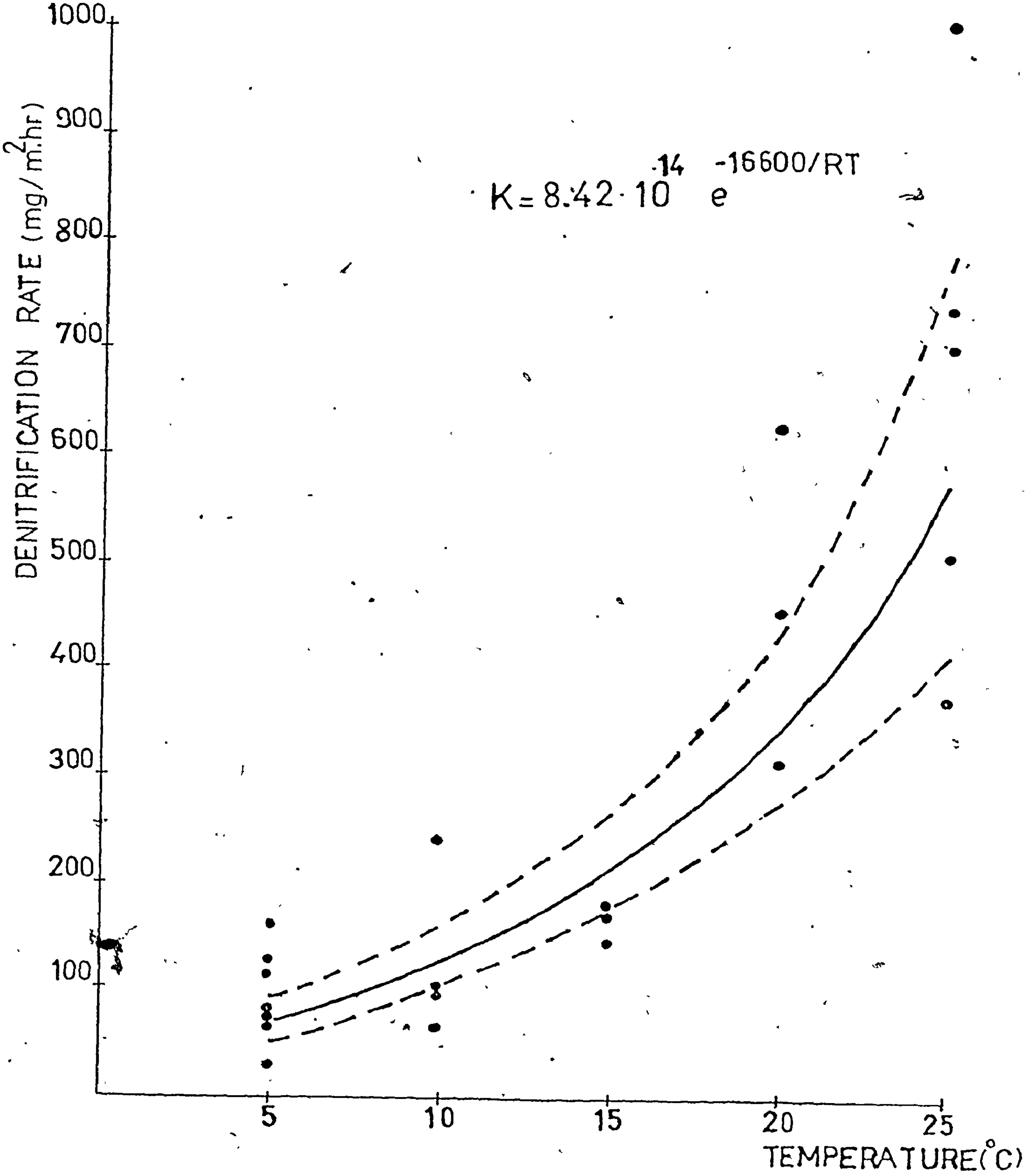
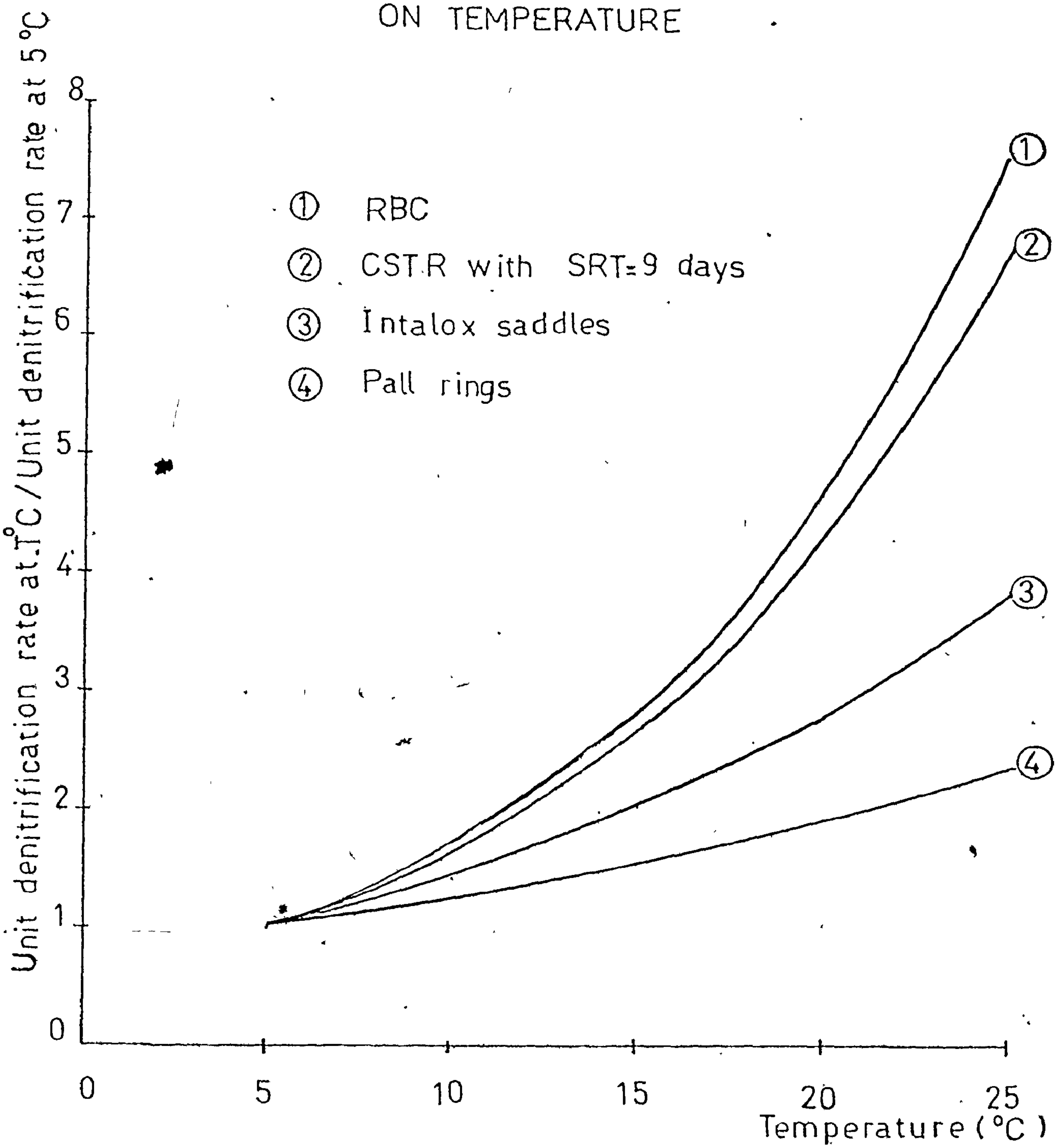


FIGURE NO 21 DENITRIFICATION RATE DEPENDENCY ON TEMPERATURE



5.4 Comparison of Temperature Dependency Curve with Other Literature Values

It is not surprising that, the energy of activation for denitrification by the RBC which is 16,600 cal/mole is not far different from the laboratory results of Dawson and Murphy (1971), energy of activation of 16,800 cal/mole, and Sutton's (1976), hydraulically well defined CSTR and Batch, energy of activation values of 15,300 and 15,900 cal/mole for different SRT values. Since the reactions are basically the same for different systems, only the constant A_o should differ (Figure 20).

5.5 Comparison of Temperature Dependency of Various Denitrification Units

Figure 21 gives the Arrhenius temperature dependency of various denitrification units which were run under similar operating conditions. Details concerning the CSTR and Intalox packed column denitrification results are available from Sutton (1976) and the Pall Ring packed column results are from Wilson (1975). Figure 21 shows that the denitrification dependency of RBC system is greater than either the CSTR or packed columns.

An advantage of the RBC over other denitrification units arises from a volumetric comparison. The greater volumetric efficiency of the RBC over the packed columns is indicated in Figure 22 and over suspended growth systems in Figure 23. This coupled with the ease of operation makes the RBC one of the most competitive type of processes for denitrification.

FIGURE NO. 22 VOLUMETRIC EFFICIENCIES OF VARIOUS DENITRICATION UNITS

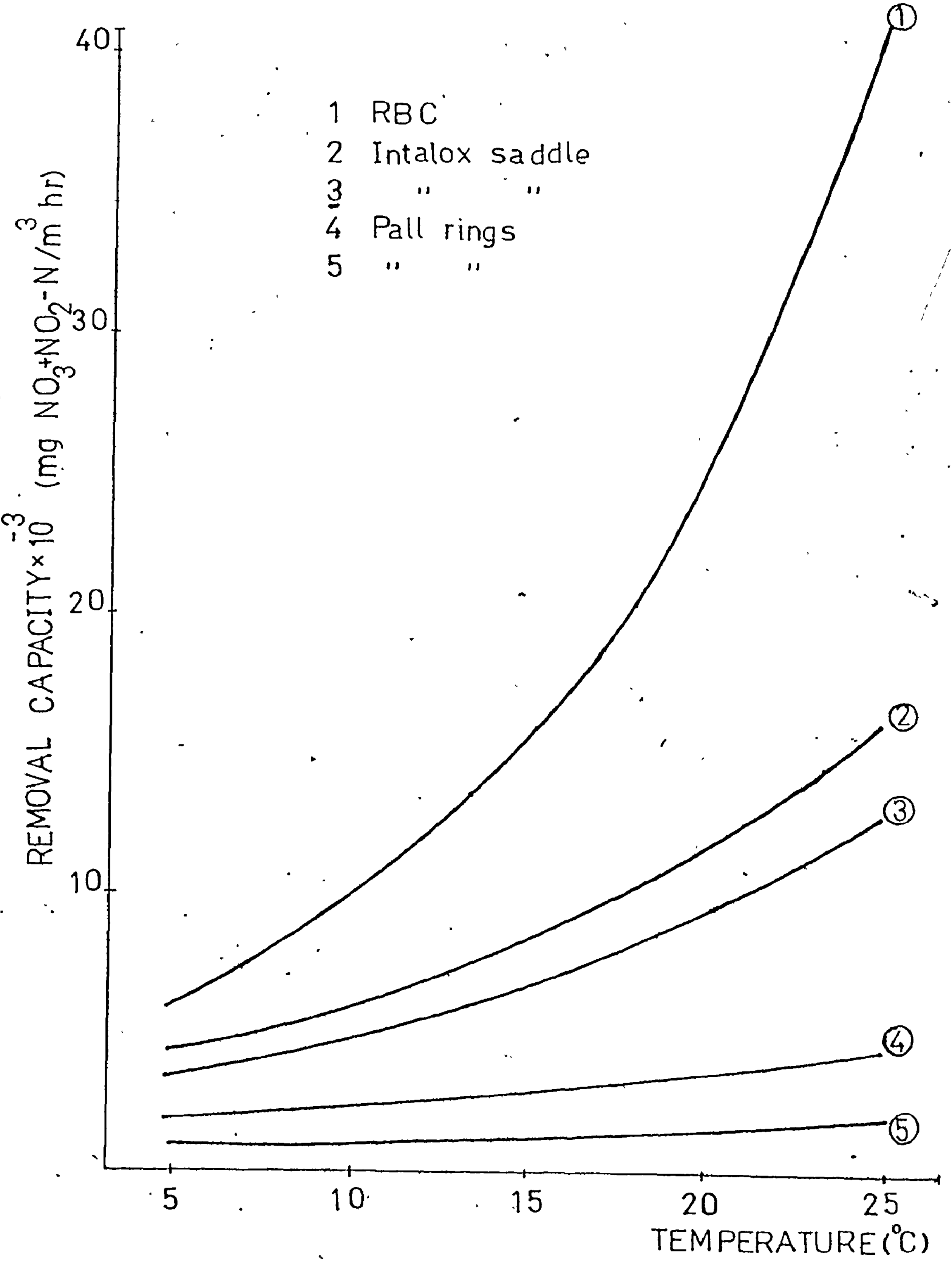
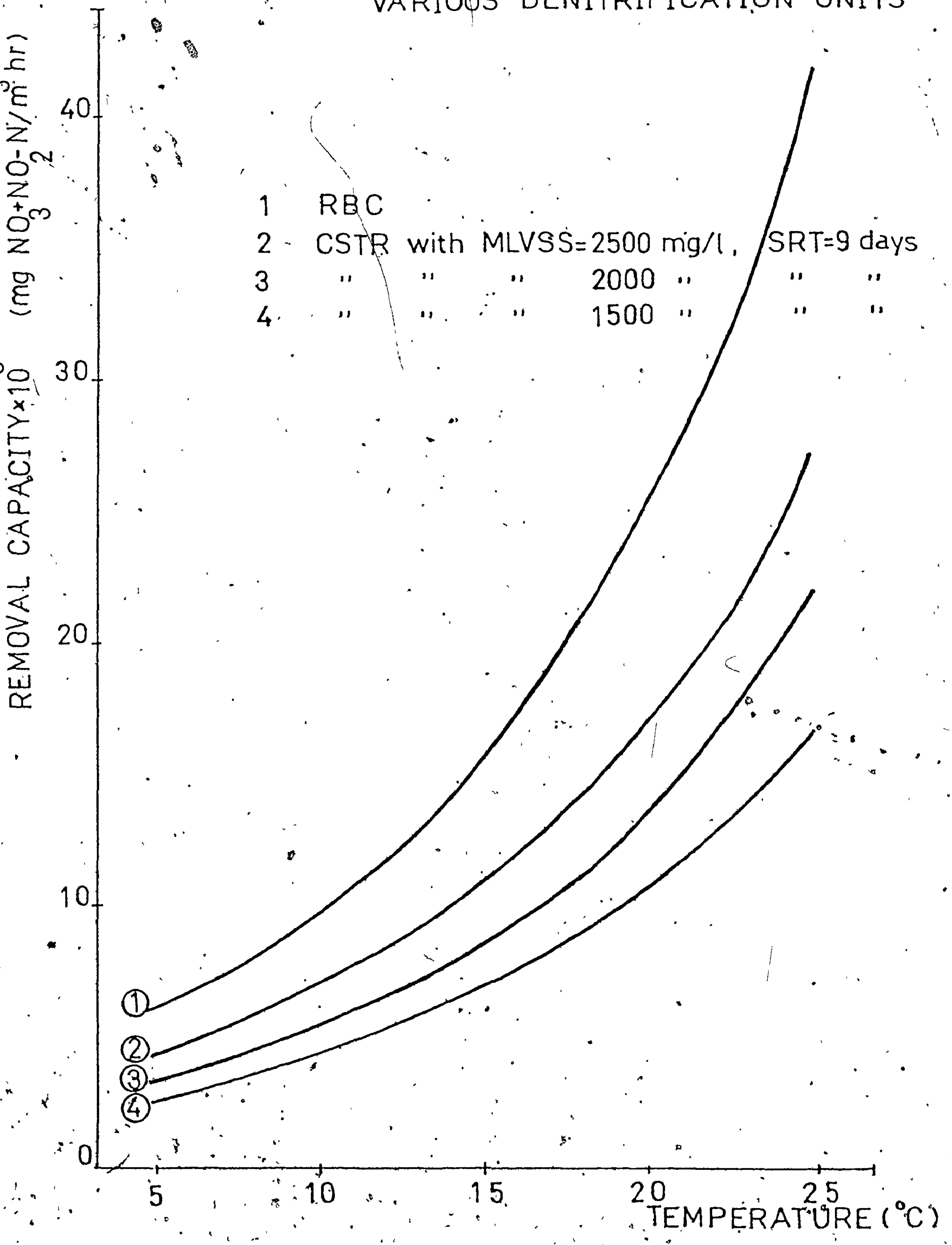


FIGURE NO 23 VOLUMETRIC EFFICIENCIES OF VARIOUS DENITRIFICATION UNITS



6. CONCLUSIONS

(1) A general design method, based on hydraulic simulation can be derived, as a result of this study. Hydraulically, each compartment of completely submerged RBC can be modelled as 2 CSTR's with interchange flow. If the flow between the CSTR's can be determined, it is possible to predict whether the entire disc volume will be effective for denitrification.

(2) The denitrification reaction rates can be expressed as zero order reactions, rather than first order reactions, for the NO_3+NO_2-N concentration ranges studied for RBC.

(3) The temperature dependency of denitrification obtained with an RBC is independent of the hydraulic loading for the range studied (2.5 to 4.0 l/min). It can be empirically described using an Arrhenius relationship with an apparent energy of activation of 16500 cal/g-mole.

(4) The denitrification rates of the RBC are more sensitive to temperature changes than the corresponding rates for CSTR or packed columns under similar operating conditions.

(5) The RBC has higher denitrification rates on a volumetric basis compared with either suspended growth systems (for MLSS range of 1500 to 2500 mg/l) or packed columns.

7. RECOMMENDATIONS

(1) Further research is required to optimize the disc spacing to provide a sufficient area for growth and at the same time provide sufficient interflow transfer into the volume occupied by the discs.

(2) Further experiments should be carried out to assess the effect of DO on denitrification rates, under actual pilot plant conditions. Nitrification and denitrification units might be operated more efficiently by keeping the oxygen level of the nitrification step at minimum so that the influent level of dissolved oxygen in the denitrification unit is minimized.

(3) Further experiments should be done to study the denitrification rates at other hydraulic loadings.

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APPENDIX 1

TABLE 1-1

EXPERIMENTAL PROGRAM FOR 4 STAGES IN SERIES
(Altered experimental program due to unreasonable amount of NO_3-N needed as spike)

Temperature	Hydraulic Loading	Date of Run	Run No.
5	4	10/7	R-5
10	4	17/7	R-6
15	4	3/7	R-4
20	4	23/7	R-7
20	4	24/7	R-8
20	4	30/7	R-9
25	4	17/6	R-1
25	4	19/6	R-2
25	4	16/8	R-11**
25	4	17/8	R-12**
25	4	21-22/8	R-12-13**
25	2	26/6	R-3

**These runs were for rate comparisons under natural pH and controlled pH conditions

TABLE 1-2

EXPERIMENTAL PROGRAM FOR SINGLE STAGE OPERATION

Temperature	Hydraulic Loading	Date	Run No.
5	2.5 l/min	17/9/75	R-19
5	"	18/9/75	R-20
10	"	22/10/75	R-31
10	"	23/10/75	R-32
15	"	11/9/75	R-17
15	"	12/9/75	R-18
20	"	10/10/75	R-27
20	"	11/10/75	R-28
25	"	25/9/75	R-22
25	"	26/9/75	R-23
25	"	28/9/75	R-24

TABLE 1-3

EXPERIMENTAL PROGRAM FOR SINGLE STAGE OPERATION

Temperature	Hydraulic Loading	Date	Run No.
5	4.0 l/min	17/9	R-19
5	"	19/9	R-20
5	"	21/9	R-21
5	"	22/10	R-31
10	"	22/10	R-31
10	"	23/10	R-32
20	"	10/10	R-27
25	"	3/10	R-25

*Due to operational difficulties double run for each temperature level was not obtained.

ROTATING BIOLOGICAL CONTACTOR

FOUR STAGE IN SERIES OPERATION

ALL CONCENTRATIONS ARE IN PPM

		UNFILTERED			FILTERED						
Date	Designation	COD	D.O.	TKN	COD	TOC	NH_3-N	NO_2-N	NO_3-N	TKN	
17 06	IDNAF-C*PM	182	5.5	2.8	37	37	0.2	0.4	7.3	1.8	
17 06	EE-1-C*PM		0.3		33	22	0.1	0.0	0.0	1.5	
17 06	EE-2-C		0.1		34	19	0.0	0.0	0.0	1.2	
17 06	EE-3-C*PM		0.1		28	17	0.0	0.0	0.0	0.5	
17 06	EE-C*PM	52	0.1	2.3	30	16	0.1	0.0	0.0	2.3	
19 06	IDNAF-C*PM	468	5.7	1.7	52	57	0.2	0.3	20.7	1.0	
19 06	EE-1-C*PM		0.6		106	53	0.3	0.0	0.0	1.7	
19 06	EE-2-C*PM		0.2		76	39	0.1	2.2	0.1	1.0	
19 06	EE-3-C*PM		0.2		89	31	0.0	0.0	0.0	0.8	
19 06	EE-C*PM	145	0.0	2.0	84	28	0.1	0.0	0.0	0.3	
26 06	IDNAF-C*PM	158		2.9	35	26	0.2	0.5	17.3	2.3	
26 06	EE-1-C*				81	12	0.3	0.3	2.8	1.1	
26 06	EE-2-C*				88	13	0.2	0.2	0.3	1.1	
26 06	EE-3-C*				96	13	0.5	0.0	0.0	1.5	
26 06	EE-C*	52		1.5	94	10	0.6	0.2	0.1	0.6	
03 07	IDNAF-C*PM	185	5.1	3.9	111	27	0.3	1.3	17.7	2.7	
03 07	EE-1-C*		1.5		42	24	0.2	3.4	11.0	3.0	
03 07	EE-2-C*		0.4		33	16	0.2	3.7	5.0	2.2	
03 07	EE-3-C*		0.2		31	14	0.3	0.9	0.8	2.0	
03 07	EE-C*	71	0.2	3.7	31	12	0.2	0.0	0.0	3.4	
10 07	IDNAF-C*PM	191	7.2	1.0	48	39	0.0	0.8	13.3	2.9	
10 07	EE-1-C*		4.1		52	38	0.0	0.3	10.1	1.0	
10 07	EE-2-C*		1.9		35	36	0.0	1.2	10.3	1.6	
10 07	EE-3C*		0.8		51	35	0.2	1.9	7.3	1.2	
10 07	EE-C*	155	0.4	1.8	59	36	0.1	0.0	0.0	1.3	
17 07	IDNAF-C*PM	162	6.3	2.1	53	26	0.1	0.4	16.0	1.2	
17 07	EE-1-C*		2.9		53	23	0.1	0.1	3.3	0.7	
17 07	EE-2-C*		1.2		35	21	0.1	0.1	4.9	0.6	
17 07	EE-3-C*		0.5		36	22	0.1	0.1	1.5	0.6	
17 07	EE-C*	32		1.1	30	13	0.1	0.7	0.3	0.6	
23 07	IDNAF-C*PM	174	7.2		51	19	0.0	0.6	38.4	1.8	CL
23 07	EE-1C*PM		1.4		39	12	0.1	1.4	32.6	1.8	CL
23 07	EE-2C*PM		0.2		32	10	0.1	1.6	21.4	1.4	CL
23 07	EE-3C*PM		0.2		36	14	0.1	1.4	22.6	1.2	CL
23 07	EE-C*PM			4.4	26	10	0.2	0.9	25.1	2.0	CL
29 07	IDNAF-C*PM	358	5.4	1.5	345	100	1.5	0.1	12.5	0.5	OP
29 07	EE-1C*PM		1.1		465	65	0.5	0.6	9.3	1.3	OP
29 07	EE-2C*PM		0.5		338	58	0.4	0.5	[illegible]	[illegible]	OP
29 07	EE-3C*PM		0.15		326	45	0.5	0.2	2.1	1.3	OP
29 07	EE-C*PM	339	0.15	2.4	192	34	0.5	0.0	0.0	1.1	OP
15 08	IDNAF-C*PM	560	4.3	1.7	980	30	0.3	0.0	42.0	1.1	
15 08	EE-1C*PM		1.7		620	85	0.3	0.3	23.0	0.8	
15 08	EE-2C*PM		0.3		530	53	0.3	0.4	11.0	1.1	
15 08	EE-3C*PM		0.1		630	57	0.3	0.4	3.3	0.9	
15 08	EE-C*PM	383	0.0	2.9	390	40	0.3	0.3	[illegible]	1.3	
17 08	IDNAF-C*PM	500		2.2	695	65	0.3	0.1	[illegible]	1.5	

FOUR STAGE IN SERIES OPERATION

17	08	EE-1C*PM				460	63	3.3	0.4	42.0	0.9	
17	08	EE-2C*PM				350	51	3.4	0.6	13.0	1.3	
17	08	EE-3C*PM				277	39	2.3	0.5	3.3	1.3	
17	08	EE-C*PM	212		1.9	242	41	0.3	0.3	1.5	0.8	
21	08	IONEBE-C*AM	525	3.5	11.3	560	58	8.6	0.2	39.0	9.9	PC
21	08	EE-1C*AM		0.65		470	57	7.6	1.3	13.0	8.2	PC
21	08	EE-2C*AM		0.4		385	42	5.5	1.5	5.8	6.9	PC
21	08	EE-3C*AM		0.20		355	34	5.0	1.0	1.5	6.1	PC
21	08	EE-C*AM	265	0.16	11.2		31	5.9	0.1	0.2	6.8	PC
21	08	IONEBE-C*PM	565		12.0	625	70	8.8	0.2	45.0	9.7	PC
21	08	EE-1C*PM				530	55	6.3	1.3	21.0	7.1	PC
21	08	EE-2C*PM				475	45	6.4	1.1	6.5	7.1	PC
21	08	EE-3C*PM				480	39	4.9	0.8	1.2	5.5	PC
21	08	EE-C*PM	330		10.2	395	34	5.9	0.4	0.2	6.9	PC

CL STANDS FOR CARBON LIMITATION IN THE SYSTEM

PD STANDS FOR PUMPING DISORDER

OP STANDS FOR VARIOUS OPERATIONAL PROBLEMS

PC STANDS FOR PH CONTROL BY BUFFER ADDITION

OC STANDS FOR OXIGEN LEVEL CONTROL BY STRIPPING BY N2 GAS

IONEBE-C*,AND IONAF-C* STANDS FOR THE COMPOSITE SAMPLE TAKEN FROM FEED AFTER METHANOL ADDITION

EE-1C*,EE-2C*,EE-3C*, AND EE-C* STAND FOR THE SAMPLES TAKEN FROM FIRST,SECOND,THIRD AND FORTH STAGES RESPECTIVELY

ROTATING BIOLOGICAL CONTACTOR

FOUR STAGE IN SERIES OPERATION

Date	Designation	MLSS	MLVSS	Flow Rate	Alkalinity	pH	HACH-NO_3-N	Temp.
17 05	IDNAF-C*PM			3.9		7.50	14.5	24.2
	EE-1C*PM			3.9		7.50	4.75	25.2
	EE-2C*PM			3.9		7.65	1.60	25.4
	EE-3C*PM			3.9		7.55	0.60	25.4
	EE-4C*PM			3.9		7.50	0.40	25.4
19 05	IDNAF-C*PM			4.0			18.00	25.8
	EE-1C*PM			4.0			5.10	25.4
	EE-2C*PM			4.0			2.90	25.5
	EE-3C*PM			4.0			1.10	25.5
	EE-4C*PM			4.0			0.60	25.5
26 06	IDNAF-C*PM	15	11	2.0	125	7.28		26.0
	EE-1C*PM	143	107	2.0	168	7.70		25.1
	EE-2C*PM	35	27		194	7.75		25.1
	EE-3C*PM	36	28	2.0	202	7.72		25.1
	EE-4C*PM	29	22	2.0	200	7.70		25.1
03 07	IDNAF-C*PM			4.0	125	7.48		14.4
	EE-1C*PM	68	48	4.0	138	7.72		14.4
	EE-2C*PM	36	28	4.0	171	7.84		14.4
	EE-3C*PM	29	24	4.0	175	7.92		14.4
	EE-4C*PM	24	21	4.0	181	7.92		14.4
16 7	IDNAF-C*PM	14	10	4.0	101			
	EE-2-C*PM	43	33	4.0	123	7.68		6.00
	EE-3*PM	28	21	4.0	130	7.22		6.00
	EE-4C*PM	26	19	4.0	143	7.78		6.3
23 07	IDNAF-C*	15	7	4.1	69	7.52		19.8
	EE-1C*	12	8	4.1	127	7.82		20.8
	EE-2C*	18	14	4.1	167	8.22		20.8
	EE-3C*	19	15	4.1	181	8.32		21.0
	EE-4C*	12	9	4.1	183	8.45		21.2
29 07	IDNAF-C*			4.0	127	7.65		19.6
	EE-1C*			4.0	241	7.72		20.2
	EE-2C*			4.0	300	7.83		20.4
	EE-3C*			4.0	317	7.65		20.6
	EE-4C*			4.0	327	7.75		20.8
16 08	IDNAF-C*PM			4.0	108	7.38	38.00	22.0
	EE-1C*PM			4.0	181	7.90	23.00	23.00
	EE-2C*PM			4.0	243	8.20	12.00	23.5
	EE-3C*PM			4.0	277	8.25	5.50	23.5
	EE-4C*PM			4.0	261	8.25	1.50	23.5
18 08	IDNAF-C*PM	76	56	4.1	65	7.30	47.5	21.5
	EE-1C*PM	36	35	4.1	165	7.95	31.25	21.5
	EE-2C*PM	66	50	4.1	230	8.40	15.00	21.5
	EE-3C*PM	54	43	4.1	271	8.50	5.00	21.5
	EE-4C*PM	26	19	4.1	281	8.48	1.75	21.5
21 08	IDNAF-C*PM	45	27	4.0	196	7.28	42.50	23.2
	EE-1C*PM	69		4.0	271	7.55	20.00	[illegible]

ROTATING BIOLOGICAL CONTACTOR

FOUR STAGE IN SERIES OPERATION

EE-2C*PM	74	53	4.0	265	7.62	6.00	24.00
EE-3C*PM	56	37	4.0	344	7.62	3.00	24.0
EE-4C*PM	64.	31.	4.0	371	7.60	0.00	24.0

IONEBE-C* AND IONAF-C* STANDS FOR THE COMPOSITE SAMPLE TAKEN FROM FEED AFTER METHANOL ADDITION

EE-1C*, EE-2C*, EE-3C* AND EE-4C* STAND FOR THE SAMPLES TAKEN FROM FIRST, SECOND, THIRD AND FORTH STAGES RESPECTIVELY
TEMPERATURES ARE GIVEN IN DEGREE CENTGRADE

FLOW RATES ARE GIVEN IN LITER/MINUTE

MLSS AND MLVSS MEASUREMENTS ARE GIVEN IN MILIGRAM/LITER

HACH NO3-N AND ALKALINITIES ARE GIVEN IN MILIGRAM /LITER

SINGLE STAGE OPERATION.

		UNFILTERED---			FILTERED						
DATE	SAMPLE NAME	COD	DO	TKN	COD	TOC	NH3N	NO2N	NO3N	TKN	NOTE
29 08	IDNEBE-C*PM	278	2.10	13.9	294	60	8.8	0.6	13.0	10.6	
29 08	EE-1C*PM	193	0.45		161	33	7.2	0.4	2.1	11.1	
29 08	EE-4	56	0.45	11.7	145	13	8.5	1.6	12.4	10.4	PD
03 09	IDNBE-C*PM	261	5.50	8.7	274	53	6.4	0.4	8.6	7.0	
03 09	EE-1C*	40	1.35	6.3	72	11	5.5	0.5	7.2	6.3	PD
03 09	EE-4C*PM	213	1.45	6.5	221	45	5.1	0.3	4.4	5.5	
11 09	IDNAF-C*1PM	184	5.7	8.2	210	42	6.8	0.3	15.0	7.5	
11 09	EE-1C*1PM	46		9.2	88	18	6.9		26.4	8.1	PD
11 09	EE-4-C*1PM	124	1.30	6.9	149	30	5.2	0.7	3.1	6.3	
11 09	IDNAF-C*3PM	126	5.6	8.8	184	42	7.2	0.2	12.0	8.1	
11 09	EE-1C*3PM	54		9.1	82	13	8.1	0.7	25.3	8.1	PD
11 09	EE-4-C*3PM	122	1.30	7.1	173	30	5.8	0.7	5.0	7.1	
12 09	IDNAF-C*3PM	195	6.2	6.3	183	68	4.4	0.6	14.0	5.7	
12 09	EE-1C*3PM	50	2.3	6.3	30	45	3.9	1.5	47.5	5.6	PD
12 09	EE-4-C*3PM	118	1.5	3.9	71	51	1.7	1.9	3.3	3.5	
12 09	IDNAF-C*1PM	178	6.3	5.3	164	71	3.4	0.9	11.1	4.5	
12 09	EE-1C*1PM	38	2.20	4.7	33	41	3.3	1.3	42.7	4.3	PD
12 09	EE-4C*1PM	104	1.30	5.8	69	63	1.4	1.9	2.3	2.6	
17 09	IDNAF-C*1PM	166	6.9	4.8	50	40	3.2	0.3	12.9	4.6	
17 09	EE-1-C*1PM	56	3.9	4.3	35	15	2.8	0.6	11.0	3.1	
17 09	EE-4-C*1PM	139	3.5	4.2	41	32	2.5	1.0	9.2	3.0	
17 09	IDNAF-C*3PM	37	6.9	5.1	49	37	3.2	0.3	13.7	3.9	
17 09	EE-1-C*3PM	55	3.9	4.9	33	15	3.1	0.5	13.1	3.9	
17 09	EE-4-C*3PM	130	3.5	4.9	35	31	2.9	1.0	9.3	3.6	
18 09	IDNAF-C*3PM	149		3.0	45	43	0.1	0.2	24.0	1.8	
18 09	EE-1C*3PM	59		2.4	31		0.2	0.6	32.4	1.3	
18 09	EE-4C*3PM	120		3.1	35	28	0.1	1.6	12.0	1.7	
18 09	IDNAF-C*1PM	157	6.70	2.6	43	37	0.1	0.2	25.0	1.6	
18 09	EE-1C*1PM	53	4.30	2.1	28	16	0.1	0.6	23.0	1.5	
18 09	EE-4C*1PM	120	2.70	2.2	33	31	0.1	1.6	19.0	1.4	
21 09	IDNAF-C*5PM	24	6.30	1.0	16	9	0.0	0.1	15.3	0.8	
21 09	EE-1C*5PM	28	1.70	2.2	20	15	0.0	0.3	12.8	2.0	PD
21 09	EE-4C*5PM	152	3.50	2.3	31	40	0.0	0.5	9.9	2.0	
21 09	IDNAF-C*7PM	40	6.70	1.2	40	9	0.0	0.0	15.3	1.2	
21 09	EE-1C*7PM	65	1.70	1.2	35	15	0.0	0.3	24.7	0.9	PD
21 09	EE-4C*7PM	197	2.50	1.3	66	41	0.0	0.5	12.0	1.3	
26 09	IDNAF-C*1PM	193	5.4	1.1	103	51	0.1	1.0	11.7	0.7	
26 09	EE-1C*1PM	23	0.3	4.3	22	13	0.0	4.1	7.2	0.3	PD
26 09	EE-4C*1PM	98	0.2	1.6	44	13	0.1	1.4	1.5	1.3	
28 09	IDNAF-C*1PM	207	5.7	1.3	149	53	0.1	2.2	23.7	1.6	

SINGLE STAGE OPERATION

```
 2 03 EE-4C*1PM      9-     0.3   3.4    39     23  0.1  2.6  1.1  1.3

03 10 IDNAF-C*1PM   247     5.30  1.1   166     50  0.3  3.6 25.4  1.0
03 10 EE-4-C*1PM    128     0.60  3.2    55     31  0.3  3.6  2.1  2.3

03 10 IDNAF-C*3PM   236     4.50  1.3   136     59  0.2  3.8 25.2  1.0
03 10 EE-4-C*3PM    167     0.60  1.6    57     31  0.2  4.2  5.4  1.4

09 10 IDNAF-C*PM    114     5.40  1.6   239     29  3.3  3.1 33.9  1.1
09 10 EE-4-C*1PM    156     0.80  3.8   125     27  0.5  3.5  0.0  3.5

10 10 IDNAF-C*4PM   326     5.4   1.7   354     65  0.2  2.8 27.2  1.3
10 10 EE-1-C*4PM    159     0.50  1.8   165     33  0.2  2.2  4.7  1.7
10 10 EE-4-C*2PM    126     0.8   1.9   120     27  0.3  3.1  6.9  1.6

11 10 IDNAF-C*6PM   355     5.3   1.3   160     61  0.2  2.9 26.1  1.3
11 10 EE-10*6PM     162     0.5   1.3   171     35  0.2  2.3 10.7  1.7

15 10 IDNAF-C*PM    160     5.5   2.5   156     32  0.0  1.9 22.1  1.2
15 10 EE-10*        218     1.3   1.4   204     41  0.4  4.2  7.9  1.0
15 10 EE-40*        170     0.7   1.1    58     19  0.4  3.9  2.7  0.6

16 10 IDNAF-C*      177           1.1   180     45  0.7  0.6  0.0  0.9
16 10 EE-10*        192           0.7   193     35  0.3  3.5 10.2  0.2
16 10 EE-40*         95           2.0    50     15  3.5  2.1  5.6  1.5

22 10 IDNAF-C*      139     5.3   4.8   119     27  0.2  1.1 15.9  4.1
22 10 EE-10*         86     1.7   3.2   108     18  0.2  1.9 13.4  2.6

23 10 IDNAF-C*PM    150           3.8   143     29  0.2  0.5 17.5  2.1
23 10 EE-10*         83           4.2   115     20  0.2  2.0 13.0  3.9
23 10 EE-40*         72           2.6    85     47  0.5  2.6 10.3  1.7
```

CL STANDS FOR CARBON LIMITATION IN THE SYSTEM

PD STANDS FOR PUMPING DISORDER

OP STANDS FOR VARIOUS OPERATIONAL PROBLEMS

PC STANDS FOR PH CONTROL BY BUFFER ADDITION

OC STANDS FOR OXIGEN LEVEL CONTROL BY STRIPPIG BY N2 GAS

IDNEBE-C* AND IDNAF-C* STANDS FOR THE COMPOSITE SAMPLE TAKEN FROM FEED AFTER METHANOL ADDITION

EE-1C* AND EE-4C* STAND FOR THE COMPOSITE SAMPLE TAKEN FROM FIRST AND FORTH STAGES RESPECTIVELY

SINGLE STAGE OPERATION

DATE	SAMPLE	MLSS	MLVSS	FLOW RATE	ALK-	PH	HACH NO3-N	TEMP-ERATURE
29 08	IDNAF-C PM	27	22			7.13	16.00	12.00
	EE-1C*PM		49	1.80		7.25	4.00	14.30
	EE-4C*PM	21	12	0.97		7.13	16.00	14.80
03 09	IDNAF-C*PM					7.31	9.20	12.00
	EE-1C*PM			0.97		7.25	7.00	14.80
	EE-4C*PM			1.30		.35	4.00	14.30
11 09	IDNAF-C PM	17.			150		12.50	13.40
	EE-1C*PM	17		3.90	144		11.50	14.60
	EE-4C*PM	15		2.45	186		5.00	14.80
12 09	IDNAF-C*PM	25	15		148	7.45	17.00	13.40
	EE-1C*PM	13		3.9	148	7.45	16.00	14.60
	EE-4C*PM	38	27	2.45	188		5.00	14.80
17 09	IDNAF-C*PM						15.00	4.50
	EE-1C*PM			2.47			14.00	5.00
	EE-4C*PM			3.90			8.50	4.70
18 09	IDNAF-C*PM	3	2		108	7.05	17.00	4.40
	EE-1C*PM	9	5	2.50	115		15.50	5.70
	EE-4C*PM	14	9	4.00	124		17.50	
21 09	IDNAF-C*PM	6				7.33		4.40
	EE-1C*PM	12		4.00		7.70	15.50	5.70
	EE-4C*PM	18		4.00		7.52	17.00	5.50
26 09	IDNAF-C*PM							25.70
	EE-1C*PM			4.00			26.00	25.00
	EE-4C*PM			2.50			6.00	25.00
03 19	IDNAF-C*PM						25.00	25.60
	EE-1C*PM						15.30	
	EE-4C*PM			4.10				
08 10	IDNAF-C*PM					7.03	18.00	21.70
	EE-1C*PM			4.00		7.35		20.50
	EE-4C*PM					7.15	22.00	20.00
10 10	IDNAF-C*PM			2.50				20.00
	EE-1C*PM			4.00		7.45	4.50	20.00
	EE-4C*PM.							
15 10	IDNAF-C*PM				138	7.10		
	EE-1C*PM			3.20	165	7.40	8.00	15.00
	EE-4C*PM			1.80		7.38	4.00	15.50
16 10	IDNAF-C PM							
	EE-1C*PM			3.20				15.25
	EE-4C*PM			1.80				15.00
22 10	IDNAF-C*PM							
	EE-1C*PM			4.00				
	EE-4C*PM			2.50				10.00

APPENDIX 2

The following are included in this appendix:

Computer Program DYEL:

Calculates dye recovery, mean dye residence time, residence time distribution, and also lists the dye study results.

Program FLBTCS:

Calculates the average flow rates between inner and outer CSTR'S of a single stage RBC. Also it gives the dye concentration of inner CSTR at any time after pulse dye injection.

Program DEDBIS:

Calculates ideal response of two CSTR with interchange flow for pulse dye injection using Dedrick's and Bischoff's formula.

Program LINRG

Program CONF95

```
      PROGRAM DYEL(INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT)
C     PROGRAM FOR THE CALCULATION OF DYE RECOVERY,MEAN DYE RESIDENCE TIME,
C     E(RESIDENCE TIME DISTRIBUTIONS) AND F(C/CO) VALUES.
C
C     DEFINITIONS
C     DET=THEORETICAL DETENTION TIME OF THE REACTOR,IN MIN.
C     DYE=AMOUNT OF THE DYE ADDED,IN LIT.
C     DT=THE SAMPLING INTERVAL,IN MIN.
C     ET=RESIDENCE TIME DISTRIBUTION BASED ON DIMENSIONLESS TIME,DIMEN
C     SIONLESS
C     F=THE AREA UNDER ET CURVE,DIMENSIONLESS
C     TEBAR=MEAN RESIDENCE TIME BASED ON THE DYE MEASUREMENTS,IN MIN.
C     THETA=DIMENSIONLESS TIME
C     VTOTA=VOLUME OF THE REACTOR,IN LIT.
C     VT=HYDRAULIC LOADING,IN LIT./MIN.
C     N=THE NOUMBER OF SAMPLESS COLLECTED
C     C(N)=THE MEASURED DYE CONCENTRATIONS AT TIME=N*DT AFTER PULSE
C     DYE INJECTION,IN PPB
C                                INPUTS
C     VTOTA,VT,DYIN,DYCON,DT,N,DET
C                                OUTPUTS
C     VTOTA,VT,DET,DYIN,DYCON,C(N),PER,TEBAR,DT
      DIMENSION RE(500),TIME(500),CUL(500),FIT(500)
      DIMENSION ET(500)
      DIMENSION C(500),THETA(500),F(500),Q(500),E(500),Y(500),X(500)
      DIMENSION CTBDET(500),CI(500),CB(500),T(500)
      DIMENSION TE(500)
      DIMENSION STE(500)
      READ(5,1)VTOTA,VT,DYIN,DYCON,DT
    1 FORMAT(3F10.4,E10.2,F10.4)
      READ(5,2)N,DET
    2 FORMAT(I7,F10.4)
      READ(5,3)(C(I),I=1,N)
    3 FORMAT(5F10.2)
      WRITE(6,51)
   51 FORMAT(10X,///////////////////////////////////////////)
      WRITE(6,997)
  997 FORMAT(20X,11HINPUT  DATA,//)
      WRITE(6,995)
  995 FORMAT(10X,≠FOUR STAGE IN SERIES OPERATION≠,10X)
      WRITE(6,111)
  111 FORMAT(10X,≠TEMPERATURE=15 DEG. C≠,10X)
      WRITE(6,306) VT
  306 FORMAT(10X,≠FLOW RATE=≠,F6.2,≠LIT./MIN.≠,5X)
      WRITE(6,305) VTOTA
  305 FORMAT(10X,≠VOLUME OF THE REACTOR=≠,F7.1,≠LIT.≠,10X)
      WRITE(6,307) DET
  307 FORMAT(10X,≠THEORETICAL DETENTION TIME=≠,F7.2,≠MIN≠,10X,1X)
      WRITE(6,102) DT
  102 FORMAT(10X,≠DT=≠,F5.2,≠MIN≠,10X)
```

```
      WRITE(6,308) DYIN
  308 FORMAT(10X,≠THE AMOUNT OF DYE INJECTED=≠,F7.4,≠LIT.≠,10X)
      WRITE(6,309) DYCON
  309 FORMAT(10X,≠CONCENTRATION OF THE DYE ADDED=≠,F10.2,≠PPB≠,///)
      WRITE(6,990)
  990 FORMAT(15X,≠DYE MEASUREMENTS≠,//)
      WRITE(6,991) (C(I),I=1,N)
  991 FORMAT(5X,5F10.2,/)
C     CALCULATION OF TIME VALUES
      TIME(1)=0.0
      DO 10 I=2,N
      KL=I-1
   10 TIME(I)=TIME(KL)+DT
C     CALCULATIONS OF THETA VALUES
      THETA(1)=0.0
      DO 900 I=2,N
      THETA(I)=TIME(I)/DET
  900 CONTINUE
C     CALCULATION OF DYE RECOVERY
      CUL(1)=0.0
      DO 800 I=2,N
      LUL=I-1
      AMT=0.5*(C(I)+C(LUL))*DT*VT*10.**(-6)
      CUL(I)=CUL(LUL)+AMT
  800 CONTINUE
      DYE=DYCON*DYIN*10.**(-6)
      PER=CUL(N)/DYE*100.
      CTBDET(1)=0.0
      CI(1)=0.0
      DO 81 I=2,N
      KL=I-1
      CB(KL)=(C(KL)+C(I))*0.50
      T(I)=I*DT-0.5*DT
      CTBDET(I)=CB(KL)*T(I)*DT+CTBDET(KL)
      CI(I)=CI(KL)+CB(KL)*DT
   81 CONTINUE
      TEBAR=CTBDET(N)/CI(N)
C     CONVERSION OF E CURVE TO F CURVE
C     CALCULATION Q VALUES
      Q(1)=0.0
      DO 8 I=2,N
      KM=I-1
      Q(I)=Q(KM)+0.5*(C(I)+C(KM))*DT
    8 CONTINUE
      TOTQ=Q(N)
      DO 700 I=1,N
      E(I)=C(I)/TOTQ
      ET(I)=E(I)*DET
  700 CONTINUE
      AMT=0.0
      F(1)=AMT
      DO 4 I=2,N
      ILK=I-1
      F(I)=F(ILK)+0.5*(E(I)+E(ILK))*DT
```

```
YEL        73/73   TS                            FTN 4.5+410        02/26/76  19.47.25        PAGE    3
              /7                                                              /73
           IF(F(I).GT.0.98) GO TO 4
           L=I
         4 CONTINUE
           STE(1)=0.00
           DO 21 I=2,N
           KL=I-1
           TE(I)=(E(KL)+E(I))*0.5*DT*T(I)
           STE(I)=STE(KL)+TE(I)
        21 CONTINUE
           TONE=STE(N)
           WRITE(6,180)
       180 FORMAT(10X,//////////)
           WRITE(6,310)
       310 FORMAT(10X,34HTEST RESULTS AND CALCULATED VALUES,////)
           WRITE(6,311) PER
       311 FORMAT(10X,≠DYE RECOVERY=≠,F7.2,≠PER CENT≠,5X,/)
           WRITE(6,858) TEBAR
       858 FORMAT(10X,≠MEAN DYE RESIDENCE BASED ON C=≠,F6.2,≠MIN≠,10X)
           WRITE(6,123) TONE
       123 FORMAT(10X,≠MEAN DYE RESIDENCE BASED ON E=≠,F6.2,≠MIN≠,///)
           WRITE(6,942)
       942 FORMAT(10X,5HTHETA,12X,1HE,2X,8X,2HET,1X,10X,2X,1HF,2X,//)
           DO 25 I=1,N
           WRITE(6,324) (THETA(I),E(I),ET(I),F(I))
       324 FORMAT(10X,F6.3,7X,F6.3,7X,F6.3,7X,F6.3,3X)
           IF(I.EQ.50) GO TO 389
           IF(I.EQ.100) GO TO 389
           GO TO 25
       389 WRITE(6,388)
       388 FORMAT(10X,////////////////////////////////////)
           WRITE(6,811)
       811 FORMAT(10X,5HTHETA,12X,1HE,2X,6X,2HET,1X,10X,2X,1HF,2X,//)
        25 CONTINUE
           END

                     --E N T R Y   P O I N T S--
DYEL                     3B   INPUT=                    43B   OUTPUT=                          3B   TAPE5=
TAPE6=

                     --E X T E R N A L S--
END.       INPCI.      INPCR.      OUTCI.      OUTCR.      Q8NTRY.      XTOI.

                     --S T A T E M E N T   L A B E L S--
    412B                 .2      F       415B                  .3      F       417B                 .4     D       323B
      0B                 .10     ID        0B                  .21     ID        0B                 .25    D       405B
    421B                 .91     ID        0B                  .102    F       470B                 .111   F       441B
    547B                 .180    F       521B                  .305    F       453B                 .306   F       446B
    461B                 .308    F       474B                  .309    F       503B                 .310   F       524B
    532B                 .324    F       563B                  .388    F       570B                 .389           401B
      0B                 .800    ID        0B                  .811    F       575B                 .858   F       540B
      0B                 .942    F       556B                  .990    F       512B                 .991   F       516B
```

```
                INPUT  DATA

      FOUR STAGE IN SERIES OPERATION
      TEMPERATURE=10 DEG. C
      FLOW RATE=  4.00LIT./MIN.
      VOLUME OF THE REACTOR=  408.0LIT.
      THEORETICAL DETENTION TIME= 102.00MIN
      DT= 4.00MIN
      THE AMOUNT OF DYE INJECTED=  .0220LIT.
      CONCENTRATION OF THE DYE ADDED=2380000.00PPB


          DYE MEASUREMENTS

        0.00       6.50      26.00      42.00      60.00
       73.00      85.00      95.00     103.00     108.00
      108.00     108.00     107.00     104.50     101.00
       97.00      93.50      90.00      86.00      82.00
       79.00      75.50      72.00      68.50      65.00
       61.00      58.00      54.50      51.50      49.00
       46.50      44.00      42.00      40.50      38.50
       37.00      35.00      33.50      32.00      30.50
       29.00      28.00      26.50      25.50      24.50
       23.50      22.50      21.75      21.00      20.00
       19.50      18.50      18.00      17.50      16.50
       16.00      15.25      14.50      14.00      13.25
       12.75      12.00      11.50      11.00      10.50
       10.00       9.50       9.00       8.50       8.25
        8.00       7.50       7.25       7.00       6.75
        6.50       6.40       6.25       6.10       6.00
        5.75       5.50       5.40       5.25       5.20
        5.05       5.00       4.90       4.80       4.50
        4.50       4.25       4.00       3.90       3.75
        3.50       3.50       3.40       3.25       3.00
        3.00       2.90       2.75       2.60       2.50
```

```
TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY= 100.17PER CENT
MEAN DYE RESIDENCE BASED ON C=110.67MIN
MEAN DYE RESIDENCE BASED ON E=110.67MIN


THETA            E             ET            F

 0.000         0.000         0.000         0.000
  .039          .000          .051          .001
  .078          .002          .202          .006
  .118          .003          .327          .016
  .157          .005          .467          .032
  .196          .006          .568          .052
  .235          .006          .661          .076
  .275          .007          .739          .104
  .314          .008          .801          .134
  .353          .008          .840          .166
  .392          .008          .840          .199
  .431          .008          .840          .232
  .471          .008          .832          .265
  .510          .008          .813          .297
  .549          .008          .786          .328
  .588          .007          .755          .359
  .627          .007          .727          .388
  .667          .007          .700          .416
  .706          .007          .669          .442
  .745          .006          .638          .468
  .784          .006          .615          .493
  .824          .006          .587          .516
  .863          .005          .560          .539
  .902          .005          .533          .560
  .941          .005          .506          .581
  .980          .005          .475          .600
 1.020          .004          .451          .618
 1.059          .004          .424          .635
 1.098          .004          .401          .651
 1.137          .004          .381          .667
 1.176          .004          .362          .681
 1.216          .003          .342          .695
 1.255          .003          .327          .708
 1.294          .003          .315          .721
 1.333          .003          .299          .733
 1.373          .003          .288          .744
 1.412          .003          .272          .755
 1.451          .003          .261          .766
 1.490          .002          .249          .776
 1.529          .002          .237          .785
 1.569          .002          .226          .794
 1.608          .002          .218          .803
 1.647          .002          .206          .811
 1.686          .002          .198          .819
 1.725          .002          .191          .827
 1.765          .002          .183          .834
 1.804          .002          .175          .841
 1.843          .002          .169          .848
 1.882          .002          .163          .854
 1.922          .002          .156          .861
```

```
THETA          E         ET        F

1.961        .001       .152      .867
2.000        .001       .144      .872
2.039        .001       .140      .878
2.078        .001       .136      .883
2.118        .001       .128      .889
2.157        .001       .124      .894
2.196        .001       .119      .898
2.235        .001       .113      .903
2.275        .001       .109      .907
2.314        .001       .103      .911
2.353        .001       .099      .915
2.392        .001       .093      .919
2.431        .001       .089      .923
2.471        .001       .086      .926
2.510        .001       .082      .929
2.549        .001       .078      .933
2.588        .001       .074      .936
2.627        .001       .070      .938
2.667        .001       .066      .941
2.706        .001       .064      .944
2.745        .001       .062      .946
2.784        .001       .058      .948
2.824        .001       .056      .951
2.863        .001       .054      .953
2.902        .001       .053      .955
2.941        .000       .051      .957
2.980        .000       .050      .959
3.020        .000       .049      .961
3.059        .000       .047      .963
3.098        .000       .047      .965
3.137        .000       .045      .966
3.176        .000       .043      .968
3.216        .000       .042      .970
3.255        .000       .041      .971
3.294        .000       .040      .973
3.333        .000       .039      .975
3.373        .000       .039      .976
3.412        .000       .038      .978
3.451        .000       .037      .979
3.490        .000       .035      .980
3.529        .000       .035      .982
3.569        .000       .033      .983
3.608        .000       .031      .984
3.647        .000       .030      .986
3.686        .000       .029      .987
3.725        .000       .027      .988
3.765        .000       .027      .989
3.804        .000       .026      .990
3.843        .000       .025      .991
3.882        .000       .023      .992
```

```
                INPUT  DATA

FOUR STAGE IN SERIES OPERATION
TEMPERATURE=15 DEG. C
FLOW RATE=  4.00LIT./MIN.
VOLUME OF THE REACTOR=  408.0LIT.
THEORETICAL DETENTION TIME= 102.00MIN
DT= 4.00MIN
THE AMOUNT OF DYE INJECTED=  .0197LIT.
CONCENTRATION OF THE DYE ADDED=2380000.00PPB


     DYE MEASUREMENTS

   .50       7.50      15.00      26.00      42.00
 57.00      69.00      77.00      83.00      86.50
 88.50      89.50      90.00      90.00      89.50
 88.50      87.00      85.00      83.00      80.00
 76.50      73.00      69.00      66.00      62.50
 59.00      56.00      53.00      50.00      48.00
 46.00      43.50      41.50      39.50      37.50
 36.00      34.50      32.50      30.50      29.00
 27.50      26.50      25.00      24.00      22.75
 21.75      21.00      19.90      18.50      18.00
 17.00      16.50      15.75      14.75      14.00
 13.00      12.50      11.50      11.00      10.50
 10.00       9.75       9.50       9.00       8.50
  8.25       8.00       7.50       7.40       7.00
  6.90       6.50       6.30       6.00       5.60
  5.50       5.20       4.90       4.50       4.50
  4.40       4.35       4.25       4.10       4.00
  3.90       3.75       3.60       3.50       3.50
  3.45       3.30       3.20       3.10       3.00
  2.60       2.50       2.25       2.10       2.00
```

```
TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  98.48PER CENT

MEAN DYE RESIDENCE BASED ON C=108.77MIN
MEAN DYE RESIDENCE BASED ON E=108.77MIN


THETA               E              ET              F

 0.000            .000            .004           0.000
  .039            .001            .066            .001
  .078            .001            .133            .005
  .118            .002            .230            .012
  .157            .004            .371            .024
  .196            .005            .504            .041
  .235            .006            .610            .063
  .275            .007            .680            .088
  .314            .007            .733            .116
  .353            .007            .764            .146
  .392            .008            .782            .176
  .431            .008            .791            .207
  .471            .008            .795            .238
  .510            .008            .795            .269
  .549            .008            .791            .300
  .588            .008            .782            .331
  .627            .008            .769            .361
  .667            .007            .751            .391
  .706            .007            .733            .420
  .745            .007            .707            .448
  .784            .007            .676            .476
  .824            .006            .645            .502
  .863            .006            .610            .526
  .902            .006            .583            .550
  .941            .005            .552            .572
  .980            .005            .521            .593
 1.020            .005            .495            .613
 1.059            .005            .468            .632
 1.098            .004            .442            .649
 1.137            .004            .424            .666
 1.176            .004            .406            .683
 1.216            .004            .384            .698
 1.255            .004            .367            .713
 1.294            .003            .349            .727
 1.333            .003            .331            .740
 1.373            .003            .318            .753
 1.412            .003            .305            .765

 1.451            .003            .287            .777
 1.490            .003            .270            .788
 1.529            .003            .256            .798
 1.569            .002            .248            .808
 1.608            .002            .234            .817
 1.647            .002            .221            .826
 1.686            .002            .212            .835
 1.725            .002            .201            .843
 1.765            .002            .192            .851
 1.804            .002            .186            .858
 1.843            .002            .176            .865
 1.882            .002            .163            .872
 1.922            .002            .159            .878
```

THETA	E	ET	F
1.961	.001	.150	.884
2.000	.001	.146	.890
2.039	.001	.139	.895
2.078	.001	.130	.901
2.118	.001	.124	.906
2.157	.001	.115	.910
2.196	.001	.110	.915
2.235	.001	.102	.919
2.275	.001	.097	.923
2.314	.001	.093	.927
2.353	.001	.088	.930
2.392	.001	.086	.934
2.431	.001	.084	.937
2.471	.001	.080	.940
2.510	.001	.075	.943
2.549	.001	.073	.946
2.588	.001	.071	.949
2.627	.001	.066	.952
2.667	.001	.065	.954
2.706	.001	.062	.957
2.745	.001	.061	.959
2.784	.001	.057	.961
2.824	.001	.056	.964
2.863	.001	.053	.966
2.902	.000	.049	.968
2.941	.000	.049	.970
2.980	.000	.046	.971
3.020	.000	.043	.973
3.059	.000	.040	.975
3.098	.000	.040	.976
3.137	.000	.039	.978
3.176	.000	.038	.979
3.216	.000	.038	.981
3.255	.000	.036	.982
3.294	.000	.035	.984
3.333	.000	.034	.985
3.373	.000	.033	.986
3.412	.000	.032	.988
3.451	.000	.031	.989
3.490	.000	.031	.990
3.529	.000	.030	.991
3.569	.000	.029	.993
3.608	.000	.028	.994
3.647	.000	.027	.995
3.686	.000	.027	.996
3.725	.000	.023	.997
3.765	.000	.022	.998
3.804	.000	.020	.999
3.843	.000	.019	.999
3.882	.000	.018	1.000

```
            INPUT  DATA.

FOUR STAGE IN SERIES OPERATION
TEMPERATURE=20 DEG.C
FLOW RATE=  4.00LIT./MIN.
VOLUME OF THE REACTOR=  408.0LIT.
THEORETICAL DETENTION TIME= 102.20MIN
DT= 4.00MIN
THE AMOUNT OF DYE INJECTED=  .0235LIT.
CONCENTRATION OF THE DYE ADDED=2380000.00PPB


      DYE MEASUREMENTS.

     .10        6.00      17.50      27.50      40.00
   52.50       61.00      70.00      79.00      85.00
   89.50       92.50      94.00      94.00      93.50
   92.00       90.50      88.50      86.50      84.00
   81.00       77.50      75.00      71.50      68.50
   65.50       62.50      60.00      57.50      55.00
   52.00       49.00      47.00      44.00      42.00
   40.50       39.00      37.00      35.00      34.00
   32.50       31.00      29.50      28.00      27.00
   26.00       24.50      23.50      22.50      21.50
   20.50       20.00      19.00      18.00      17.00
   16.00       15.50      14.50      14.00      13.00
   12.75       12.00      11.50      11.00      10.50
   10.00        9.50       9.00       8.50       8.25
    8.00        7.50       7.25       7.00       6.75
    6.50        6.40       6.25       6.10       6.00
    5.75        5.50       5.40       5.25       5.10
    5.05        5.00       4.90       4.80       4.50
    4.50        4.25       4.00       3.90       3.75
    3.50        3.50       3.40       3.25       3.00
    3.00        2.90       2.75       2.60       2.50
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TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  90.24PER CENT

MEAN DYE RESIDENCE BASED ON C=117.18MIN
MEAN DYE RESIDENCE BASED ON E=117.18MIN


 THETA              E              ET              F

 0.000             .000           .001          0.000
  .039             .000           .049           .001
  .078             .001           .142           .005
  .117             .002           .223           .012
  .157             .003           .324           .023
  .196             .004           .425           .037
  .235             .005           .494           .055
  .274             .006           .567           .076
  .313             .006           .640           .100
  .352             .007           .688           .126
  .391             .007           .725           .153
  .431             .007           .749           .182
  .470             .007           .761           .212
  .509             .007           .761           .241
  .548             .007           .757           .271
  .587             .007           .745           .301
  .626             .007           .733           .329
  .665             .007           .717           .358
  .705             .007           .701           .386
  .744             .007           .680           .413
  .783             .006           .656           .439
  .822             .006           .628           .464
  .861             .006           .607           .488
  .900             .006           .579           .511
  .939             .005           .555           .533
  .978             .005           .531           .555
 1.018             .005           .506           .575
 1.057             .005           .486           .594
 1.096             .005           .466           .613
 1.135             .004           .445           .631
 1.174             .004           .421           .648
 1.213             .004           .397           .664
 1.252             .004           .381           .679
 1.292             .003           .356           .694
 1.331             .003           .340           .707
 1.370             .003           .328           .720
 1.409             .003           .316           .733
 1.448             .003           .300           .745
 1.487             .003           .283           .756
 1.526             .003           .275           .767
 1.566             .003           .263           .778
 1.605             .002           .251           .788
 1.644             .002           .239           .797
 1.683             .002           .227           .807
 1.722             .002           .219           .815
 1.761             .002           .211           .824
 1.800             .002           .198           .832
 1.840             .002           .190           .839
 1.879             .002           .182           .847
 1.918             .002           .174           .854
```

THETA	E	ET	F
1.957	.002	.166	.860
1.996	.002	.162	.867
2.035	.002	.154	.873
2.074	.001	.146	.879
2.114	.001	.138	.884
2.153	.001	.130	.889
2.192	.001	.126	.894
2.231	.001	.117	.899
2.270	.001	.113	.904
2.309	.001	.105	.908
2.348	.001	.103	.912
2.387	.001	.097	.916
2.427	.001	.093	.920
2.466	.001	.089	.923
2.505	.001	.085	.927
2.544	.001	.081	.930
2.583	.001	.077	.933
2.622	.001	.073	.936
2.661	.001	.069	.939
2.701	.001	.067	.941
2.740	.001	.065	.944
2.779	.001	.061	.946
2.818	.001	.059	.949
2.857	.001	.057	.951
2.896	.001	.055	.953
2.935	.001	.053	.955
2.975	.001	.052	.957
3.014	.000	.051	.959
3.053	.000	.049	.961
3.092	.000	.049	.963
3.131	.000	.047	.965
3.170	.000	.045	.967
3.209	.000	.044	.969
3.249	.000	.043	.970
3.288	.000	.041	.972
3.327	.000	.041	.974
3.366	.000	.040	.975
3.405	.000	.040	.977
3.444	.000	.039	.978
3.483	.000	.036	.980
3.523	.000	.036	.981
3.562	.000	.034	.983
3.601	.000	.032	.984
3.640	.000	.032	.985
3.679	.000	.030	.986
3.718	.000	.028	.987
3.757	.000	.028	.989
3.796	.000	.028	.990
3.836	.000	.026	.991
3.875	.000	.024	.992

```
            INPUT  DATA

     FOUR STAGE IN SERIES OPERATION
     TEMPERATURE=25 DEG.C
     FLOW RATE=  4.00LIT./MIN.
     VOLUME OF THE REACTOR=  408.0LIT.
     THEORETICAL DETENTION TIME= 102.00MIN
     DT= 4.00MIN
     THE AMOUNT OF DYE INJECTED=  .0250LIT.
     CONCENTRATION OF THE DYE ADDED=2380000.00PPB


         DYE MEASUREMENTS

      2.50      5.75     10.50     18.00     28.00
     39.50     50.50     60.00     69.50     77.50
     84.50     91.00     96.90    100.00    103.00
    104.50    105.25    105.50    105.40    104.50
    103.50    101.50     99.00     96.00     93.50
     90.00     87.00     84.00     80.50     77.50
     74.25     71.00     68.00     65.25     62.50
     60.00     57.00     54.00     51.00     48.50
     46.25     43.75     41.50     39.50     37.50
     35.25     33.50     31.75     30.00     28.50
     26.90     25.50     24.00     22.75     21.50
     20.25     19.00     17.75     16.50     15.50
     14.50     13.50     12.75     12.00     11.00
     10.50      9.75      9.00      8.50      8.00
      7.50      7.00      6.50      6.00      5.75
      5.50      5.25      4.90      4.50      4.40
      4.10      3.90      3.70      3.50      3.35
      3.10      3.00      2.90      2.60      2.50
      2.49      2.48      2.45      2.10      2.00
      1.75      1.60      1.40      1.25      1.00
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TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  98.95PER CENT
MEAN DYE RESIDENCE BASED ON C=116.19MIN
MEAN DYE RESIDENCE BASED ON E=116.19MIN


THETA            E            ET          F

 0.000         .000         .017        0.000
  .039         .000         .040         .001
  .078         .001         .073         .003
  .118         .001         .125         .007
  .157         .002         .194         .013
  .196         .003         .274         .023
  .235         .003         .350         .035
  .275         .004         .416         .050
  .314         .005         .482         .067
  .353         .005         .537         .087
  .392         .006         .586         .109
  .431         .006         .631         .133
  .471         .007         .672         .159
  .510         .007         .693         .186
  .549         .007         .714         .213
  .588         .007         .724         .241
  .627         .007         .729         .270
  .667         .007         .731         .299
  .706         .007         .730         .327
  .745         .007         .724         .356
  .784         .007         .717         .384
  .824         .007         .703         .412
  .863         .007         .686         .439
  .902         .007         .665         .466
  .941         .006         .648         .491
  .980         .006         .624         .516
 1.020         .006         .603         .540
 1.059         .006         .582         .564
 1.098         .005         .558         .586
 1.137         .005         .537         .607
 1.176         .005         .515         .628
 1.216         .005         .492         .648
 1.255         .005         .471         .667
 1.294         .004         .452         .685
 1.333         .004         .433         .702
 1.373         .004         .416         .719
 1.412         .004         .395         .735
 1.451         .004         .374         .750
 1.490         .003         .353         .764
 1.529         .003         .336         .777
 1.569         .003         .321         .790
 1.608         .003         .303         .803
 1.647         .003         .288         .614
 1.686         .003         .274         .825
 1.725         .003         .260         .838
 1.765         .002         .244         .846
 1.804         .002         .232         .855
 1.843         .002         .220         .864
 1.882         .002         .208         .872
 1.922         .002         .198         .880
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THETA	E	ET	F
1.961	.002	.186	.888
2.000	.002	.177	.895
2.039	.002	.166	.901
2.078	.002	.158	.908
2.118	.001	.149	.914
2.157	.001	.140	.919
2.196	.001	.132	.925
2.235	.001	.123	.930
2.275	.001	.114	.934
2.314	.001	.107	.939
2.353	.001	.100	.943
2.392	.001	.094	.947
2.431	.001	.088	.950
2.471	.001	.083	.954
2.510	.001	.076	.957
2.549	.001	.073	.960
2.588	.001	.068	.962
2.627	.001	.062	.965
2.667	.001	.059	.967
2.706	.001	.055	.970
2.745	.001	.052	.972
2.784	.000	.049	.974
2.824	.000	.045	.975
2.863	.000	.042	.977
2.902	.000	.040	.979
2.941	.000	.038	.980
2.980	.000	.036	.982
3.020	.000	.034	.983
3.059	.000	.031	.984
3.098	.000	.030	.986
3.137	.000	.028	.987
3.176	.000	.027	.988
3.216	.000	.026	.989
3.255	.000	.024	.990
3.294	.000	.023	.991
3.333	.000	.021	.992
3.373	.000	.021	.993
3.412	.000	.020	.993
3.451	.000	.018	.994
3.490	.000	.017	.995
3.529	.000	.017	.995
3.569	.000	.017	.996
3.608	.000	.017	.997
3.647	.000	.015	.997
3.686	.000	.014	.998
3.725	.000	.012	.998
3.765	.000	.011	.999
3.804	.000	.010	.999
3.843	.000	.009	1.000
3.882	.000	.007	1.000

```
          INPUT   DATA

  FOUR STAGE IN SERIES OPERATION AND ALL BIOMAS WAS     STRIPPED OFF
  TEMPERATURE=15 DEG. C
  FLOW RATE=  4.00LIT./MIN.
  VOLUME OF THE REACTOR=  408.0LIT.
  THEORETICAL DETENTION TIME= 102.20MIN
  DT= 5.00MIN
  THE AMOUNT OF DYE INJECTED=  .0200LIT.
  CONCENTRATION OF THE DYE ADDED=2380000.00PPB


       DYE MEASUREMENTS

    0.00        .05       2.00       7.00      12.50
   22.50      28.00      35.00      41.50      47.50
   54.00      60.00      64.50      70.00      75.00
   77.00      77.50      78.00      78.00      77.50
   76.50      75.00      72.00      69.00      67.00
   64.00      61.50      59.00      56.00      53.50
   51.00      48.00      46.00      43.00      40.00
   37.50      35.00      32.50      30.00      28.00
   26.00      24.00      22.50      20.50      19.00
   17.50      16.00      14.50      13.50      12.50
   11.50      10.50       9.50       8.50       7.50
    7.00       6.50       6.00       5.00       4.50
    4.00       3.50       3.50       3.50       3.50
    3.00       3.00       2.50       2.50       2.00
    2.00       2.00       2.00       2.00       1.50
    1.50       1.50       1.50       1.50       1.50
    1.50       1.00       1.00       1.00       1.00
    1.00
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TEST RESULTS AND CALCULATED VALUES

DYE RECOVERY=  95.32PER CENT
MEAN DYE RESIDENCE BASED ON C=130.54MIN
MEAN DYE RESIDENCE BASED ON E=130.54MIN

THETA            E            ET           F

 0.000        0.000        0.000        0.000
  .049         .000         .000         .000
  .098         .000         .018         .000
  .147         .001         .063         .002
  .196         .001         .113         .007
  .245         .002         .203         .014
  .294         .002         .252         .026
  .342         .003         .315         .039
  .391         .004         .374         .056
  .440         .004         .428         .076
  .489         .005         .487         .098
  .538         .005         .541         .123
  .587         .006         .581         .151
  .636         .006         .631         .181
  .685         .007         .676         .212
  .734         .007         .694         .246
  .783         .007         .698         .280
  .832         .007         .703         .314
  .881         .007         .703         .349
  .930         .007         .698         .383
  .978         .007         .689         .417
 1.027         .007         .676         .450
 1.076         .006         .649         .483
 1.125         .006         .622         .514
 1.174         .006         .604         .544
 1.223         .006         .577         .573
 1.272         .005         .554         .600
 1.321         .005         .532         .627
 1.370         .005         .505         .652
 1.419         .005         .482         .676
 1.468         .004         .460         .699
 1.517         .004         .432         .721
 1.566         .004         .414         .742
 1.614         .004         .387         .762
 1.663         .004         .360         .780
 1.712         .003         .338         .797
 1.761         .003         .315         .813
 1.810         .003         .293         .828
 1.859         .003         .270         .842
 1.908         .002         .252         .854
 1.957         .002         .234         .866
 2.006         .002         .216         .877
 2.055         .002         .203         .887
 2.104         .002         .185         .897
 2.153         .002         .171         .906
 2.202         .002         .158         .914
 2.250         .001         .144         .921
 2.299         .001         .131         .928
 2.348         .001         .122         .934
 2.397         .001         .113         .940
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THETA	E	ET	F
2.446	.001	.104	.945
2.495	.001	.095	.950
2.544	.001	.086	.954
2.593	.001	.077	.958
2.642	.001	.068	.962
2.691	.001	.063	.965
2.740	.001	.059	.968
2.789	.001	.054	.971
2.838	.000	.045	.973
2.886	.000	.041	.975
2.935	.000	.036	.977
2.984	.000	.032	.979
3.033	.000	.032	.980
3.082	.000	.032	.982
3.131	.000	.032	.983
3.180	.000	.027	.985
3.229	.000	.027	.986
3.278	.000	.023	.987
3.327	.000	.023	.988
3.376	.000	.018	.989
3.425	.000	.018	.990
3.474	.000	.018	.991
3.523	.000	.018	.992
3.571	.000	.018	.993
3.620	.000	.014	.994
3.669	.000	.014	.994
3.718	.000	.014	.995
3.767	.000	.014	.996
3.816	.000	.014	.996
3.865	.000	.014	.997
3.914	.000	.014	.998
3.963	.000	.009	.998
4.012	.000	.009	.999
4.061	.000	.009	.999
4.110	.000	.009	1.000
4.159	.000	.009	1.000

```
              INPUT  DATA

      SINGLE STAGE OPERATION
      TEMPERATURE=15 DEG. C
      FLOW RATE=  2.50LIT./MIN.
      VOLUME OF THE REACTOR=  100.0LIT.
      THEORETICAL DETENTION TIME=  16.00MIN
      DT= 2.00MIN
      THE AMOUNT OF DYE INJECTED=  .0090LIT.
      CONCENTRATION OF THE DYE ADDED=2380000.00PPB


          DYE MEASUREMENTS

   540.00     295.00     225.00     195.00     175.00
   158.00     142.00     130.00     120.00     112.00
   105.00      98.00      94.00      88.00      84.00
    80.00      76.00      73.00      69.00      66.00
    64.00      62.00      60.00      60.00      58.00
    46.50      44.50      43.00      41.00      39.50
    38.50      37.00      35.50      34.00      32.50
    31.50      30.00      28.50      27.00      26.00
    24.50      23.50      22.30      21.50      20.50
    19.50      18.75      18.00      17.30      16.70
    16.00      15.30      14.90      14.15      14.00
    13.40      13.00      12.80      12.30      12.00
    11.70      11.20      10.90      10.60      10.20
    10.00       9.80       9.60       9.30       9.00
     8.70       8.40       8.20       8.00       7.80
     7.60       7.30       7.00       6.85       6.40
     6.20       5.90       5.60       5.40       5.20
     5.00       4.80       4.60       4.40       4.20
     4.00       4.00       4.00       4.00       4.00
     4.00       4.00       4.00       4.00       4.00
     4.00       4.00       4.00       4.00       4.00

     3.60       3.60       3.60       3.60       3.60
     3.30       3.20       3.10       2.90       2.70
     2.60       2.45       2.30       2.10       1.95
     1.75       1.60       1.50       1.35       1.25
     1.75       1.60       1.50       1.35       1.25
```

```
TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  97.65PER CENT

MEAN DYE RESIDENCE BASED ON C= 43.75MIN
MEAN DYE RESIDENCE BASED ON E= 43.75MIN


THETA             E            ET             F

 0.000          .065         1.033          0.000
  .125          .035          .564           .100
  .250          .027          .430           .162
  .375          .023          .373           .212
  .500          .021          .335           .256
  .625          .019          .302           .296
  .750          .017          .272           .332
  .875          .016          .249           .365
 1.000          .014          .229           .394
 1.125          .013          .214           .422
 1.250          .013          .201           .448
 1.375          .012          .187           .472
 1.500          .011          .180           .495
 1.625          .011          .168           .517
 1.750          .010          .161           .538
 1.875          .010          .153           .557
 2.000          .009          .145           .576
 2.125          .009          .140           .594
 2.250          .008          .132           .611
 2.375          .008          .126           .627
 2.500          .008          .122           .642
 2.625          .007          .119           .657
 2.750          .007          .115           .672
 2.875          .007          .115           .686
 3.000          .007          .111           .700
 3.125          .006          .089           .713
 3.250          .005          .085           .724
 3.375          .005          .082           .734
 3.500          .005          .078           .744
 3.625          .005          .076           .754
 3.750          .005          .074           .763
 3.875          .004          .071           .772
 4.000          .004          .068           .781
 4.125          .004          .065           .789
 4.250          .004          .062           .797
 4.375          .004          .060           .805
 4.500          .004          .057           .812
 4.625          .003          .055           .819
 4.750          .003          .052           .826
 4.875          .003          .050           .832
 5.000          .003          .047           .838
 5.125          .003          .045           .844
 5.250          .003          .043           .849
 5.375          .003          .041           .855
 5.500          .002          .039           .860
 5.625          .002          .037           .864
 5.750          .002          .036           .869
 5.875          .002          .034           .873
 6.000          .002          .033           .878
 6.125          .002          .032           .882
```

```
                INPUT   DATA

SINGLE STAGE OPERATION
TEMPERATURE =16 DEG. C
FLOW RATE=   4.00LIT./MIN.
VOLUME OF THE REACTOR=    40.0LIT.
THEORETICAL DETENTION TIME=   10.00MIN
DT= 1.00MIN
THE AMOUNT OF DYE INJECTED=   .0100LIT.
CONCENTRATION OF THE DYE ADDED=2380000.00PPB


       DYE MEASUREMENTS

  570.00      376.00      296.00      254.00      198.00
  195.00      175.00      160.00      150.00      142.00
  130.00      122.00      112.00      105.00      100.00
   96.00       92.00       88.00       84.00       79.00
   74.00       73.00       71.00       68.00       65.00
   63.00       61.00       59.00       58.00       54.00
   53.00       52.00       51.00       48.00       47.00
   45.00       44.00       43.00       41.00       40.00
   39.00       37.00       36.00       35.00       33.00
   32.00       31.00       30.00       29.00       28.00
   27.00       26.00       25.00       24.00       23.00
   22.50       21.80       21.00       20.30       20.00
   19.00       18.60       18.00       17.60       17.00
   16.70       16.00       15.90       15.30       15.00
   14.70       14.50       14.00       13.80       13.50
   13.30       12.90       12.60       12.30       12.00
   11.80       11.60       11.20       11.00       10.70
   10.50       10.30       10.00        9.80        9.60
    9.40        9.20        8.50        8.30        7.60
    7.50        7.40        7.20        7.20        7.20
    6.80        6.60        6.40        6.20        6.30
    6.00        5.90        5.70        5.60        5.50
    5.40        5.20        5.30        5.30        5.10
    5.00        4.50        3.90        3.90        3.90
    3.90        3.90        3.80        3.70        3.60
    3.50        3.50        3.50        3.50        3.40
    3.00        3.00        2.50        2.50        2.60
    2.00        2.00        2.00        2.00        2.00
```

```
TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  93.54PER.CENT

MEAN DYE RESIDENCE BASED ON C= 25.74MIN
MEAN DYE RESIDENCE BASED ON E= 25.74MIN


THETA              E             ET              F

 0.000           .102          1.024          0.000
  .100           .068           .676           .085
  .200           .053           .532           .145
  .300           .046           .456           .195
  .400           .036           .356           .235
  .500           .035           .350           .271
  .600           .031           .314           .304
  .700           .029           .287           .334
  .800           .027           .270           .362
  .900           .026           .255           .388
 1.000           .023           .234           .413
 1.100           .022           .219           .435
 1.200           .020           .201           .456
 1.300           .019           .189           .476
 1.400           .018           .180           .494
 1.500           .017           .172           .512
 1.600           .017           .165           .529
 1.700           .016           .158           .545
 1.800           .015           .151           .560
 1.900           .014           .142           .575
 2.000           .013           .133           .589
 2.100           .013           .131           .602
 2.200           .013           .128           .615
 2.300           .012           .122           .627
 2.400           .012           .117           .639
 2.500           .011           .113           .651
 2.600           .011           .110           .662
 2.700           .011           .106           .673
 2.800           .010           .104           .683
 2.900           .010           .097           .693
 3.000           .010           .095           .703
 3.100           .009           .093           .712
 3.200           .009           .092           .721
 3.300           .009           .086           .730
 3.400           .008           .084           .739
 3.500           .008           .081           .747
 3.600           .008           .079           .755
 3.700           .008           .077           .763
 3.800           .007           .074           .771
 3.900           .007           .072           .778
 4.000           .007           .070           .785
 4.100           .007           .066           .792
 4.200           .006           .065           .798
 4.300           .006           .063           .805
 4.400           .006           .059           .811
 4.500           .006           .057           .817
 4.600           .006           .056           .822
 4.700           .005           .054           .828
 4.800           .005           .052           .833
 4.900           .005           .050           .838
```

```
THETA          E         ET         F

5.000        .005      .049      .843
5.100        .005      .047      .848
5.200        .004      .045      .852
5.300        .004      .043      .857
5.400        .004      .041      .861
5.500        .004      .040      .865
5.600        .004      .039      .869
5.700        .004      .038      .873
5.800        .004      .036      .877
5.900        .004      .036      .880
6.000        .003      .034      .884
6.100        .003      .033      .887
6.200        .003      .032      .890
6.300        .003      .032      .894
6.400        .003      .031      .897
6.500        .003      .030      .900
6.600        .003      .029      .903
6.700        .003      .029      .906
6.800        .003      .027      .908
6.900        .003      .027      .911
7.000        .003      .026      .914
7.100        .003      .026      .916
7.200        .003      .025      .919
7.300        .002      .025      .922
7.400        .002      .024      .924
7.500        .002      .024      .926
7.600        .002      .023      .929
7.700        .002      .023      .931
7.800        .002      .022      .933
7.900        .002      .022      .935
8.000        .002      .021      .938
8.100        .002      .021      .940
8.200        .002      .020      .942
8.300        .002      .020      .944
8.400        .002      .019      .946
8.500        .002      .019      .948
8.600        .002      .019      .949
8.700        .002      .018      .951
8.800        .002      .018      .953
8.900        .002      .017      .955
9.000        .002      .017      .956
9.100        .002      .017      .958
9.200        .002      .016      .960
9.300        .001      .015      .961
9.400        .001      .014      .963
9.500        .001      .013      .964
9.600        .001      .013      .965
9.700        .001      .013      .967
9.800        .001      .013      .968
9.900        .001      .013      .969
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```
                INPUT  DATA

         SINGLE STAGE OPERATION AND ALL BIOMASS STRIPPED
         TEMPERATURE=15 DEG. C
         FLOW RATE=   4.00LIT./MIN.
         VOLUME OF THE REACTOR=   100.0LIT.
         THEORETICAL DETENTION TIME=   25.00MIN
         DT= 1.00MIN
         THE AMOUNT OF DYE INJECTED=   .0100LIT.
         CONCENTRATION OF THE DYE ADDED=2380000.00PPB


             DYE MEASUREMENTS

        498.00      264.00      242.00      214.00      200.00
        190.00      180.00      170.00      162.00      154.00
        146.00      140.00      132.00      125.00      120.00
        114.00      108.00      102.00       99.00       95.00
         88.00       84.00       80.00       76.00       74.00
         70.00       67.00       65.00       63.00       61.00
         58.00       57.00       55.00       53.00       51.00
         49.00       48.00       47.00       45.00       44.00
         43.00       42.00       40.00       39.00       38.00
         37.00       35.00       34.00       33.00       32.00
         32.00       31.00       30.00       29.00       28.00
         28.00       27.00       26.00       26.00       25.00
         24.00       24.00       23.00       22.00       22.00
         22.00       21.00       20.00       20.00       19.00
         19.00       18.00       18.00       17.00       16.00
         16.00       16.00       15.00       14.00       14.00
         14.00       15.00       13.00       12.00       12.00
         12.00       11.00       11.00       10.00       10.00
         10.00       10.00       10.00        9.00        9.00
          9.00        8.00        8.00        8.00        8.00
          8.00        7.80        7.70        7.60        7.50
          7.30        7.10        7.00        6.90        6.70
          6.60        6.50        6.30        6.20        6.00
          5.90        5.80        5.60        5.50        5.30
          5.20        5.00        4.90        4.80        4.60
          4.50        4.40        4.20        4.00        3.94
          3.80        3.70        3.50        3.40        3.20
          3.10        2.90        2.80        2.70        2.50
          2.40        2.20        2.10        2.00        1.80
          1.70        1.60        1.40        1.30        1.10
```

```
TEST RESULTS AND CALCULATED VALUES


DYE RECOVERY=  99.37PER CENT

MEAN DYE RESIDENCE BASED ON C= 28.57MIN
MEAN DYE RESIDENCE BASED ON E= 28.57MIN


THETA            E           ET           F

 0.000         .084        2.106        0.000
  .040         .045        1.116         .064
  .080         .041        1.023         .107
  .120         .036         .905         .146
  .160         .034         .846         .181
  .200         .032         .803         .214
  .240         .030         .761         .245
  .280         .029         .719         .275
  .320         .027         .685         .303
  .360         .026         .651         .329
  .400         .025         .617         .355
  .440         .024         .592         .379
  .480         .022         .558         .402
  .520         .021         .529         .424
  .560         .020         .507         .444
  .600         .019         .482         .464
  .640         .018         .457         .483
  .680         .017         .431         .501
  .720         .017         .419         .518
  .760         .016         .402         .534
  .800         .015         .372         .550
  .840         .014         .355         .564
  .880         .014         .338         .578
  .920         .013         .321         .591
  .960         .013         .313         .604
 1.000         .012         .295         .616
 1.040         .011         .283         .628
 1.080         .011         .275         .639
 1.120         .011         .266         .650
 1.160         .010         .258         .660
 1.200         .010         .245         .670
 1.240         .010         .241         .680
 1.280         .009         .233         .689
 1.320         .009         .224         .699
 1.360         .009         .216         .707
 1.400         .008         .207         .716
 1.440         .008         .203         .724
 1.480         .008         .199         .732
 1.520         .008         .190         .740
 1.560         .007         .186         .747
 1.600         .007         .182         .755
 1.640         .007         .178         .762
 1.680         .007         .169         .769
 1.720         .007         .165         .776
 1.760         .006         .161         .782
 1.800         .006         .156         .788
 1.840         .006         .148         .795
 1.880         .006         .144         .800
 1.920         .006         .140         .806
 1.960         .005         .135         .812
```

```
THETA          E        ET        F

2.000        .005     .135     .817
2.040        .005     .131     .822
2.080        .005     .127     .827
2.120        .005     .123     .832
2.160        .005     .118     .837
2.200        .005     .118     .842
2.240        .005     .114     .847
2.280        .004     .110     .851
2.320        .004     .110     .855
2.360        .004     .106     .860
2.400        .004     .101     .864
2.440        .004     .101     .868
2.480        .004     .097     .872
2.520        .004     .093     .876
2.560        .004     .093     .879
2.600        .004     .093     .883
2.640        .004     .089     .887
2.680        .003     .085     .890
2.720        .003     .085     .894
2.760        .003     .080     .897
2.800        .003     .080     .900
2.840        .003     .076     .903
2.880        .003     .076     .906
2.920        .003     .072     .909
2.960        .003     .068     .912
3.000        .003     .068     .915
3.040        .003     .068     .918
3.080        .003     .063     .920
3.120        .002     .059     .923
3.160        .002     .059     .925
3.200        .002     .059     .927
3.240        .003     .063     .930
3.280        .002     .055     .932
3.320        .002     .051     .934
3.360        .002     .051     .936
3.400        .002     .051     .938
3.440        .002     .047     .940
3.480        .002     .047     .942
3.520        .002     .042     .944
3.560        .002     .042     .946
3.600        .002     .042     .947
3.640        .002     .042     .949
3.680        .002     .042     .951
3.720        .002     .038     .952
3.760        .002     .038     .954
3.800        .002     .038     .955
3.840        .001     .034     .957
3.880        .001     .034     .958
3.920        .001     .034     .959
3.960        .001     .034     .961
```

```
   THETA            E              ET             F

   4.000          .001           .034           .962
   4.040          .001           .033           .964
   4.080          .001           .033           .965
   4.120          .001           .032           .965
   4.160          .001           .032           .967
   4.200          .001           .031           .969
   4.240          .001           .030           .970
   4.280          .001           .030           .971
   4.320          .001           .029           .972
   4.360          .001           .028           .973
   4.400          .001           .028           .975
   4.440          .001           .027           .976
   4.480          .001           .027           .977
   4.520          .001           .026           .978
   4.560          .001           .025           .979
   4.600          .001           .025           .980
   4.640          .001           .025           .981
   4.680          .001           .024           .982
   4.720          .001           .023           .983
   4.760          .001           .022           .984
   4.800          .001           .022           .985
   4.840          .001           .021           .985
   4.880          .001           .021           .986
   4.920          .001           .020           .987
   4.960          .001           .019           .988
   5.000          .001           .019           .989
   5.040          .001           .019           .989
   5.080          .001           .018           .990
   5.120          .001           .017           .991
   5.160          .001           .017           .991
   5.200          .001           .016           .992
   5.240          .001           .016           .993
   5.280          .001           .015           .993
   5.320          .001           .014           .994
   5.360          .001           .014           .994
   5.400          .001           .013           .995
   5.440          .000           .012           .996
   5.480          .000           .012           .996
   5.520          .000           .011           .996
   5.560          .000           .011           .997
   5.600          .000           .010           .997
   5.640          .000           .009           .998
   5.680          .000           .009           .998
   5.720          .000           .008           .998
   5.760          .000           .008           .999
   5.800          .000           .007           .999
   5.840          .000           .007           .999
   5.880          .000           .006          1.000
   5.920          .000           .005          1.000
   5.960          .000           .005          1.000
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73/73    TS                              FTN 4.5+410        02/26/76  17.51.06           PAGE    1
 /7                                                                   /73
      PROGRAM FLBTCS(INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT)

C     PROGRAM TO CALCULATE THE MAGNITUDE OF FLOW BETWEEN TWO CSTRS

C     DEFINITIONS
C     CA(N)=THE MEASURED DYE CONCENTRATION OF OUTER CSTR,AT TIME =N*DT
C     AFTER PULSE DYE INJECTION,IN PPB
C     VT=HYDRAULIC LOADING, IN LIT./MIN.
C     VA=VOLUME OF THE OUTER CSTR,IN LIT.
C     CBT(N)=CALCULATED DYE CONCENTRATION OF INNER CSTR,AT TIME=N*DT
C     AFTER PULSE DYE INJECTION,IN PPB
C     DT=THE SAMPLING INTERVAL,IN MIN.
C     ABFLR=CALCULATED FLOW RATE BETWEEN TWO CSTRS,IN LIT./MIN.
C     N=THE FLOW RATE BET*EEN TWO CSTRS ARE CLCULATED N TIMES
C     DET=THE THEORETICAL DETENTION TIME OF OUTER CSTR IF THERE WERE
C     NO INNER CSTR,IN MIN.
C     L=NOUMBER OF OUTER CSTR DYE CONCENTRATIONS INSERTED

      DIMENSION CAV(151),SDYELO(151),DYELO(151),DYINDI(151),CBT(151)
      DIMENSION CBAV(151),SCBAV(151),ABFLR(151),THETA(151),SCAV(151)
      DIMENSION MDYINB(151),CA(151),CAVA(151),TIME(151)

      READ(5,388) DYIN,DYCON,DET,L
  388 FORMAT(F10.4,E10.2,F10.2,I10)
      READ(5,1) DT,VT,N,VA,VB,VTOTA
    1 FORMAT(2F10.2,I10,3F10.2)
      READ(5,2) (CA(I),I=1,L)
    2 FORMAT(5F10.2)

      WRITE(6,51)
   51 FORMAT(10X,/////////////////////////////////////////////////////)
      WRITE(6,997)
  997 FORMAT(20X,11HINPUT  DATA,//)
      WRITE(6,995)
  995 FORMAT(10X,≠SINGLE STAGE OPERATION≠,10X)
      WRITE(6,111)
  111 FORMAT(10X,≠TEMPERATURE =15 DEG. C≠,10X)
      WRITE(6,306) VT
  306 FORMAT(10X,≠FLOW RATE=≠,F6.2,≠LIT./MIN.≠,5X)
      WRITE(6,305) VTOTA
  305 FORMAT(10X,≠VOLUME CF THE REACTOR=≠,F7.1,≠LIT.≠,10X)
      WRITE(6,158) VA
  158 FORMAT(10X,≠VOLUME CF THE OUTER CSTR=≠,F6.2,≠LIT.≠,10X)
      WRITE(6,159) VB
  159 FORMAT(10X,≠VOLUME CF THE INNER CSTR=≠,F6.2,≠LIT.≠,10X)
      WRITE(6,102) DT
  102 FORMAT(10X,≠DT=≠,F5.2,≠MIN≠,10X)
      WRITE(6,308) DYIN
  308 FORMAT(10X,≠THE AMOUNT OF DYE INJECTED=≠,F7.4,≠LIT.≠,10X)
      WRITE(6,309) DYCON
  309 FORMAT(10X,≠CONCENTRATION OF THE DYE ADDED=≠,F10.2,≠PPB≠,///)

C     CALCULATION OF THE TOTAL AMOUNT CFDYE WHICH EXIST IN OUTER CSTR
      DO 3 I=1,L
      CAVA(I)=CA(I)*VA
    3 CONTINUE
C     CALCULATION OF THE AVARAGE DYE CONCENTRATION IN OUTER CSTR
```

```
          M=L-1
          DO 4 I=1,M
          K=I+1
          CAV(I)=0.5*(CA(I)+CA(K))
        4 CONTINUE
C         CALCULATION OF THE AMOUNT OF DYE WHICH HAS LEFT THE REACTOR
          SDYELO(1)=0.0
          DO 5 I=2,L
          K=I-1
          DYELO(I)=CAV(K)*DT*VT
          SDYELO(I)=SDYELO(K)+DYELO(I)
        5 CONTINUE
C         CALCULATION OF THE TOTAL AMOUNT OF DYF CONTAINED IN INNER CSTR
          DYINDI(1)=0.0
          DO 6 I=2,L
          DYINDI(I)=CAVA(1)-CAVA(I)-SDYELO(I)
        6 CONTINUE
          CBT(1)=0.0
          DO 7 I=2,L
          CBT(I)=DYINDI(I)/VB
        7 CONTINUE
C         CALCULATION OF THE AVARAGE DYE CONCECTRATION IN INNER CSTR
          DO 8 I=2,L
          K=I-1
          CBAV(K)=(CBT(I)+CBT(K))*0.5
        8 CONTINUE
C         CALCULATION OF THE SUMS OF AVARAGE DYE CONCENTRATIONS
          SCBAV(1)=CBAV(1)
          SCAV(1)=CAV(1)
          DO 9 I=2,M
          K=I-1
          SCBAV(I)=SCBAV(K)+CBAV(I)
          SCAV(I)=SCAV(K)+CAV(I)
        9 CONTINUE
C         CALCULATION OF THE FLOW RATE BETWEEN INNER AND OUTER CSTRS
          IK=N-1
          DO 21 I=1,IK
          K=I+1
          ARFLR(I)=DYINDI(K)/(DT*(SCAV(I)-SCBAV(I)))
       21 CONTINUE
C         CALCULATION OF TIME VALUES
          TIME(1)=0.0
          DO 20 I=2,L
          KL=I-1
       20 TIME(I)=TIME(KL)+DT
C         CALCULATION OF THE THETA VALUES
          THETA(1)=0.0
          DO 10 I=2,L
       10 THETA(I)=TIME(I)/OEI
```

```
FLBTCS       73/73   TS                              FTN 4.5+410          02/26/76  17.51.06          PAGE     3
                /7                                                                         /73
        C        PRINT OUT STATEMENTS
                 WRITE(6,959)
             959 FORMAT(20X,≠CALCULATED VALUES≠,10X,///)
                 WRITE(6,14)
              14 FORMAT(10X,5HTHETA,6X,5HABFLR,4X,3HCBT,9X,≠CA≠,///)
                 DO 55 I=1,L
                 IF(I.EQ.10) GO TO 99
                 IF(I.EQ.28) GO TO 99
                 IF(I.EQ.46) GO TO 99
                 IF(I.EQ.62) GO TO 99
                 IF(I.EQ.82) GO TO 99
                 IF(I.EQ.100) GO TO 99
                 IF(I.EQ.140) GO TO 99
                 GO TO 333
              99 WRITE(6,97)
              97 FORMAT(10X,////)
                 WRITE(6,113)
             113 FORMAT(10X,5HTHETA,6X,5HABFLR,4X,3HCBT,9X,≠CA≠,///)
             333 WRITE(6,11)(THETA(I),CBT(I),CA(I))
              11 FORMAT(10X,F6.2,7X,6X,F6.2,7X,F4.2,/)
                 IF(I.GT.N) GO TO 54
                 WRITE(6,19) (ABFLR(I))
              19 FORMAT(10X,9X,F6.2,7X)
                 GO TO 55
              54 WRITE(6,56)
              56 FORMAT(10X,/)
              55 CONTINUE
                 END

                        --E N T R Y   P O I N T S--
 3TCS                      3B   INPUT=                   43B   OUTPUT=                      3B   TAPE5=
 PE6=

                        --E X T E R N A L S--
END.        INPCI.      INPCR.     OUTCI.     Q8NTRY.

                        --S T A T E M E N T   L A B E L S--
   363B                 .2      F       366B          .3     ID        0B           .4     ID       0B
     0B                 .6      ID        0B          .7     ID        0B           .8     ID       0B
     0B                 .10     ID        0B          .11    F       510B           .14    F      474B
   514B                 .20     ID        0B          .21    ID        0B           .51    F      370B
   351B                 .55     D       353B          .56    F       517B           .97    F      501B
   325B                 .102    F       445B          .111   F       407B           .113   F      503B
   427B                 .159    F       436B          .305   F       421B           .306   F      414B
   451B                 .309    F       460B          .333           331B           .388   F      357B
   467B                 .995    F       402B          .997   F       376B
```

```
              INPUT  DATA

SINGLE STAGE OPERATICN
TEMPERATLRE =15 DEG. C
FLOW RATE=  4.00LIT./MIN.
VOLUME OF THE REACTOR=  100.0LIT.
VOLUME OF THE CUTER CSTR= 40.00LIT.
VOLUME OF THE/ INNER CSTR= 60.00LIT.
DT= 1.00MIN
THE AMCUNT OF CYE INJECTED=  .0010LIT.
CONCENTRATION CF THE DYE ADDED=2380000.00PPB


              CALCULATED VALUES


THETA        ABFLR       CBT            CA


  0.00                     0.00        570.00
             13.84
   .10                    97.80        376.00
             11.94
   .20                   128.73        296.00
             10.53
   .30                   138.40        254.00
             11.15
   .40                   160.67        198.00
               9.90
   .50                   149.57        195.00
               9.60
   .60                   150.57        175.00
               9.35
   .70                   149.40        160.00
               9.05
   .80                   145.73        150.00
               8.76
```

THETA	ABFLR	CBT	CA
.90		141.33	142.00
	8.73		
1.00		140.27	130.00
	8.66		
1.10		137.20	122.00
	8.77		
1.20		136.07	112.00
	8.85		
1.30		133.50	105.00
	8.91		
1.40		130.00	100.00
	8.95		
1.50		126.13	96.00
	9.02		
1.60		122.53	92.00
	9.12		
1.70		119.20	88.00
	9.26		
1.80		116.13	84.00
	9.51		
1.90		114.03	79.00
	9.87		
2.00		112.27	74.00
	10.03		
2.10		108.03	73.00
	10.26		
2.20		104.57	71.00
	10.58		
2.30		101.93	68.00
	10.98		
2.40		99.50	65.00
	11.37		
2.50		96.57	63.00
	11.81		
2.60		93.77	61.00
	12.31		

7

THETA	ABFLR	CBT	CA
2.70		91.14	59.00
2.80	12.76	87.87	58.00
2.90	13.64	86.80	54.00
3.00	-I	83.90	53.00
3.10		81.07	52.00
3.20		78.30	51.00
3.30		77.00	48.00
3.40		74.50	47.00
3.50		72.77	45.00
3.60		70.47	44.00
3.70		68.23	43.00
3.80		66.77	41.00
3.90		64.73	40.00
4.00		62.77	39.00
4.10		61.57	37.00
4.20		59.80	36.00
4.30		58.10	35.00
4.40		57.17	33.00

THETA	ABFLR	CBT	CA
4.50		55.67	32.00
4.60		54.23	31.00
4.70		52.87	30.00
4.80		51.57	29.00
4.90		50.33	28.00
5.00		49.17	27.00
5.10		48.07	26.00
5.20		47.03	25.00
5.30		46.07	24.00
5.40		45.17	23.00
5.50		43.98	22.50
5.60		42.97	21.80
5.70		42.08	21.00
5.80		41.17	20.30
5.90		40.03	20.00
6.00		39.39	19.00

```
              INPUT  DATA

SINGLE STAGE OPERATION
TEMPERATURE =15 DEG. C
FLOW RATE=  2.50LIT./MIN.
VOLUME OF THE REACTOR=  100.0LIT.
VOLUME OF THE OUTER CSTR= 40.00LIT.
VOLUME OF THE INNER CSTR= 60.00LIT.
DT= 2.00MIN
THE AMOUNT OF DYE INJECTED=  .0090LIT.
CONCENTRATION OF THE DYE ADDED=2380000.00PPB


              CALCULATED VALUES


THETA         ABFLR      CBT            CA


 0.00                     0.00         540.00
             10.92
  .13                   128.54         295.00
              9.76
  .25                   153.54         225.00
              8.88
  .38                   156.04         195.00
              8.29
  .50                   153.96         175.00
              7.95
  .63                   151.42         158.00
              7.86
  .75                   149.58         142.00
              7.85
  .88                   146.25         130.00
              7.93
 1.00                   142.50         120.00
              8.05
```

```
THETA        ABFLR      CBT          CA

  1.13                 138.17       112.00
             8.23
  1.25                 133.79       105.00
             8.53
  1.38                 130.00        98.00
             8.78
  1.50                 124.67        94.00
             9.22
  1.63                 121.08        88.00
             9.68
  1.75                 116.58        84.00
            10.26
  1.88                 112.42        80.00
               -I
  2.00                 108.58        76.00

  2.13                 104.38        73.00

  2.25                 101.13        69.00

  2.38                  97.50        66.00

  2.50                  93.42        64.00

  2.63                  89.50        62.00

  2.75                  85.75        60.00

  2.88                  80.75        60.00

  3.00                  77.17        58.00

  3.13                  80.48        46.50

  3.25                  78.02        44.50
```

THETA	ABFLR	CBI	CA
3.38		75.38	43.00
3.50		73.21	41.00
3.63		70.85	39.50
3.75		68.27	38.50
3.88		66.13	37.00
4.00		64.10	35.50
4.13		62.21	34.00
4.25		60.44	32.50
4.38		58.44	31.50
4.50		56.88	30.00
4.63		55.44	28.50
4.75		54.13	27.00
4.88		52.58	26.00
5.00		51.48	24.50
5.13		50.15	23.50
5.25		49.04	22.30
5.38		47.75	21.50
5.50		46.66	20.50

THETA	ABFLR	CBT	CA
5.63		45.66	19.50
5.75		44.57	18.75
5.88		43.54	18.00
6.00		42.53	17.30
6.13		41.52	16.70
6.25		40.62	16.00
6.38		39.78	15.30
6.50		38.79	14.90
6.63		38.08	14.15
6.75		37.01	14.00
6.88		36.27	13.40
7.00		35.43	13.00
7.13		34.49	12.80
7.25		33.78	12.30
7.38		32.97	12.00
7.50		32.18	11.70

THETA	ABFLR	CBT	CA
7.63		31.56	11.20
7.75		30.84	10.90
7.88		30.14	10.60
8.00		29.54	10.20
8.13		28.83	10.00
8.25		28.14	9.80
8.38		27.47	9.60
8.50		26.88	9.30
8.63		26.32	9.00
8.75		25.78	8.70
8.88		25.27	8.40
9.00		24.71	8.20
9.13		24.17	8.00
9.25		23.64	7.80
9.38		23.13	7.60
9.50		22.71	7.30
9.63		22.32	7.00
9.75		21.84	6.85
9.88		21.59	6.40

THETA	ABFLR	CBT	CA
10.13		20.89	5.90
10.25		20.61	5.60
10.38		20.29	5.40
10.50		19.98	5.20
10.63		19.69	5.00
10.75		19.41	4.80
10.88		19.15	4.60
11.00		18.91	4.40
11.13		18.69	4.20
11.25		18.48	4.00
11.38		18.15	4.00
11.50		17.81	4.00
11.63		17.48	4.00
11.75		17.15	4.00
11.88		16.81	4.00
12.00		16.48	4.00
12.13		16.15	4.00
12.25		15.81	4.00

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     73/73   TS                               FTN 4.5+410        03/23/76  19.25.19       PAGE     1
       /7                                                                   /73

          PROGRAM DEDBIS(INPUT,TAPE5=INPUT,OUTPUT,TAPE6=OUTPUT)
C         X=THE TIME PASSED AFTER PULSE DYE INJECTION, IN MINUTE
C         Y=THE MEASURED DYE CONCENTRATION AT TIME T/ THE DYE CONCENTRATION
C         AT TIME JUST AFTER PULSE DYE INJECTION
C         TH1,TH2=THE HYDRAULIC LOADING AND INTERFLOW RATES RESPECTIVELY ,
C         LITER PER MINUTES
C         NOB=NOUMBER OF OBSERVATIONS
C         NP=NOUMBER OF PARAMETERS
C         MIT,EPS1,EPS2,FLAM,FNU,= SOME PREASSIGNED VALUES IN UWHAUS SEARCH
          DIMENSION Y(17),TH(2),DIFF(2),SIGNS(2),SCRAT(100)
          COMMON X(17)
          EXTERNAL FUN
          WRITE(5,800)
          WRITE(6,801)
          WRITE(6,802)
          WRITE(6,803)
          WRITE(6,804)
          WRITE(6,805)
          WRITE(6,806)
      800 FORMAT(10X,≠ CALCULATION OF INTERFLOW BETWEEN INNER AND   ≠,//)
      801 FORMAT(10X,≠ OUTER CSTR BY FITTING THE IMPULSE DYE INJECTI-≠,//)
      802 FORMAT(10X,≠ ON RESULTS TO THE DEDRIC AND BISCHOFF S FOR-≠,//)
      803 FORMAT(10X,≠ MULA                        ≠,////)
      804 FORMAT(10X,≠ UWHAUS SUBROUTINE HAS BEEN EMPLOYED TO FIT THE ≠,//)
      805 FORMAT(10X,≠ DATA TO THE FORMULA                            ≠,////)
      806 FORMAT(10X,≠ HYDRAULIC LOADING=2.5 LITER PER MINUTE         ≠,///)
          READ(5,1) NOB,NP,MIT,EPS1,EPS2
        1 FORMAT(3I10,2F10.6)
          READ(5,11) FLAM,FNU
       11 FORMAT(2F10.2)
          READ(5,2) (X(I),I=1,4)
          READ(5,2) (X(I),I=5,8)
          READ(5,2) (X(I),I=9,12)
          READ(5,2) (X(I),I=13,16)
          X(17)=32.00
          READ(5,2)  (Y(I),I=1,4)
          READ(5,2) (Y(I),I=5,8)
          READ(5,2) (Y(I),I=9,12)
          READ(5,2) (Y(I),I=13,16)
          Y(17)=0.140
        2 FORMAT(4F10.3)
          READ(5,3) (TH(I),I=1,2)
        3 FORMAT(2F10.5)
          DO 10 I=1,NP
          DIFF(I)=0.01
       10 SIGNS(I)=0.0
          CALL UWHAUS(TFLMI,FUN,NOB,Y,NP,TH,DIFF,SIGNS,EPS1,EPS2,MIT,FLAM,F
         1NU,SCRAT)

          END
```

```
      73/73    TS                                      FTN 4.5+410         03/23/76  19.25.19          PAGE      1
        /7                                                                            /73

             SUBROUTINE FUN(NPROB,TH,F,NOB,NP)
             DIMENSION TH(2),F(17)
             COMMON X(17)
             VA=40.00
             VB=60.00
             C=(TH(1)/VA)+(TH(2)/VA)*(1.+VA/VB)
             R=SQRT(0.25*(C**2.)-((TH(1)*TH(2))/(VA*VB)))
             SR1=-0.5*(C)-R
             SR2=-0.5*(C)+R
             RK=(1./(2.*P))*(SR2+TH(2)/VB)
             RL=(1./(2.*R))*(SR1+TH(2)/VB)
             DO 2 I=1,NOB
                F(I)=RK*EXP(+SR2*X(I))-RL*EXP(+SR1*X(I))
           2 CONTINUE
             RETURN
             END

                     --C O M M O N   B L O C K S--

 //

                     --E X T E R N A L S--

 EXP.       SQRT.

                     --S T A T E M E N T   L A B E L S--

        0B

                     --V A R I A B L E   M A P--

       64B                                EXP.      R             B.E.F.
 A      0B              17                FUN       -          57B ENTRY
  U    65B                                NOB       I  AU       0B
  U     0B                                NPROB     I  AU       0B
       66B                                RK        R          72B
       73B                                SQRT.     R             B.E.F.
       71B                                SR2       R          74B
  U     0B              2                 VA        R          67B
       70B                                X         R           0B //          17

 IT LENGTH          17 STATEMENTS          19 SYMBOLS
 E USED     MODEL 73 COMPILATION          .021 SECONDS
```

```
      73/73   TS                                             FTN 4.5+410          03/23/76  16.02.24        PAGE     1
        /7                                                                                   /73

            SUBROUTINE UWHAUS(NPROB,MODEL,NOB,Y,NP,TH,DIFF,SIGNS,EPS1,EPS2,
          1  MIT, FLAM, FNU, SCRAT)
            DIMENSION SCRAT(1)
            IA=1
            IB=IA+NP
            IC=IB+NP
            ID=IC+NP
            IE=ID+NP
            IF=IE+NP
            IG=IF+NOB
            IH=IG+NOB
            II = IH + NP * NOB
            IJ = IH
               CALL  HAUS59(NPROB,MODEL,NOB,Y,NP,TH,DIFF,SIGNS,EPS1,EPS2,MIT
          1  ,FLAM,FNU,SCRAT(IA), SCRAT(IB), SCRAT(IC), SCRAT(ID),
          2  SCRAT(IE), SCRAT(IF), SCRAT(IG), SCRAT(IH), SCRAT(II),
          3  SCRAT(IJ)  )
            RETURN
            END

                    --E X T E R N A L S--

US59


                    --V A R I A B L E   M A P--

   0B                             EPS1      R A       0B
   0B                             FLAM      R A       0B
   0B                             HAUS59    R         SUBROUTINE
 132B                             IB        I       137B
 133B                             ID        I       134B
 135B                             IF        I       136B
 130B                             IH        I       131B
 140B                             IJ        I       141B
   0B                             MODEL     I A       0B
   0B                             NP        I A       0B
   0B                             SCRAT     R AU      0B
   0B                             TH        R A       0B
  75B ENTRY                       Y         R A       0B

LENGTH         20 STATEMENTS       26 SYMBOLS
ISED    MODEL 73 COMPILATION      .114 SECONDS
```

```
      73/73   TS                                      FTN 4.5+410       03/23/76  16.02.24      PAGE     1
       /7                                                                           /73
      SUBROUTINE HAUS59(NPRBO, MODEL, NBO, Y,NQ,TH,DIFZ,SIGNS,EP1S,EP2S,
     1MIT,FLAM,FNU,     Q,P,E,PHI,TB,F,R,A,D,DELZ)
C                FORTRAN II VERSION
C                H. J. WERTZ
C     ADAPTED FOR THE CDC 6400  (J. F. MACGREGOR)
C
C     DIMENSION TH(NQ), DIFZ(NQ), SIGNS(NQ), Y(NBO)
C     DIMENSION Q(NQ), P(NQ), E(NQ), PHI(NQ), TB(NQ)
C     DIMENSION F(NBO), R(NBO)
C     DIMENSION A(NQ,NQ), D(NQ,NQ), DELZ(NBO,NQ)
      DIMENSION TH(1), DIFZ(1), SIGNS(1), Y(1), Q(1), P(1), E(1),
     1   PHI(1), TB(1), F(1), R(1), A(1), D(1), DELZ(1)
      ACOS(X) = ATAN(SQRT(1.0/X**2 - 1.0))
      NP = NQ
      NPROB = NPRBO
      NOB = NBO
      EPS1 = EP1S
      EPS2 = EP2S
      NPSQ = NP * NP
       NSCRAC = 5*NP+NPSQ +2*NOB+NP*NOB
      WRITE (06,1000) NPROB,NOB,NP,NSCRAC
      WRITE (06,1001)
       CALL GASS60(1, NP, TH, TEMP, TMEP)
      WRITE (06,1002)
       CALL GASS60(1, NP, DIFZ, TEMP, TEMP)
      IF(MINO(NP-1,50-NP,NOB-NP,MIT-1,999-MIT))99,15,15
   15 IF(FNU-1.0)99, 99, 16
   16 CONTINUE
      DO 19 I=1,NP
      TEMP = ABS(DIFZ(I))
      IF(AMIN1(1.0-TEMP, ABS(TH(I))))99, 99, 19
   19 CONTINUE
      GA = FLAM
      NIT = 1
      LAOS = 0
      IF(EPS1) 5,70,70
    5 EPS1 = 0
   70 SSQ = 0
      CALL MODEL(NPROB, TH, F, NOB, NP)
      DO 90 I = 1, NOB
      R(I) = Y(I) - F(I)
   90 SSQ=SSQ+R(I)*R(I)
      WRITE (06,1003) SSQ
C
C                                               BEGIN ITERATION
C
  100 GA = GA / FNU
      INTCNT = 0
      WRITE(06,1004)  NIT
  101 JS = 1 - NOB
      DO 130 J=1,NP
      TEMP = TH(J)
      P(J)=DIFZ(J)*TH(J)
      TH(J)= TH(J)+P(J)
      Q(J)=0
      JS = JS + NOB
      CALL MODEL(NPROB, TH, DELZ(JS), NOB, NP)
```

```
          IJ = JS-1
          DO 120 I = 1, NOB
          IJ = IJ + 1
          DELZ(IJ) = DELZ(IJ) - F(I)
  120     Q(J) = Q(J) + DELZ(IJ) * R(I)
          Q(J)= Q(J)/P(J)                            Q=XT*R (STEEPEST DESCENT)
C
  130     TH(J) = TEMP
          IF(LAOS) 131,131,414
  131     DO 150 I = 1, NP
          DO 151 J=1,I
          SUM = 0
          KJ = NOB*(J-1)
          KI = NOB*(I-1)
          DO 160 K = 1, NOB
          KI = KI + 1
          KJ = KJ + 1
  160     SUM = SUM + DELZ(KI) * DELZ(KJ)
          TEMP= SUM/(P(I)*P(J))
          JI = J + NP*(I-1)
          D(JI) = TEMP
          IJ = I + NP*(J-1)
  151     D(IJ) = TEMP
  150     E(I) = SQRT(D(JI))
  666     CONTINUE
          DO 153  I = 1, NP
          IJ = I-NP
          DO 153 J=1,I
          IJ = IJ + NP
          A(IJ) = D(IJ) / (E(I)*E(J))
          JI = J + NP*(I-1)
  153     A(JI) = A(IJ)
C                                                    A= SCALED MOMENT MATRIX
          II = - NP
          DO 155 I=1,NP
          P(I)=Q(I)/E(I)
          PHI(I)=P(I)
          II = NP + 1 + II
  155     A(II) = A(II) + GA
C
          I=1
           CALL MATIN(A, NP, P, I, DET)              P/E = CORRECTION VECTOR
C
           STEP=1.0
          SUM1=0.
          SUM2=0.
          SUM3=0.
          DO 231 I=1,NP
          SUM1=P(I)*PHI(I)+SUM1
          SUM2=P(I)*P(I)+SUM2
          SUM3= PHI(I)  *  PHI(I)  + SUM3
  231     PHI(I) = P(I)
           TEMP = SUM1/SQRT(SUM2*SUM3)
          TEMP = AMIN1(TEMP, 1.0)
          TEMP = 57.295*ACOS(TEMP)
          WRITE(06,1041)   DET,TEMP
  170     DO 220 I = 1, NP
```

```
      P(I) = PHI(I) *STEP / E(I)
      TB(I) = TH(I) + P(I)
  220 CONTINUE
      WRITE(06,7000)
 7000 FORMAT(30H0TEST POINT PARAMETER VALUES      )
      WRITE(06,2006)   (TB(I),I=1,NP)
      DO 221 I = 1, NP
      IF(SIGNS(I)) 221, 221, 222
  222 IF(SIGN(1.0,TH(I))*SIGN(1.0,TB(I))) 663, 221, 221
  221 CONTINUE
      SUMB=0
      CALL MODEL(NPROB, TB, F, NOB, NP)
      DO 230 I=1,NOB
      R(I)=Y(I)-F(I)
  230 SUMB=SUMB+R(I)*R(I)
      WRITE(06,1043)   SUMB
      IF(SUMB - (1.0+EPS1)*SSQ) 662, 662, 663
  663 IF( AMIN1(TEMP-30.0, GA)) 665, 665, 664
  665 STEP=STEP/2.0
      INTCNT = INTCNT + 1
      IF(INTCNT - 36) 170, 2700, 2700
  664 GA=GA*FNU
      INTCNT = INTCNT + 1
      IF(INTCNT - 36) 665, 2700, 2700
  662 WRITE(06,1007)
      DO 669 I=1,NP
  669 TH(I)=TB(I)
       CALL GASS60(1, NP, TH, TEMP, TEMP)
      WRITE(06,1040)   GA,SUMB
      IF(EPS2) 229,229,225
  229 IF(EPS1) 270,270,265
  225 DO 240 I = 1, NP
      IF(ABS(P(I))/(1.E-20+ABS(TH(I)))-EPS2) 240, 240, 241
  241 IF(EPS1) 270,270,265
  240 CONTINUE
      WRITE(06,1009)   EPS2
      GO TO 280
  265 IF(ABS(SUMB - SSQ) - EPS1*SSQ) 266, 266, 270
  266 WRITE(06,1010)   EPS1
      GO TO 280
  270 SSQ=SUMB
      NIT=NIT+1
      IF(NIT - MIT) 100, 100, 280
 2700 WRITE(06,2710)
 2710 FORMAT(//115H0**** THE SUM OF SQUARES CANNOT BE REDUCED TO THE SUM
     1OF SQUARES AT THE END OF THE LAST ITERATION - ITERATING STOPS   /)
C
C                                                    END ITERATION
C
  280 WRITE(06,1011)
      WRITE(06,2001)  (F(I),I=1,NOB)
      WRITE(06,1012)
      WRITE(06,2001)  (R(I),I=1,NOB)
      WRITE(06,1017)
      CALL GASS60(4,NP,TEMP,TEMP,D)
 1017 FORMAT(////16H XPRIME-X MATRIX)
      SSQ=SUMB
```

```
      IDF=NOB-NP
      WRITE(06,1015)
      I=0
       CALL MATIN(D, NP, P, I, DET)
      DO 7692 I=1,NP
      II = I + NP*(I-1)
 7692 E(I) = SQRT(D(II))
      DO 340 I=1,NP
      JI = I + NP*(I-1) - 1
      IJ = I + NP*(I-2)
      DO 340 J = I, NP
      JI = JI + 1
      A(JI) = D(JI) / (E(I)*E(J))
      IJ = IJ + NP
 340   A(IJ) = A(JI)
       CALL GASS60(3, NP, TEMP, TEMP, A)
      IF(IDF) 341, 410, 341
  341 SDEV = SSQ/FLOAT(IDF)
      WRITE(06,1014) SDEV,IDF
       SDEV = SQRT(SDEV)
      DO 391 I=1,NP
      P(I)=TH(I)+2.0*E(I)*SDEV
391   TB(I)=TH(I)-2.0*E(I)*SDEV
      WRITE(06,1039)
       CALL GASS60(2, NP, TB, P, TEMP)
      LAOS = 1
      GO TO 101
 414  DO 415 K = 1, NOB
      TEMP = 0.
      DO 420 I=1,NP
      DO 420 J=1,NP
      ISUB = K+NOB*(I-1)
      DEBUG1 = DELZ(ISUB)
C     DEBUG1 = DELZ(K + NOB*(I-1))
      ISUB = K+NOB*(J-1)
      DEBUG2 = DELZ(ISUB)
C     DEBUG2 = DELZ(K + NOB*(J-1))
      IJ = I + NP*(J-1)
      DEBUG3 = D(IJ)/(DIFZ(I)*TH(I)*DIFZ(J)*TH(J))
 420  TEMP = TEMP + DEBUG1 * DEBUG2 * DEBUG3
       TEMP = 2.0*SQRT(TEMP)*SDEV
      R(K)=F(K)+TEMP
 415  F(K)=F(K)-TEMP
      WRITE(06,1008)
      IE=0
      DO 425 I=1,NOB,10
      IE=IE+10
      IF(NOB-IE) 430,435,435
  430 IE=NOB
  435 WRITE(06,2001)  (R(J),J=1,IE)
  425 WRITE(06,2006)  (F(J),J=1,IE)
  410 WRITE(06,1033)  NPROB
      RETURN
   99 WRITE(06,1034)
      GO TO 410
10000FORMAT(36H1NON-LINEAR ESTIMATION, PROBLEM NUMBER   I3,// I5,
    1  14H OBSERVATIONS, I5, 11H PARAMETERS  I14, 17H SCRATCH REQUIRED)
```

```
1001  FORMAT(/25H0INITIAL PARAMETER VALUES  )
1002  FORMAT(/54H0PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS )
1003  FORMAT(/25H0INITIAL SUM OF SQUARES =    E12.4)
1004  FORMAT(/////45X,13HITERATION NO.  I4)
1007  FORMAT(/32H0PARAMETER VALUES VIA REGRESSION  )
1008  FORMAT(////54H0APPROXIMATE CONFIDENCE LIMITS FOR EACH FUNCTION VAL
     1UE     )
10090FORMAT(/62H0ITERATION STOPS - RELATIVE CHANGE IN EACH PARAMETER LE
     1SS THAN    E12.4)
10100FORMAT(/62H0ITERATION STOPS - RELATIVE CHANGE IN SUM OF SQUARES LE
     1SS THAN    E12.4)
1011  FORMAT(22H1FINAL FUNCTION VALUES  )
1012  FORMAT(////10H0RESIDUALS  )
1014  FORMAT(//24H0VARIANCE OF RESIDUALS =     ,E12.4,1H,I4,
     120H DEGREES OF FREEDOM    )
1015  FORMAT(////19H0CORRELATION MATRIX    )
1033  FORMAT(//19H0END OF PROBLEM NO.  I3)
1034  FORMAT(/16H0PARAMETER ERROR   )
10390FORMAT(/71H0INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER (ON LI
     1NEAR HYPOTHESIS)     )
10400FORMAT(/9H0LAMBDA =E10.3,40X,33HSUM OF SQUARES AFTER REGRESSION =
     1E15.7)
1041  FORMAT(14H DETERMINANT =  E12.4, 6X, 25H ANGLE IN SCALED COORD. =
     1  F5.2, 8H0EGREES    )
1043  FORMAT(28H0TEST POINT SUM OF SQUARES =     E12.4)
2001  FORMAT(/10E12.4)
2006  FORMAT(10E12.4)
      END

                       --E X T E R N A L S--

ATAN.       GASS60     MATIN      MODEL      OUTCI.     OUTCR.     SQRT.      TAPE6=

                       --S T A T E M E N T   L A B E L S--

      100B             .15              47B              .16              53B               .19     D        70B
      102B             .90     ID        0B              .99            1136B               .100            127B
      134B             .120    ID        0B              .130    ID        0B               .131            223B
        0B             .151    ID        0B              .153    ID        0B               .155    ID        0B
        0B             .170            413B              .220    ID        0B               .221     D       463B
      454B             .225            563B              .229            561B               .230    ID        0B
        0B             .240     D      601B              .241            577B               .265            606B
      613B             .270            516B              .280            626B               .340    ID        0B
      754B             .391    ID        0B              .410           1133B               .414           1011B
        0B             .420    ID        0B              .425     D     1114B               .430           1076B
     1100B             .662            541B              .663            520B               .664            533B
      525B             .666            271B              .669    ID        0B               .1000    F     1213B
     1227B             .1002    F     1234B              .1003    F     1243B               .1004    F     1250B
     1254B             .1008    F     1261B              .1009    F     1271B               .1010    F     1302B
     1313B             .1012    F     1317B              .1014    F     1322B               .1015    F     1332B
     1207B             .1033    F     1336B              .1034    F     1342B               .1039    F     1346B
     1357B             .1041    F     1367B              .1043    F     1377B               .2001    F     1404B
     1406B             .2700           624B              .2710    F     1171B               .7000    F     1164B
        0B
```

```
         SUBROUTINE MATIN(A, NVAR, B, NB, DET)
         DIMENSION A(NVAR, 1), B(NVAR, 1)
          PIVOTM = A(1,1)
          DET = 1.0
         DO 550 ICOL = 1, NVAR
          PIVOT = A(ICOL, ICOL)
         PIVOTM = AMIN1(PIVOT, PIVOTM)
          DET = PIVOT * DET
   C
   C     DIVIDE PIVOT ROW BY PIVOT ELEMENT
   C
          A(ICOL, ICOL) = 1.0
         PIVOT = AMAX1(PIVOT, 1.E-20)
          PIVOT = A(ICOL, ICOL)/PIVOT
         DO 350 L=1,NVAR
    350   A(ICOL, L) = A(ICOL, L)*PIVOT
         IF (NB) 371,371,372
    372  DO 370 L=1,NB
    370   B(ICOL, L) = B(ICOL, L)*PIVOT
   C
   C     REDUCE NON-PIVOT ROWS
   C
    371  DO 550 L1=1,NVAR
         IF (L1-ICOL) 551,550,551
    551   T = A(L1, ICOL)
          A(L1, ICOL) = 0.
         DO 450 L=1,NVAR
    450   A(L1, L) = A(L1, L) - A(ICOL, L)*T
         IF (NB) 552,550,552
    552  DO 500 L=1,NB
    500   B(L1, L) = B(L1, L)-B(ICOL,L)*T
    550  CONTINUE
         RETURN
         END

                   --S T A T E M E N T   L A B E L S--

  0B               .370  IO         0B            .371          628            .372          46B
  0B               .500  IO         0B            .550   D     1329            .551          65B
113B

                   --V A R I A B L E   M A P--

 0B                VAR-DIM            AMAX1       R                INTRINSIC
    INTRINSIC                         B           R  A       CB                VAR-DIM
 0B                                   ICOL        I   U    154B
151B                                  L1          I   U    153B
140B ENTRY                            NB          I  AU      0B
  0B                                  PIVOT       R        147B
150B                                  T           R        152B
```

```
73/73   TS                                   FTN 4.5+410        03/23/76  16.02.24        PAGE     1
     /7                                                                    /73

          SUBROUTINE GASS60(ITYPE, NQ, A, B, C)
         DIMENSION A(NQ),B(NQ),C(NQ,NQ)
          NP = NQ
          NR = NP/10
          LOW = 1
          LUP = 10
 10      IF( NR )15,20,30
 15      RETURN
 20      LUP=NP
         IF (LOW-LUP) 30,30,15
   30    WRITE(06,500)  (J,J=LOW,LUP)
         GO TO (40,60,80,80), ITYPE
   40    WRITE(06,600)  (A(J),J=LOW,LUP)
         GO TO 100
   60    WRITE(06,600)  (B(J),J=LOW,LUP)
         GO TO 40
   80    IF(ITYPE.EQ.4)  GO TO 70
         DO 90 I=LOW,LUP
   90    WRITE(06,720)  I,(C(J,I),J=LOW,I)
         GO TO 71
   70    DO 72 I=LOW,LUP
   72    WRITE(06,721)  I,(C(I,J),J=LOW,I)
   71    CONTINUE
         LOW2=LUP+1
         IF (LOW2-NP)  96,96,100
   96    IF (ITYPE.EQ.4)  GO TO 97
         DO 95 I=LOW2,NP
   95    WRITE(06,720)  I,(C(J,I),J=LOW,LUP)
         GO TO 100
   97    DO 98 I=LOW2,NP
   98    WRITE(06,721)  I,(C(I,J),J=LOW,LUP)
 100      LOW = LOW + 10
          LUP = LUP + 10
          NR = NR - 1
          GO TO 10
 500     FORMAT(/I8,9I12)
 600     FORMAT(10E12.4)
 720     FORMAT(1H0,I3,1X,F7.4,9F12.4)
 721     FORMAT(1H0,I3,1X,E10.4,9E12.4)
   1     CONTINUE
         RETURN
         END

                  --E X T E R N A L S--

GOTOER.   OUTCI.     OUTCR.     TAPE6=
```

```
RLEQ.RM         20474       42   SL-SYSIO     11/10/75 COMPASS  3. 75115
CLSF.SQ         20536      131   SL-SYSIO     11/10/75 COMPASS  3. 75115
/CLSV.FO/       20567        7
CLSV.SQ         20676      123   SL-SYSIO     11/10/75 COMPASS  3. 75115
/GET.FO/        21021        7
/GET.RT/        21030       11
GET.SQ          21041     1002   SL-SYSIO     11/10/75 COMPASS  3. 75115
Z.SO            22043      101   SL-SYSIO     11/10/75 COMPASS  3. 75115
FSU.SQ          22144      104   SL-SYSIO     11/10/75 COMPASS  3. 75115
 //             22250       21

     1.624 CP SECONDS                 34362B CM STOPAGE USED                   7 TABLE MOVES
```

CALCULATION OF INTERFLOW BETWEEN INNER AND OUTER CSTR BY FITTING THE IMPULSE DYE INJECTION RESULTS TO THE DEDRIC AND BISCHOFF S FORMULA

UWHAUS SUBROUTINE HAS BEEN EMPLOYED TO FIT THE DATA TO THE FORMULA

HYDRAULIC LOADING=2.5 LITER PER MINUTE

```
NON-LINEAR ESTIMATION, PROBLEM NUMBER***.
  17 OBSERVATIONS,     2 PARAMETERS              82 SCRATCH REQUIRED

 ITIAL PARAMETER VALUES
      1          2
  .2500E+01   .1400E+02

PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS
      1          2
  .1000E-01   .100CE-01

 ITIAL SUM OF SQUARES =    .1115E-01



                                              ITERATION NO.   1
DETERMINANT =    .9841E+00       ANGLE IN SCALED COORD. = 2.94DEGREES
TEST POINT PARAMETER VALUES
  .2688E+01   .1052E+02
TEST POINT SUM OF SQUARES =    .5723E-02

PARAMETER VALUES VIA REGRESSION
      1          2
  .2688E+01   .1052E+02

 MBDA =  .100E-02                                    SUM OF SQUARES AFTER REGRESSION =   .5723121E-0



                                              ITERATION NO.   2
DETERMINANT =    .9931E+C0       ANGLE IN SCALED COORD. = 2.57DEGREES
TEST POINT PARAMETER VALUES
  .2664E+01   .1C41E+02
TEST POINT SUM OF SQUARES =    .5696E-02

PARAMFTER VALUES VIA REGRESSION
      1          2
  .2664E+01   .1041E+02

 AMBDA =  .100E-03                                   SUM OF SQUARES AFTER REGRESSION =   .5695983E-0
```

```
                                               ITERATION NO.    3
DETERMINANT =    .9934E+00         ANGLE IN SCALED COORD. = 4.66DEGREES

TEST POINT PARAMETER VALUES
  .2663E+01   .1038E+02

TEST POINT SUM OF SQUARES =    .5695E-02

PARAMETER VALUES VIA REGRESSION

       1          2
  .2663E+01   .1038E+02

LAMBDA =  .100E-04                                             SUM OF SQUARES AFTER REGRESSION =    .5694891E-02


                                               ITERATION NO.    4
DETERMINANT =    .9935E+00         ANGLE IN SCALED COORD. = 4.22DEGREES

TEST POINT PARAMETER VALUES
  .2663E+01   .1038E+02

TEST POINT SUM OF SQUARES =    .5695E-02

PARAMETER VALUES VIA REGRESSION

       1          2
  .2663E+01   .1038E+02

LAMBDA =  .100E-05                                             SUM OF SQUARES AFTER REGRESSION =    .5694764E-02


                                               ITERATION NO.    5
DETERMINANT =    .9935E+00         ANGLE IN SCALED COORD. = 4.32DEGREES

TEST POINT PARAMETER VALUES
  .2663E+01   .1037E+02

TEST POINT SUM OF SQUARES =    .5695E-02

PARAMETER VALUES VIA REGRESSION

       1          2
  .2663E+01   .1037E+02
```

```
LAMBDA =  .100E-06                                                   SUM OF SQUARES AFTER REGRESSION =   .5694740E-0


                                       ITERATION NO.   6
DETERMINANT =    .9936E+00       ANGLE IN SCALED COORD. = 4.30DEGREES
TEST POINT PARAMETER VALUES
  .2663E+01    .1037E+02
TEST POINT SUM OF SQUARES =    .5595E-02

PARAMETER VALUES VIA REGRESSION

       1            2
  .2663E+01    .1037E+02

LAMBDA =  .100E-07                                                   SUM OF SQUARES AFTER REGRESSION =   .5694735E-0

ITERATION STOPS - RELATIVE CHANGE IN SUM OF SQUARES LESS THAN    .1000E-05
```

```
FINAL FUNCTION VALUES

   .1000E+01   .5738E+00   .3999E+00   .3242E+00   .2869E+00   .2648E+00
   .2490E+00   .2359E+00   .2243E+00   .2134E+00
   .2033E+00   .1936E+00   .1844E+00   .1757E+00   .1674E+00   .1594E+00
   .1519E+00


RESIDUALS

   .7105E-14  -.2776E-01   .1606E-01   .3677E-01   .3710E-01   .2719E-01
   .1302E-01   .4083E-02  -.2252E-02  -.6442E-02
  -.9261E-02  -.1261E-01  -.1043E-01  -.1369E-01  -.1237E-01  -.1144E-01
  -.1189E-01


XPRIME-X MATRIX

        1           2

 1  .3258E-01

 2 -.3472E-03   .5737E-03



CORRELATION MATRIX

        1           2

 1  1.0000

 2   .0803      1.0000


VARIANCE OF RESIDUALS =   .3796E-03,  15 DEGREES OF FREEDOM

INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER (ON LINEAR HYPOTHESIS)

        1           2
   .2880E+01   .1201E+02
   .2447E+01   .8742E+01



APPROXIMATE CONFIDENCE LIMITS FOR EACH FUNCTION VALUE

   .1000E+01   .6042E+00   .4215E+00   .3361E+00   .2955E+00   .2741E+00
   .1000E+01   .5433E+00   .3783E+00   .3124E+00   .2793E+00   .2556E+00

   .2591E+00   .2466E+00   .2352E+00   .2245E+00
   .2389E+00   .2253E+00   .2133E+00   .2024E+00
```

```
     1.773 CP SECONDS            34423B CM STORAGE USED              7 TABLE MOVES

   CALCULATION OF INTERFLOW BETWEEN INNER AND

   OUTER CSTR BY FITTING THE IMPULSE DYE INJECTI-

   ON RESULTS TO THE DEDRIC AND BISCHOFF S FOR-

   MULA


   UWHAUS SUBROUTINE HAS BEEN EMPLOYED TO FIT THE

   DATA TO THE FORMULA


   HYDRAULIC LOADING=4.00LITER PER MINUTE
```

```
NON-LINEAR ESTIMATION, PROBLEM NUMBER***
  21 OBSERVATIONS,    2 PARAMETERS                98 SCRATCH REQUIRED

 ITIAL PARAMETER VALUES
      1          2
  .4000E+01   .1400E+02

PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS
      1          2
  .1000E-01   .1000E-01

 ITIAL SUM OF SQUARES =   .1346E-01


                                          ITERATION NO.   1
DETERMINANT =   .1001E+01      ANGLE IN SCALED COORD. = 1.49DEGREES
TEST POINT PARAMETER VALUES
  .4001E+01   .1128E+02
  ST POINT SUM OF SQUARES =   .9095E-02

 RAMETER VALUES VIA REGRESSION
      1          2
  .4001E+01   .1128E+02

LAMBDA =  .100E-02                                     SUM OF SQUARES AFTER REGRESSION =   .9094594E-02


                                          ITERATION NO.   2
 ETERMINANT =   .9983E+00      ANGLE IN SCALED COORD. = 2.22DEGREES
 EST POINT PARAMETER VALUES
  .3992E+01   .1107E+02
 EST POINT SUM OF SQUARES =   .9047E-02

 ARAMETER VALUES VIA REGRESSION
      1          2
  .3992E+01   .1107E+02

 AMBDA =  .100E-03                                     SUM OF SQUARES AFTER REGRESSION =   .9046588E-02
```

```
                                            ITERATION NO.   3
DETERMINANT =    .9974E+00       ANGLE IN SCALED COORD. = 2.81DEGREES
TEST POINT PARAMETER VALUES
 .3991E+01    .1103E+02
TEST POINT SUM OF SQUARES =    .9044E-02

PARAMETER VALUES VIA REGRESSION

    1            2
 .3991E+01    .1103E+02

LAMBDA =   .100E-04                                      SUM OF SQUARES AFTER REGRESSION =    .9044100E-02


                                            ITERATION NO.   4
DETERMINANT =    .9973E+00       ANGLE IN SCALED COORD. = 2.86DEGREES
TEST POINT PARAMETER VALUES
 .3991E+01    .1102E+02
TEST POINT SUM OF SQUARES =    .9044E-02

PARAMETER VALUES VIA REGRESSION

    1            2
 .3991E+01    .1102E+02

  BDA =   .100E-05                                       SUM OF SQUARES AFTER REGRESSION =    .9043873E-02


                                            ITERATION NO.   5
DETERMINANT =    .9973E+00       ANGLE IN SCALED COORD. = 2.88DEGREES
TEST POINT PARAMETER VALUES
 .3991E+01    .1102E+02
EST POINT SUM OF SQUARES =    .9044E-02

PARAMETER VALUES VIA REGRESSION

    1            2
 .3991E+01    .1102E+02
```

```
MBDA =  .100E-06                                                  SUM OF SQUARES AFTER REGRESSION =   .9043838E-02


                                           ITERATION NO.   6
TERMINANT =   .9972E+00        ANGLE IN SCALED COORD. = 2.88DEGREES
ST POINT PARAMETER VALUES
.3991E+01   .1102E+02
ST POINT SUM OF SQUARES =   .9044E-02

RAMETER VALUES VIA REGRESSION
    1           2
.3991E+01   .1102E+02

MBDA =  .100E-07                                                  SUM OF SQUARES AFTER REGRESSION =   .9043831E-02

ERATION STOPS - RELATIVE CHANGE IN SUM OF SQUARES LESS THAN   .1000E-05
```

```
FINAL FUNCTION VALUES
   .1000E+01    .7057E+00    .5276E+00    .4183E+00    .3500E+00    .3060E+00
   .2765E+00    .2558E+00    .2404E+00    .2282E+00
   .2180E+00    .2094E+00    .2012E+00    .1938E+00    .1868E+00    .1802E+00
   .1739E+00    .1679E+00    .1621E+00    .1565E+00
   .1511E+00


RESIDUALS
   .7105E-14   -.4674E-01   -.8580E-02    .2669E-01   -.2962E-02    .3603E-01
   .3047E-01    .2418E-01    .2261E-01    .2080E-01
   .9971E-02    .4843E-02   -.5153E-02   -.9758E-02   -.1181E-01   -.1222E-01
  -.1293E-01   -.1389E-01   -.1508E-01   -.1849E-01
  -.2910E-01


XPRIME-X MATRIX
        1              2

  1  .1954E-01

  2  .2113E-03    .8293E-03


CORRELATION MATRIX
        1              2

  1   1.0000

  2   -.0525        1.0000

VARIANCE OF RESIDUALS =    .4760E-03,  19 DEGREES OF FREEDOM

INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER (ON LINEAR HYPOTHESIS)
        1              2
   .4303E+01    .1254E+02
   .3678E+01    .9502E+01
```

```
$J03,650,031LINR,3,1000,300,,,  DOUG BEECROFT
$SCHED,SCR=5,CORE=52
$FTNU(S,X,L,P)
      PROGRAM LINRG                                                     LI
C                                                                       LI
C        DOUG BEECROFT, ENVIRCNMENTAL PROTECTION SERVICE, SEPTEMBER 1972LI
C                                                                       LI
C        THIS PROGRAM USES LEAST SQUARES TO ESTIMATE THE REGRESSION     LI
C        COEFFICIENTS FOR ANY LINEAR FUNCTION INVOLVING LESS THAN TEN   LI
C        INDEPENDENT VARIABLES.  CUTPUT INCLUDES MEANS AND STANDARD     LI
C        DEVIATIONS FOR ALL VARIAELES, THE CORRELATION MATRIX,          LI
C        REGRESSICN COEFFICIENTS, AN ANALYSIS OF VARIANCE TABLE, THE    LI
C        SQUARE OF THE MULTIPLE CCRRELATION COEFFICIENT, AND A TABLE OF LI
```

```
C        RESIDUALS.  THE REQUIRED DATA CARDS ARE LISTED BELOW.
C
C                 A.  COL.  1- 8  PROBLM, AN EIGHT CHARACTER ALPHANUMERIC
C                                 CODE TO BE USED IN IDENTIFYING THE
C                                 PROBLEM.
C
C                     COL.  9-11  NPTS, THE NUMBER OF OBSERVATIONS.  NPTS
C                                 MUST BE LESS THAN 251.
C
C                     COL. 12-13  NVAR, THE TOTAL NUMBER OF VARIABLES (THE
C                                 NUMBER OF INDEPENDENT VARIABLES + 1).
C                                 NVAR MUST BE LESS THAN 11.
C
C                     COL. 14-15  NDEPND, THE NUMBER OF THE DEPENDENT
C                                 VARIABLE, THAT IS, THE COLUMN OF THE INPU
C                                 DATA MATRIX CONTAINING THE VALUES OF THE
C                                 DEPENDENT VARIABLE.
C
C                 B.  COL.  1-72  VARIABLE FORMAT CARD WITH WHICH THE INPUT
C                                 DATA IS TO BE READ.  SEE THE BMD MANUAL,
C                                 PAGES 22-28, FOR A MORE COMPLETE
C                                 DESCRIPTION OF THIS TYPE OF CARD.
C
C                 C.  THE INPUT DATA.  EACH CARD CONTAINS ONE OBSERVATION O
C                                 EACH VARIABLE.  THE GENERAL FORM OF THE
C                                 INPUT DATA IS THE SAME AS FOR THE BMD
C                                 PROGRAMS (BMD MANUAL, PAGES 11-12).
C
C                 D.  EOF CARD (STANDARD C.C.I.W. GREY-STRIPED EOF)
C
C        NOTE -- CARDS A THROUGH C MAY BE REPEATED AS OFTEN AS DESIRED.
C
      COMMON CORMAT,NINDEP
      REAL MEANS(10),COEFF(9)
      DIMENSION DATMAT(250,10),DATUSE(250,10),RESID(250),VARFMT(9)
      DIMENSION CORMAT(10,10),S(10),SPARE(9),IVAR(10),YFIT(250)
      EQUIVALENCE (DATUSE(1),YFIT(1)), (DATUSE(251),RESID(1))
      EQUIVALENCE (VARFMT,DATUSE)
C
C        READ CONTROL INFORMATION
C
   10 READ 99, PROBLM,NPTS,NVAR,NDEPND,VARFMT
   99 FORMAT (A8,I3,2I2/9A8)
      IF (IFEOF(60).EQ.-1) STOP
      DO 100  I=1,NPTS
  100 READ (60,VARFMT) (DATMAT(I,J),J=1,NVAR)
      NINDEP=NVAR-1
C
C        COMPUTE MEANS OF ALL VARIABLES, CENTRE DATA
C
      DO 200  I=1,NVAR
      MEANS(I)=0.0
      DO 300  J=1,NPTS
  300 MEANS(I)=MEANS(I)+DATMAT(J,I)
      MEANS(I)=MEANS(I)/NPTS
      DO 200 J=1,NPTS
  200 DATUSE(J,I)=DATMAT(J,I)-MEANS(I)
C
C        COMPUTE SUM OF SQUARES OF DEVIATIONS FROM MEAN FOR VARIABLES
C
      DO 500  I=1,NVAR
      S(I)=0.0
```

```
      DO 600  J=1,NPTS
  600 S(I)=S(I)+DATUSE(J,I)**2
      SAVE=SQRT(S(I))
      DO 500  J=1,NPTS
  500 DATUSE(J,I)=DATUSE(J,I)/SAVE
C
C         PRINT CONTROL INFORMATION, MEANS, AND STANDARD DEVIATIONS
C
      PRINT 44, PROBLM,NPTS,NVAR,NDEPND
   44 FORMAT (27H1MULTIPLE LINEAR REGRESSION
     1        /13H0PROBLEM CODE,A23
     2        /23H NUMBER OF OBSERVATIONS,10X,I3
     3        /20H NUMBER OF VARIABLES,I16
     4        /29H DEPENDENT VARIABLE IS NUMBER,I7/
     5        /30H0MEANS AND STANDARD DEVIATIONS
     6  //11X,42HVARIABLE NO.     MEAN    STANDARD DEVIATION/)
      DO 1030  I=1,NVAR
      SAVE=SQRT(S(I)/(NPTS-1))
 1030 PRINT 22,I,MEANS(I),SAVE
   22 FORMAT (16X,I2,2F15.5)
C
C         COMPUTE AND PRINT CORRELATION MATRIX
C
      DO 700  I=1,NVAR
      DO 700  J=1,NVAR
      CORMAT(I,J)=0.0
      DO 700  K=1,NPTS
  700 CORMAT(I,J)=CORMAT(I,J)+DATUSE(K,I)*DATUSE(K,J)
      PRINT 88,(I,I=1,NVAR)
   88 FORMAT (/19H0CORRELATION MATRIX//9X,10(7X,I2))
      DO 800  I=1,NVAR
  800 PRINT 77,I,(CORMAT(I,K),K=1,NVAR)
   77 FORMAT (8X,I1,3X,10F9.5)
C
C         TRANSFER DEPENDENT VARIABLE TO LAST ROW AND LAST COLUMN
C
      DO 18  I=1,NVAR
   18 IVAR(I)=I
      IF (NDEPND.EQ.NVAR) GO TO 32
      DO 17  I=1,NVAR
      SWAP=CORMAT(I,NVAR)
      CORMAT(I,NVAR)=CORMAT(I,NDEPND)
   17 CORMAT(I,NDEPND)=SWAP
      DO 16  I=1,NVAR
      SWAP=CORMAT(NVAR,I)
      CORMAT(NVAR,I)=CORMAT(NDEPND,I)
   16 CORMAT(NDEPND,I)=SWAP
      IVAR(NDEPND)=NVAR
      IVAR(NVAR)=NDEPND
C
C         COMPUTE PRODUCT OF TRANSPOSE MATRIX OF X VALUES WITH Y VALUES
C
   32 DO 900  I=1,NINDEP
      SPARE(I)=0.0
      L=IVAR(I)
      DO 900  K=1,NPTS
  900 SPARE(I)=SPARE(I)+DATUSE(K,L)*DATUSE(K,NDEPND)
C
C         COMPUTE INVERSE OF CORRELATION MATRIX
C
      CALL MATINV
C
```

```
C         COMPUTE AND PRINT REGRESSION COEFFICIENTS
C
          PRINT 66
       66 FORMAT (//24H REGRESSION COEFFICIENTS
        1    //11X,27HVARIABLE NO.    COEFFICIENT/)
          CONST=MEANS(NDEPND)
          DO 1000  I=1,NINDEP
          COEFF(I)=0.0
          L=IVAR(I)
          DO 400  K=1,NINDEP
      400 COEFF(I)=COEFF(I)+CORMAT(I,K)*SPARE(K)
          COEFF(I)=COEFF(I)*SQRT(S(NDEPND)/S(L))
          CONST=CONST-COEFF(I)*MEANS(L)
     1000 PRINT 55, L,COEFF(I)
       55 FORMAT (14X,I2,E21.5)
          PRINT 14, CONST
       14 FORMAT (/11X,38HCONSTANT TERM IN PREDICTION EQUATION =,F12.5/)
C
C         PRINT ANALYSIS OF VARIANCE AND CORRELATION COEFFICIENT
C
          REGSS=0.0
          DO 1040  I=1,NPTS
          YFIT(I)=CONST
          DO 1050  J=1,NINDEP
          L=IVAR(J)
     1050 YFIT(I)=YFIT(I)+COEFF(J)*DATMAT(I,L)
          RESID(I)=DATMAT(I,NDEPND)-YFIT(I)
     1040 REGSS=REGSS+YFIT(I)*DATMAT(I,NDEPND)
          TOTAVG=NPTS*MEANS(NDEPND)**2
          TOTSS=TOTAVG+S(NDEPND)
          RESSS=TOTSS-REGSS
          REGSS=S(NDEPND)-RESSS
          REGMS=REGSS/NINDEP
          I=NPTS-1
          J=NPTS-NVAR
          VARYNC=RESSS/J
          F=REGMS/VARYNC
          CORRCO=REGSS/S(NDEPND)
          PRINT 1107,TOTSS,NPTS,TOTAVG,S(NDEPND),I,REGSS,NINDEP,REGMS,F,
        1    RESSS,J,VARYNC,CORRCO
     1107 FORMAT (21H0ANALYSIS OF VARIANCE/1H0,12X,71HSOURCE OF VARIATION
        1SUM OF SQUARES   DEGREES OF FREEDOM   MEAN SQUARE,10X,1HF
        2    /1H0,12X,19HTOTAL (UNCORRECTED),F16.4,I15/1H ,27X,4HMEAN,
        3    F16.4,14X,1H1/1H ,14X,17HTOTAL (CORRECTED),F16.4,I15/1H ,21X
        4    10HREGRESSION,F16.4,I15,F21.4,F15.4/1H ,23X,8HRESIDUAL,F16.4
        5    I15,F21.4/33H0CORRELATION COEFFICIENT (R**2) =,F9.5)
C
C         PRINT TABLE OF RESIDUALS
C
          PRINT 12
       12 FORMAT (19H1TABLE OF RESIDUALS
        1         /1H0,4X,29HOBSERVATION NO.    OBSERVED Y,8X,8HFITTED Y,8
        2          8HRESIDUAL/)
          DO 1060  I=1,NPTS
     1060 PRINT 13, I,DATMAT(I,NDEPND),YFIT(I),RESID(I)
       13 FORMAT (10X,I3,10X,F11.5,6X,F11.5,5X,F10.5)
          GO TO 10
          END
          SUBROUTINE MATINV
C
C         MATRIX INVERSION
C
```

```
      COMMON A,N
      DIMENSION A(10,10),INDEX(10,3)
      EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM),(AMAX,T,SWAP)
      DO 60  J=1,N
   60 INDEX(J,3)=0
C
C        SEARCH FOR PIVOT ELEMENT
C
      DO 550  I=1,N
      AMAX=0.0
      DO 105  J=1,N
      IF (INDEX(J,3).EQ.1) GO TO 105
      DO 100  K=1,N
      IF (INDEX(K,3)-1) 80,100,715
   80 IF (AMAX.GE.ABS(A(J,K))) GO TO 100
      IROW=J
      ICOLUM=K
      AMAX=ABS(A(J,K))
  100 CONTINUE
  105 CONTINUE
      INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
      INDEX(I,1)=IROW
      INDEX(I,2)=ICOLUM
      IF (IROW.EQ.ICOLUM) GO TO 310
C
C        INTERCHANGE ROWS
C
      DO 200  L=1,N
      SWAP=A(IROW,L)
      A(IROW,L)=A(ICOLUM,L)
  200 A(ICOLUM,L)=SWAP
C
C        REDUCE NON-PIVOT ROWS
C
  310 PIVOT=A(ICOLUM,ICOLUM)
      A(ICOLUM,ICOLUM)=1.0
      DO 350  L=1,N
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
      DO 550  L1=1,N
      IF (L1.EQ.ICOLUM) GO TO 550
      T=A(L1,ICOLUM)
      A(L1,ICOLUM)=0.0
      DO 450  L=1,N
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
  550 CONTINUE
C
C        INTERCHANGE COLUMNS
C
      DO 710  I=1,N
      L=N+1-I
      IF (INDEX(L,1).EQ.INDEX(L,2)) GO TO 710
      JROW=INDEX(L,1)
      JCOLUM=INDEX(L,2)
      DO 705  K=1,N
      SWAP=A(K,JROW)
      A(K,JROW)=A(K,JCOLUM)
  705 A(K,JCOLUM)=SWAP
  710 CONTINUE
      DO 730  K=1,N
      IF (INDEX(K,3).NE.1) GO TO 715
```

```
C                                                                       L
C         PRINT ERROR MESSAGE                                           L
C                                                                       L
  715 PRINT 99                                                          L
   99 FORMAT (61H0INVERSE OF MATRIX CANNOT BE COMPUTED -- EXECUTION TERML
     1INATED)                                                           L
      STOP                                                              L
      END                                                               L
```

```
      PROGRAM CON95                                                     CON9501
C                                                                       CON950
C        DOUG BEECROFT, ENVIRONMENTAL PROTECTION SERVICE, OCTOBER 1972  CON950
C                                                                       CON950
C        THIS PROGRAM COMPUTES THE 95 PERCENT CONFIDENCE LIMITS FOR ANY CON950
C        LINEAR REGRESSION EQUATION.  THE NECESSARY DATA CARDS ARE      CON950
C        LISTED BELOW.                                                  CON950
C                                                                       CON950
C             A.  COL.   1- 8  PROBLM, AN EIGHT CHARACTER ALPHANUMERIC   CON950
C                              CODE USED TO IDENTIFY THE PROBLEM.       CON950
C                                                                       CON950
C                 COL.   9-11  NPTS, THE NUMBER OF OBSERVATIONS USED IN CON950
C                              COMPUTING THE REGRESSION COEFFICIENTS.   CON950
C                              NPTS MUST BE LESS THAN 501.              CON950
C                                                                       CON950
C                 COL.  12-13  NVAR, THE TOTAL NUMBER OF VARIABLES      CON950
C                              INVOLVED IN THE REGRESSION (THE NUMBER OF CON950
C                              INDEPENDENT VARIABLES + 1).  NVAR MUST BE CON950
C                              LESS THAN 11.                            CON950
C                                                                       CON950
C                 COL.  14-16  NLIM, THE NUMBER OF CONFIDENCE LIMITS TO CON950
C                              BE COMPUTED.                             CON950
C                                                                       CON950
C                 COL.  17-30  VARYNC, THE RESIDUAL MEAN SQUARE OR      CON950
C                              VARIANCE ABOUT THE REGRESSION.  THIS     CON950
C                              STATISTIC IS GIVEN IN THE ANALYSIS OF    CON950
C                              VARIANCE TABLE COMPUTED BY LINRG OR STPRG.CON950
C                              THE NUMBER MUST CONTAIN A DECIMAL POINT. CON950
C                                                                       CON950
C             B.  THE COMPUTED REGRESSION COEFFICIENTS.  EACH           CON950
C                              COEFFICIENT, BEGINNING WITH THE CONSTANT CON950
C                              TERM AND FOLLOWED BY THE VARIABLE        CON950
C                              COEFFICIENTS, IN ORDER, MUST OCCUPY 15   CON950
C                              COLUMNS OF THE CARD.  IF NVAR IS GREATER CON950
C                              THAN 5, TWO CARDS WILL BE REQUIRED.      CON950
C                                                                       CON950
C             C.  COL.   1-72  VARIABLE FORMAT CARD TO BE USED IN READINGCON950
C                              THE INPUT DATA.  SEE THE BMD MANUAL, PAGESCON950
C                              22-28 FOR A DESCRIPTION OF THIS TYPE OF  CON950
C                              CARD.  ONLY THE INDEPENDENT VARIABLE     CON950
C                              VALUES NEED BE READ IN.                  CON950
C                                                                       CON950
C             D.  THE INPUT DATA.  THE RAW DATA FROM WHICH THE          CON950
C                              REGRESSION COEFFICIENTS WERE CALCULATED. CON950
C                              THE OBSERVED VALUES OF THE DEPENDENT     CON950
C                              VARIABLE MUST NOT BE INCLUDED.  VALUES   CON950
C                              OF THE OTHER VARIABLES MUST APPEAR IN THE CON950
C                              SAME ORDER AS THEIR RESPECTIVE           CON950
C                              COEFFICIENTS IN CARD B.                  CON950
C                                                                       CON950
C             E.  COL.   1-72  VARIABLE FORMAT CARD TO BE USED IN READINGCON950
C                              THE POINTS AT WHICH CONFIDENCE LIMITS ARE CON950
```

```
C                                           TO BE COMPUTED.                     CON950
C                                                                               CON950
C                     F.  THE POINTS AT WHICH LIMITS ARE TO BE COMPUTED.  THE   CON950
C                                 GENERAL FORM IS SIMILAR TO THE INPUT DATA,CON950
C                                                                               CON950
C                  G.  EOF CARD (STANDARD C.C.I.W. GREY-STRIPED EOF)           CON950
C                                                                               CON950
C             NOTE -- CARDS A THROUGH F MAY BE REPEATED AS OFTEN AS DESIRED. CON950
C                                                                               CON950
      COMMON COVINV,NVAR                                                        CON950
      DIMENSION COVINV(10,10),TVALUES(33),POINT(10),XMATRX(500,10)              CON950
      DIMENSION VARFMT(9),COEFF(10)                                             CON950
      DATA TVALUES /12.706,4.303,3.182,2.776,2.571,2.447,2.365,2.306,           CON950
     1     2.262,2.228,2.201,2.179,2.160,2.145,2.131,2.120,2.110,2.101,         CON950
     2     2.093,2.086,2.080,2.074,2.069,2.064,2.060,2.056,2.052,2.048,         CON950
     3     2.045,2.042,2.021,2.000,1.9607                                       CON950
C                                                                               CON950
C             READ AND PRINT CONTROL INFORMATION                                CON950
C                                                                               CON950
   60 READ 99, PROBLM,NPTS,NVAR,NLIM,VARYNC,(COEFF(I),I=1,NVAR)                 CON950
   99 FORMAT (A8,I3,I2,I3,F14.4/5F15.5,5X)                                      CON950
      IF (IFEOF(60).EQ.-1) STOP                                                 CON950
      READ 88, VARFMT                                                           CON950
   88 FORMAT (9A8)                                                              CON950
      DO 100  I=1,NPTS                                                          CON950
      XMATRX(I,1)=1.0                                                           CON950
  100 READ (60,VARFMT) (XMATRX(I,J),J=2,NVAR)                                   CON950
      PRINT 77, PROBLM,NPTS,NVAR,NLIM,VARYNC                                    CON950
   77 FORMAT (23H195 PERCENT CONFIDENCE LIMITS/                                 CON950
     1        13H0PROBLEM CODE,A23/                                             CON950
     2        23H NUMBER OF OBSERVATIONS,I13/                                   CON950
     3        20H NUMBER OF VARIABLES,I16/                                      CON950
     4        32H NUMBER OF LIMITS TO BE COMPUTED,I4/                           CON950
     5        21H RESIDUAL MEAN SQUARE,F19.4///                                 CON950
     6        24H0REGRESSION COEFFICIENTS//11X,                                 CON950
     7        22HVARIABLE    COEFFICIENT/)                                      CON950
      DO 300  I=2,NVAR                                                          CON950
      J=I-1                                                                     CON950
  300 PRINT 55, J,COEFF(I)                                                      CON950
   55 FORMAT (I16,F17.5)                                                        CON950
      PRINT 44, COEFF(1)                                                        CON950
   44 FORMAT (/10X,38HCONSTANT TERM IN PREDICTION EQUATION =,F12.5///           CON950
     1              18H0CONFIDENCE LIMITS//10X,                                 CON950
     2              43HLIMIT NO.    LOWER LIMIT    FITTED Y    UPPER LIMIT/)CON950
C                                                                               CON950
C             COMPUTE INVERSE OF COVARIANCE MATRIX                              CON950
C                                                                               CON950
      DO 700  I=1,NVAR                                                          CON95
      DO 700  J=1,NVAR                                                          CON951
      COVINV(I,J)=0.0                                                           CON951
      DO 700  K=1,NPTS                                                          CON951
  700 COVINV(I,J)=COVINV(I,J)+XMATRX(K,I)*XMATRX(K,J)                           CON95
```

```
C                                                                           CON95
C         COMPUTE COVARIANCE MATRIX                                         CON95
C                                                                           CON95
      CALL MATINV                                                           CON95
C                                                                           CON95
C         READ IN THE CO-ORDINATES OF THE POINT AND COMPUTE THE FITTED Y    CON95
C                                                                           CON95
      READ 68, VARFMT                                                       CON95
      DO 70  J=1,NLIM                                                       CON95
      POINT(1)=1.0                                                          CON95
      READ (60,VARFMT)  (POINT(I),I=2,NVAR)                                 CON95
      YFIT=COEFF(1)                                                         CON95
      DO 200  I=2,NVAR                                                      CON95
  200 YFIT=YFIT+COEFF(I)*POINT(I)                                           CON95
C                                                                           CON95
C         COMPUTE PRODUCT OF THE POINT AND THE COVARIANCE MATRIX            CON95
C                                                                           CON95
      CONFID=0.0                                                            CON95
      DO 800  I=1,NVAR                                                      CON95
      SPARE=0.0                                                             CON95
      DO 900  K=1,NVAR                                                      CON95
  900 SPARE=SPARE+POINT(K)*COVINV(K,I)                                      CON95
  800 CONFID=CONFID+SPARE*POINT(I)                                          CON9
C                                                                           CON9
C         CHOOSE APPROPRIATE T VALUE AND COMPUTE CONFIDENCE LIMIT           CON9
C                                                                           CON9
      IJK=NPTS-NVAR                                                         CON9
      IF (IJK.GT.30) GO TO 10                                               CON9
      T=TVALUES(IJK)                                                        CON9
      GO TO 20                                                              CON9
   10 IF ( IJK.GT.35) GO TO 30                                              CON9
      T=TVALUES(30)                                                         CON9
      GO TO 20                                                              CON9
   30 IF (IJK.GT.50) GO TO 40                                               CON9
      T=TVALUES(31)                                                         CON9
      GO TO 20                                                              CON9
   40 IF (IJK.GT.90) GO TO 50                                               CON9
      T=TVALUES(32)                                                         CON9
      GO TO 20                                                              CON9
   50 T=TVALUES(33)                                                         CON9
   20 CONFID=SQRT(CONFID*VARYNC)*T                                          CON9
      UP=YFIT+CONFID                                                        CON9
      DOWN=YFIT-CONFID                                                      CON9
   70 PRINT 66, J,DOWN,YFIT,UP                                              CON9
   66 FORMAT (I15,F18.5,F11.5,F14.5)                                        CON9
      GO TO 60                                                              CON9
      END
```

```
      SUBROUTINE MATINV                                                  CON951
C                                                                        CON951
C         MATRIX INVERSION                                               CON951
C                                                                        CON951
      COMMON A,N                                                         CON951
      DIMENSION A(10,10),INDEX(10,3)                                     CON951
      EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM),(AMAX,T,SWAP)              CON951
      DO 60  J=1,N                                                       CON951
   60 INDEX(J,3)=0                                                       CON951
C                                                                        CON951
C         SEARCH FOR PIVOT ELEMENT                                       CON951
C                                                                        CON951
      DO 550  I=1,N                                                      CON951
      AMAX=0.0                                                           CON951
      DO 105  J=1,N                                                      CON951
      IF (INDEX(J,3).EQ.1) GO TO 105                                     CON951
      DO 100  K=1,N                                                      CON951
      IF (INDEX(K,3)-1) 80,100,715                                       CON951
   80 IF (AMAX.GE.ABS(A(J,K))) GO TO 100                                 CON951
      IROW=J                                                             CON951
      ICOLUM=K                                                           CON951
      AMAX=ABS(A(J,K))                                                   CON951
  100 CONTINUE                                                           CON951
  105 CONTINUE                                                           CON951
      INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1                                  CON951
      INDEX(I,1)=IROW                                                    CON951
      INDEX(I,2)=ICOLUM                                                  CON951
      IF (IROW.EQ.ICOLUM) GO TO 310                                      CON951
C                                                                        CON951
C         INTERCHANGE ROWS                                               CON951
C                                                                        CON951
      DO 200  L=1,N                                                      CON951
      SWAP=A(IROW,L)                                                     CON951
      A(IROW,L)=A(ICOLUM,L)                                              CON951
  200 A(ICOLUM,L)=SWAP                                                   CON951
C                                                                        CON951
C         REDUCE NON-PIVOT ROWS                                          CON951
C                                                                        CON951
  310 PIVOT=A(ICOLUM,ICOLUM)                                             CON951
      A(ICOLUM,ICOLUM)=1.0                                               CON951
      DO 350  L=1,N                                                      CON951
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT                                      CON951
      DO 550  L1=1,N                                                     CON951
      IF (L1.EQ.ICOLUM) GO TO 550                                        CON951
      T=A(L1,ICOLUM)                                                     CON951
      A(L1,ICOLUM)=0.0                                                   CON951
      DO 450  L=1,N                                                      CON951
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T                                      CON951
  550 CONTINUE                                                           CON952
C                                                                        CON952
C         INTERCHANGE COLUMNS                                            CON952
C                                                                        CON952
```

```
PAN(2.3)/MASTER      INTEGER WORD SIZE = 1 , * OPTION IS  OFF , O OPTION IS  OFF

      DO 710  I=1,N                                                     CON952
      L=N+1-I                                                           CON952
      IF (INDEX(L,1).EQ.INDEX(L,2)) GO TO 710                           CON952
      JROW=INDEX(L,1)                                                   CON952
      JCOLUM=INDEX(L,2)                                                 CON952
      DO 705  K=1,N                                                     CON952
      SWAP=A(K,JROW)                                                    CON952
      A(K,JROW)=A(K,JCOLUM)                                             CON952
  705 A(K,JCOLUM)=SWAP                                                  CON952
  710 CONT[illegible]UE                                                 CON952
      DO 7[illegible]  K=1,N                                            CON952
      IF (INDEX(K,3).NE.1) GO TO 715                                    CON952
  730 CONTINUE                                                          CON952
      RETURN                                                            CON952
C                                                                       CON952
C         PRINT ERROR MESSAGE                                           CON952
C                                                                       CON952
  715 PRINT 99                                                          CON952
   99 FORMAT (61H0INVERSE OF MATRIX CANNOT BE COMPUTED -- EXECUTION TERMCON952
     1INATED)                                                           CON952
      STOP                                                              CON952
      END                                                               CON952

SASI FORTRAN DIAGNOSTIC RESULTS FOR MATINV

    NO ERRORS
```

APPENDIX 3

In this appendix, the following are included:

Table 3-1: Calculation of reaction rate constants for hydraulic loading of 2.5 l/min, assuming zero order kinetics.

Table 3-2: Calculation of reaction rate constants for hydraulic loading of 4.0 l/min, assuming zero order kinetics (Analytical results of parallel and series operation are included).

Table 3-3: Same as table 1, but for first order kinetics.

Table 3-4: Same as table 2, but for first order kinetics.

Zero Order Kinetics

In order to determine K and SB values of equation 17 and 18 (page 50,53), n was taken to be zero.

$$v\ S_o - K\ A_A - v_B\ S_A + v_B\ S_B - v\ S_A = 0 \qquad (1)$$

$$v_B\ S_A - K\ A_B - v_B\ S_B = 0 \qquad (2)$$

Equation (1) and (2) yields:

$$K = \frac{v(S_o-S_A)}{A}$$

$$S_B = SA - \frac{K\ A_B}{v_B}$$

The calculations are shown on Table 3-1 and 3-2 of this appendix for hydraulic loadings of 2.5 l/min and 4.0 l/min respectively.

First Order Kinetics

(a) For hydraulic loading of 4 l/min (Table 3-4)

Formula 17 and 18 yields:

$$K = 2.45\ \frac{S_A}{S_B} - 2.45 \qquad (1)$$

$$S_B^{\ 2} - (0.956\ S_A - 0.285\ S_o)\ S_B - 0.329\ S_A^{\ 2} = 0$$

by inserting:

$v = 4$ l/min

$V_B = 14$ l/min

$A_B = 5.7\ m^2$

$A_A = 1.9\ m^2$

$n = 1$

(b) For hydraulic loading of 2.5 l/min (Table 3-3)

Formula 17 and 18 gives

$$K = 2.10 \frac{S_A}{S_B} - 2.10$$

$$S_B^2 - (0.879\ S_A - 0.208\ S_o)\ S_B - 0.329\ S_A^2 = 0$$

TABLE 3-1

ate	Run No.	Temp. ^{o}C	Hydraulic Loading (l/min)	S_o ppm	S_A ppm	$S_o - S_A$ ppm	$K = \frac{(S_o - S_A)\,v}{A}$ mg/m^2-min	$K\,\frac{A_B}{V_B}$	$S_B = S_A - K\,\frac{A_B}{V_B}$ (ppm)	K mg/m^2-hr	lnK
7/9/75	18	5	2.5	13.6	10.25	3.35	1.10	0.52	9.73	66.11	4.18
8/9/75	18	5	2.5	25.20	17.10	8.10	2.66	1.26	15.84	159.60	5.07
2/10/75		10	2.5	17.00	12.30	4.70	1.54	0.73	11.57	92.40	4.53
3/10/75		10	2.5	18.00	12.90	5.10	1.67	0.79	12.11	100.20	4.61
1/9/75		15	2.5	13.75	4.75	9.00	2.96	1.27	3.48	177.60	5.17
2/9/75		15	2.5	13.30	4.70	8.60	2.82	1.33	3.37	169.20	5.13
0/10/75		20	2.5	30.00	6.90	23.10	7.59	3.60	3.30	455.40	6.12
1/10/75		20	2.5	29.00	13.00	16.00	5.26	2.49	10.51	315.60	5.75
5/9/75		25	2.5	32.00	6.20	25.80	8.48	4.02	2.18	528.80	6.23
8/9/75		25	2.5	22.90	3.85	19.05	6.26	2.97	0.88	375.60	5.92
6/9/75		25	2.5	29.00	2.80	26.20	16.78	----	0.00	1007.36	6.91

TABLE 3-2

Date	Run No.	Temp. ^{o}C	Hydrualic Loading 1/min	S_o (ppm)	S_A (ppm)	S_o-S_A (ppm)	$K=\frac{(S_o-S_A)v}{A}$ mg/m^2-min	$K\frac{A_B}{v_B}$	$S_B=S_A-K\frac{A_B}{v_B}$	K mg/m^2-hr	lnK
17/9/75		5	4	13.60	12.65	0.95	0.49	0.19	12.46	30.00	3.40
18/9/75		5	4	26.20	23.60	2.60	1.36	0.55	23.05	82.10	4.40
21/9/75		5	4	15.35	11.45	3.90	2.05	0.83	10.62	123.15	4.81
22/10/75		5	4	17.00	15.30	1.70	0.89	0.36	14.94	53.68	3.98
10/7/75		5	4	14.10	10.40	3.70	1.94	0.78	9.62	116.84	4.76
22/10/75		10	4	17.00	14.90	2.10	1.10	0.44	14.46	66.31	4.19
23/10/75		10	4	18.00	15.00	3.00	1.57	0.63	14.37	94.73	4.55
17/3/75		10	4	17.00	9.40	7.60	3.99	1.62	7.78	239.99	5.48
3/7/75		15	4	19.00	14.40	4.60	2.42	0.98	13.42	145.26	4.97
10/10/75		20	4	30.00	10.00	20.00	10.52	4.28	5.72	631.57	6.44
3/10/75		25	4	30.00	7.65	22.35	11.76	4.78	2.87	705.94	6.55
16/8/75		25	4	40.00	16.7	23.30	12.26	4.99	11.71	735.75	6.60
17/8/75		25	4	54.00	42.00	12.00	6.31	2.56	39.44	378.94	5.93

TABLE 3-3

Date	S_o ppm	0.208 S_o	S_A ppm	0.879 S_A	0.879 S_A- 0.208 S_o	0.329 S_A^2	a S_B^2-b S_B-c=o	$\sqrt{b^2-4ac}$
17/9/75	13.60	2.82	10.25	9.00	6.18	34.56	$S_B^2-6.18\ S_B-34.56$	13.28
18/9/75	25.20	5.24	17.10	15.03	9.79	96.20	$S_B^2-9.79\mathrm{SB}-9620$	21.93
22/10/75	17.00	3.53	12.30	10.86	7.33	49.77	$S_B^2-7.33\ S_B-49.77$	15.89
23/10/75	18.00	3.74	12.90	11.33	7.59	54.74	$S_B^2-7.59\ S_B-54.74$	16.63
11/9/75	13.75	2.86	4.75	4.17	1.31	7.42	$S_B^2-1.31\ S_B-7.42$	5.60
12/9/75	13.30	2.76	4.70	4.13	1.37	7.26	$S_B^2-1.37\ S_B-7.26$	5.56
10/10/75	30.00	6.24	6.90	6.06	-0.18	15.66	$S_B^2+0.18\ S_B-15.66$	7.91
11/10/75	29.00	6.03	13.00	11.42	5.39	55.60	$S_B^2-5.39\ S_B-55.60$	15.85
25/9/75	32.00	6.65	6.20	5.44	-1.21	12.64	$S_B^2+1.21\ S_B-12.64$	7.21
28/9/75	22.90	4.76	3.85	3.38	-1.38	4.87	$S_B^2+1.38\ S_B-4.87$	4.62
26/9/75	29.00	6.03	2.80	2.46	-3.57	2.57	$S_B^2+3.57\ S_B-2.57$	4.79

TABLE 3-3 (Cont'd)

$-b+\sqrt{b^2-4ac}$	$-b-\sqrt{b^2-4ac}$	S_B	$K=2.10\frac{S_A}{S_B}\,2.10$	lnk
19.66	-7.10	9.73	0.112	-2.18
31.72	-12.14	15.86	0.165	-1.80
23.22	-8.56	11.61	0.124	-2.08
24.22	-9.04	12.11	0.138	-1.98
6.91	-4.29	3.45	0.79	-0.23
6.93	-4.19	3.46	0.76	-0.27
7.73	-8.09	3.86	1.68	-0.51
21.24	-10.46	10.62	0.47	-0.75
6.00	-8.41	3.00	2.23	-0.80
3.24	-6.00	1.62	2.89	+1.06
+1.22	-8.36	0.61	7.53	2.01

TABLE 3-4

Date	S_o (ppm)	$0.285\ S_o$ (ppm)	S_A (ppm)	$0.956\ S_A$ (ppm)	$0.956\ S_A - 0.285 S_o$ (ppm)	$0.329 S_A^2$	$a\ S_B^2 - bS_B - c = 0$	$\sqrt{b^2-4ac}$
17/9/75	13.60	3.87	12.65	12.09	8.22	52.64	$S_B^2 - 8.22\ S_B - 52.64$	16.67
18/9/75	26.20	7.46	23.60	22.56	15.10	183.23	$S_B^2 - 15.10\ S_B - 183.23$	30.99
21/9/75	15.35	4.37	11.45	10.94	6.57	43.13	$S_B^2 - 6.57\ S_B - 43.13$	14.68
22/9/75	17.00	4.84	14.90	14.24	9.40	73.04	$S_B^2 - 9.40\ S_B - 73.04$	19.50
10/7/75	14.10	4.01	10.40	9.94	5.93	35.58	$S_B^2 - 5.93\ S_B - 35.38$	13.32
22/10/75	17.00	4.84	15.30	14.62	9.78	77.01	$S_B^2 - 9.78\ S_B - 77.01$	20.09
23/10/75	18.00	5.13	15.00	14.34	9.21	74.02	$S_B^2 - 9.21\ S_B - 74.02$	19.51
17/7 /75	17.00	4.84	9.40	8.98	4.14	29.07	$S_B^2 - 4.14\ S_B - 29.07$	11.55
3/7/75	19.00	5.41	14.40	13.76	8.35	68.22	$S_B^2 - 8.35\ S_B - 68.22$	18.50
10/10/75	30.00	8.55	10.00	9.56	1.01	32.90	$S_B^2 - 1.01\ S_B - 32.90$	11.51
3/10/75	30.00	8.55	7.65	7.31	-1.24	19.253	$S_B 2 \overset{+}{-} 1.24\ S_B - 19.35$	8.86
16/8/75	40.00	11.40	23.30	22.27	10.87	178.61	$S_B^2 - 10.87\ S_B - 178.61$	28.85
17/8/75	54.00	15.39	42.00	40.15	24.76	580.35	$S_B^2 - 24.76\ S_B - 580.75$	54.15

TABLE 3-4 (Cont'd)

$-b+\sqrt{b^2-4ac}$	$-b-\sqrt{b^2-4ac}$	S_B (ppm)	$K = 2.45 \frac{S_A}{S_B} - 2.45$	lnk
24.89	-8.45	12.44	0.041	-3.18
46.09	-15.89	23.04	0.059	-2.83
21.25	-8.11	10.62	0.191	-1.65
28.90	-10.10	14.45	0.076	-2.57
19.25	-7.39	9.62	0.195	-1.63
29.87	-10.31	14.93	0.060	-2.81
28.72	-10.30	14.36	0.109	-2.21
15.69	-7.41	7.84	0.468	-0.75
26.85	-9.95	13.42	0.178	-1.72
12.52	-10.50	6.26	1.463	0.38
7.62	-10.10	3.81	2.470	0.90
39.72	-17.98	19.86	0.431	-0.84
78.91	-29.39	39.46	0.157	-1.85

APPENDIX 4

ANALYSIS OF VARIANCE

The analysis of variance results for the linearized Arrhenius models were obtained by using computer program (Appendix 2). The mean square pure errors were calculated using repeats. F test was applied to check lack of fit for 95% confidence level.

ANOVA NO. 1 (For hydraulic loading of 2.5 l/min) (Zero order kinetics)

Linearized Arrhenius model:

$$\ln K = -\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right) + \ln A_o e^{-E/RT_o}$$

$$\ln K = -7792\left(\frac{1}{T}-\frac{1}{T_o}\right) + 5.35$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total(uncorrected)	330.2041	11		
Mean	323.2488	1		
Total(corrected)	6.9553			
Regression	5.4942	1	5.4942	33.84
Residual	1.4611	9	0.1623	
Pure Error	0.9614	6	0.1603	
Lack of Fit	0.4996	3	0.1663	1.03

$$\frac{\text{Lack of fit}}{\text{Pure Error}} = 1 < 4.75$$

Pure Error Estimates:

$$P_E^2 = \sum_{i=1}^{m} \sum_{=1}^{K} (y_i - \bar{y}_i)^2 = 2x(0.44)^2 + (0.04)^2 x2 + (0.02)^2 x2 + (0.185)^2 x2 + (0.12)^2 + (0.43)^2 + (0.55)^2 = 0.9614$$

where P_E^2 = pure error square,

$\bar{y}_i$ = mean of observations at ith condition,

y_{ij} = yth observation at ith condition,

K = number of observation at each condition, and

m = number of conditions studied.

ANOVA NO. 2 (For hydraulic loading = 4 l/min, zero order kinetics)

Linearized Arrhenius Model:

$$\ln K = -8753 \left(\frac{1}{T} - \frac{1}{T_o}\right) + 5.35$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total (uncorrected)	348.6450	13		
Mean	335.6864	1		
Total (corrected)	12.9586	12		
Regression	9.8983	1	9.8983	35.57
Residual	3.0603	11	0.2782	
Pure Error	2.5544	8	0.3193	
Lack of Fit	0.5059	3	0.1686	0.53

Pure Error Estimate:

$$P_E^2=(0.49)^2+(0.87)^2+(0.13)^2+(0.54)^2+(0.29)^2+(0.74)^2 +(0.55)^2+(0.19)^2+(0.19)^2+(0.43)^2+(0.24)^2 = 2.5544$$

$$\frac{\text{Lack of Fit}}{\text{Pure Error}} = \frac{0.1686}{0.3193} = 0.528 < F_{0.95}\ (3,8) = 4.0662$$

ANOVA NO. 3 (For combined data of 2.5 l/min and 4.0 l/min operation and zero order kinetics)

Linearized Arrhenius Model:

$$\ln K = -8357 \quad (\frac{1}{T} - \frac{1}{T_o}) + 5.34$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F
Total(uncorrected)	678.8491	24		
Mean	658.2490	1		
Total(corrected)	20.6001	23		
Regression	16.0295	1		35.57
Residual	4.5706	22		
Pure Error	1.8717	14	0.1336	
Lack of Fit	2.6989	8	0.3373	2.52

Pure Error Estimate

$$P_{E_c}^2 = \frac{P_{E_{2.5}}^2 \times v_{2.5} + P_{E_{4.0}}^2 \times v_{4.0}}{v_{2.5} + v_{4.0}} = \frac{6 \times 0.96145 + 8 \times 2.5544}{6 + 8}$$

$$= 1.8717$$

where: $P_{E_C}^2$ = Pure error square of combined data

$P_{E_{2.5}}^2$ = Pure error square of data for 2.5 l/min hydraulic loading

$P_{E_{4.0}}^2$ = Pure error square of data for 4.0 l/min hydraulic loading

$v_{2.5}$ = degree of freedom 2.5 l/min hydraulic loading data

$v_{4.0}$ = degree of freedom 4.0 l/min hydraulic loading data

$$\frac{\text{Lack of Fit}}{\text{Pure Error}} = \frac{0.3373}{0.1336} = 2.52 < F_{0.95}\ (8,14) = 2.70$$

Therefore, statistically it is possible to use same kinetic expression for 2.5 l/min and 4.0 l/min hydraulic loading for zero order kinetics assumption.

<u>ANOVA 4</u> Hydraulic loading = 4.0 l/min and first order kinetic assumption

Linearized Arrhenius Model:

$$\ln K = -8063\left(\frac{1}{T} - \frac{1}{T_o}\right) + (-1.34)$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total(uncorrected)	51.5043	13		
Mean	33.1841	1		
Total(corrected)	18.3202	12		
Regression	8.3984	1	8.3984	9.31
Residual	9.9218	11	0.9020	
Pure Error	7.9832	8	0.9979	
Lack of Fit	1.9386	3	0.6462	0.64

<u>Pure Error Estimate:</u>

$$P_E^2 = (0.80)^2+(0.458)^2+(0.72)^2+(0.19)^2+(0.74)^2+(0.88)^2$$
$$+ (0.28)^2+(1.16)^2+(1.49)^2+(0.24)^2+1.25)^2 = 7.9832$$

<u>ANOVA NO.5</u> Hydraulic loading = 2.5 l/min and first order kinetic assumption

Linearized Arrhenius Equation

$$\ln K = -13857\left(\frac{1}{T} - \frac{1}{T_o}\right) - 0.57$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total (uncorrected)	22.9571	11		
Mean	2.2113	1		
Total (corrected)	20.7458	10		
Regression	17.3758	1	17.3758	46.40
Residual	3.3699	9	0.3744	
Pure Error	1.6779	6	0.2796	
Lack of Fit	1.6919	3	0.5639	2.01

Pure Error Estimation:

$$P_E^2 = (0.19)^2 x2 + (0.05)^2 x2 + (0.026)^2 x2 + (0.625)^2 x2 + (0.72)^2 + (0.49)^2 + (0.23)^2 = 1.6779$$

ANOVA NO.6 (For combined data of 2.5 l/min and 4.0 l/min operation hydraulic loading and first order kinetics)

Linearized Arrhenius Equation:

$$\ln K = -11214 \left(\frac{1}{T} - \frac{1}{T_o}\right) - 0.92606$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total (uncorrected)	74.4614	24		
Mean	27.5247	1		
Total (corrected)	46.9367	23		
Regression	28.8633	1	28.8633	35.1342
Residual	18.0734	22	0.8215	
Pure Error	5.2809	14	0.3772	
Lack of Fit	12.7925	8	1.5990	

Pure Error Estimate

$$P_{E_C}^2 = \frac{(7.9832) \times 8 + 1.6779 \times 6}{14} = 5.2809$$

$$\frac{\text{Lack of Fit}}{\text{Pure Error}} = \frac{1.5990}{0.3772} = 4.23 > F_{0.95}(8,14) = 2.70$$