

FLOC BLANKET CLARIFICATION

Investigations in the design, operation and performance evaluation of floc blanket sedimentation as a clarification process in the chemical treatment of water.

A thesis submitted to the University of London in part fulfilment of the Degree of Doctor of Philosophy.

by

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March, 1975

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NOTE

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It is intended, however, that parts of this thesis will be contained in various papers to be published both by The Water Research Centre and the technical press.

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The Medmenham Laboratory of the Water Research Centre, prior to April 1st 1974, was known as The Water Research Association.

SUMMARY

The thesis is concerned with investigations into the design, operation and performance evaluation of floc blanket sedimentation as a clarification process in the chemical treatment of water.

Included in the thesis is an extensive review of previous work on floc blanket sedimentation with attention also given to the literature on other factors which can influence clarification performance.

The principal experimental investigations were made with three tanks of different sizes, 0.3 m diameter, 1.2 m square and 3.5m diameter, operated in parallel. Particular value can be given to the quality of the results because a large quantity of experimental data was used in the statistical analyses, though the results are specific to the water quality encountered and chemical treatment employed in the investigations.

The thesis records the investigations into the effect of raw water quality inlet conditions, vertical baffles and inclined tube modules on blanket behaviour and resultant clarification performance. A qualitative theory of upflow floc blanket clarification has been developed which is found to require modification when applied to shallow layer inclined settling.

Investigations with a hydraulic model of the 1.2 m tank were commenced giving some qualitative results. These results indicated that, with careful choice of a sediment, such a model can be used for examination of floc blanket sedimentation. The model was used to confirm the effect of inclined tube modules on the blanket concentration.

Analyses of the floc blanket sedimentation and clarification data for comparison with other published results showed that improvements could be made to the theories and analyses of the settling of concentrated suspensions and floc blanket clarification. The results were comparable with other published data.

It is considered that the investigations have improved the understanding of the floc blanket clarification process and should lead to greater confidence in the design and efficient use of floc blanket sedimentation.

ACKNOWLEDGEMENTS

The author is grateful to the Director of The Water Research Centre for his permission to utilise his employment at the WRC as the basis of this thesis.

The author is also grateful to his Supervisor, Dr.D.G.Miller, the Treatment Division Manager at the WRC, and to his Director of Studies, Dr.D.N.Sutherland, Lecturer in the Department of Chemical Engineering of Imperial College, for their useful criticisms and encouragement.

The author thanks all members of the staff of the WRC who may have provided assistance in some form or other, particularly of the Treatment Division, and of the Publications, Library, Workshop and Economics sections.

Acknowledgement is also extended to Paterson Candy International Ltd. for providing the WRC with the large diameter tank without which this project might never have been started.

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1. INTRODUCTION

1.1. General

1.1.1. Chemical clarification.

Chemical clarification is often necessary to render a water supply potable and aesthetically acceptable. The principal undesirable impurities removed by such clarification are suspended solids and dissolved coloured organic substances. Chemical clarification involves the processes of coagulation and flocculation, the particulate products of which are removed by one or more suitable solid-liquid separation techniques.

The terms coagulation and flocculation are however occasionally confused. Their precise definitions are dependent upon the particular field of chemistry. The discussion by Palin (1956)* and the definitions by LaMer and Healy (1963), Van Duuren (1969), TeKippe and Ham (1971) and Packham (1972) have been considered so that the terms might be defined suitably for the technology of chemical clarification in municipal water supply.

The term "coagulation" describes the process of the addition of a coagulant under conditions which will lead to the formation of a "floc" consisting of insoluble hydrolysis products of the coagulant together with the impurities. The mechanism of this process is complex. Chemical precipitation is involved in the removal of humic substances while removal of the particulates involves coprecipitation and chemical destabilization. Included in the definition is only that mechanism of floc growth which is brought about by what is termed perikinetic transport whereby particle collisions are effected by diffusion through micro-dimensions. The factors involved in the stages of coagulation control the resultant floc quality.

The term "flocculation" refers to the process of floc growth whereby the products of coagulation are agglomerated under conditions in which particle diffusion is brought about by hydraulic and/or mechanical mixing, otherwise known as orthokinetic flocculation. The resultant size and shape of floc created by this process influences the efficiency of the subsequent

*All references are tabulated in alphabetical order of first author at the end of the thesis.

separation process. Flocculation is thus mostly influenced by the engineering of the process and can be considerably time dependent. However, it is recognized that no distinct boundary between coagulation and flocculation exists.

The controlling factors of coagulation are the selection of the chemical conditions and the efficiency of mixing the coagulant into the water. The mixing should be accomplished within a small fraction of a minute to ensure all undesirable impurities are contacted with the coagulant as it hydrolyses and precipitates. There are reasons to suggest that after the initial mixing additional mixing time of a few minutes is useful to assist perikinetic flocculation, the formation of primary flocs, which results in improved orthokinetic flocculation.

Flocculation besides being time dependent is also greatly influenced by the volumetric concentration of the particles and the velocity gradient of the liquid at the particle surface. In practice the velocity gradient is measured in terms of the energy input to the bulk of the liquid. With high concentrations of particles associated with floc blankets the importance of time and velocity gradient are substantially reduced.

Floc properties, such as size, shape, density and structural strength, cannot be measured easily or accurately. Structural strength governs the size the particles are likely to reach. The process of flocculation involves both floc growth and breakup so that even at equilibrium conditions the flocs will exist as a size range. The theoretical analysis of such floc systems is therefore difficult. In real systems the feed water quality will vary in an indeterminate manner in addition to diurnal and seasonal variations. Such variations can put demands on the chemical management but can also cause changes in the quality of the floc and its potential for removal by the selected separation technique such as sedimentation. For example, Yadav (1970) has reported that at Medmenham there are raw water conditions when the normal floc blanket treatment rates cannot be maintained. His results indicate that the relationship between suspended solids, colour and other parameters can change substantially from that which is normally experienced thereby affecting the floc formation characteristics and physical properties.

1.1.2. Floc blanket sedimentation.

Sedimentation in water treatment can mean settling in horizontal or upward flow. In horizontal flow sedimentation the flocs are allowed to settle to the bottom of the sedimentation tank essentially unhindered by the presence of other flocs. Upward flow sedimentation, which is mostly used in the United Kingdom in potable water treatment, uses the principle of the floc blanket. A floc blanket is a fluidized bed formed by the accumulation of flocs. Sedimentation in a floc blanket therefore occurs under hindered flow conditions. The concentrations of solids in the blanket are not as great as occur in thickening.

A floc blanket tank normally has a hopper-shaped base with a vertical parallel walled upper section. The water which has undergone suitable chemical coagulation is fed downwards into the bottom of the hopper-shaped base. The expanding upward flow allows flocculation to occur and large floc particles to remain in suspension within the tank. The initially slow accumulation of particles improves flocculation until the suspension reaches a maximum concentration related to the floc quality and the upflow velocity of the water. A floc blanket can then be said to exist. Further accumulation of floc causes the volume of the floc blanket to increase which occurs by the upper surface of the blanket rising. The floc blanket surface level is controlled by removing solids from the blanket by a suitable method.

The mechanism of clarification with a floc blanket is complex involving flocculation, entrapment and sedimentation. In practice the contact time with the floc blanket is usually greater than one hour. This is well in excess of the requirements for floc growth to control the efficiency of the process. A process of physical entrapment akin to surface capture in deep bed filtration no doubt occurs through the floc blanket as will a process of mechanical entrapment and straining in that small particles will not be able to pass through the even smaller voids between the larger particles. The efficiency of entrapment is affected by the relative spacing of the suspended particles, which in turn is related to floc quality and water velocity, and the particle size range and distribution. Above and at the surface of the floc blanket sedimentation and elutriation occurs.

The clarification efficiency is therefore ultimately dependent on the rate of elutriation. The rate of elutriation, however, is dependent on the efficiency of entrapment by the floc blanket.

Fig. 1.1. schematically presents the elements of floc blanket clarification.

1.1.3. Floc blanket clarification research.

Because of the unpredictable, uncontrollable and largely undefinable nature of water sources and therefore of flocs, floc blanket clarification is a difficult area of research. Research is therefore likely to be more rewarding along practical and empirical lines than by theoretical approaches.

The objectives of floc blanket clarification are to provide suitable conditions for coagulation and flocculation, to sustain a floc blanket of good and uniform fluid mechanical quality especially at its upper interface, to select conditions likely to cause efficient entrapment of the smaller flocs within the blanket and to minimize entrainment from the tank. These objectives should be pursued with due consideration to the optimal relationship of the sedimentation system with any following process.

Research into floc blanket clarification needs to involve coagulation (particularly those aspects affecting flocculation), flocculation, the hydraulic design of floc blanket tanks and the relationship between the rate of elutriation and floc quality parameters. A necessary biproduct of such research is that not only should methods be developed that are useful in the design of the process but also those which can be used for the day-to-day performance analysis and control of operation. It is therefore necessary, for the water industry, that whenever possible such methods should involve not only simple mathematical expressions but also simple laboratory techniques.

1.2. Tank Design

1.2.1. Types of tank.

The basic requirements of floc blanket clarification are satisfied by the simple upflow design, in which the inlet flow is dispersed uniformly across the inlet plan section and the collection at the outlet is uniform over the

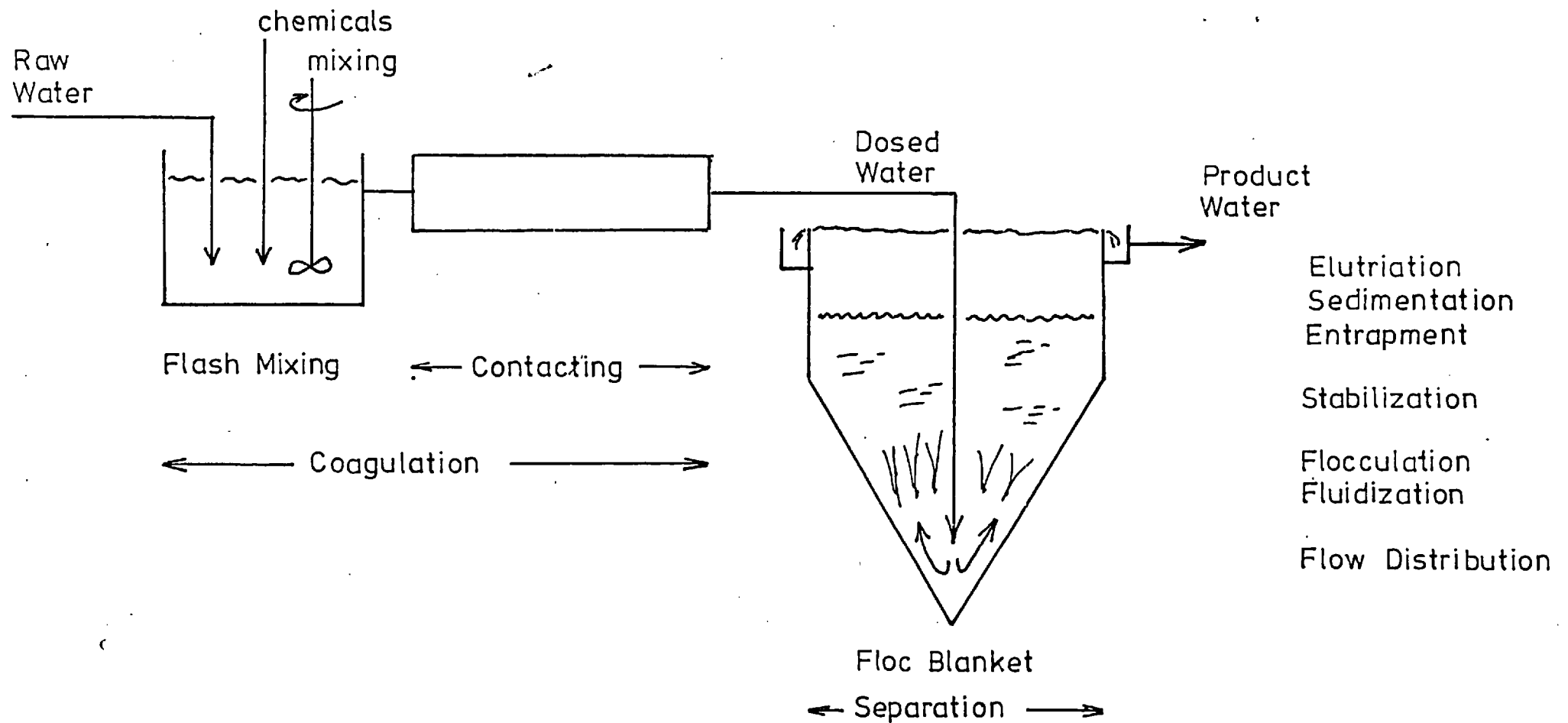


FIG 1.1 ELEMENTS OF FLOC BLANKET CLARIFICATION

outlet plan section. A hopper shape in the base of the tank assists the flow distribution. It has been generally recognised that the square plan hopper tank deteriorates in performance before circular tanks. However, the square plan permits economies in construction.

The ultimate economy in construction occurs with the removal of the hopper section. As advances are made in producing tanks with nominally flat bottoms, multi-hoppered tanks have been conceived and constructed. The problems in their design then become those of efficient multi-inlet flow distribution, the assurance of blanket stability and floc settlement.

It is known that the Russians attempted to use flat-bottom tanks, Mackrle *et al* (1957) and Calise and Homer (1960). Flow distribution was attempted by distribution pipes with downward facing holes under a perforated plate acting as the flat bottom of the blanket zone. Operating experiences were difficult due to blocking of the perforated plate which influenced the flow distribution.

Other flat-bottom tanks are known to exist but it is not known how well they function. Dawson (1970) has reported tanks rated at 1.2 m per h for 2.4 m blankets in 3.6 m deep flat-bottom tanks. Flow distribution is by downward discharge near the bottom of the tanks in a series of 25 mm diameter pipes at 0.9 m centres. The only operational difficulty mentioned was the distribution of sludge solids of varying quality on the tank floor.

Ardern (1964) has reported the construction of multi-hoppered tanks where each tank is built with four hoppers. Webster (1966) has also reported the construction of multi-hoppered tanks but in a 2 by 4 hopper arrangement. Clerke and Reid (1966) have reported the construction of shallow trough-bottom tanks with a pipe distribution system.

Perry and Hale (1972) have designed flat-bottom tanks for the new Burnham Works of the Medway Water Board. The particular interest in this new works is the parallel construction of square and circular hopper tanks along with the flat-bottom tanks for comparison of almost equal upflow area. The results of parallel operation are awaited.

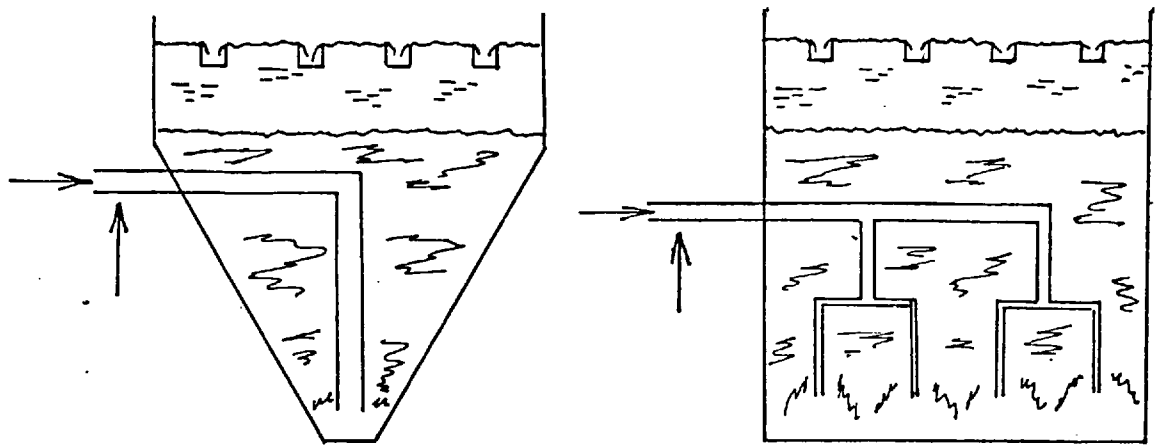
A proprietary design of flat-bottom tank is available known as the Pulsator Flocculator Clarifier, Degremont (1965). Flow distribution is

by horizontal pipes with downward facing jets. These are each covered by a "tranquilizer", (an inverted V-shaped baffle), such that a system of troughs is formed. The flow is pulsed which is said to improve the clarification function of the blanket. Hallquist and Weijman-Hane (1963) have reported the evaluation of a pilot plant but found it difficult to reach a decisive conclusion. Holland (1973) has reported experience with operational plant including the comparison with parallel operated Accentrifloc tanks. It might well be that the function of the pulsations is to maintain good flow distribution and provide suitable scouring of the tank floor.

Other complex designs do exist. Few of these were designed as floc-blanket clarifiers but were conceived as solids contact units, not only for clarification by coagulation, but also for softening and other processes. Barham et al (1956) have made an extensive patent review of clarification, sedimentation and thickening equipment which traces the developments of such equipment. Prager (1950) confined his review specifically to floc-blanket clarifiers. Hartung (1951) has presented a study of eight different designs of solids contact units used in water treatment. Such contact designs can be sub-grouped into premix and premix-recirculation tanks, see Fig. 1.2.

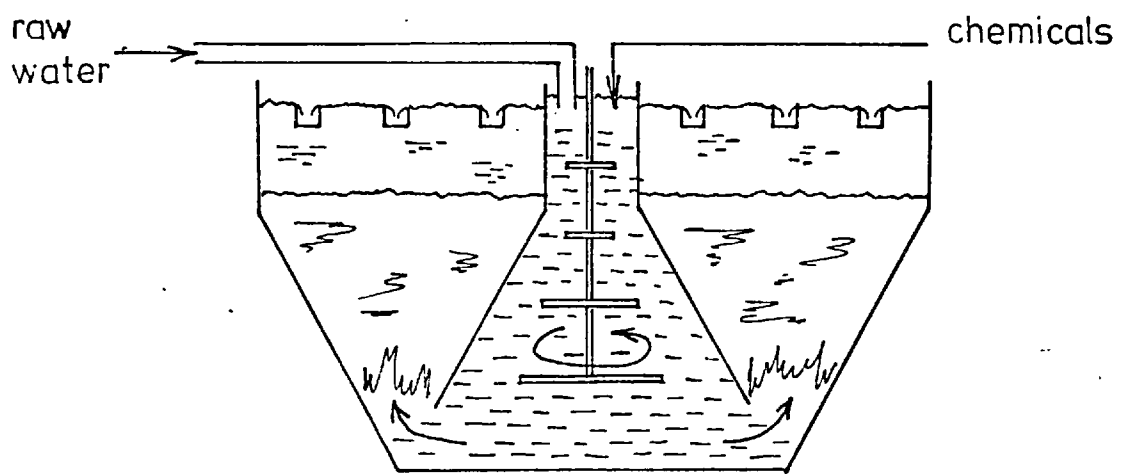
The elements of the simple premix tank consist of a central inlet to a circular tank. The inlet feeds the central part of the tank which is mechanically agitated. The shroud of this premix zone acts as the inner containing wall of the annular, blanket region.

Operational variables sometimes associated with this design of plant are the degree of mechanical agitation, as effected by speed and less easily by the design of the impeller or sludge scraper, and shroud depth. The shroud is often fitted with an adjustable skirt such that the effective inlet velocity to the blanket can be varied. The skirt can not always be used as an operational variable and will be used solely to adjust initially for any discrepancy in construction which might cause poor flow distribution to the annular blanket. The shroud is sometimes constructed so that flow to the blanket is through an upward annular orifice of fixed dimension.

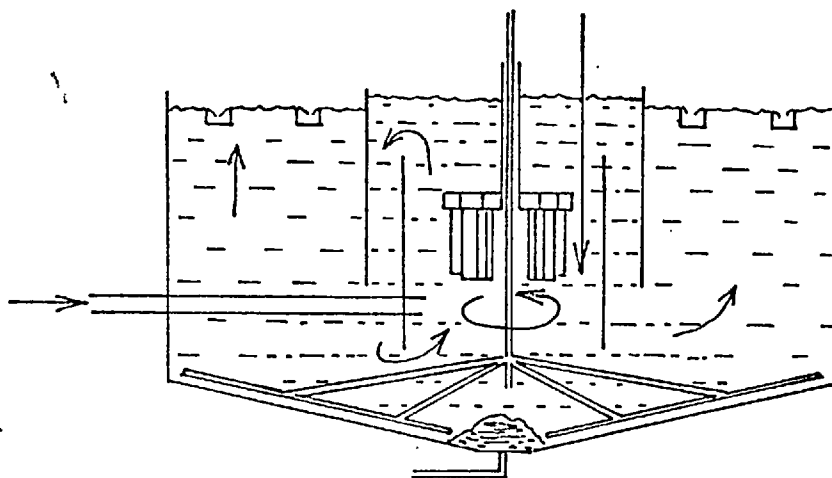


Single hopper

Flat bottom



Premix compartment + blanket



Premix-Recirculation + unhindered settling

FIG 1.2 SOLIDS- CONTACT CLARIFIERS

It might be possible to regard this design as an approach to a flat-bottomed tank, with the central premix zone acting as the flow distributor. It is recognized that too much stirring can cause the agitation to be carried into the blanket with resulting blanket hydraulic instability.

It is usually accepted that this design provides premixing causing improvement in blanket performance due to improved floc quality. As identified from coagulation time investigations, any improvement is more likely to be due to the time component of the mixing between the addition of coagulant and entry to the blanket than due to orthokinetic floc growth. However, no evidence is known to exist which can demonstrate that such a design of tank will operate better, or worse, than a single hopper tank provided with the same coagulation time. The mechanical and operational disadvantages of a simple premix tank must be offset by constructional advantages.

The premix-recirculation design employs the additional concept of recirculation of flocculated material to provide flocculation seeding. This concept can be extended to the accepted principle of concentration benefit to flocculation. The recirculation is achieved by drawing the flow from the premix zone upwards to be distributed downwards under a second shroud. The upward flow pumped from the premix zone must exceed the treatment rate to cause the circulation required. Flow in excess of the treatment rate is drawn under the inner shroud back into the premix zone, to provide the recirculation Fig. 1. 2.

The concept of floc seeding may be valid to this design of tank in lime softening and other precipitation-crystallization processes but there is no known substantial evidence to support this in simple coagulation-flocculation. The concentration effect on flocculation is unlikely to be used to full advantage, especially in fluctuating load plants other than when frequent shut down occurs, because of the need to adjust the recirculation to suit. Further, the contact provided by the blanket is likely to be much greater than that due to the premixing of recirculated solids. It is conceivable that recirculation of solids causes physical degeneration of the floc structure. This, although providing weighting and improved quality of the resultant floc, can create an additional coagulant requirement for its recoagulation.

It is also conceivable that the recirculation can cause other difficulties in the control of coagulation e.g. the use of polyelectrolytes.

A premix-recirculation tank cannot be considered as a floc blanket tank unless the recirculation shroud continues low enough into the tank so that an effective blanket can be maintained easily above the lower rim of the shroud.

1.2.2. Common design features.

In the upflow hopper design the coagulation chemicals are added to the feed channel. In the premix-type tank the chemicals are added to the premix zone and hence also before entry of the feed to the floc blanket. The principal difference is that the flow condition in the feed channel to the hopper tank is primarily plug flow whereas the coagulation time in the premix tank is well-mixed, together with recycle in the recirculation design.

In practice premix tanks are constructed with greater diameters than hopper tanks. Flow distribution to the extensive peripheral upflow annulus of the premix tank from a single inlet is dependent on the levelling of the skirt and the quality of the mixing in the premix zone. In the hopper tank flow distribution is achieved by flow diffusion effected by the flow reversal in the apex of the hopper, by the expanding flow conditions of the hopper and the unstable density interface supporting the blanket. The effectiveness of flow distribution is thus dependent on the relative dimensions of the inlet pipe to the hopper, the velocity of flow into the apex, the accuracy of the coincidence of the axes of the inlet and the hopper (both horizontal and vertical displacement), the contained angle of the hopper and the blanket solids concentration.

By installing a simple device, premix and recirculation conditions similar to contact-type tanks can be provided in hopper tanks. In premix-type tanks such conditions are created mechanically; in hopper tanks they are created hydraulically. Premixing is provided by fitting a large diameter inlet pipe suitably fitted with a tangentially located feed nozzle, orifice plates and longitudinal baffles, Fig. 1.3. The fluid-mechanical quality of the flow approaching the blanket can be controlled by varying the

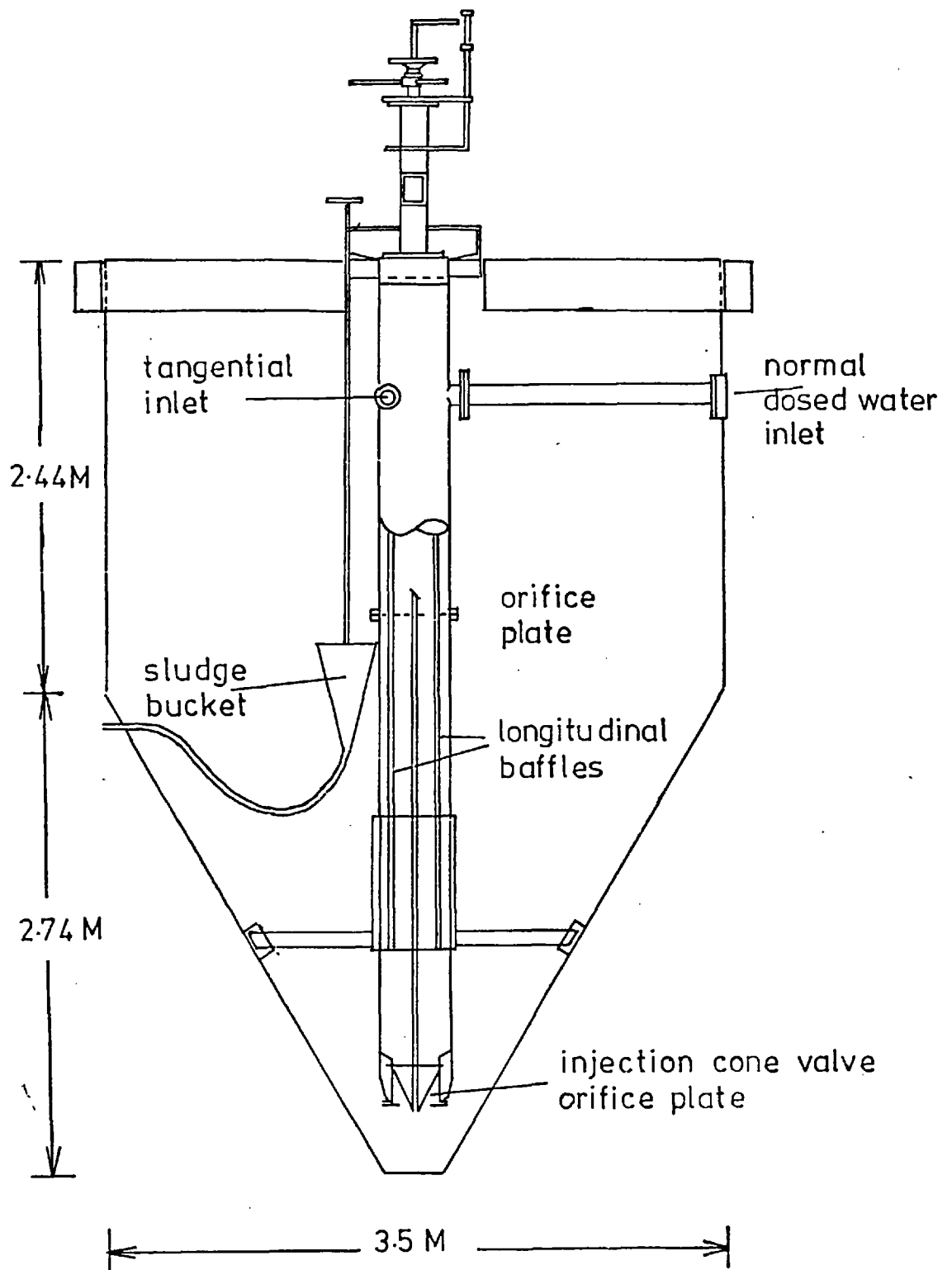


FIG 1.3
2.4

3.5 M DIAMETER TANK FITTED WITH THE HIGH
SHEAR — HIGH VELOCITY DEVICE

inlet flow velocity . This is achieved by using a cone valve as the inlet orifice. Recirculation from the blanket to the feed is achieved by fitting a venturi device in the axially placed feed pipe, Fig. 1.4. The entraining velocity through the venturi is also controlled by a cone valve.

In premix-type tanks designed for floc blanket operation the walls of the annular upflow zone are usually constructed for expanding upward flow similar to the hopper tank.

It is the usual practice to construct the retaining walls of the upward diffusing flow at about 60° to the horizontal. It is claimed that this angle is required to prevent sludge settling. Hansen and Culp (1967) in their development of tube settling found that the self-cleaning action of the tubes was enhanced as the angle was increased to 60° . A similar observation has been reported by Weijman-Hane and Hallquist (1963) for lamella sedimentation. However, circular tanks are sometimes constructed with a 45° angle since there is no problem of sludge hanging in corners as with square-plan tanks. Aitken (1945) has commented that the total depth of a tank is limited by excavation difficulties, while the tank-side slope cannot be reduced much below 1.75: 1 if true vertical flow is to be simulated. The angle of approximately 63° for a circular tank represents the special case of the diameter equalling the depth of the hopper. The slope of the hopper walls is chosen primarily on a basis of construction cost and self-cleaning action of sludge than for flow distribution requirements.

Floc blanket level is controlled by a means of removing floc from the blanket. The most effective method is by including one or more small hoppers within the structure of the tank so that the rim of the small hopper acts as an overflow weir at the required level. In upflow hopper tanks such small hoppers usually take the form of either corner pockets, in square plan tanks, or of suspended "buckets". The benefit of buckets is that their level can be adjusted. In premix tanks pockets can be constructed as sections of the upflow annulus. Level control hoppers to be successful need to be of adequate overflow area. The necessary area can be estimated simply by a mass balance. The additional value of level control hoppers is that if their capacities are suitable, determined by their depth, only a

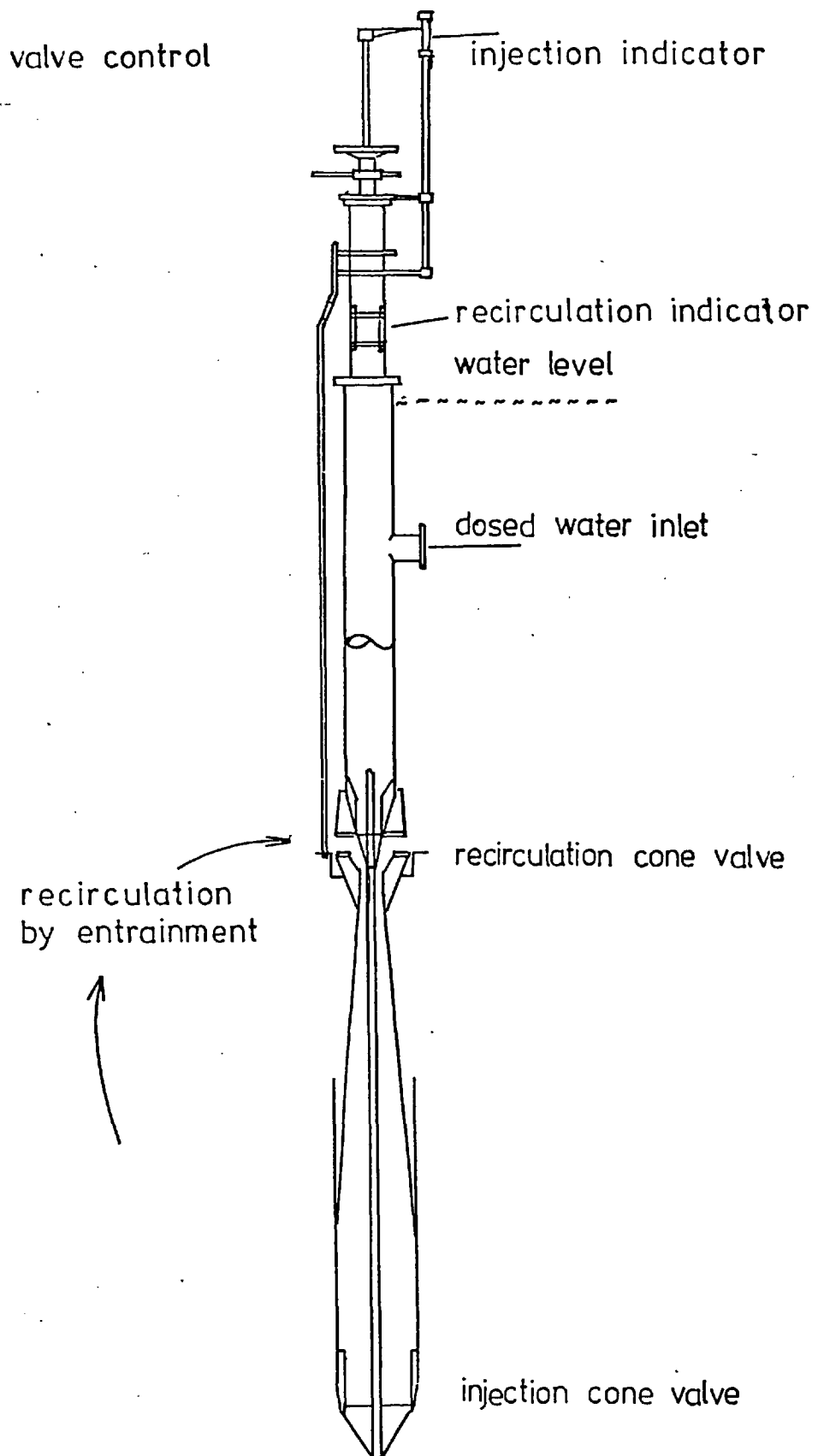


FIG 1.4 THE VARIABLE INJECTION VELOCITY AND
2.3 RECIRCULATION RATE DEVICE

low frequency of desludging will be necessary resulting in a preliminary thickening of the excess floc from the blanket.

The final feature of design is the clarified flow offtake. An adequate depth of flow is necessary between the upper surface of the floc blanket and the overflow channels. This is to allow entrained particles in uneven flow distribution to return to the blanket and to prevent the flow profile to the overflow channels from influencing the entrainment. Circular tanks are fitted with radial and peripheral overflow channels and square tanks with parallel channels. The important features of overflow channels are their spacing, levelling and notching of their rims, all to ensure even draw-off from the whole surface area.

1.3. Factors Affecting Performance

1.3.1. Chemical factors.

The process of chemical coagulation still lacks empirical and practical knowledge. Various attempts have, however, been made to establish the dependence of the coagulant dose on the quality of the raw water for control purposes: Hudson (1965), Lewis (1968), Rojanschi and Rameder (1971) and Elenin et al (1972). Jeffery (1971) has suggested that it ought to be possible to control coagulant dosing automatically from settled water turbidity in floc-blanket clarification. The application of these approaches remain to be verified for all sources of water and their clarification processes.

Coagulation investigations are usually made using "jar-test"* studies. Miller et al (1965) have demonstrated the validity of the jar-test for support in the operation of clarification systems. However, whereas the results

*A "jar-test" is a laboratory bench test. Fractions from a large sample of the water to be tested are contained in a series of large beakers. With these fractions parallel examination can be made of coagulant dose, coagulant aid dose and different pH on the quality of coagulation. The number of beakers is limited by the facility for parallel simultaneous stirring. Two speeds of stirring are usually preferred. A high speed is needed for the mixing-in of the primary coagulant and a slow speed for flocculation. After adequate stirring the flocs formed are allowed to settle for a standard time and the quality of the supernatant is examined and related to the chemical treatment.

for colour removal are reproduced in both the jar-test and the pilot plant units, turbidity figures do not match since the fluid conditions are not equivalent.

The effect of pH on the coagulation of dilute mineral suspensions with aluminium sulphate has been demonstrated by Packham (1960a, 1960b, 1965). The conclusions were that the amounts of coagulant required to coagulate the mineral suspensions was clearly affected by the pH, due to its effect on the insolubility of the hydrolysis products and that the results obtained were largely independent of the nature of the material in suspension.

The coagulation of organic colour has been examined by Hall and Packham (1965). They showed that humic acid can be removed more thoroughly than fulvic acid, and that within each class of substance, there are some fractions which can be removed more easily than the remainder.

There is an optimum pH for coagulation, the value of which depends on the nature of the suspended solids and dissolved organic substances present and on their relative proportions. Other chemical factors will also affect coagulation to some degree, for example Elenin et al (1972) included alkalinity in their analyses.

McCarty et al (1966) have reviewed the influence of inorganic phosphates on coagulation. In general the presence of pyrophosphate ($P_2O_7^{-4}$) or triphosphate ($P_3O_{10}^{-5}$) salts has been shown to interfere with the efficiency of the coagulation-flocculation-sedimentation process. McCarty noted that for the various studies many of the physical and chemical variables affecting the contribution of phosphates to the coagulation process were not adequately controlled or defined, thus a concise demonstration of the inter-relationships has yet to be produced. Sadhukhan and Kaymahashay (1972) in an evaluation of phosphate removal by alum coagulation produced results similar to previously published data, namely, there is an optimum pH and an optimum coagulant to phosphate ratio for phosphate removal. They also showed that suspended solids did not interfere with the phosphate removal whereas biodegradable organic matter did interfere.

The commercial choice of primary coagulant is normally limited to aluminium sulphate, ferric sulphate and chlorinated ferrous sulphate and is dependent on availability, cost and raw water quality. There is no known

comprehensive statement of which coagulant might be preferred. The choice will often depend on raw water quality since iron and aluminium hydroxides have different optimum pH ranges for maximum precipitation.

Zeta potential has been suggested frequently as a method of examining coagulation efficiency. Zeta potential is calculated from the electrophoretic mobility of particles in an applied electrical field. However, Mohtadi and Rao (1973) have shown that there is only some correlation between zeta potential and flocculation. Although charge neutralization is an important factor in coagulation, the extent of charge neutralization required for effective coagulation depends on the nature of the clay, the type of coagulant and the conditions of coagulation and flocculation.

1.3.2. Floc quality.

The exact dependence of floc properties on the choice of coagulant and raw water quality has yet to be established. These factors control what might be simply called "floc quality", or "floc character", a rather ill defined and vague term denoting the potential processing characteristics of the suspension, sometimes called the "treatability" of the suspension.

Experience indicates that waters with high solids contents will flocculate quickly forming large granular-looking flocs. Highly coloured waters require a substantially greater flocculation time forming less dense and structurally weaker flocs which are smaller and woolly-looking. The presence of solids is almost certain to improve the density of the floc by weighting them. Floc quality as applied to sedimentation describes the ability of the coagulation products to produce a suspension of the best settling characteristics. The principal floc parameters involved are particle size, shape, density and structural strength.

The floc quality within the sedimentation system will depend on the flocculation conditions up to and including that stage. Pretreatment must therefore endeavour to prepare flocs which are suitable for removal. Floc properties are unlikely to be homogeneous at any one time nor consistent with time. A sedimentation system must be able to deal with a spectrum of floc characteristics. A tank will, however, be selective in removing flocs which are suitable for removal under the conditions of operation.

The terms "weak" and "strong" floc which are commonly used represent the suitability of floc for removal under given conditions.

Chemical clarification can be improved by using suitable aids for coagulation and flocculation. Such aids might be weighting or floc bonding agents, polyelectrolytes, which help to form heavier and bigger flocs.

1.3.3. Temperature.

The influence of temperature as a quality variable of the feed water is still queried. Annual variation in temperature is to a great extent synonymous with the general quality of feed water. The influence of temperature on sedimentation rates in real systems will therefore be difficult to identify.

Rao (1968) has reviewed the effect of physical factors on the coagulation of water. Rao concluded that various physical factors including temperature affect the coagulation process to a great extent. His review indicates that clarification is hindered by low temperatures affecting both the settling rate and the coagulation reactions.

Webster (1966) has reported effects of temperature on coagulation and the application of activated silica as a coagulant aid. Rao and Sastry (1972) have shown that large changes in temperature can substantially affect coagulation reactions. Mohtadi and Rao (1973) have since shown that:

- (i) Temperature has no significant effect on the zeta potential of a clay particle dispersed in water.
- (ii) The optimum pH for a given degree of flocculation varies with temperature when alum is used. However, when flocculation is carried out at optimum pH conditions temperature has no effect.

Bond (1959, 1965) has examined the influence of temperature on the behaviour of floc suspensions. He showed that in the case of hindered settling the settling velocity of individual particles increases (usually linearly) with increase in temperature. However, in the case of plant experiments, the effects of other variables was so great that the dependence of particle settling velocity on temperature could only be demonstrated to a limited extent.

Hunter (1971) has observed that winter and summer conditions required different blanket concentrations to maintain the same performance. Although raw water analyses show differences which could account for some of this, it is suggested that the change in water temperature of the order of 15°C is largely responsible.

It is well accepted that temperature, via liquid density differences, can influence the efficiency of horizontal sedimentation. Hudson (1972) has considered this effect of temperature. He estimated that for normal blanket concentrations density variations equivalent to temperature changes up to about 2°C will have insignificant effects. Little (1967) and CDTRA (1970) have observed that vertical flow tanks appear particularly sensitive to density changes. The smallest density change that could give rise to vertical currents was found to be 2 g per litre. Such a change could arise from temperature fluctuations of about 1.5°C or from concentration differences. It is presumed that these observations were not made on flocc-blanket systems. Degremont (1965) have commented that a raw water change of 1°C per hour is sufficient to reduce the efficiency of a clarifier and that a salinity variation of 1 g per litre per hour has the same effect. One might suspect that with the type of turbulent motion associated with fluidized systems, density differences may need to be more severe to be of similar effect when occurring through a blanket. Density effects will be related to the density gradients throughout the vessel which will be limited by the dimensions of the vessel and the flow rate through the vessel.

1.3.4. Hydraulic factors.

Ever since the blanket principle has been commonly applied it has been recognized that results obtained from small scale plant are not necessarily representative of a full scale system. It has always been appreciated that the basic difference lies in the greater hydraulic sensitivity of the larger system. However, the causes of the sensitivity and its mechanics do not appear to have been fully appreciated. All that is well known is the manner in which the sensitivity manifests itself in the phenomenon of "boiling" as is visually witnessed. This is the appearance at the surface of the blanket of water of excessive upflow velocity. Boiling describes the rolling

cloud-like distribution of the floc carried out of the blanket by such poor flow conditions.

The existence of flow that causes boiling is related to the efficiency of flow reversal and distribution which are governed primarily by the geometry of the flow conditions. The weight of the solids in the floc blanket will also assist flow distribution.

Only Hale (1971) has provided some practical information of the hydraulic stability of large scale floc-blanket clarifiers. Hale demonstrated that the treatment rate of hopper-bottom tanks could be limited due to a circulation motion of the blanket. As a result of investigating the circulation mechanism of a particular tank with the aid of a hydraulic model Hale decreased the effect and thereby increased the treatment capacity of the tank. The investigations of Hale were similar to those of Burdych (1964). Burdych, however, did not use suspensions in his tanks although his conclusions were similar. Bond (1965) examined the solids concentration distribution in floc-blankets and produced a series of iso-concentration maps for different treatment rates. It is possible to assume a circulation mechanism, of the type observed by Burdych and Hale, compatible with the concentration profiles.

Ives (1968) as a result of a quantitative examination of floc-blanket clarification identified as the principal requirement that the flow across any horizontal layer of the clarifier should be uniform. Consequently the clarifier must be symmetrical and there should be no obstructions to the clear plan by pockets or concentrators.

Burdych (1964) as part of his investigations made an extensive theoretical analysis of the flow patterns in hopper tanks. His analysis did not allow for the presence of a suspension and assumed the inflowing liquid to have the same density as the liquid in the bulk of the tank. Hale also in his model tests did not employ a suspension. Gould (1969) has, however, indicated the possibility of using model suspensions in the hydraulic modelling of sedimentation.

Tesarik (1967) has given some theoretical consideration to the expanding inlet flow zone. Theoretical development of the flow pattern is difficult, even for plane flow of a viscous fluid in the diffuser. Tesarik

noted that a dimensionless criterion analogous to the Reynolds number could enable one to distinguish the flow regime.

The investigations of Burdych (1964) and Hale (1971) demonstrated that the inlet flow conditions were at fault. Tesarik (1967) noted that the flow entering the diffuser-shaped floc-blanket zone is turbulent. Turbulent flow will have vortices separating from it. The separated vortex flows upward in the flow direction and dissolves due to the viscosity of the fluid, but may still reach the upper level of the blanket. However, Tesarik does not appear to have taken this mechanism too seriously since he suggested that the perturbations of the vortices breaking through the top of the blanket draw only a few floc from the surface layer. Further explanation of the insignificance of this phenomenon was that the concentration in the eruptions is less than that of the blanket. Larson (1968), however, has suggested that this mechanism should be regarded more seriously. In fact both writers provided some evidence that the eruptions can be of significant dimensions.

Ives (1968) has ascribed to this phenomenon the concepts of submerged jets or diffuser flow. He was primarily considering the mechanism by which the inlet velocity energy is dissipated. Ives suggested that the inlet velocity energy is lost in a fairly localized volume of water in some small interval of time, or the energy persists in a submerged or diffuser flow. Ives further describes the nature of the flow in the bottom of the tank as including boundary separation, streaming and recirculation patterns.

Gould (1967a, 1967b) has suggested that density effects are the main cause of the problems at limiting flow, the onset of blanket instability associated with boiling, whereby density differences between the feed and settling sludge streams influence the flow distribution. Gould proposed that by adding the correct quantity of concentrated sludge to the incoming water, the resulting suspension can be made to have the same density as that of the suspension in the blanket. Gould has described how a form of sludge recirculation, devised in model experiments, may be obtained by placing baffles near the inlet pipe.

Bond (1965) has considered sludge recirculation in another context. The concentration of a suspension is dependent on the relative velocity

difference between the suspension and the supporting fluid. Thus, if the suspension is encouraged to move upward by the introduction of particles at its base the upflow rate of the supporting fluid can be equivalently increased. This can be achieved by recirculating fresh sludge from the concentrator back to the dosing point. Bond emphasised that the recirculation of solids is to impart an increased upward velocity to the blanket particles and not for the purpose of providing fresh nuclei to assist coagulation.

1.4. Previous Investigations

1.4.1. General.

Miller et al (1965, 1966), Miller and West (1966) and Yadav (1970) have made extensive investigations into floc-blanket clarification. They showed the qualitative effects on clarification of changing certain variables. They showed that clarification deteriorated with increase in upward flow velocity and reduction of supernatant depth and that clarification improved, with diminishing return, with increase in blanket depth and increase in polyelectrolyte dose. Others have shown similar results but were usually more concerned in putting some quantitative analysis to the process.

Similar qualitative analyses have been made by Ullman (1970) on non-blanket type clarifiers on paper mill effluents and by Ulmgren and Andersson (1972) on sewage. In these two applications feed quality to the clarifier can be held relatively constant. These two investigations found decisive break-points in the dependence of product quality on treatment rate. Such transitions have not been demonstrated with floc-blanket clarification. Vostrcil (1971), however, noted that by decreasing treatment rate to increase the blanket solids concentration there is a value of concentration beyond which it is not worth increasing the concentration to obtain further improvement in clarification.

1.4.2. Coagulation.

Miller and West (1968) have provided some comparison between using aluminium sulphate and ferric chloride as coagulants. They showed that ferric chloride coagulation was less dependent on pH than aluminium sulphate. They also showed that there was a noticeable difference between

the performances of the iron and aluminium floc blankets for changes in the coagulant dose. This behaviour contrasted with the similarity of the results for the two coagulants in the effects of changing blanket depth and upflow velocity.

Yadav (1970) and Vostrecil (1971) have examined the effect of different polyelectrolytes and of varying polyelectrolyte dose on floc blanket performance. They and Farnsworth and Dick (1972) showed that there is a limit to improvement in floc quality as polyelectrolyte dose is increased. Data are available (WRA unpublished) which can be used to demonstrate that, for a constant raw water quality, coagulant dose and treatment rate, a given polyelectrolyte only differs from the effect of another on blanket density and product quality in its relative effectiveness in improving floc properties. The ultimate effects of different polyelectrolytes in sedimentation are the same, Fig. 1.5. (in which the upper figure affirms the comparability of the data): a limiting return on improved clarification with increasing blanket concentration.

The inclusion of delay time between the addition of coagulant and entry into the floc-blanket has been shown by Miller and West (1968) to have significant effect on clarification efficiency. There is a limiting return on improved clarification with increase in delay time. Rott (1969) has also shown improvements in clarification are possible by suitable mixing and delay time conditions. The gain could not be ascribed by Miller and West to improvement in the initial mixing of the coagulant but they could show it to be dependent on the type of flow conditions as shown by residence time distribution measurement, during the delay time of a few minutes. A far greater delay exists within a floc blanket, so why the difference? It can only be assumed that improved primary floc formation, perikinetic flocculation, prior to orthokinetic flocculation (floc growth in the blanket), caused the improvement.

1.4.3. Hydraulic.

There has not been much practical analysis of the hydraulic behaviour of floc blanket sedimentation reported in addition to the investigations mentioned in Sect. 1.3.4. Hirsch (1969) and Hale (1971) have reported residence time distribution analysis results for full scale plant.

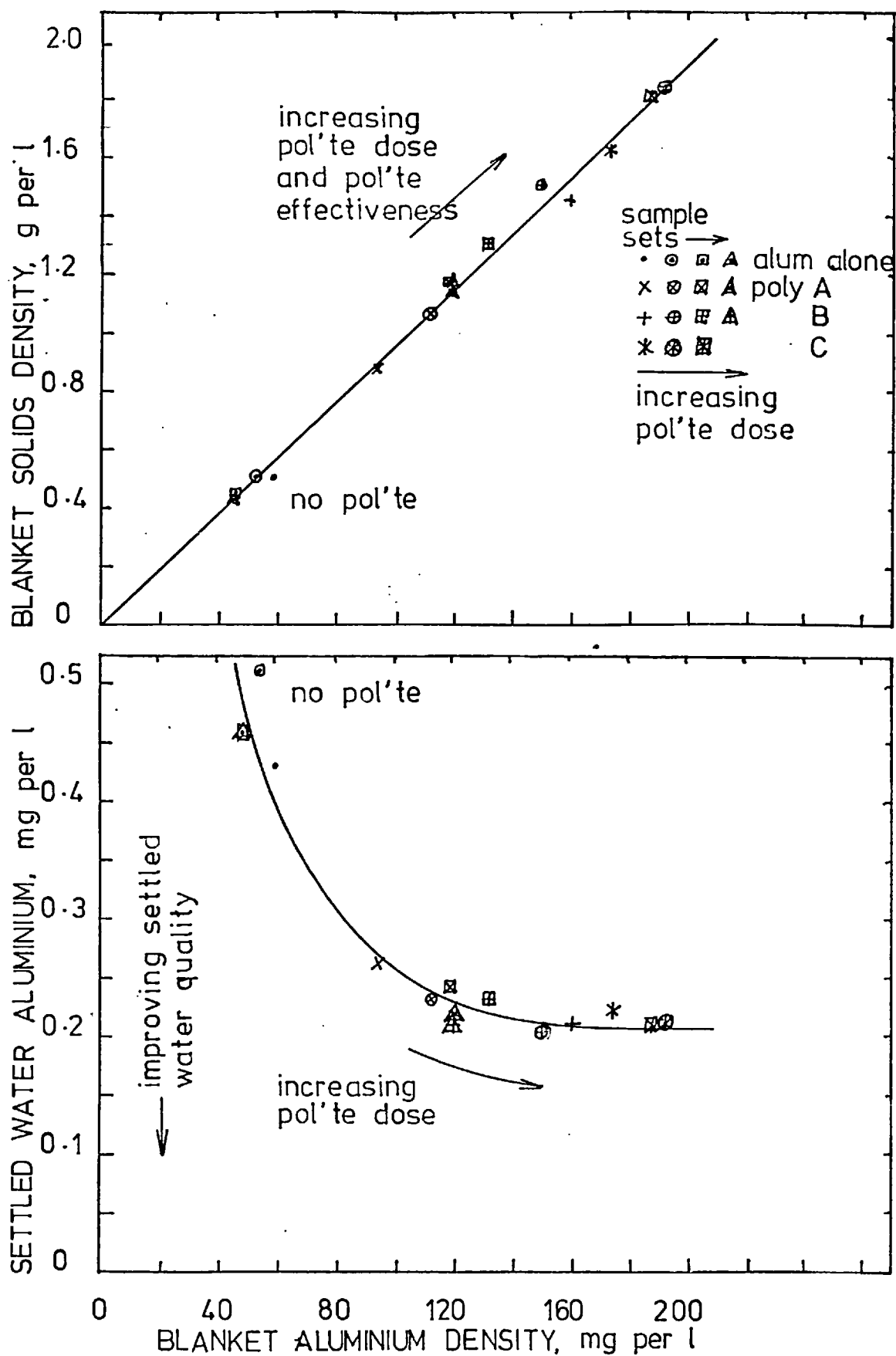


FIG 1.5 EFFECT OF POLY'TE ON BLANKET DENSITY AND ON SETTLED WATER QUALITY

Residence time distribution is an established technique, viz Naor and Shinnar (1963), Wolf and Resnick (1963), Dawkins (1963), Levenspiel (1966) and Murrill et al (1968).

In many of the early references, as well as a number of the more recent ones, values and ratios of the prominent time values and distributions of the residence time distribution curves have been employed. To the most part they only represent the first steps in the statistical analysis of the distribution curves. Both Hirsch (1969) and Hale (1971) were guilty of using such techniques in attempts to provide definitive analyses of distribution data.

Hale (1971) used residence time distribution analysis to show the existence of bulk circulation patterns in a particular square hopper-bottomed floc blanket tank. Hale examined the possibility of using various horizontal baffle devices to modify the flow but eventually devised a frusto-conical baffle which, when attached to the inlet, assisted the immediate inlet flow distribution.

The general applications of baffles to fluidized bed engineering have been reviewed by Harrison and Grace (1971) for gas-solid systems. However, vertical baffle systems can be seen to act in a number of ways. In gas fluidization the baffles limit bubble growth. A closely spaced baffle system is likely to have a significant pressure drop and thereby act as a flow distributor. A strategically designed system can control flow circulation patterns. Evenly distributed large vertical surfaces will reduce the mean hydraulic diameter within the containing vessel thereby reducing the hydraulic scale factor.

All these mechanisms contribute to the hydraulic and hydrodynamic stabilities of a fluidized system which are of substantial importance for floc suspensions.

When a deep vertical system becomes closely spaced enough to be identified as either a lamella complex or a matrix of tubes, such systems have been shown to contribute to the settling process when the surfaces are inclined. This is known as shallow layer inclined settling. Reconsideration of simple sedimentation theory has also led to the development of inclined shallow layer settling techniques e.g. Hansen and Culp (1967) and Dunkers

and Forsell (1971). Of the various results so far reported none are on the specific application to floc-blanket clarification. The principal theoretical work published so far for settling of concentrated suspensions between inclined plates refers to batch settling and not to continuous, constant level conditions as in floc-blanket clarification.

Both moderately spaced vertical deep baffles and inclined tube settling have been investigated during this project. At the time of commencing their evaluation it was not believed that it would be entirely relevant to the principal investigation. However, it later became apparent as the project progressed that their value and effects in floc-blanket sedimentation were entirely relevant.

1.4.4. Flocculation.

Harris et al (1966) showed that for a continuous stirred-tank reactor the flocculation rate expressed as the change in number of primary floc particles could be given by:

$$\frac{n_o}{n} = (1 + KGct) \quad \dots\dots\dots 1.1$$

where

n_o , n number concentration of primary particles before flocculation and after flocculation,

K flocculation constant depending on the nature and size of the suspension,

c floc volumetric concentration,

t flocculation time, sec,

G velocity gradient, sec^{-1} , which can be calculated from:

$$G = \sqrt{\frac{P}{V\mu}} \text{ sec}^{-1} \quad \dots\dots\dots 1.2$$

where

P total mechanical power applied, Nm/sec,

V total volume of fluid, m^3 ,

μ viscosity, Ns/m^2 .

The term Gt is sometimes referred to as the Camp Number, Ca .

Argaman and Kaufman (1970) developed the relationship further to distinguish between the contributions to the flocculation by the processes of

aggregation and break-up and experimentally demonstrated the viability of their new relationship.

$$\frac{n_o}{n} = \frac{1 + K_A Gt}{1 + K_B G^2 t} \quad \dots\dots\dots 1.3$$

where K_A and K_B , sec, are respectively the general aggregation and break-up constants. Their values are dependent on the floc quality and concentration and on the hydromechanical conditions of the suspension. Argaman and Kaufman have shown the order of magnitude of these constants for dilute suspensions in mechanical flocculators. Examination of the flocculation equation 1.3 indicates that flocculation time for a floc blanket should be no greater than for a flocculator for primary floc particle removal.

For ideal floc settling the settled water quality will only represent those primary particles not removed by flocculation. However, the settled water quality in practice is also related to floc growth and size distribution within the blanket. The value of the flocculation equation is limited to only indicating the time necessary to minimize the primary particle concentration.

A general conclusion from not only Harris et al (1966) but also TeKippe and Ham (1971) is that a tapered-velocity-gradient path results in the greatest removal of turbidity. If this is so even for concentrated suspensions it might be hoped that hopper tanks provide a similar benefit with their tapering upflow velocity.

Ives (1968) has shown how tapered-velocity flocculation might be used in the design of floc-blanket clarification. His method is to calculate the rate of floc growth and to produce flocs large enough to settle. The calculations determine the choice of upflow velocity and blanket depth. The calculations require certain physical data and assume that horizontal isometric velocity fronts exist across the blanket. The evidence of Bond (1965), Burdych (1964) and Hale (1971) on blanket circulation discourages the acceptance of isometric velocity fronts. The floc growth rate also assumes the existence of monosized flocs at each velocity level and not a size distribution as in practice. This leads to the assumption that there

is total floc removal across the upper surface of the blanket. It is the size distribution in fact that determines the settled water quality.

Cretu (1968, 1972) has proposed a method to design and analyse the operation of floc blankets that assumes that clarification is a transfer of coagulated material to the floc blanket. The development of his equations for tapered and parallel flow also assume isometric velocity fronts. For parallel flow:

$$C = C_o \cdot \exp \left(\frac{-b C_s \cdot z}{U} \right) \dots\dots\dots 1.4$$

where

- C concentration of unflocculated coagulant at level
z, mg/litre,
- C_o concentration of coagulant before entry to the blanket,
mg/litre,
- C_s concentration of solids in the blanket, mg/litre,
- z depth of blanket, m,
- U upflow velocity, m/hr,
- b absorption coefficient, m³/kg.hr. $\left[\approx 3.6 \text{ cm}^3/\text{g.s} \right] \text{ cm}^3/\text{g.s.}$

Cretu has found values of b of 0.55 for parallel flow and 0.83 for expanding flow. However, coagulation, flocculation, sedimentation, entrainment and hydraulic flow conditions all contribute to the value of b and for accuracy will therefore need determination for each design and application.

Vostrcil (1971) has demonstrated with pilot plant data the contribution of flocculation to floc blanket performance in terms of a modified Camp Number, C_a, derived from the headloss through the blanket, for the calculation of power dissipation.

$$C_a = \left[\left[\rho_s - \rho \right] \cdot L \cdot \frac{g}{\mu} \cdot t \right]^{\frac{1}{2}} \dots\dots\dots 1.5$$

where

- ρ_s mass density of the floc blanket, kg/m³,
- ρ density of solids free liquid, kg/m³,
- L depth of blanket, m,
- g gravitational constant, m/sec²,
- t time of passage through blanket, sec.

Vostrcil showed that clarification improved with increasing value of C_a , but that for a given system there was marginal improvement in clarification above a certain value of C_a . This value was not substantially affected by the use of polyelectrolytes. This suggests that clarification is floc volume concentration dependent.

As with complete flocculation analysis the Camp Number only indicates potential clarification by the process. The efficiency of the floc-water separation still has to be predicted. The type of clarification improvement response found by Vostrcil to increase in flocculation conditions was similar to that found by Miller et al (1965) for increase in blanket depth and injection velocity. Miller et al found such clarification improvement was the more substantial at high upflow velocities. Unfortunately they did not examine the quality of the blanket.

1.4.5. Velocity-concentration analysis.

Much has been published about the theory and practice of settling and thickening and of the maintenance of suspensions in upflow. The results published include suspensions of regular shape and uniform size distribution to suspensions of flocs or precipitates. Miller (1962) has reviewed the theory of the settling of suspensions. Some of the principal contributions to the theory have been by Steinour (1944a, b, c), Rouse (1941), Bond (1959) and Richardson et al (1954, 1960, 1961a, 1961b). Brown and La Motta (1972) have summarized the various expressions that have been developed for the analysis of the settling of suspensions. Barnea and Mizrahi (1973) have made a critical review of correlations for fluidization and sedimentation in solid multiparticle systems. As a result of their review they proposed a general correlation which was developed to unify and organize all the available published experimental data.

The general correlation proposed by Barnea and Mizrahi is dependent on the calculation of suitably modified Reynolds Number and drag coefficient. However, for non-rigid irregular-shaped floc particles only the order of magnitude of these Numbers can be determined. If accurate knowledge of velocity-concentration data is required pilot plant operation will be necessary. However, velocity-concentration data as such does not

predict clarification efficiency, though this will be established from pilot plant operation.

Barnea and Mizrahi (1973) subdivided the published correlations into theoretical, semi-theoretical and empirical derivations. The writer proposes that the theoretical derivations in the majority have the form:

$$\frac{U}{U_o} = \frac{1 - c}{1 + q_1 \cdot c}^{1/3} \dots\dots\dots 1.6$$

where

- U is the actual superficial upflow velocity, m/hr,
- U_o is the terminal velocity of a single particle, m/hr,
- q_1 is a numerical constant.

This expression is developed by considering the flow between a convenient spatial organization of the particles.

The semi-theoretical approaches are based on analogies with related fields. The principal analogy is for the "apparent" viscosity of the suspension as a function of the solids volume fraction:

$$\frac{\mu_s}{\mu_f} = F(c) \dots\dots\dots 1.7$$

where

- μ_s is the viscosity of the suspension, N.sec/m²,
- μ_f is the viscosity of the supporting liquid, N.sec/m²,
- $F(c)$ is the function of c , which can be expressed in terms of either or both binomial and exponential functions.

In the analysis of the viscosity of suspensions Landel et al (1965) (Govier and Aziz (1972)), viscosity-concentration correlations have been particularly successful using the relative viscosity and the relative concentrations, the ratio of the volumetric concentration, c , to the maximum obtainable volumetric concentration, c_m . Landel et al obtained the empirical relationship:

$$\frac{\mu_s}{\mu} = (1 - \frac{c}{c_m})^{-2.5} \dots\dots\dots 1.8$$

Bond (1959) examined the relationship developed by Rouse (1941):

$$U = U_o (1 - f_c^{2/3}) \dots\dots\dots 1.9$$

where

f Bond's constant dependent on particle shape.

However, Bond found difficulty in the evaluation of f from his upflow data. Other experimental comparisons have demonstrated a difference between sedimentation and fluidization, e.g. Loeffler and Ruth (1959), Edeline et al (1968), Richardson et al (1954, 1961a), Hale (1971).

A widely supported empirical approach is that the most convenient way of showing the variation of sedimentation velocity, U , of fluidizing velocity, with voidage e , is by means of the relationship:

$$\frac{U}{U_p} = e^{k_1} \dots\dots\dots 1.10$$

where U_p is approximately equal to the free-falling velocity of the particles for sedimentation. Edeline et al (1968) and Brown and La Motta (1971) have found this expression valid for floc suspensions. For non-spherical particles the index, k , is expected to have higher values than for spheres. Because Brown and La Motta (1971) found the value of k for the same type of floc is variable and may depend on the way in which the suspension is formed, etc., they stated that pilot studies under conditions not greatly dissimilar for those expected to be encountered in full scale units should be undertaken prior to determining final design factors.

Relationships of the form:

$$U = U_p \exp (-q_2 \cdot c), \text{ m/hr} \dots\dots\dots 1.11$$

have also been proposed and various values for q_2 have been suggested, e.g. 10 by Stevenson (1972), 5.9 by Thomas (1963), whereas Sen (1972) found 7.44 for iron flocs and 2.94 for aluminium flocs. The value of these figures, however, is dependent not only on the chemistry of the system but also on how the floc concentration, c , has been measured. There is no recognized standard for the measurement of floc volume concentration. Because of the mechanical properties of floc, concentration measurements are highly variable.

Barnea and Mizrahi (1973) point out that equation 1.10 does not fit the general experimental picture since it does not express a sharp reduction of the relative velocity for dilute suspensions. The modification has been proposed:

$$\frac{U}{U_o} = q_3 \cdot (1 - c)^{k_2} \quad \dots\dots\dots 1.12$$

where both q_3 and k_2 are functions of Reynolds Number. They also point out that this equation does not lead to a better understanding of the physical phenomena involved and this is why they developed the empirical approach based on Reynolds Number.

However, if equation 1.12 is used for floc suspensions U_o cannot be calculated but $U_o q_3$ is determined by correlation and is interpreted as the terminal velocity of the suspension at zero concentration.

1.4.6. Summary.

The previous investigations have shown:

- (i) In the evaluation of floc-blanket clarification it is important to distinguish between chemical coagulation, the formation of flocs by flocculation and the final solid-liquid separation.
- (ii) Floc-blanket clarification performance can to some extent be related qualitatively to raw water quality, chemical treatment and tank flow conditions.
- (iii) The efficiency of solid-liquid separation is dependent on the quality of the flocs produced. The quality of the floc should be the best possible to permit the highest treatment rates. Important floc properties are size, shape, density, structural strength and size range all of which are determined by the raw water quality, choice of chemical treatment and the hydrodynamic environment. In practice difficulty occurs in relating the best chemical treatment to the raw water quality and its variation.
- (iv) Clarification performance can only be quantitatively related to raw water quality, chemical treatment and tank flow conditions for systems which have been operated for prolonged periods during which comprehensive data have been collected. The statistically determined quantitative relationships will then only apply to the system from which the data were obtained.
- (v) The mechanisms contributing to floc-blanket clarification and their relative importance are not established. The mathematical models

that have been proposed for floc-blanket clarification are inadequate.

(vi) The purpose and merits of many of the various tank designs and modifications, which affect flow conditions and clarification, are not established. The influence of the scale of operation is not established either.

(vii) For design and operational purposes clarification performance should be related to the quality of the blanket, which can be conveniently examined in terms of the volumetric concentration.

Floc-blanket clarification is a fluidized bed separation for which the solids volume concentration is the easiest parameter which can be used to monitor the state of the fluidized bed. The state of the floc blanket is reflected in the clarification efficiency. The floc-blanket tank should be designed to produce even flow distribution across the area of the blanket for the whole treatment rate range. This is particularly important at the high treatment rates when blanket concentration is low.

(viii) Some of the mechanisms of floc-blanket clarification might be determined from the analyses of suitable velocity-concentration relationships. The nature of these relationships will also reflect the influence of water temperature and floc quality on clarification performance.

(ix) Floc blanket solids concentration appears to be an important parameter to be measured in floc-blanket operation. The limiting clarification efficiency with reduction in treatment rate appears to be closely related to a specific concentration of the floc of a given quality.

(x) Care must be taken in the measurement of floc-blanket solids volume concentration and in its evaluation. Further value in the measurement might be found in relating the measured concentration to an effective concentration.

(xi) Certain flow modifications might be effective in improving the hydraulic performance of floc-blanket tanks and result in improved clarification.

1.5. Scope of the Investigations

The review of previous investigations and reported practice, although indicating that a considerable amount of experience with the process

exists, shows that there is a certain lack of basic understanding in the process of floc-blanket clarification. This lack of understanding is reflected in the inability to design and operate the process with confidence and efficiency.

The principal objective of the investigations reported was to develop a comprehensive but basic understanding of floc-blanket clarification. The investigations were therefore concerned with the performance evaluation, operation and design of floc-blanket sedimentation as a clarification process in the chemical treatment of water.

In the development of methods of performance evaluation it was considered necessary to develop experimental techniques and data evaluation methods suitable for the project. This then made it possible to establish easily both how the process reacts to changes in controlled variables and how it behaves under conditions of real raw water quality variation.

Once the general behaviour characteristics are identified the effect and value of tank modifications and structural aspects of design can be examined.

With extensive investigations a considerable quantity of data accumulates. It then becomes possible to examine the effect of seasonal variations in raw water quality on clarification performance. It also becomes possible to examine consistencies in the clarification characteristics, by using velocity-concentration analysis as indicated in the review, which could lead to a more basic appreciation of the mechanisms of floc-blanket clarification.

The velocity-concentration analysis could at the same time include an evaluation of the relative usefulness of the various empirical formulae and further, compare the data of these investigations with previously published results.

The majority of the floc-blanket data were obtained with the parallel operation of three different upflow hopper tanks using directly abstracted river water. The tanks were of substantially different dimensions, 3.5 m diameter, 1.2 m square and 0.3 m diameter. The purpose of parallel operation was to compare the influence of tank dimensions and to

provide a means of direct comparison and control under the conditions of varying feed water quality.

At the beginning of the investigations there was also a 2.7 m diameter premix-recycle contact tank available which was operated in parallel with the 3.5 m tank. Various flow variables and modifications were examined in the 3.5 m tank. Certain flow modifications were also examined in the 1.2 m tank, in particular inclined settling. The inclined settling investigations included the operation of a hydraulic scale model of the 1.2 m tank using a rigid model-sized sediment.

As a result of applying one of the hydraulic modifications suitable for large tanks to full scale plant some data were also obtained for operational plant of different raw water qualities and chemical treatments.

2. EXPERIMENTAL EQUIPMENT AND METHODS

2.1. The Equipment

2.1.1. The site.

The Water Research Centre laboratories are at Medmenham, near Marlow in Buckinghamshire by the River Thames. River water is abstracted directly and continuously for laboratory purposes.

The laboratory is fed by two pumps, a low and a high output. The investigations considered were supplied by the larger pump, which feeds the tanks direct. The smaller pump maintains a large storage tank full for the smaller demands in the laboratory.

The pumps are situated in a pump house near the river. The self-priming centrifugal pumps operate with a suction of 300-600 mm Hg dependent on pumping rate, river level and the state of the screens. Screening is carried out under suction to prevent blockage of the pumps, rotameters, pressure tappings, etc., by leaves, snail shells, fish, gravel, etc. From the pump house the large capacity supply crosses a field in a buried PVC 0.100 m diameter pipe and then passes round the inside of the laboratory to the tanks. There are about 36 m of pipe through the laboratory before the coagulant dosing points.

After dosing the water passed through a series of bends and was then divided amongst the tanks feed lines. The chemicals are assumed to be thoroughly mixed before this distribution. A sample is taken for pH measurement from the feed to the 3.5 m tank after flow rate control. Fig. 2.1. is a schematic of the three hopper tanks arranged in parallel. The tanks are shown further in Fig. 2.2.

2.1.2. The 3.5 m diameter tank.

This tank was made available to the WRA by Paterson Candy International Ltd. When originally provided and these investigations were commenced, the tank was fitted with a PCI variable injection velocity and recirculation device. An interpretation of the value of this device has been discussed in Sect. 1.2.2. Fig. 2.3. is a diagram of the device. The idea is that the upper velocity cone valve controls the jet pump effect that causes entrainment from the upper blanket. The lower velocity cone valve

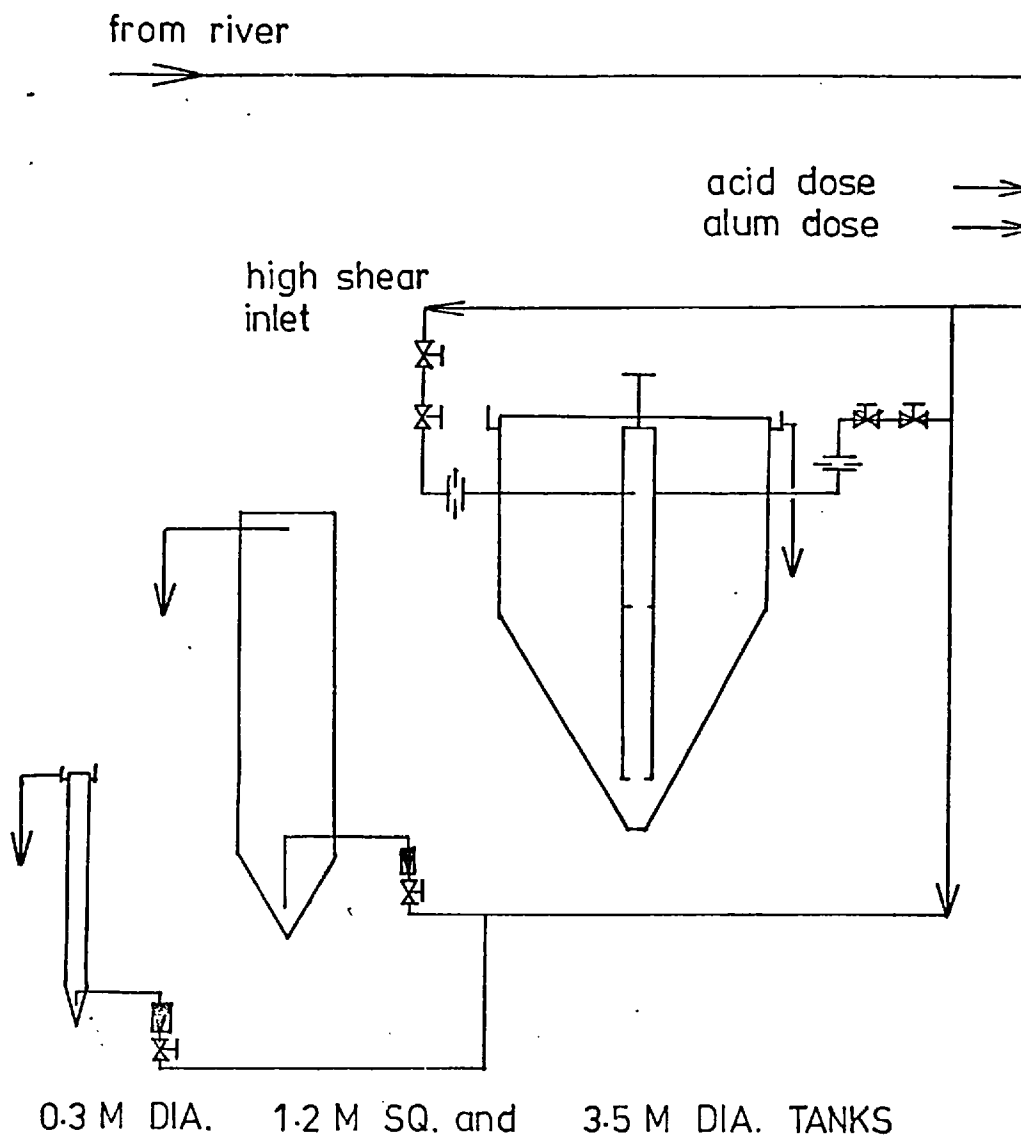
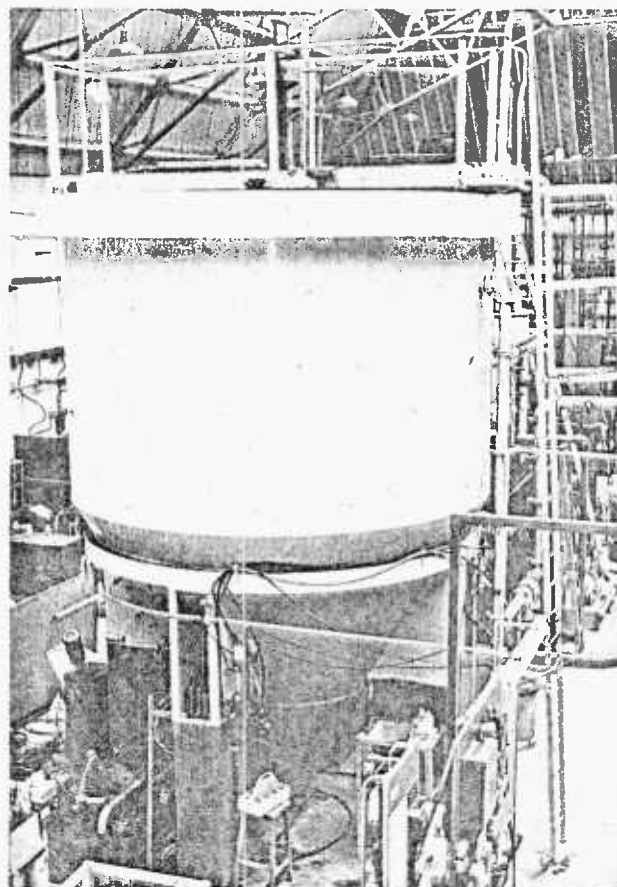
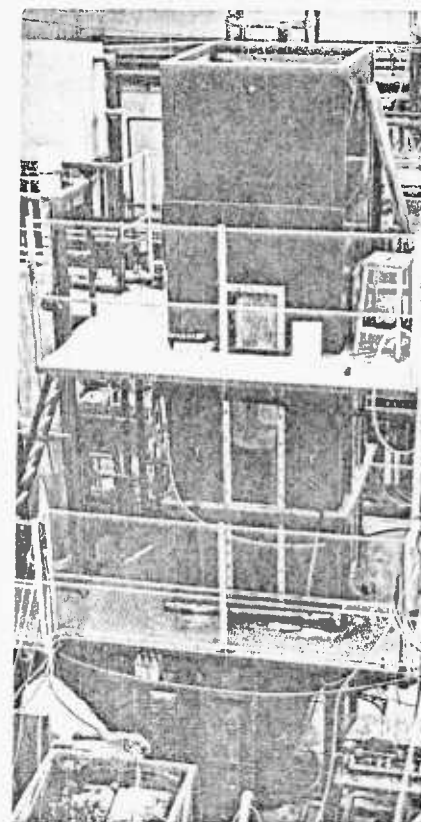


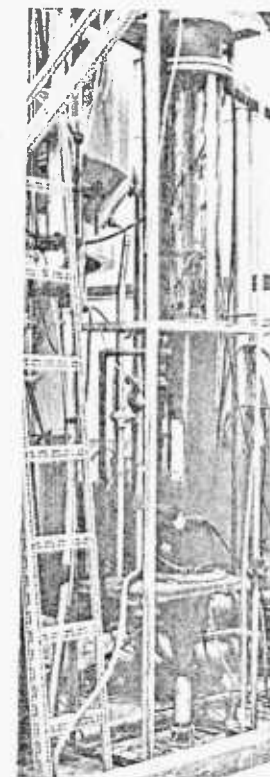
FIG 2.1 FLOW DIAGRAM OF THE SEDIMENTATION TANKS IN PARALLEL



3.5 m tank



1.2 m tank



0.3 m tank

FIG 2.2 THE LABORATORY TANKS

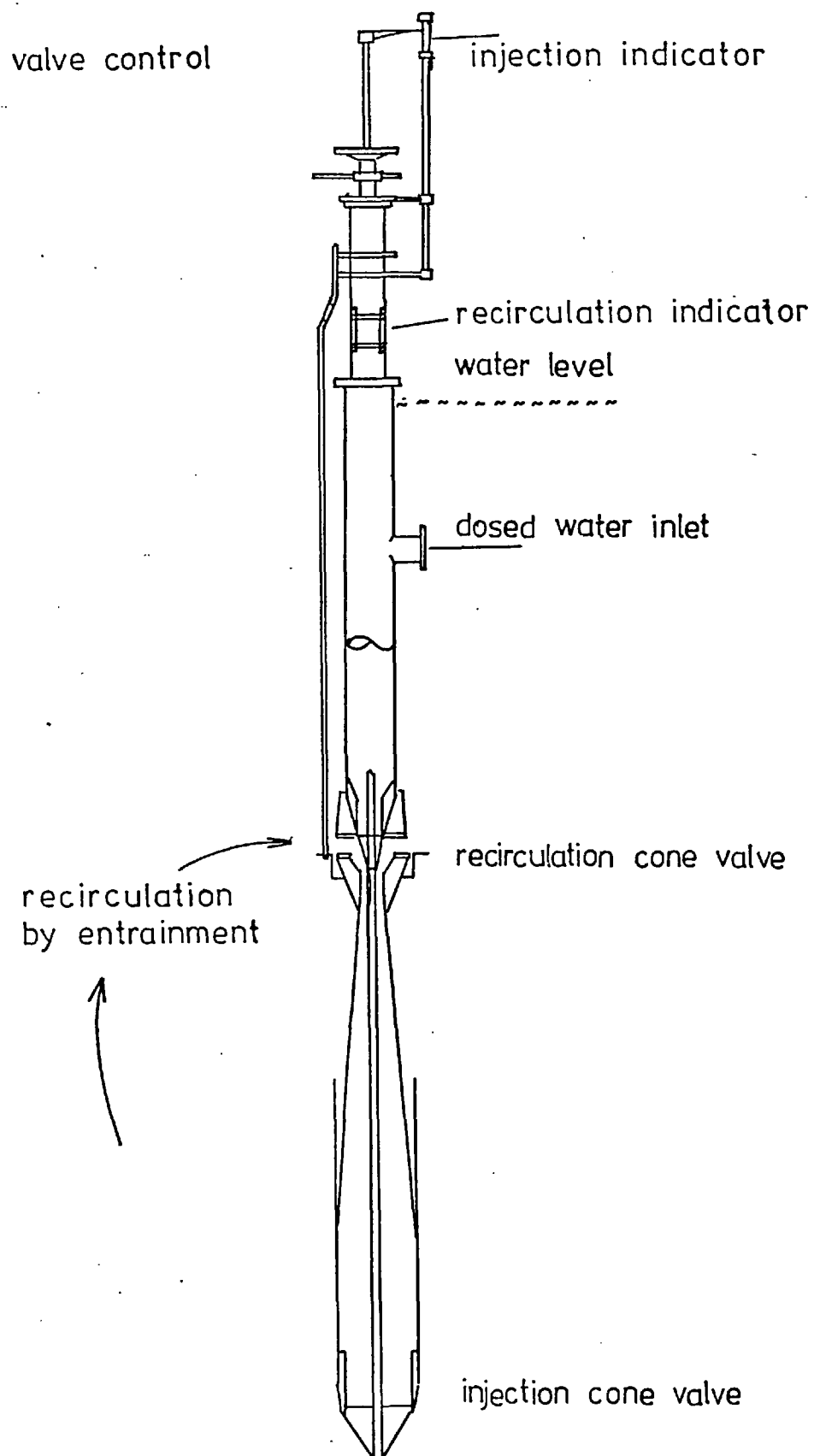


FIG 1.4 THE VARIABLE INJECTION VELOCITY AND
2.3 RECIRCULATION RATE DEVICE

controls the injection velocity, and for the equipment provided, was determined by relation to a scale calibrated to a lift of 6 inches.

Fig. 2.4. is a diagram of the basic structure of the tank giving its dimensions.

The inlet system was changed during the course of the investigations when it was considered that the variable injection-recirculation device could be of little further interest for investigation. The new device was conceived to investigate pre-injection high shear rates. An interpretation of the value of this device has also been discussed in Sect. 1.2.2. The system, as shown in Fig. 2.4., consists of two inlets each with control valves and orifice meter. A 0.075 m diameter feed line has been added which meets with the 0.1 m line at the top of the axial high shear mixing cylinder. The 0.075 m line is tangentially attached to the mixing cylinder through a nozzle. The objective is that the proportion of flow through the nozzle contributes the energy for high shear conditions. The outlet velocity from the mixing cylinder is controlled by a velocity cone valve.

The tank was provided with a suspended bucket for control of blanket level.

The overall evaluation of the investigation was dependent on the comparison of the parallel performances of the three tanks and of data obtained for different experiments for the individual tanks. Such a comparison was ultimately dependent on the accuracy of the treatment rates recorded. The orifice meters on the 3.5 m tank and the low range rotameter used on the 1.2 m tank were cross calibrated by salt dilution. The large orifice meter was found to require calibration.

2.1.3. The 1.2 m square tank.

This tank was originally constructed to be not so much an experimental unit but to produce suitable settled water for experimental filters. Fig. 2.5. shows the tank and gives the important dimensions. It was constructed, however, with Perspex windows up the centre of all four sides for the greater proportion of its parallel flow section.

This tank was primarily operated in this investigation to provide comparative performance figures on the effect of scale. It was also used to evaluate tube module performance.

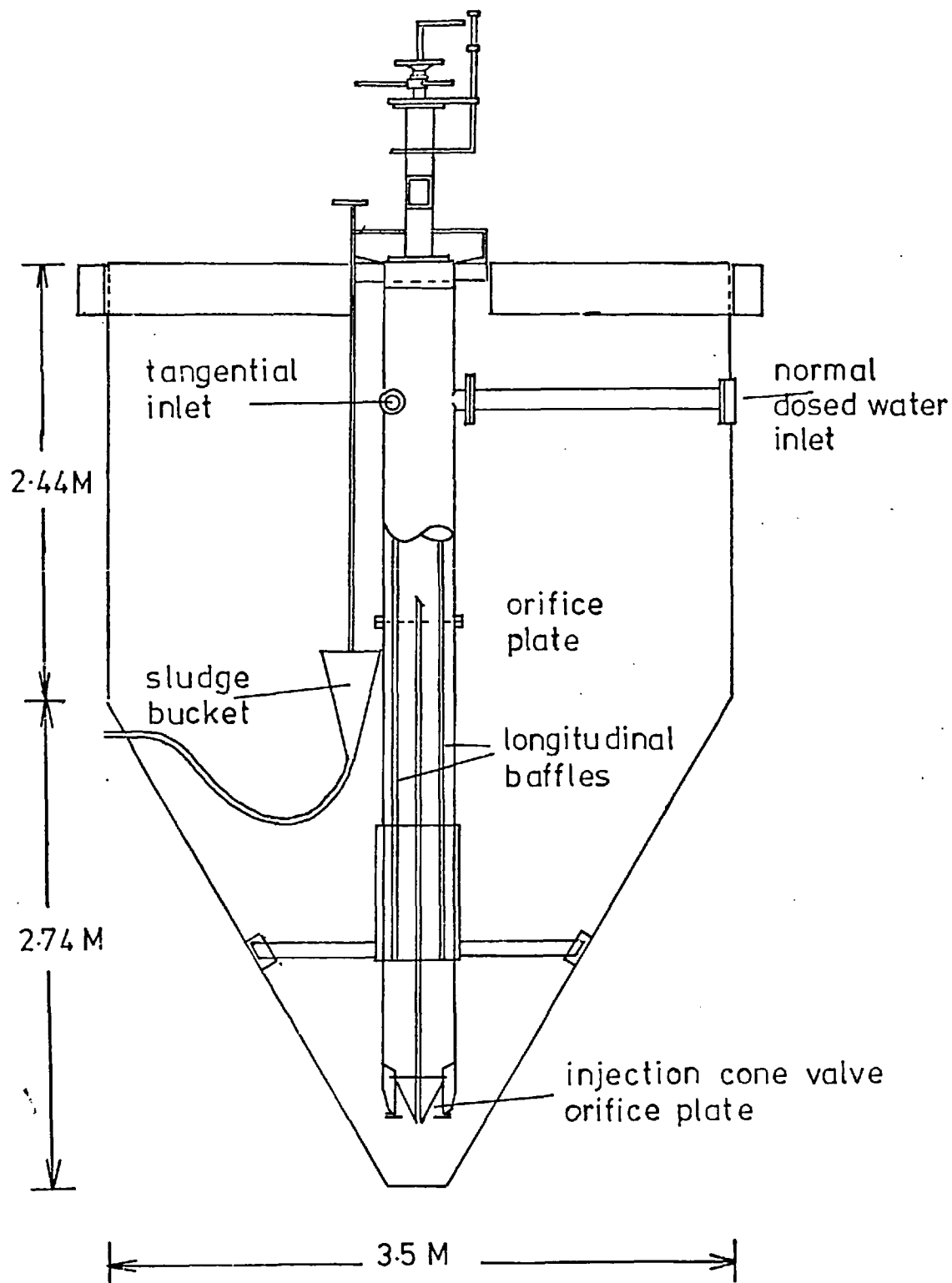


FIG 1.3 3.5 M DIAMETER TANK FITTED WITH THE HIGH
2.4 SHEAR — HIGH VELOCITY DEVICE

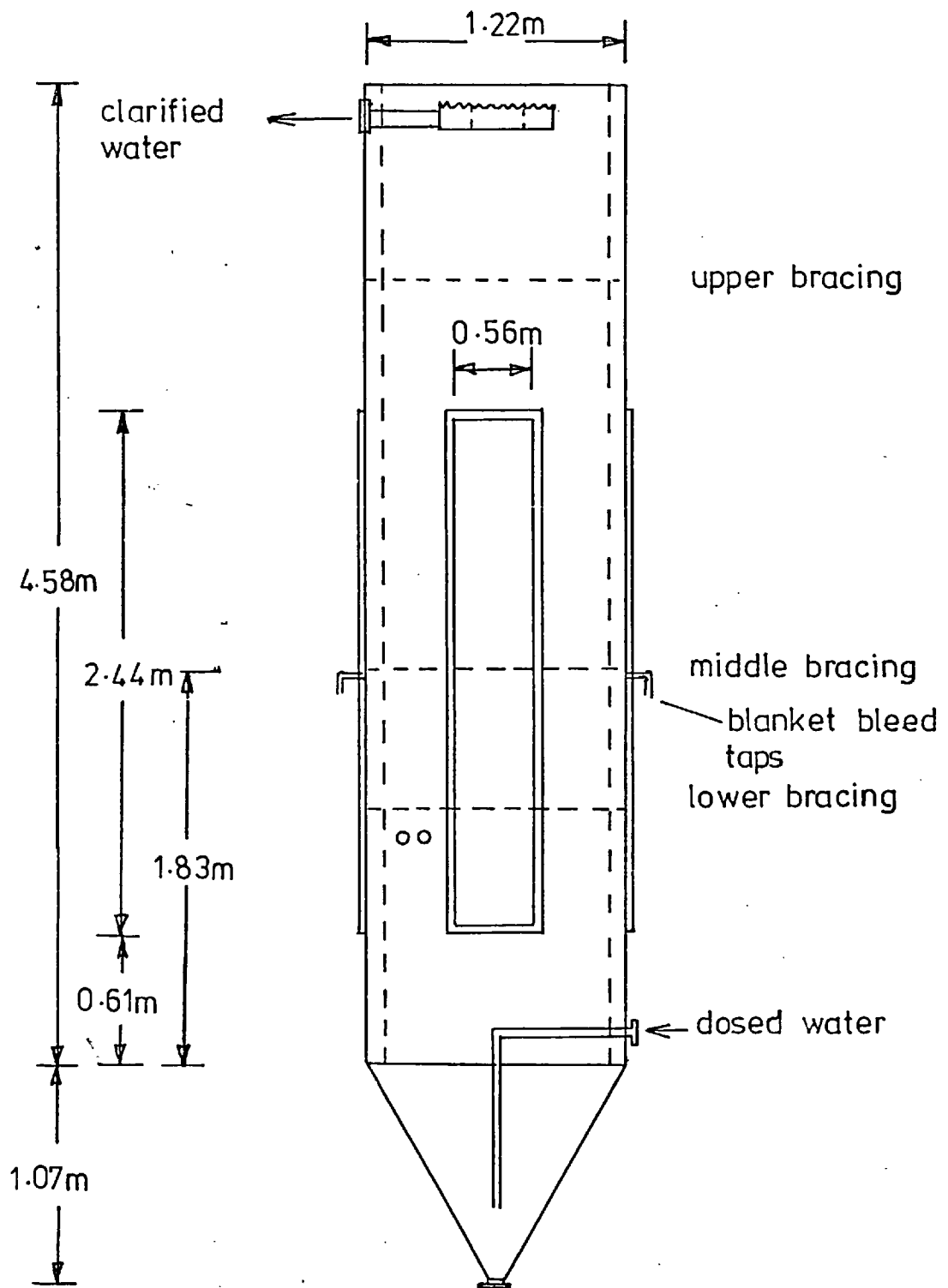


FIG 2.5 THE 1.2M SQUARE TANK

2.1.4. The 0.3 m diameter tank.

The upper section of this tank was made of Perspex so that visual observation of the upper blanket surface was possible. The necessary dimensions are given in Fig. 2.6.

The tank was only operated in this investigation for the purpose of comparison with the larger tanks.

2.2. Operation Methods

2.2.1. Chemical treatment.

The quality of the raw water ultimately influences the choice of chemical treatment and the efficiency of clarification. The raw water in the laboratory experiments was directly abstracted from the River Thames. A chemical analysis for the year Jan. - Dec., 1971, is given in Table 2.1.* Fig. 2.7 gives the quality distribution for a number of the parameters. This demonstrates that comparative extremes for a number of the parameters are only encountered for a small proportion of the year.

Because the majority of previous investigations in the laboratory had used aluminium sulphate as coagulant and because a large proportion of water treatment plant in the United Kingdom also use aluminium sulphate, this was selected as the coagulant for all the laboratory experiments reported. In order to obtain an optimal balance between colour and suspended solids removal, pH adjustment was carried out using sulphuric acid to keep the pH in the range 6.6 - 7.0 dependent on raw water quality. A stock solution of acid was made to approximately 20% wt/wt from 96% R.O.V. delivered in polycrates.

Aluminium sulphate, iron free, was used. Stock alum solution was made up in the range 12 - 27% wt/wt as $Al_2(SO_4)_3 \cdot 18H_2O$ dependent on treatment rate and raw water conditions and hence the required dosing rate.

Since the hydrolysis products of the coagulant are pH-dependent the acid was dosed first though only about 0.3 m upstream of the coagulant. Both the acid and alum were dosed into the midstream pipe flow.

Where the dose of coagulant was varied during an experiment, the dose rate was that found likely to give the best tank effluent quality.

*All tables are given in numerical order at the end of the thesis.

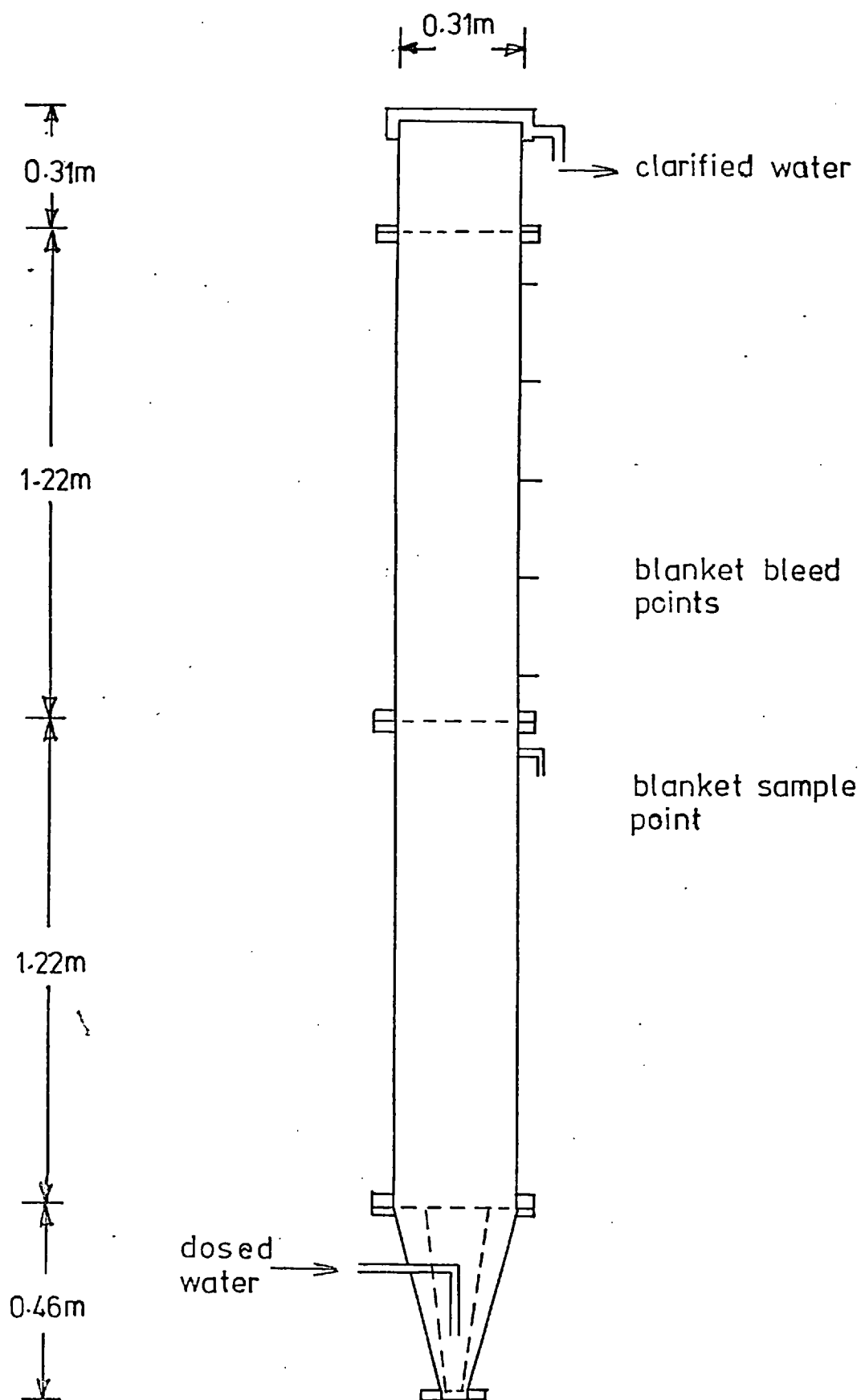


FIG 2.6 THE 0.3M DIAMETER TANK

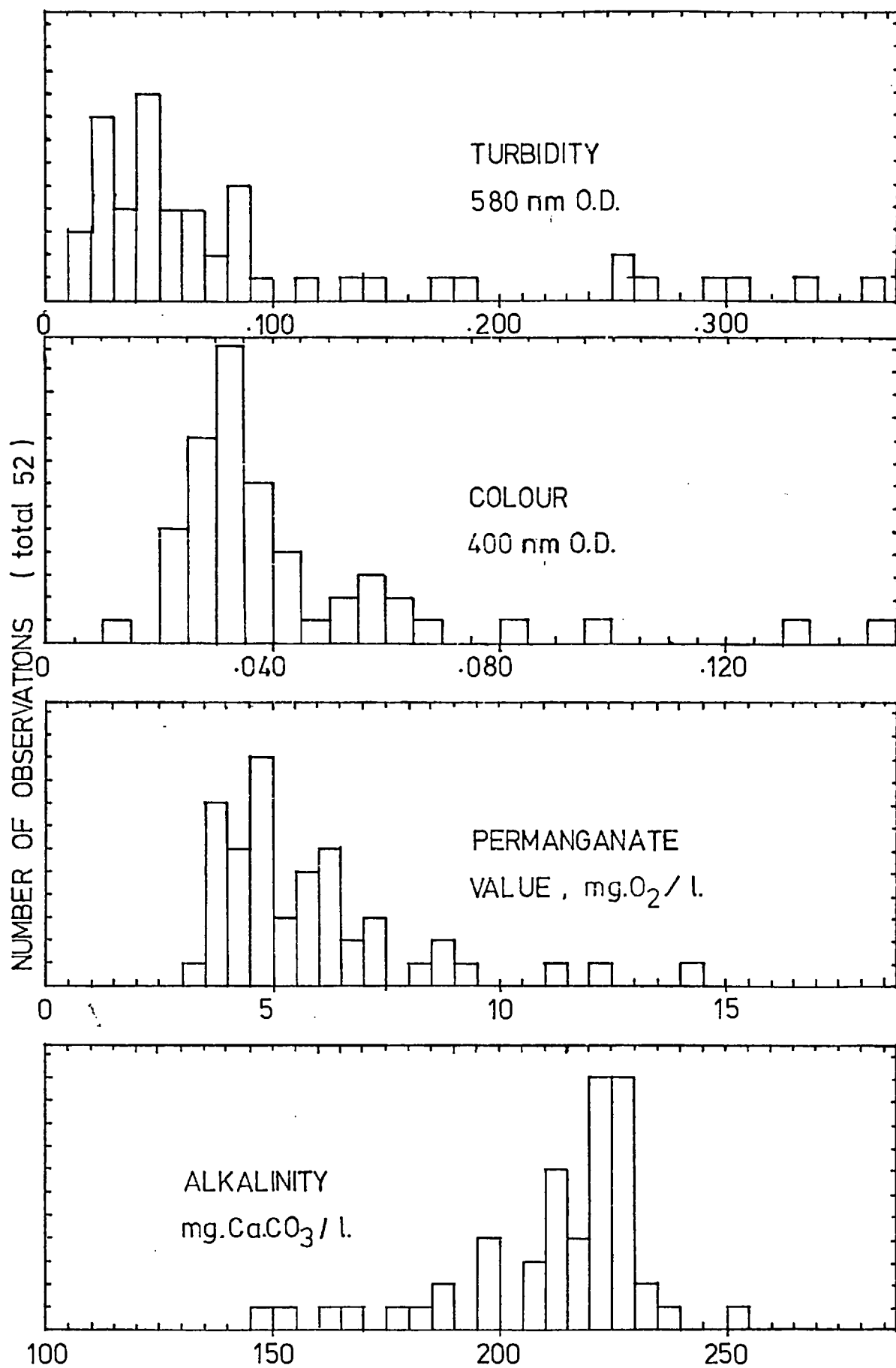


FIG 2.7 QUALITY OF RIVER THAMES AT MEDMENHAM
1971, DISTRIBUTION OF SOME PARAMETERS
(table 2.1)

2.2.2. Quality parameters.

Clarification efficiency can be measured by any parameter that can represent the product, treated water, quality. This quality can then be related to either the water quality before treatment or after the addition of the coagulant. The efficiency sought should be related to the efficiency of any following processes and the final quality desired.

Useful quality parameters are turbidity, optical density and coagulant concentration. The advantage of the first two is that they can be continuously monitored. The third and usually the second parameters are measured from grab samples. Care must, however, be taken in the interpretation of all three parameters.

In this report turbidity refers to scattered light measurement during continuous monitoring. All optical density (absorbance) measurements were made on grab samples for absorption at 580 nm* and 400nm** wavelengths in a 40 mm cell.

*The 580 nm absorption reading is representative of suspended solids if the difference in absorption reading is taken between before and after membrane filtration samples using a millipore filter of about 0.5 μ m. The value is not identical to nephelometric turbidity measurement for a variable river water, equivalence can only be attained for a specific quality of solids in which particle shape, size and colour are reproducible. The comparison of absorption and turbidity of a sample can provide an indication of the nature of the solids in suspension. However, an approximate conversion to Jackson Turbidity Units, JTU, is to multiply by 200 for a 40 mm cell reading.

**The 400 nm absorption reading is representative of visual colour and is indicative of the coloured organic compounds present in solution. Further information may be obtained by measuring the absorption at 300 nm. The colour absorption is made after membrane filtration to remove interference due to suspended solids. It can be found that, in conditions of raw water quality which are identified as difficult to clarify, the 300 nm absorption is a more pertinent indication of the interference to chemical coagulation by dissolved organic materials. In water treatment colour is commonly measured in Hazen units and an approximate conversion of the 400 nm value is to multiply a 40 mm cell reading by 380.

In order that the investigations should be realistic, certain quality criteria were born in mind. For example, an acceptable filtered water sample should have a turbidity of less than 0.25 to 0.40 Jackson Turbidity Units, JTU; if a filter has an 85 to 95 per cent efficiency then a suitable settled water turbidity is in the range of 2.5 to 5.0 JTU and is good if less than about 2.0 JTU. Similarly, for filtered water the aluminium concentration should be less than 0.1 mg Al/litre, and therefore the settled water concentration should be in the range 0.7 to 2.0 mg Al/litre and is good if less than about 0.5 mg Al/litre.

To appreciate fully the efficiency of the process the quality parameters should be assessed with reference to the flow rate through the plant. For the comparison of different plant total flow rate is an inadequate measurement, but is suitable for upflow tanks if expressed as the total flow rate per unit surface of upflow area*, e.g. ft per hr (m per hr). In this report the term "treatment rate" is used for this variable as defined. Treatment rate therefore represents the mean upflow rate or superficial fluidization velocity as identified from velocity-concentration analysis of the blanket. The term therefore does not distinguish the effect of poor flow distribution.

The general objective of the experiments was to examine how the settled water quality parameters changed in value due to variation in either controlled variables or uncontrollable raw water quality parameters. For example, how product turbidity increased with increase in treatment rate, and therefore the best operating conditions for the product quality objectives.

2.2.3. Sampling and laboratory analyses.

The type of samples taken to determine tank performance varied during the investigation depending on the aims of the individual experiments.

The effluent from the small demand storage tank was continuously monitored by a Southern-WPRL Suspended Solids Meter (a turbidimeter). From this sample twice daily samples were taken for absorption measurement at 580 nm and at 400 nm. A second sample was also taken

*Upflow area is usually assessed at the normal highest operational level of the blanket surface.

in the morning to measure the background river aluminium. At the same time the water temperature was noted. These parameters gave a simple index of raw water quality.

A continuous bleed was taken from the inlet to the 3.5 m tank and monitored for pH. Grab samples were taken from the outlet of this monitor to confirm the coagulant dose by aluminium analysis.

Continuous samples of the products of the three hopper tanks were monitored by an APV-Bowser Turbidimeter. The turbidimeter was arranged so that each sample could be monitored for 20 minutes in every hour. During experiments 1 to 6 product turbidity was measured by a Hach CR Low Range Turbidimeter. Grab samples were taken from these continuous samples for aluminium analysis and absorption measurements at 580 nm and 400 nm. The 400 nm absorption value was taken to confirm the quality of coagulation as distinguished by the degree of colour removal.

To establish the dynamics of performance within the tanks two blanket samples were taken. One was for a 30 minute settled solids volume, as measured in a 100 ml measuring cylinder and was interpreted as the blanket floc volume concentration, and the other was used to determine blanket density measured as the digestible aluminium or dried total solids.

All chemical analyses were made by the WRA analytical laboratory using WRA standard procedures.

Both turbidimeters are calibrated in Jackson Turbidity Units, JTU, by the respective manufacturers. Comparisons in the laboratory have shown the calibrations to be adequately equivalent. The APV-Bowser was calibrated a number of times during the investigations by a number of techniques and its reliability was confirmed. However, dependent upon the technique, a positive zero error could be measured and a value of approximately 0.6 JTU was obtained. The results presented in the correlations have been adjusted for this value.

The number of parameters measured for each experiment was not completely consistent throughout the investigations, partly due to investigating the relative values of the various parameters that could be easily measured and partly due to the limits of the analytical facilities. Some parameters measured were closely related to each other, e.g.

turbidity, aluminium residual and the 580 nm absorption. As expected the nature of the correlations of such duplicate parameters were the same, though the accuracy of regression could differ substantially. Although turbidity, as a measurement of product quality, and blanket settled floc volume, as a measurement of blanket quality, do not always produce the most accurate regressions, they were both shown to be representative of tank performance and the cheapest and easiest parameters to measure.

2.2.4. Blanket level control.

The dimensions of the suspended bucket provided with the 3.5 m tank were too small for it to be used as a concentrator at high treatment rates as well as to maintain blanket level. The timer controlling the frequency of bleed from the blanket was therefore always adjusted for blanket level control and the bucket was suspended with its rim at the required blanket level. The frequency and duration of bleed was dependent on blanket quality, dosed water quality and flow rate to the tank.

Blanket level control for the 0.3 m tank was by a continuous bleed at the required level. The bleed rate was kept minimal to prevent blanket growth. From experiment 17 inclusive the 1.2 m tank was fitted with a concentrator of adequate capacity for the full range of treatment rate investigated. The concentrator was constructed and positioned to act as a slurry weir. Up to experiment 16 inclusive the blanket level control was by continuous bleed from taps just below the level of the middle bracing.

At high treatment rates and hence low blanket solids concentrations, if blanket level control is by continuous bleed, a simple mass balance indicates that the bleed rate will exceed 5% of the feed rate. At the lowest blanket concentrations encountered the rate probably approached a proportion of 10% of the feed.

2.2.5. Experiment design.

In the investigations two factors hindered the design, operation and evaluation of the experiments. Because of the physical dimensions of the plant and the respective fluid flow rates, times of response were long. As a result, dependent on the experimental variables under examination, only 2 to 6 experimental runs were possible in a working day. In addition, the

raw feed water quality, or some other indeterminate factor which might influence the quality of the results might vary substantially during the experiments.

When identical plants are available to be operated in parallel, experiments can be designed to be of shorter duration and to be carried out with greater confidence. In these investigations plant were operated in parallel, but being of different size provided only reference to each other and no control, although this did allow some of the investigations to be of shorter duration than they might otherwise have been.

The initial experiments showed the difficulties of both fully randomised factorial designs and simple progression of parameter levels. The general design evolved with experience with a limit to no more than two controlled variables. The basic ranges of the controlled variables were specified at the beginning along with the objectives to determine the effects and interactions of the variables. The experiment design was basically progressive but controlled variables could be changed by more than one level according to the variable and the time available. With the progression an attempt was made to produce an even distribution of the results to avoid the development of a time related bias. This also meant that if a severe change occurred during an experiment the data could be successfully treated in two parts. As a result, over a period of 3 to 4 weeks, an experiment could appear random, but over a few days appear progressive. For example, low treatment rates give a slow response and take a long time to accumulate blanket solids and therefore considerable time is required to attain equilibrium when reducing treatment rate further. In contrast, when increasing treatment rate at high rates, equilibrium could be obtained within a few hours. Similarly, injection velocity could be examined at as many as 6 levels in a working day at the highest treatment rates.

An experimental run was made when the product turbidity appeared consistent with the conditions of operation and the blanket floc volume concentration and growth rate appeared to be relatively constant.

An experiment was continued for as long as was required to obtain satisfactory distribution of data, with adequate repetition of variable permutation likely to ensure confidence.

2.2.6. Experiment notation.

The three tanks, 0.3 m diameter, 1.2 m square and 3.5 m diameter are respectively called tanks A, B and C. This designation precedes the number of the experiment. In some cases the experiment developed into two parts which are then respectively designated a and b which follows the number of the experiment.

For example:

C17a

means tank C (which is the 3.5 m diameter tank) first part of experiment 17. All the experiments involving these three tanks are summarized in Table 2.2. in numerical order of experiment. (In this Table tank P refers to a 2.7 m diameter "Accentrifloc" premix-recirculation type tank.)

2.3. Evaluation and Presentation of Data

2.3.1. Quadratic regression analysis.

The data are not presented completely because of the quantity involved. Furthermore, it would be of little value in such form other than for comparison with data representing treatment conditions very similar to those encountered in the investigations. It is the general nature of the data as shown by the various interrelationships involved which is of importance, the data have therefore been summarized as correlations. Depending on the experiment, the results are tabulated in a concise form so that the relationships may be examined more closely if required.

When the earlier sets of data were being examined it was quickly appreciated that at least some simple correlation should be employed to facilitate their interpretation and comparison. Various hyperbolic linear regression models were tried with an attempt to give some theoretical reasoning to the models chosen. However, it was found that a quadratic would fit most data the best, using the method of least squares, and so was used as the principal model.

In the regressions, with the parameter y expressed as a function of the parameter x , y is the dependent variable and x is the independent or causal variable. Where regressions are plotted the independent variable is shown on the abscissa, or x -axis and the regressions are only drawn

over the range examined for the parameter treated as the independent variable.

Treatment rate was always taken as an independent variable since it could be changed only deliberately. Those parameters fitted to treatment rate were always regarded as having their value caused by the treatment rate. Likewise, for other compared parameters the dependent variable was assumed to be caused by that selected as the independent variable. Thus the basic hierarchy of dependent to independent variable was product quality to blanket quality to treatment rate. The validity of this hierarchy was confirmed by the development in the investigations of the qualitative theory of the mechanism of floc-blanket clarification.

With regard to the tabulation of the regressions, Table 3.5, and similar, the information presented is explained below by breaking down the headings across a typical table into sub-tables (a), (b) and (c).

Table (a):

Exp't	Fig	y Regression Variables x
A12	3.4	Product turbidity, JTU; blanket floc volume, %
B12a	3.4	Product turbidity, JTU; blanket floc volume, %

These columns state respectively; the experiment, the figure number illustrating the regression and then the dependent and independent variables.

Table (b):

$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$				
α	β	γ	$\bar{x}$	$\bar{x}^2$
1.738	0.0211	-0.0032	13.925	211.8
2.547	-0.179	+0.0027	12.015	200.6

These columns give the values of the constants determined for the general quadratic.

Table (c):

F- statistic	d. f.	Dist.
16.61	2, 77	1%
9.80	2, 30	1%

These columns define the quality of the regression representing the data. First the value of the F-statistic is given, then the degrees of freedom. From these two the quality of the regression, which can be conveniently found from standard statistical tables of F Distribution, is given in the third column. A probability of the regression not representing the data of greater than 5 per cent is signified by N.S., otherwise by 5% if greater than 1 per cent and by 1% if less than 1 per cent. The determination of the F-statistic is the variance ratio test and is equal to the ratio between the mean square due to the regression and the mean square error. The total number of observations recorded in the experiment and used in the regression are represented by the degrees of freedom, for example - 2,77 - implies a total of 79 observations with the loss of two degrees of freedom.

The confidence limits of the regressions were examined. This not only illustrated the quality of the data at the extremes of the data spectrums but also helped to justify using this method of presenting the data as regressions. Figs. 2.8. and 2.9. illustrate these two points. Fig. 2.8. provides a comparison of the 95 and 99 per cent confidence margins and illustrates the quality of the data at extremes of the regressions. Fig. 2.9. illustrates that providing attention is given to the confidence of regression as indicated by the value of the F-statistic then the quadratic regressions can be used safely for comparative purposes. For example the lower figure in Fig. 2.9. illustrates that the regressions cannot be confidently distinguished from each other when the values of the F-statistic and degrees of freedom are small. The opposite applies to the upper figure. Fig. 2.10. has been produced to emphasize this point by plotting the data points represented by the correlations.

The WRC makes use of the facilities offered by London University

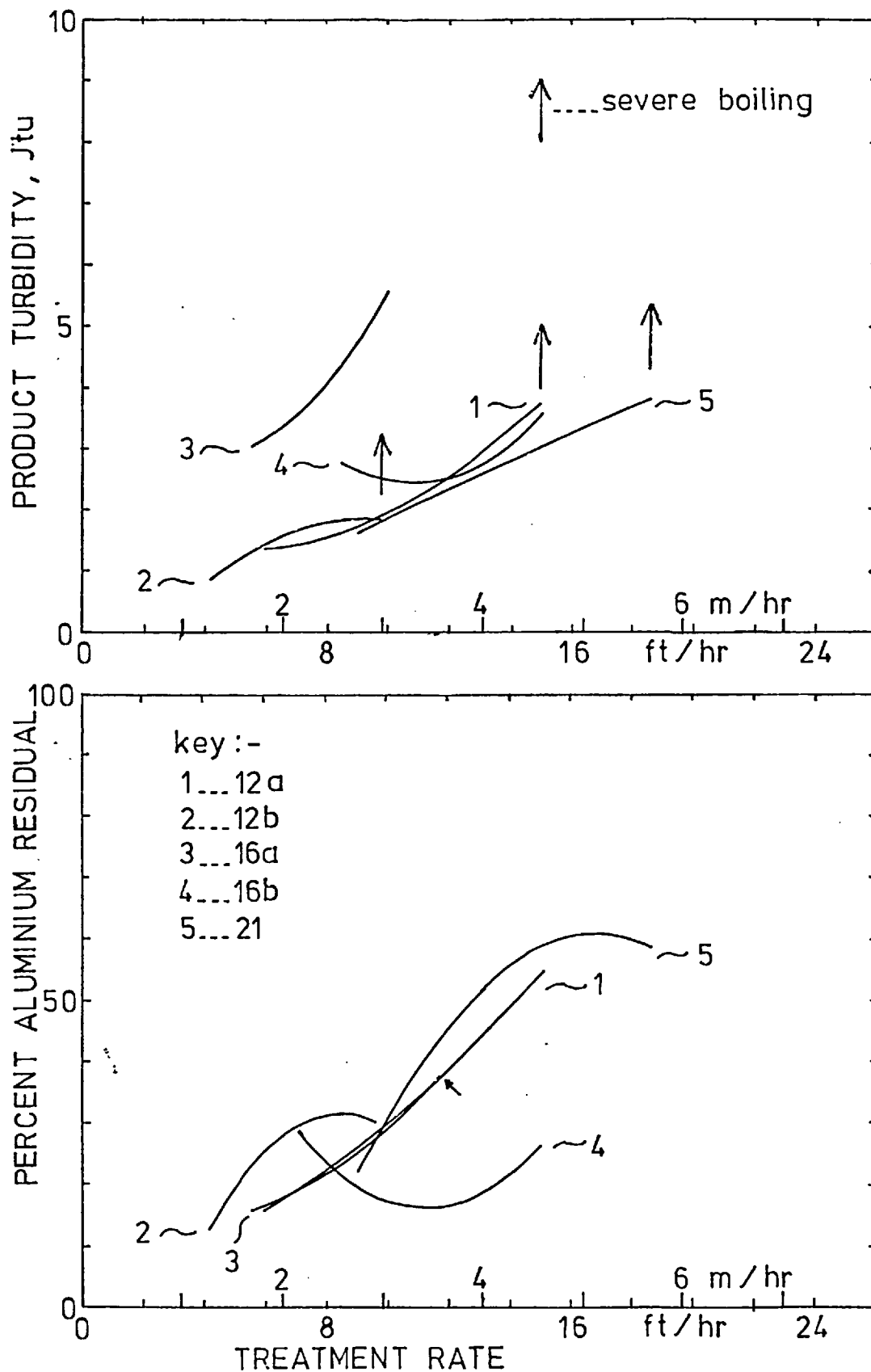


FIG 3.12 COMPARISON OF PRODUCT QUALITY—
 3.29 TREATMENT RATE RELATIONSHIPS, 1.2 m TANK
 WITHOUT TUBE MODULES (table 3.12)

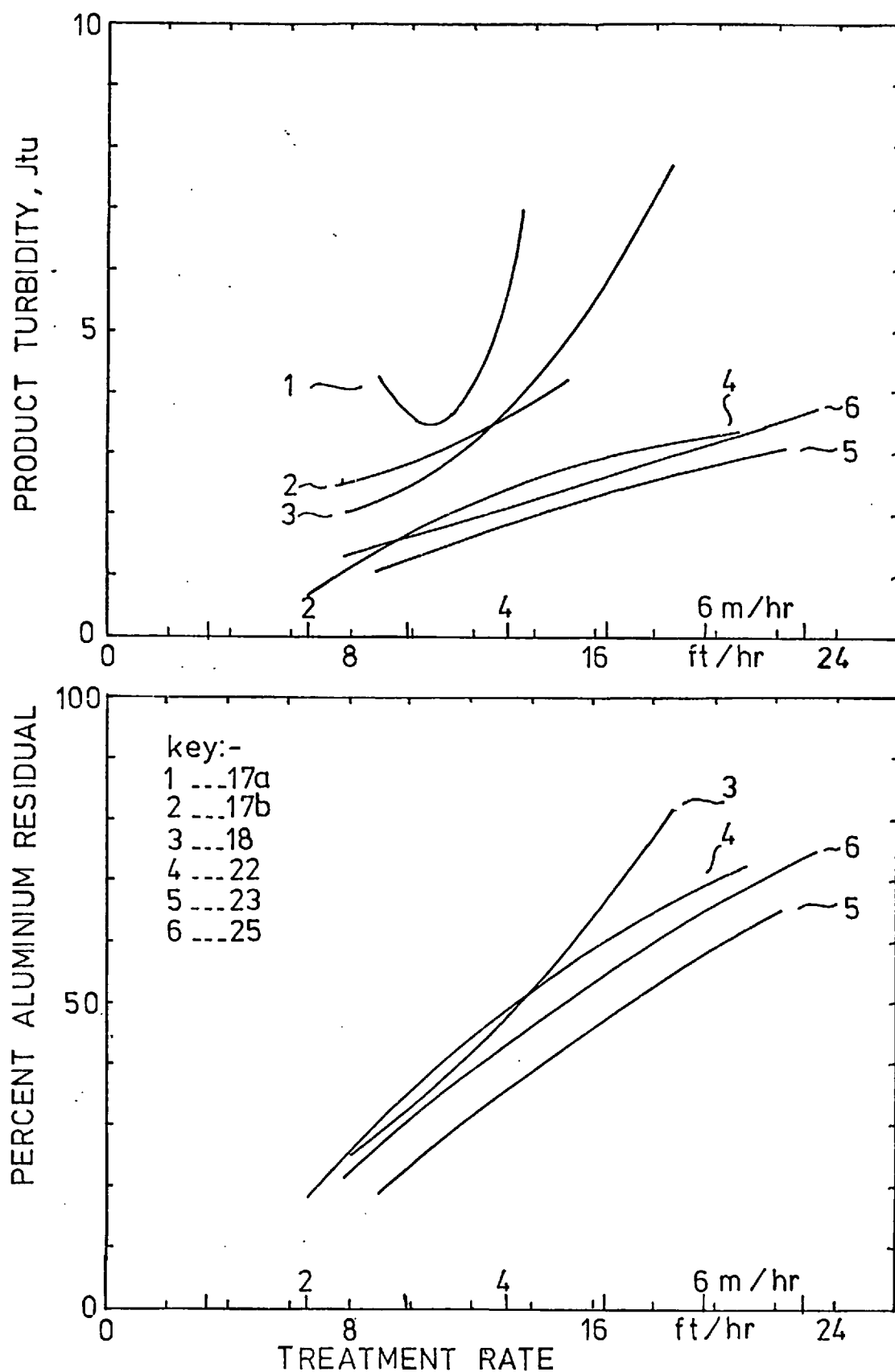


FIG 3.13 COMPARISON OF PRODUCT QUALITY—TREATMENT
 3.30 RATE RELATIONSHIPS, 1.2m TANK WITH TUBE
 MODULES (table 3.13)

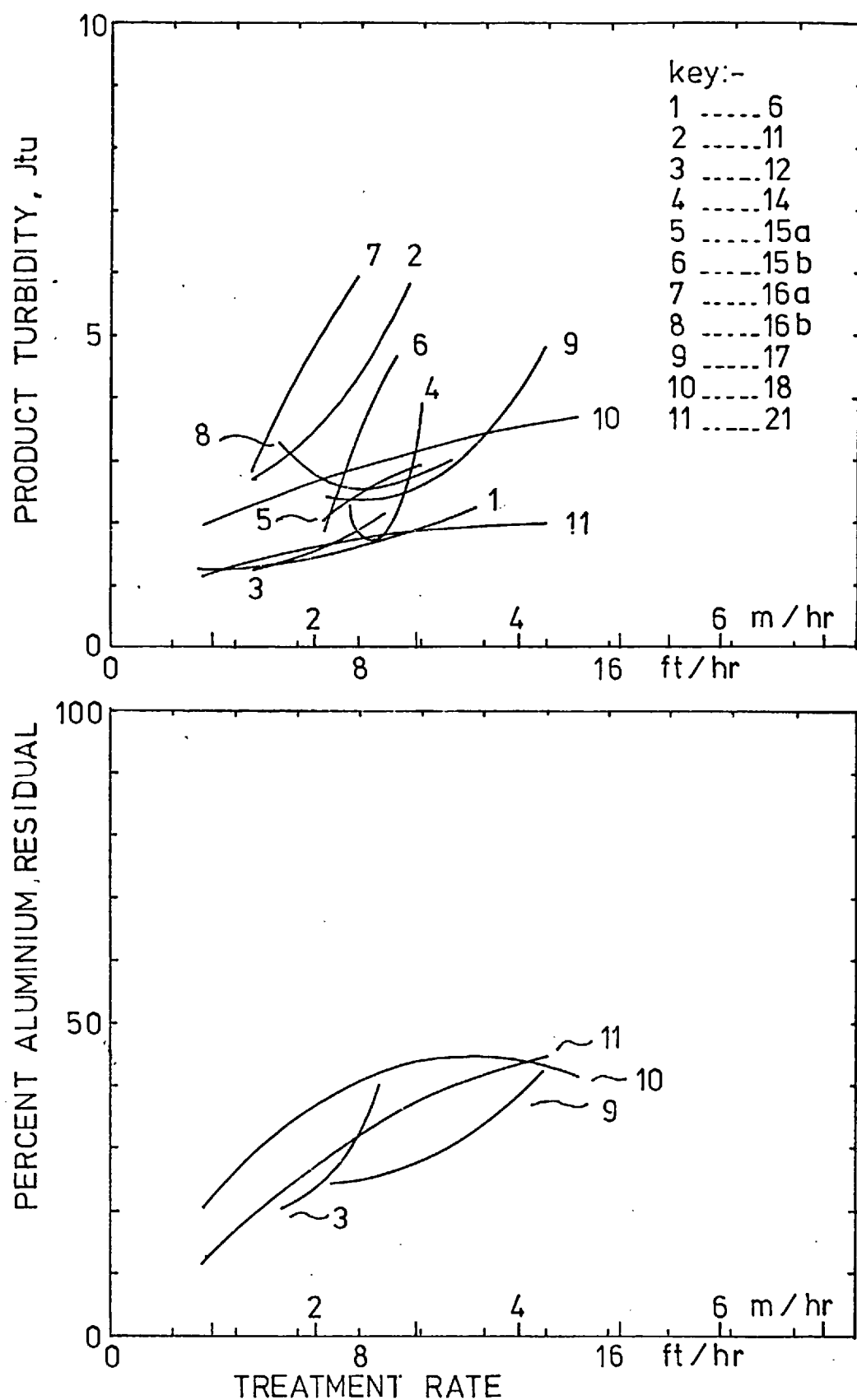


FIG 3.14 COMPARISON OF PRODUCT QUALITY—TREATMENT RATE RELATIONSHIPS, 3.5m TANK (table 3.14)

However, these two relationships were obviously substantially affected by the chemical treatment conditions. When treatment was easy there was no substantial difference between the tanks. Only when treatment was difficult did differences between the tanks become obvious. For example, these two relationships for the 0.3 m tank in Fig. 3.7. and 3.11. respectively, experiments 12, 21, 22, 23 and 25 were indistinguishable from each other, during 'summer' water conditions, but are obviously distinguished from experiments 16a, 16b, 17 and 18 of 'winter' water conditions. To some extent "easy" and "difficult" treatment is identified.

It is apparent that there is a range of blanket concentration beyond which product quality was relatively unaffected by the quality of chemical treatment, or by further increase in concentration or decrease in treatment rate, Sects. 1.4.1. and 1.4.2. The detailed analysis of the results in Sect. 4.1.3. showed that this range is coincident with the maximum flux value, which was usually within the range of 16 to 20 per cent.

For the conditions encountered during the investigations, with reference to the product turbidity - treatment rate relationship (essentially regardless of which tank), the lowest treatment rate necessary to sustain product quality independent of treatability was about 2 to 2.5 m per hr. For good treatability the highest rate was about 1.5 to 2 times as great. The ratio of these rates is relative to the viscosity range. For the temperature range of 4°C to 20°C the relative change in viscosity is about 1.6. These values of treatment rate can also be selected by examination of maximum flux concentration, Sect. 4.1.3. This implies that if hydraulic uprate is determined for good treatability conditions substantial difficulties might arise when poor treatability is encountered.

For the size range represented by the three laboratory tanks there is no conclusive evidence over a prolonged period that tank dimension causes distinctive differences in clarification performance, providing the specific blanket volumes of the tanks are equal. However, comparison of tanks over the short period of one experiment could show differences between tanks.

3.4. Effects of Inlet Flow Conditions

3.4.1. Flow injection.

The first investigations on the 3.5 m tank were with the 0.305 m diameter injection orifice plate and valve cone fitted with the recirculation

device. No significant effects were shown with varying injection velocity. See Table 3.15. and 3.16. for experiments C4 and C11. The quadratic fit for the variation of Hach turbidity with injection velocity for experiment C11, although giving a confidence of $P < 5$ per cent, did not represent a consistent effect due to increasing injection velocity. Injection velocities greater than 0.6 m per sec were not investigated because of the accuracy possible with setting the cone position to obtain the required injection velocity. It will also be seen that treatment rates no greater than 3.6 m per hr were investigated during this period. This is likely not to have assisted in showing effects due to injection velocity as the later investigations showed. At the time of these first experiments with injection velocity, 3.6 m per hr was about the limit to treatment rate. Higher rates could not be maintained with confidence, with blanket floc volume concentration reducing to 5 per cent at 3.5 m per hr treatment rates.

When the high shear rate system was installed the orifice and cone assembly was modified to a 0.222 m diameter orifice so that higher injection velocities could be attained with greater accuracy.

For the first two experiments with the high shear rate system, experiments 12 and 13, the injection velocity cone valve position was set constant at 1 in.* and 6 in.** raised from the orifice plate respectively. It was noticed that less boiling occurred in experiment 13 and higher treatment rates appeared to be attainable. As a result, a wide range of injection velocity and treatment rate was investigated, experiment 14. The results show, Fig. 3.15, Table 3.17, that the tank performance was dependent on injection velocity and treatment rate. It was noticed that the injection velocity setting greatly influenced the tank stability as identified from the amount and intensity of boiling and the product quality. The intensity of boiling was found to be quickly increased, e.g. within 10 minutes, by adjustment of the injection setting to increase the injection velocity sufficiently.

The results for experiment C15 took a similar form, Fig. 3.16. and Table 3.18, but were not as conclusive concerning the effect of injection velocity. In the analysis of the C15 data a change in raw water quality was found to necessitate analysis of the data as two groups. Unfortunately

* 25 mm } The injection indicator provided was calibrated in inches
 ** 150 mm }

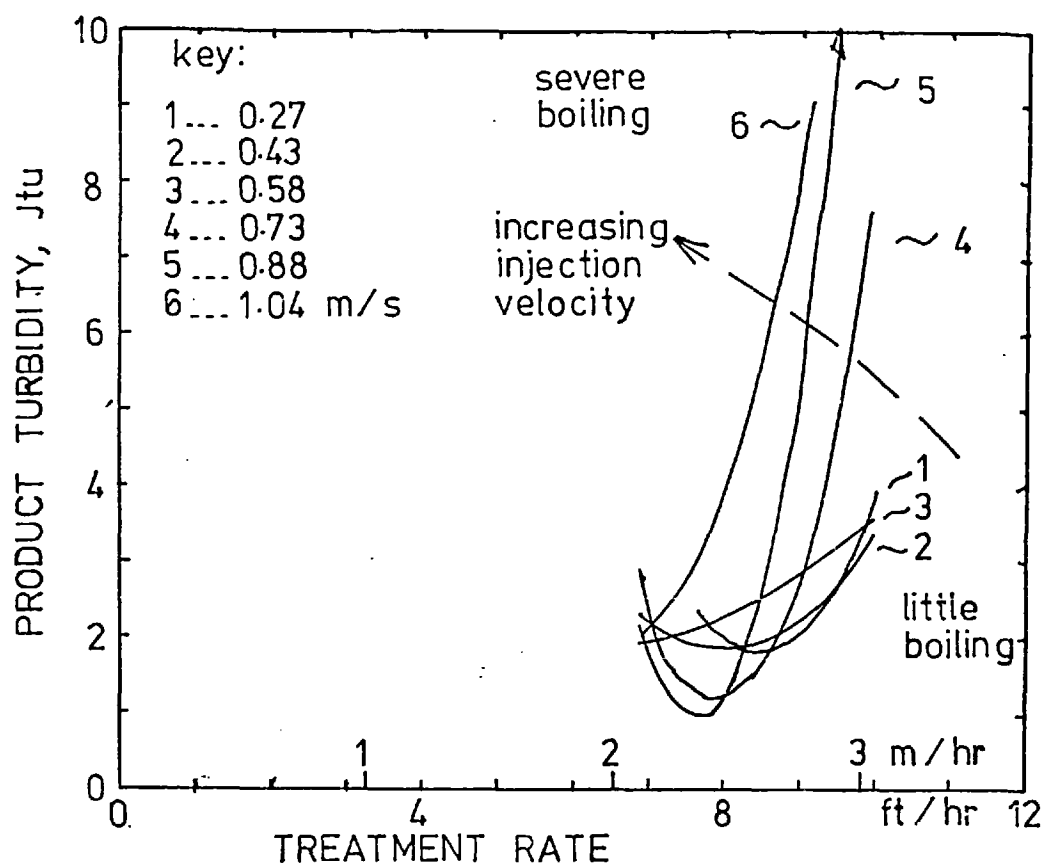


FIG 3.15 EFFECT OF INJECTION VELOCITY ON
PRODUCT TURBIDITY, EXPT C14
(table 3.17)

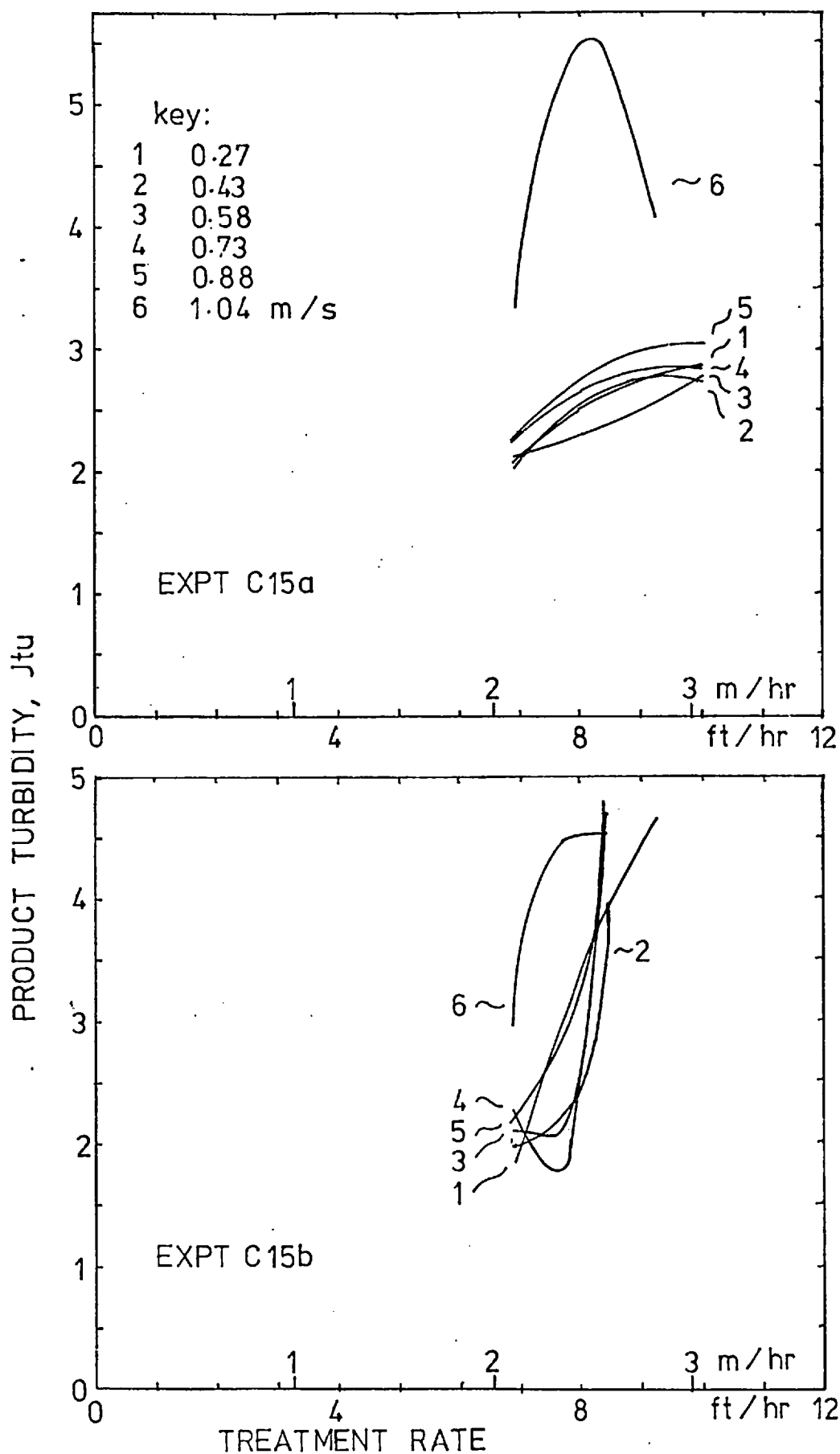


FIG 3.16 EFFECT OF INJECTION VELOCITY ON PRODUCT TURBIDITY, EXPT C15 (table 3.18)

this was not very satisfactory because of insufficient data. It was also appreciated after the event that too narrow a treatment rate range had been examined for both experiments C14 and C15.

Experiment C21 substantially demonstrated (Figs. 3.17. and 3.18. and Table 3.19. and 3.20.) that high treatment rates can be obtained at low injection velocities but not necessarily at high injection velocities. For the three highest injection velocities severe boiling prevented operation at the highest treatment rates achieved with the three lowest injection velocities.

The results of these three experiments are summarized in Table 3.21 together with experiments C17 and C18. It was concluded that the water temperature appeared to influence the effect of injection velocity on tank stability.

It was thought initially that the effect observed was related to flow conditions through the orifice which could be identified using the headloss through the device. If a change in the headloss response occurred for increasing injection velocity, or lowering of the valve cone, at high injection velocity, a discrete transition of kinetic or hydraulic flow conditions at the orifice might provide an explanation of the effect of increasing injection velocity. Headloss measurements were made, Fig. 3.19, for change in injection setting at constant treatment rate.

Fig. 3.19. shows that at a water temperature of 6°C the headloss characteristic is consistent over the greater part of the ranges of injection velocity and treatment rate of interest. Arrangements were not made to measure greater headlosses or make headloss measurements when the water was warmer. However, the indication was that further increase in injection velocity would be associated with a change to a much greater rate of increase in headloss development. This suggested the onset of flow degeneration at an injection velocity of about 1.2 m per sec for water at 6°C . Some of the variation of headloss with respect to injection setting and treatment rate is likely to be due to the selection of the pressure sampling points and their interaction with the flow patterns existing at that range of treatment rates.

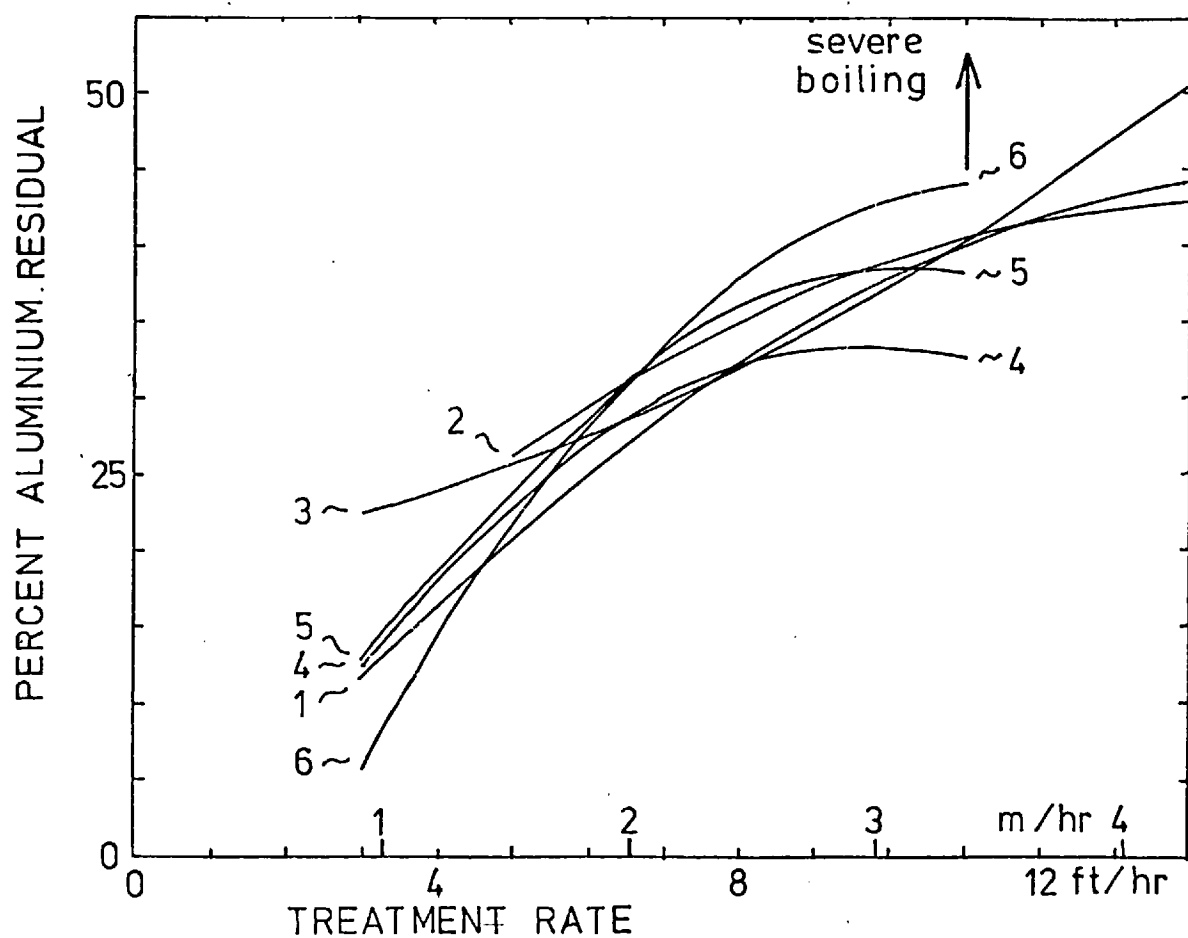
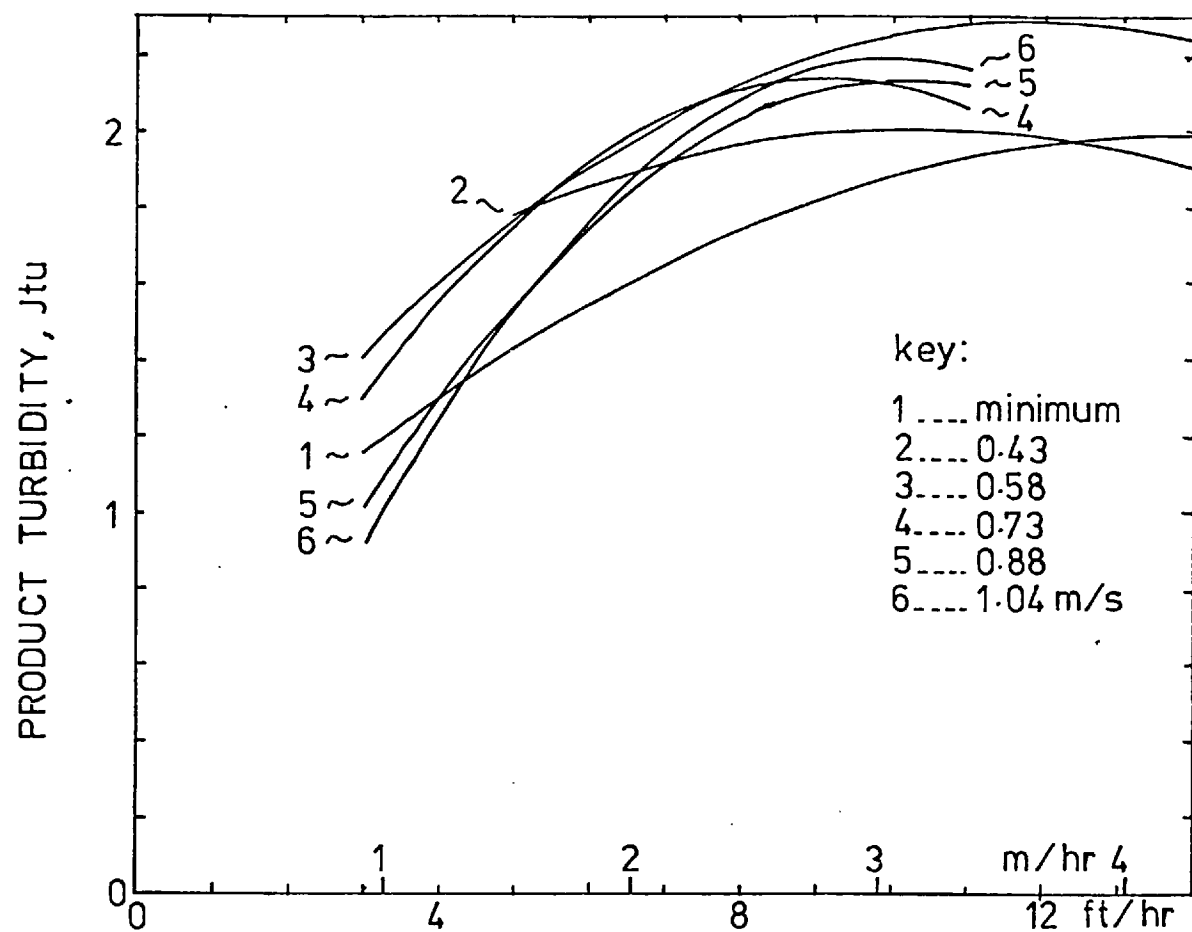


FIG 3.17 EFFECT OF INJECTION VELOCITY ON PRODUCT QUALITY, EXPT C21 (table 3.19)

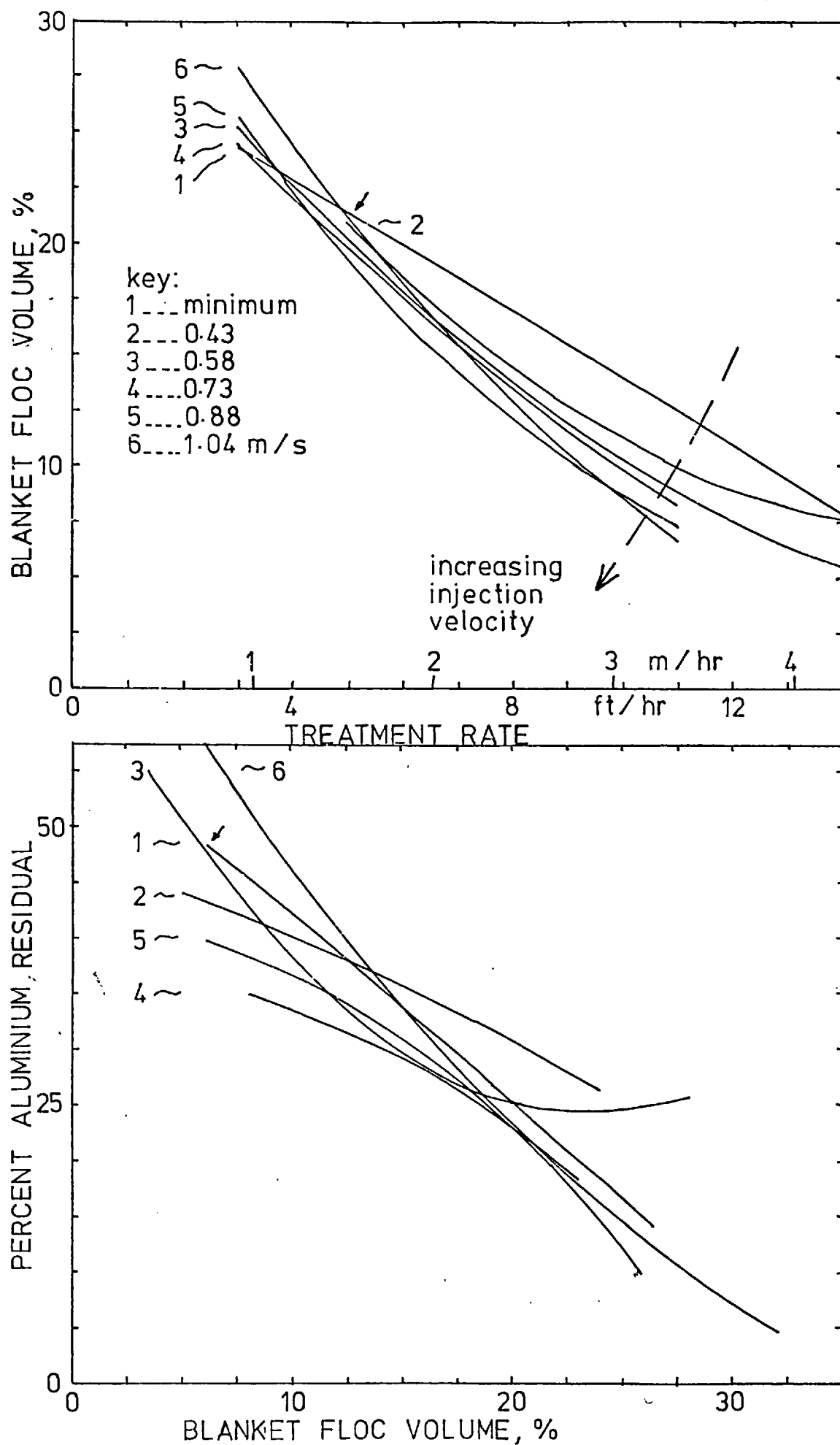


FIG 3.18 EFFECT OF INJECTION VELOCITY ON BLANKET QUALITY, EXPT C21 (table 3.20)

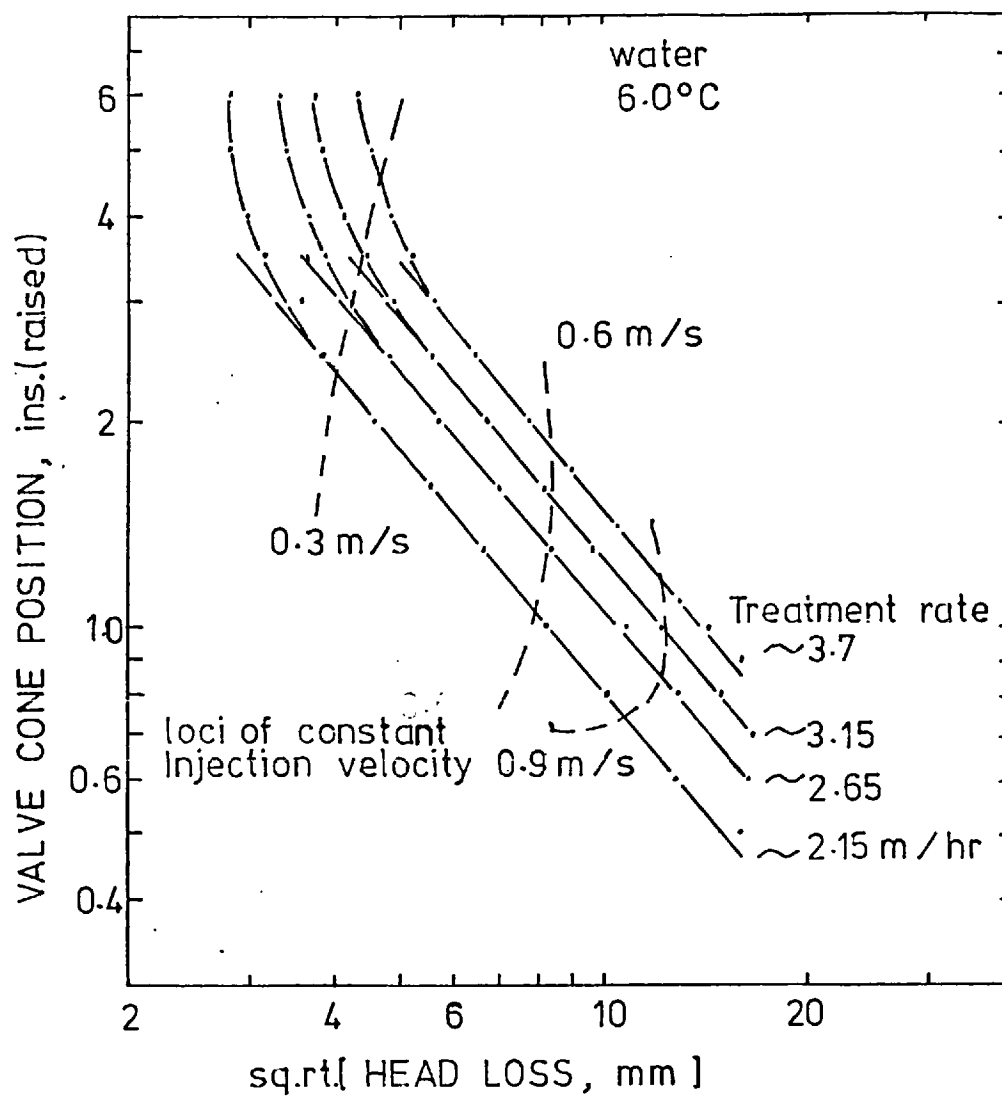


FIG 3.19 INJECTION HEAD LOSS

3.4.2. Other inlet factors.

In addition to examining the effect of controlling injection velocity the effects of other inlet factors were examined. These included conditioning the floc by pre-inlet treatment and the use of variable recirculation created by the variable recirculation and injection device. Both of these factors showed no effect and are not reported further. A premix-recirculation tank was also evaluated in terms of floc conditioning and no advantage was found for this tank over the 3.5 m tank.

The influence of the distance between the point of injection and the apex of the hopper, in the 3.5 m tank, on tank performance was also briefly examined. No effect was found.

Observation of full scale, pilot scale and model plant indicates that premature deterioration of floc-blanket stability occurs due to the poor distribution of the inlet flow. The fault can be due both to the design of the inlet and to the general tank geometry. If suitable diffusion flow conditions can be provided, after reversal and before the streaming flow enters and penetrates the blanket, then the inadequacies of the injection and flow reversal conditions can be compensated for. With this idea in mind diffusion grids were conceived, constructed and tested in the 3.5 m and 1.2 m tanks, Section A1. Both tanks were fitted with double layer grid systems as illustrated by Figs. 3.20. and 3.21.

Some effect in improved tank performance could be associated with the use of the grids but it was not possible to ascertain that the improvements were due to the grids alone.

Experiments C17 and C18 examined injection velocity with the diffusion grids. The results for these experiments are summarized in Figs. 3.22 to 3.25. These results must, however, be compared with those of experiments C14, C15 and C21 in which injection velocity was examined without diffusion grids, Sect. 3.4.1. The results are given in Figs. 3.15. to 3.18. and Tables 3.17. to 3.20. The analysis of stability, Table 3.21, using the design condition as reference, would appear to support the observation from the results that greater stability appeared to be encountered under the conditions of experiment C18. Considering both groups of results the stability related to injection velocity would appear to

scale:- 1 : 12

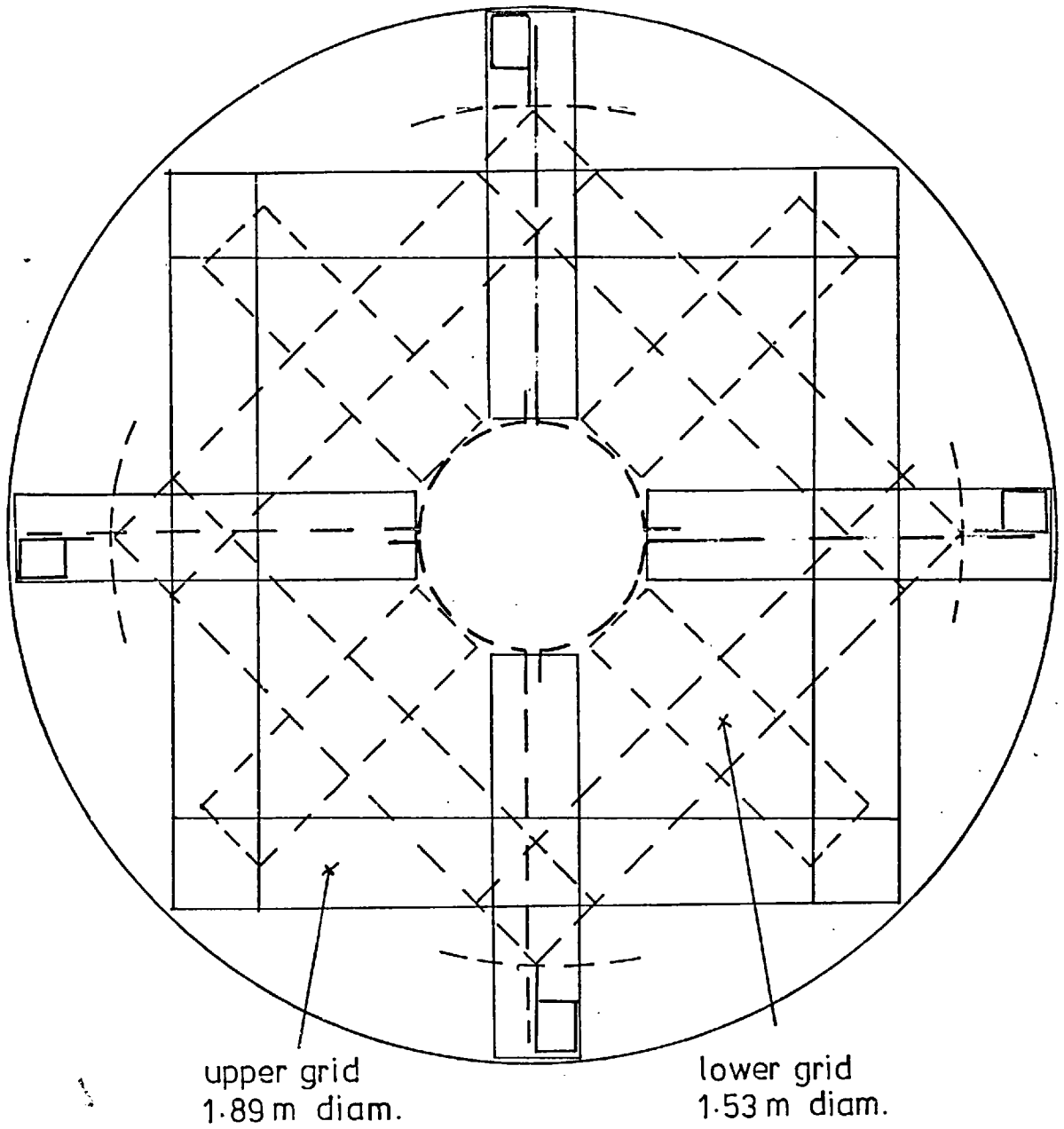
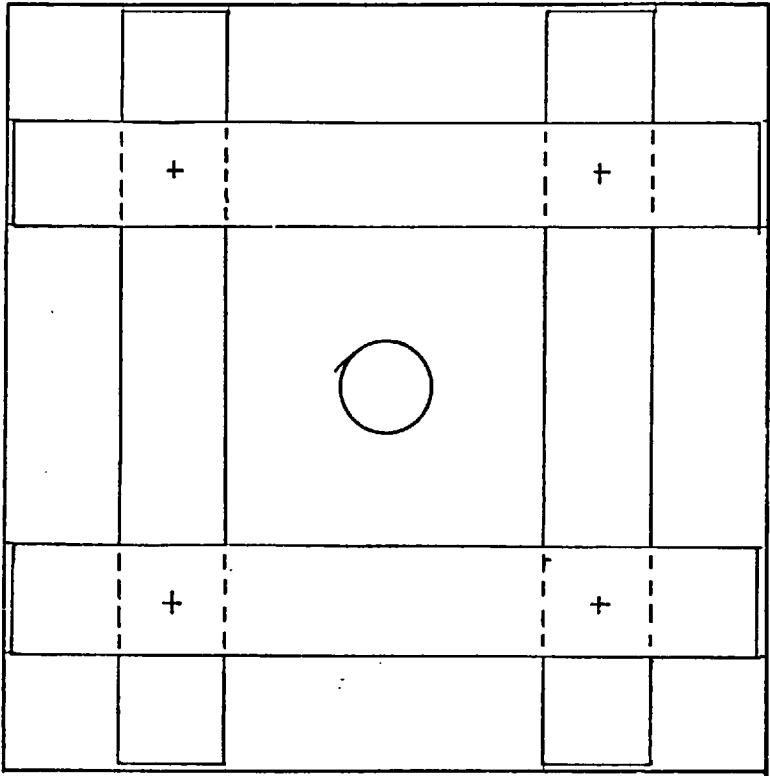
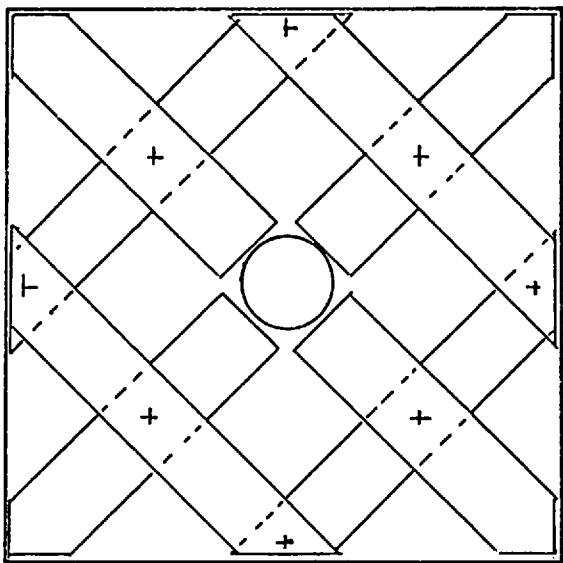


FIG 3.20 GRID GEOMETRY, 3.5 m DIAMETER TANK

scale 1:5



upper grid 0.51 m sq.



lower grid 0.37 m sq.

FIG 3.21 GRID GEOMETRY, 1.2m SQUARE TANK

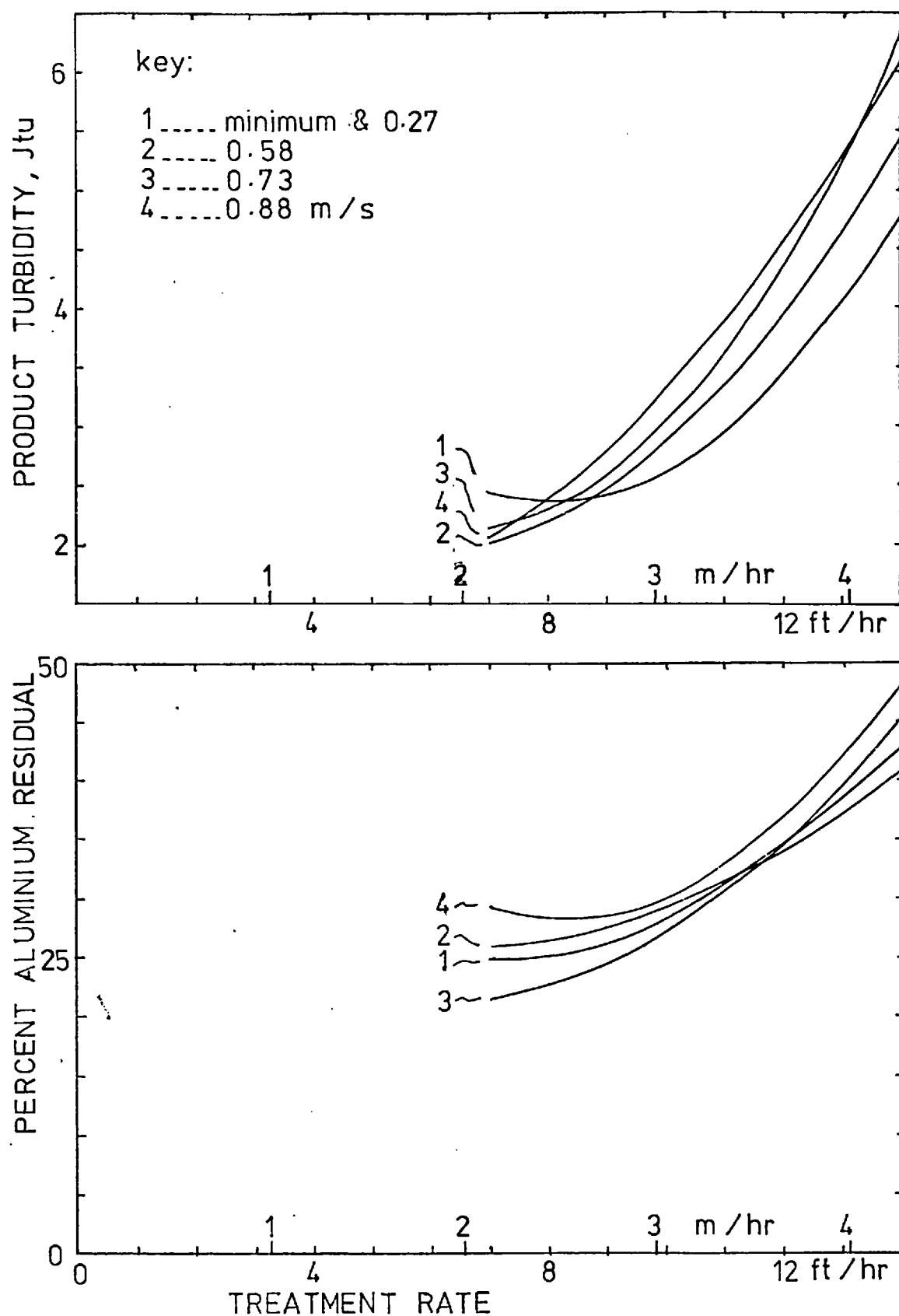


FIG 3.22 EFFECT OF INJECTION VELOCITY ON PRODUCT QUALITY, EXPT C17 (table 3.22)

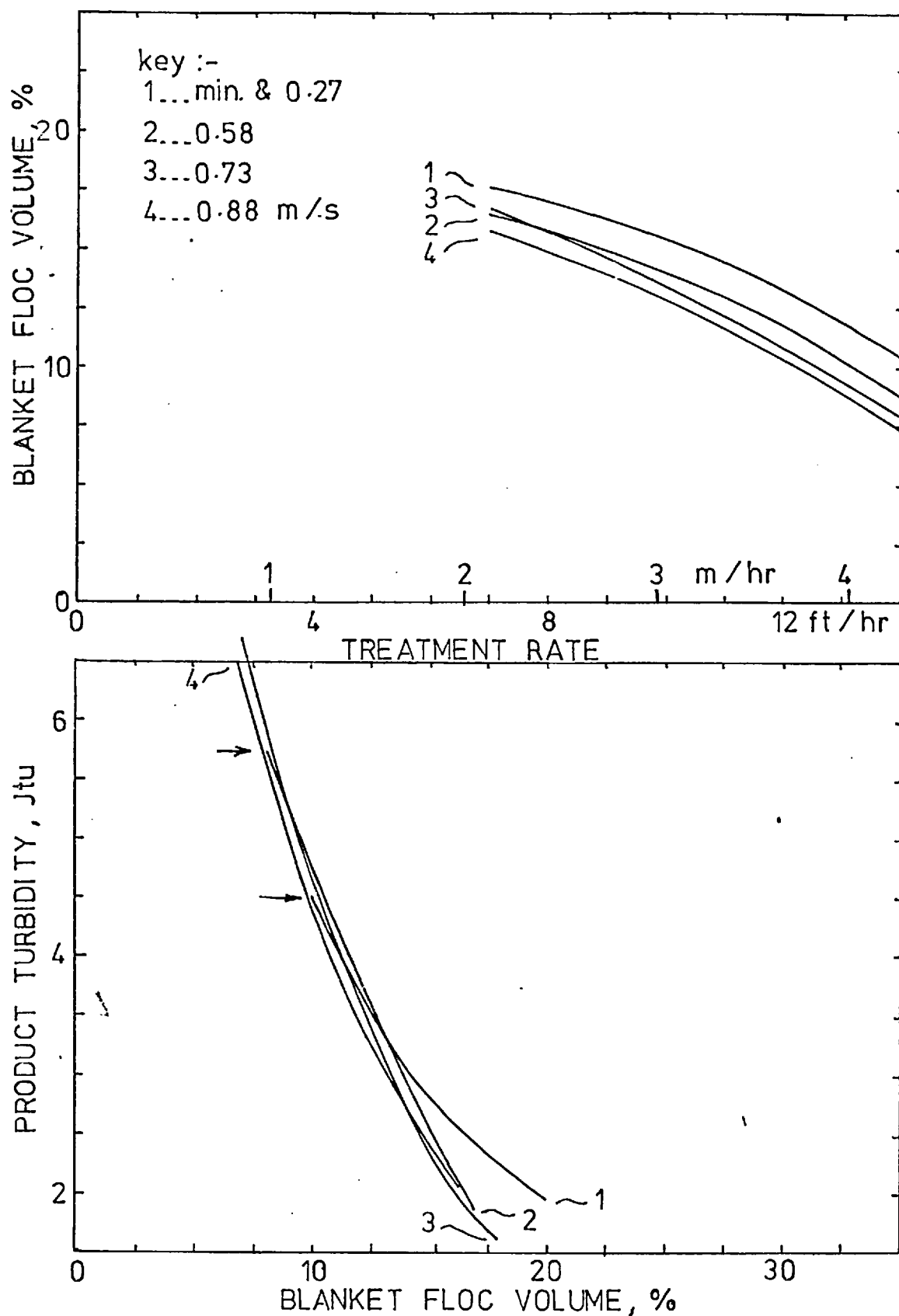


FIG 3.23 EFFECT OF INJECTION VELOCITY ON
 BLANKET QUALITY, EXPT C17 (table 3.23)

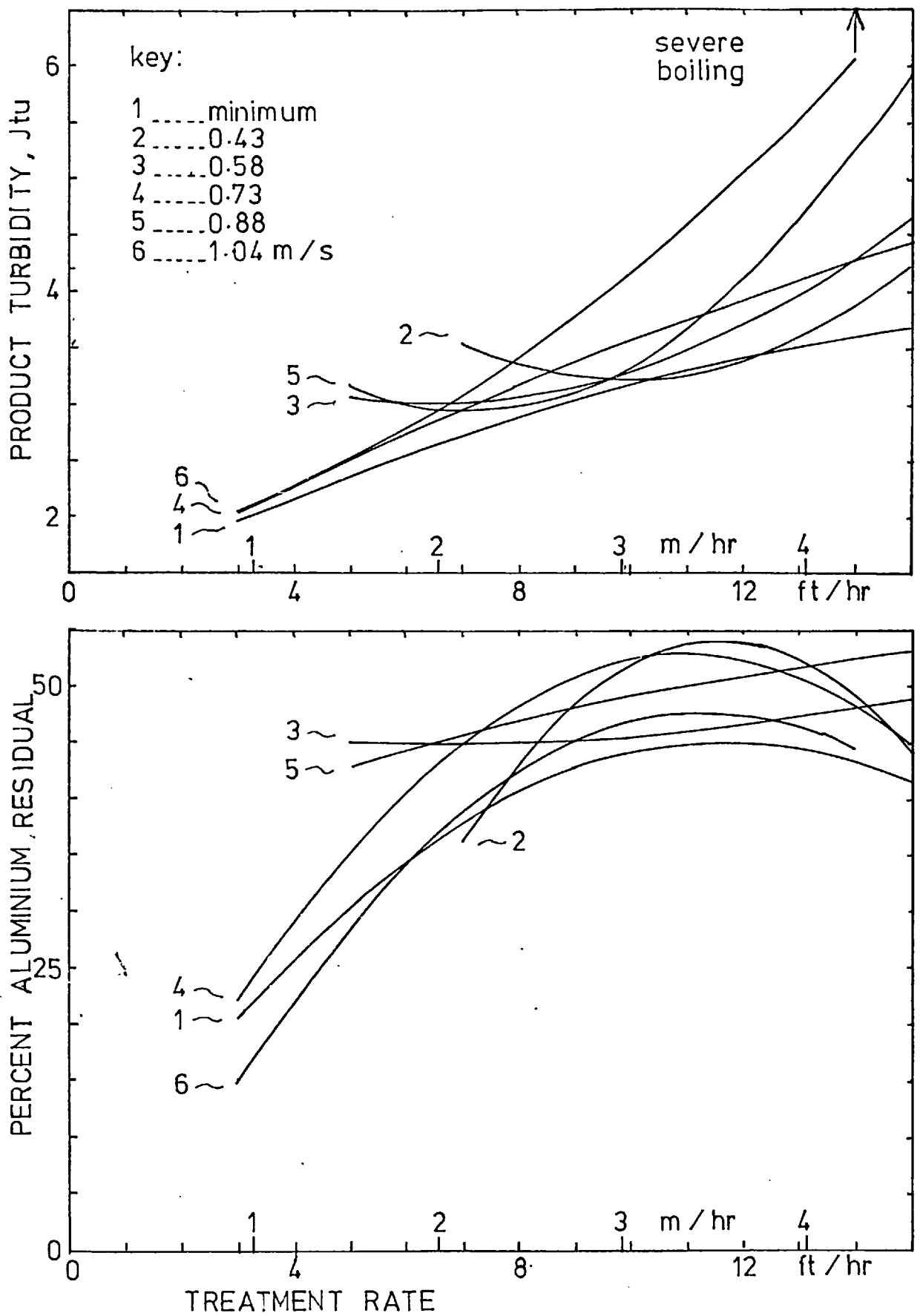


FIG 3.24 EFFECT OF INJECTION VELOCITY ON PRODUCT QUALITY, EXPT C18 (table 3.24)

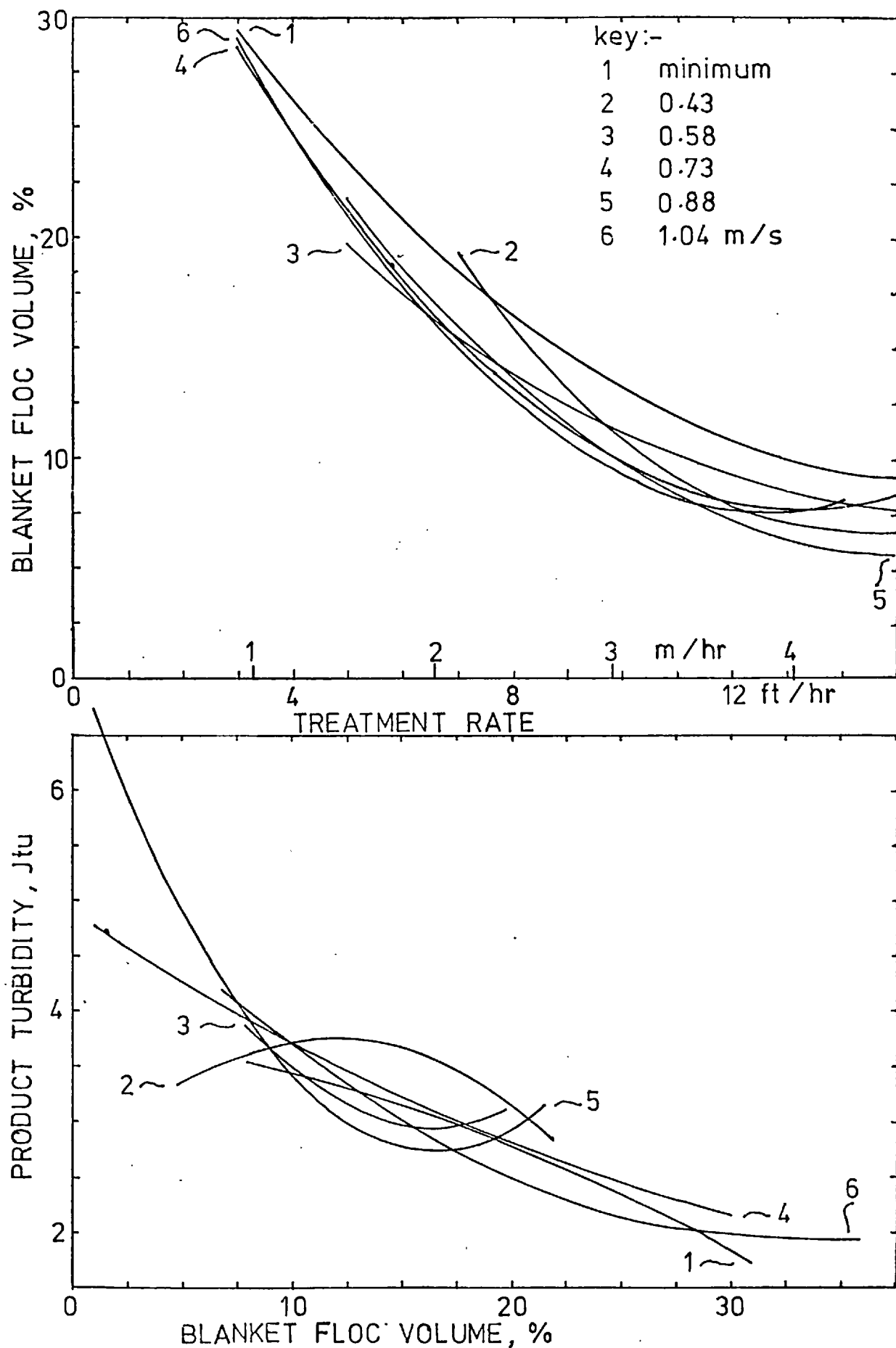


FIG 3.25 EFFECT OF INJECTION VELOCITY ON
 BLANKET QUALITY, EXPT C18 (table 3.25)

be closely related to the viscosity determined by the temperature of the water. The lower the temperature the better is the stability for high injection velocity. However, the greater the temperature the greater would appear to be the absolute treatment rate attainable. However, because of this, at high temperatures it might become easier to discern the effect of increasing injection velocity.

The 1.2 m tank was only operated for experiment B21 to examine the effect of the grid system alone, and operation at higher treatment rates was found possible. The tank was operated without grids or tube modules in experiments B12 and B16, though these two experiments differed with the inlet design, they can be used for direct comparison with experiment B21. In the application of tube modules any effect due to the grids might be found by comparing experiments B17 and B18 with B22. Comparison of the various results from the 1.2 m tank has been made in Sect. 3.3, Figs. 3.8, 3.9, 3.12 and 3.13. No substantial evidence was produced to illustrate benefit from the grids, although the fitting of the grids assisted the centering of the inlet and therefore flow bias (if noticed with the grids fitted) was small.

The full effect of improved tank performance would be for there to be no difference between the three tanks with increase in treatment rate. In experiment 21 the 1.2 m tank had about the same performance as the 3.5 m tank at the lowest injection velocities; which was only slightly worse than the 0.3 m tank. This performance relative to the 0.3 m tank was equivalent in experiment B12a, but not B12b which was worse. In experiment 16b any difference between the three tanks is difficult to distinguish. In experiment 16a the order of performance was representative of experiment 12. In experiment 17 and 18 there was little difference between the performance of the three tanks or between the two experiments. In experiment 22 the 1.2 m tank was worse in performance than the 0.3 m tank. This particular result would seem to contradict the nature of the rest of the results.

A theoretical analysis was made that suggested an improvement could have been obtained and in the general experience the 3.5 m and 1.2 m tanks were operated at higher treatment rates. Because high injection velocity conditions still caused poor performance in the presence of the grids a further examination could be justified using a third grid more closely dictated by a theoretical approach.

3.5. Effects of Control at the Blanket Surface

3.5.1. Use of inclined tube modules.

One of the developments in sedimentation has been the use of multi-layer inclined structures. The aim of such structures is to decrease the settling depth and therefore the time necessary for sedimentation. Such structures were conceived primarily for discrete settling systems, in contrast to the hindered settling conditions in a floc blanket. However, an application proposed for such structures is to place them above the blanket to act as a secondary settling or de-entrainment device. These structures are in the form of either a bank of plates all inclined in one direction or a nest of tubes also all inclined in one direction or with each vertical plane of tubes in alternate directions.

The principle of inclined tube settling for water and waste water treatment was developed by Neptune Microfloc Inc., USA, and has been recorded by Hansen and Culp (1967) and Culp et al (1968, 1969). However, little has been published about continuous settling, with constant upper surface, of concentrated suspensions between close inclined surfaces.

The WRA were given the opportunity to evaluate the application of tube modules in the laboratory by Clarke Chapman - John Thompson Ltd., who market Neptune Microfloc technology in the UK. The 1.2 m tank was used for the experiments with the concurrent investigations on the 0.3 m and 3.5 m tanks as the controls.

It must be emphasised that evaluation was the application of tube modules in upflow floc-blanket sedimentation as against unhindered settling in radial and horizontal flow designed tanks. However, some of the observations made will be relevant to these other applications. The evaluation has been prepared in greater detail for presentation elsewhere; Gregory (WRA 1973).

The general conclusion was that tube modules are unlikely to be of economic value in floc-blanket clarification although they can have hydraulic and hydrodynamic effects on floc-blanket behaviour.

3.5.1.1. Application: 1.2 m tank.

The modules had been constructed from plastic sheeting to form multi-lamella structures of tubes, the direction of inclination of the tubes

alternating with adjacent vertical lamella. Each tube is 51.0 mm square to its axis and inclined 60° to the horizontal, Fig.3.26. The height of a module was 0.53 m and originally constructed to give a length of 1.22 m. The 1.2 m tank was installed with a total of 23 lamella with the alternating inclination maintained. The lower surface of the modules was 0.31 m above the sludge bleed points to give 2.14 m parallel flow depth below the modules, Fig.2.5.

The sequence of the investigations to evaluate the tube modules is given in Table 3.26. Also listed, or referenced, are other data relevant to the evaluation which have been presented in other sections. The table notes the relative behaviour of the 1.2 m tank under the heading of 'observation'. The water temperature should be noted during these experiments. The quality of the floc encountered is noted in terms of the total blanket aluminium per per cent blanket floc volume. The performance during each experiment is noted both in terms of the product turbidity at the standard treatment rate of 2.4 m per hr and as the treatment rate associated with the standard blanket floc volume of 10 per cent. The results of operating the tank with the tube modules installed are presented in Figs.3.27. to 3.30. The overall comparison of tank performances, Sect.3.3, should also be referred to. Operating with the blanket level below the modules no difference in performance can be established compared with the performance of the tank when not fitted with tube modules. Operating with the blanket into the modules, experiments 23 and 24, an improvement is evident, as shown by the increased blanket floc volume concentration in Fig.3.28, but the improvement in product quality as indicated in Fig.3.30. was only marginal.

The interpretation of the results is considered conclusive. When operating with the blanket below the modules little improvement in performance will be obtained if the tank is naturally stable at high treatment rates. When the tank is unstable the improvement is due to the modules acting as baffles with the mechanism of shallow layer inclined settling very much secondary to the mechanism of flow stability control.

The tube modules were found to slightly improve tank performance when a stable blanket is operated within them. This would appear to be

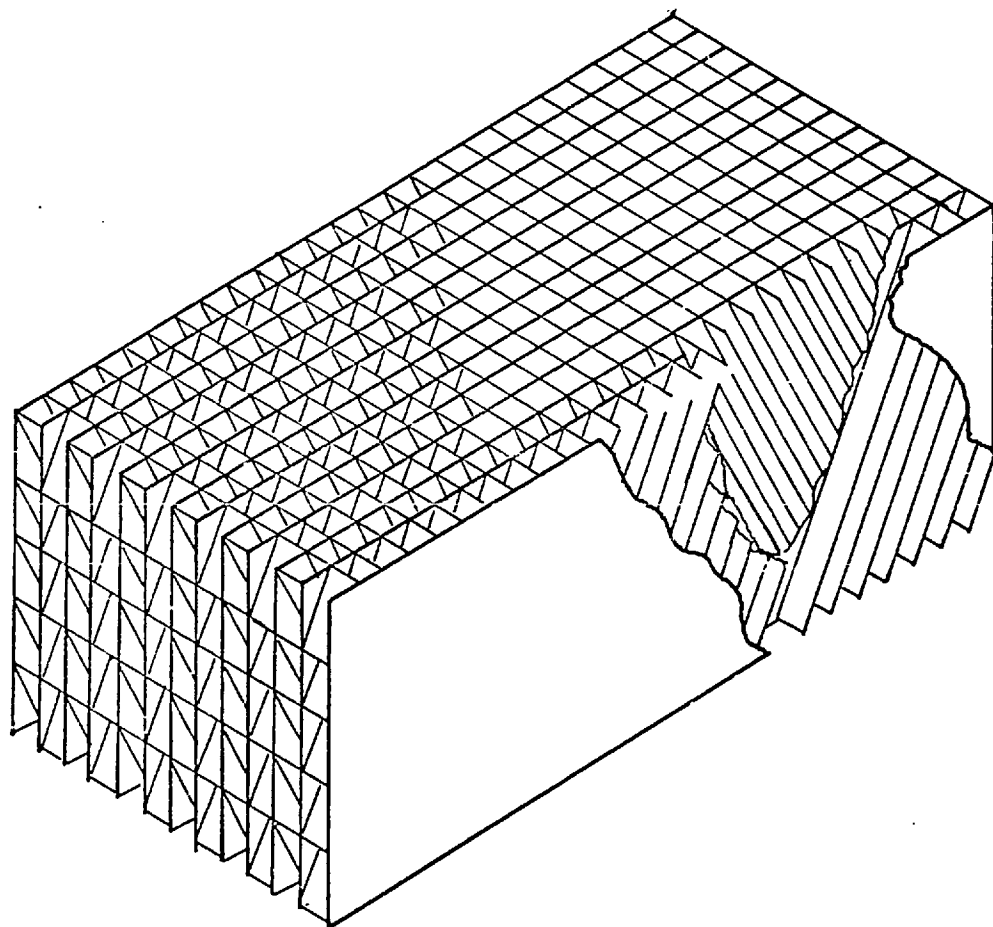


FIG 3.26 MODULE OF INCLINED TUBES

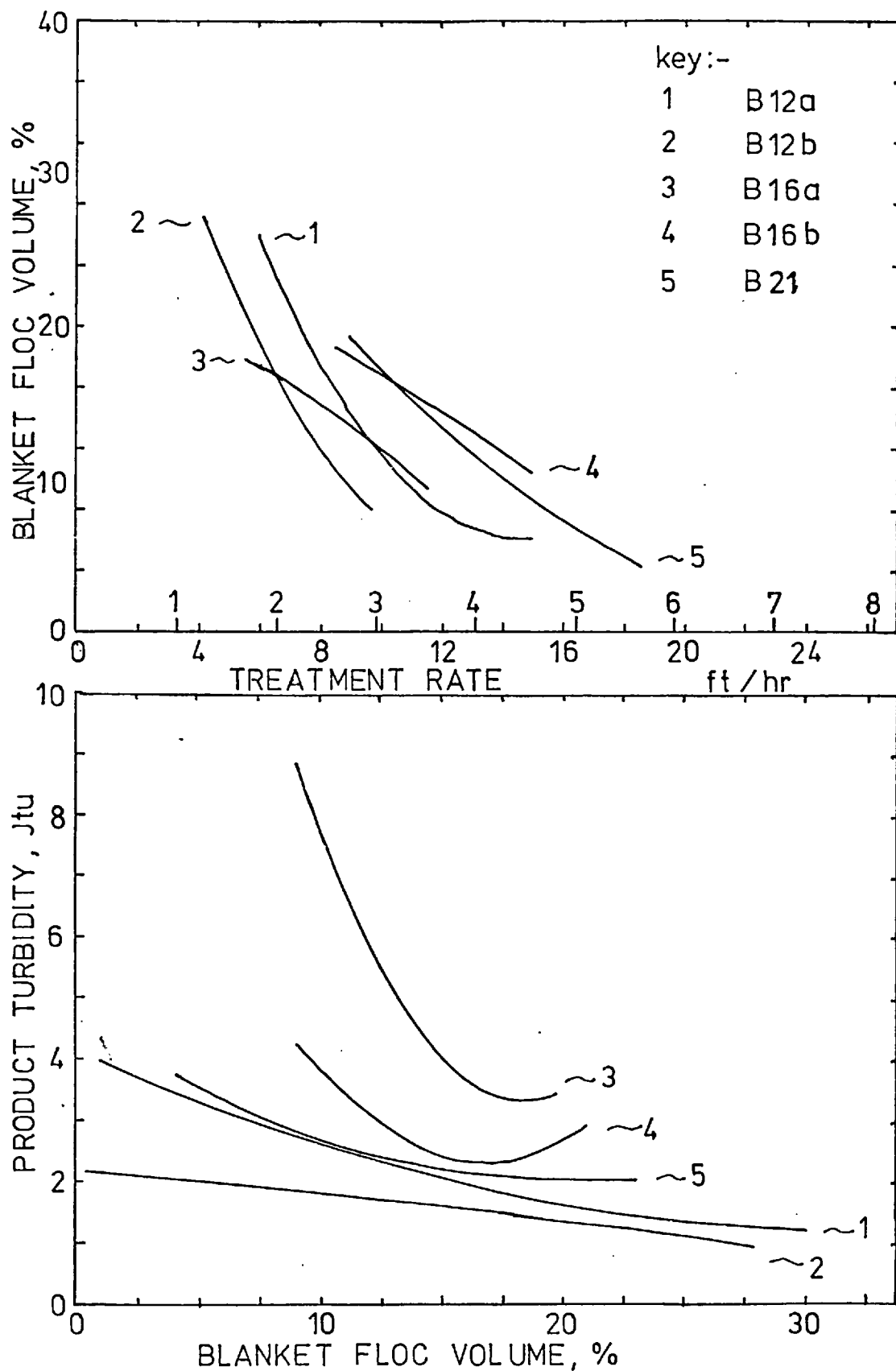


FIG 3.8 COMPARISON OF BLANKET QUALITY
3.27 RELATIONSHIPS FOR THE 1.2m TANK
WITHOUT TUBE MODULES (table 3.8)

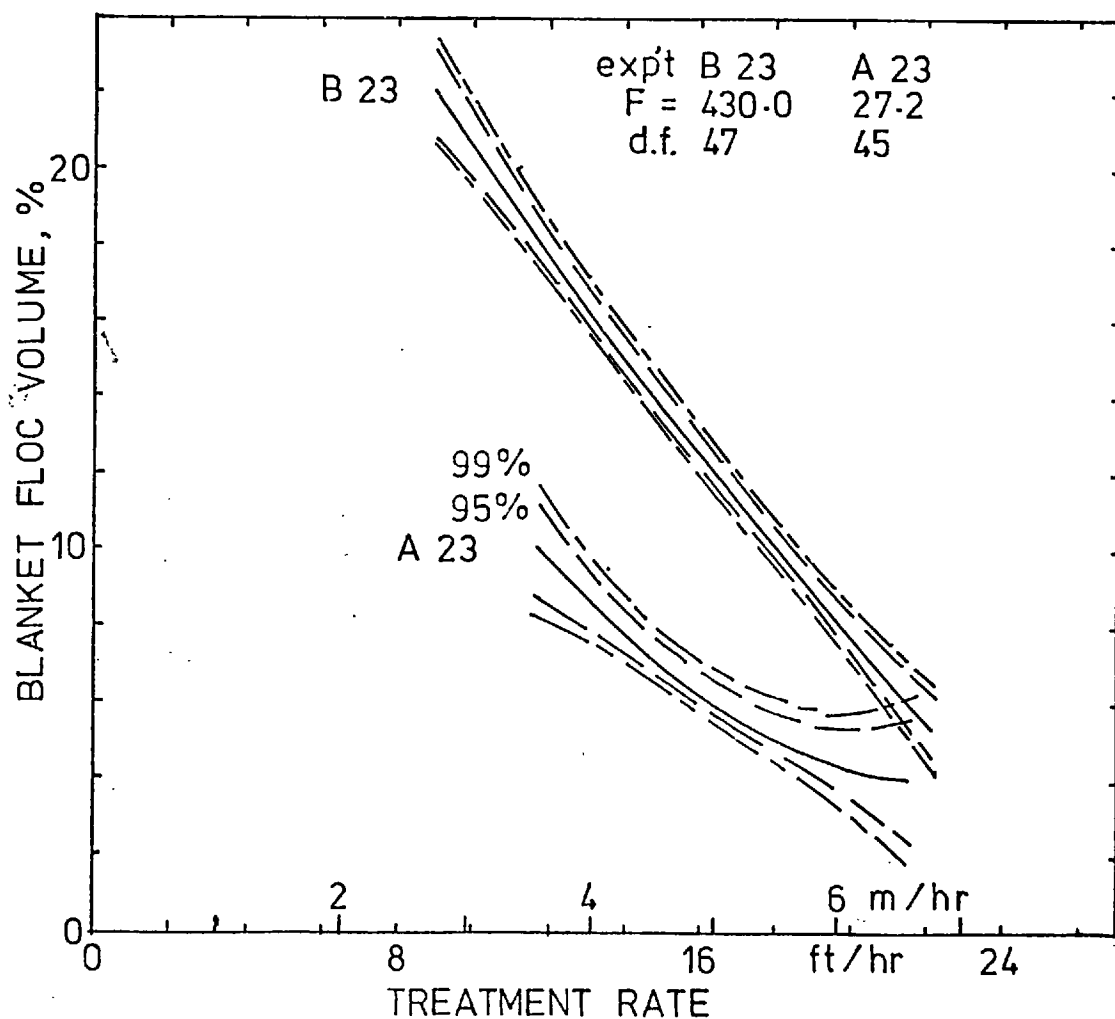
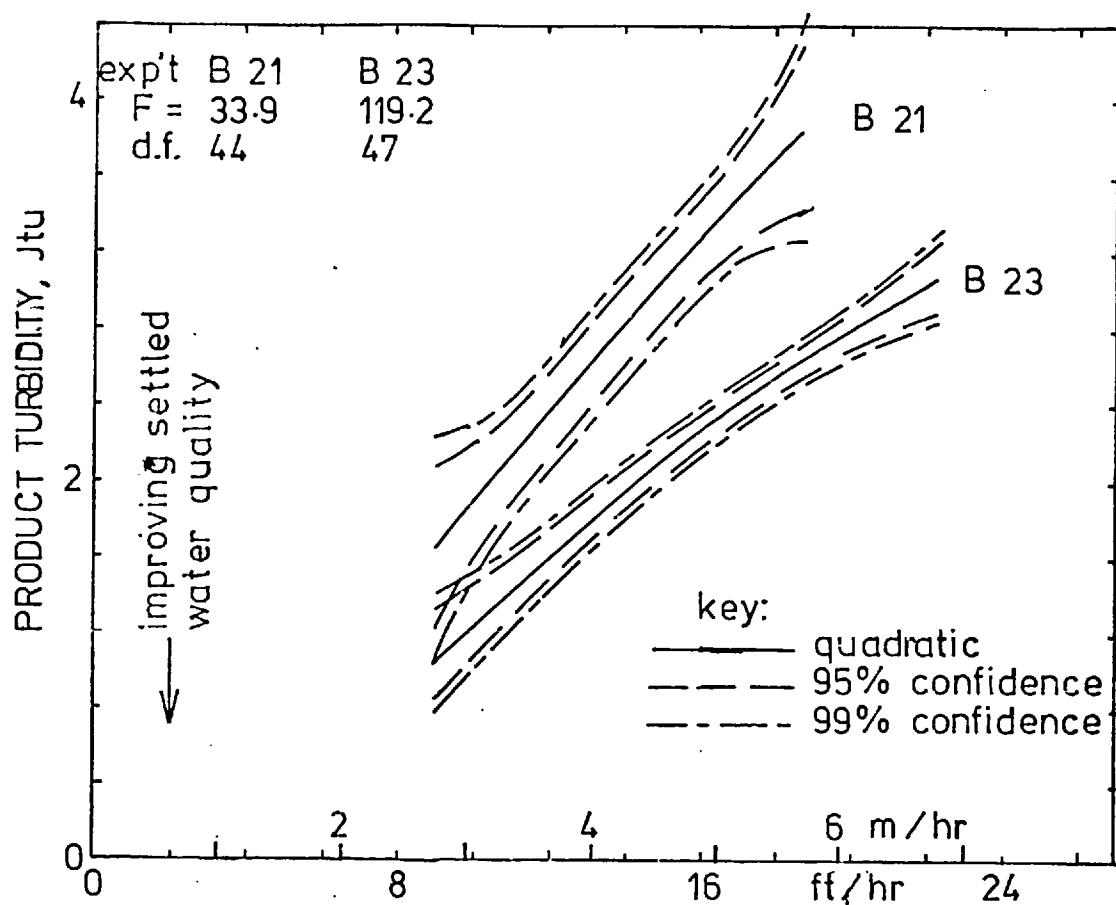


FIG 2.8 THE CONFIDENCE LIMITS IN INTERPRETATION OF THE REGRESSIONS

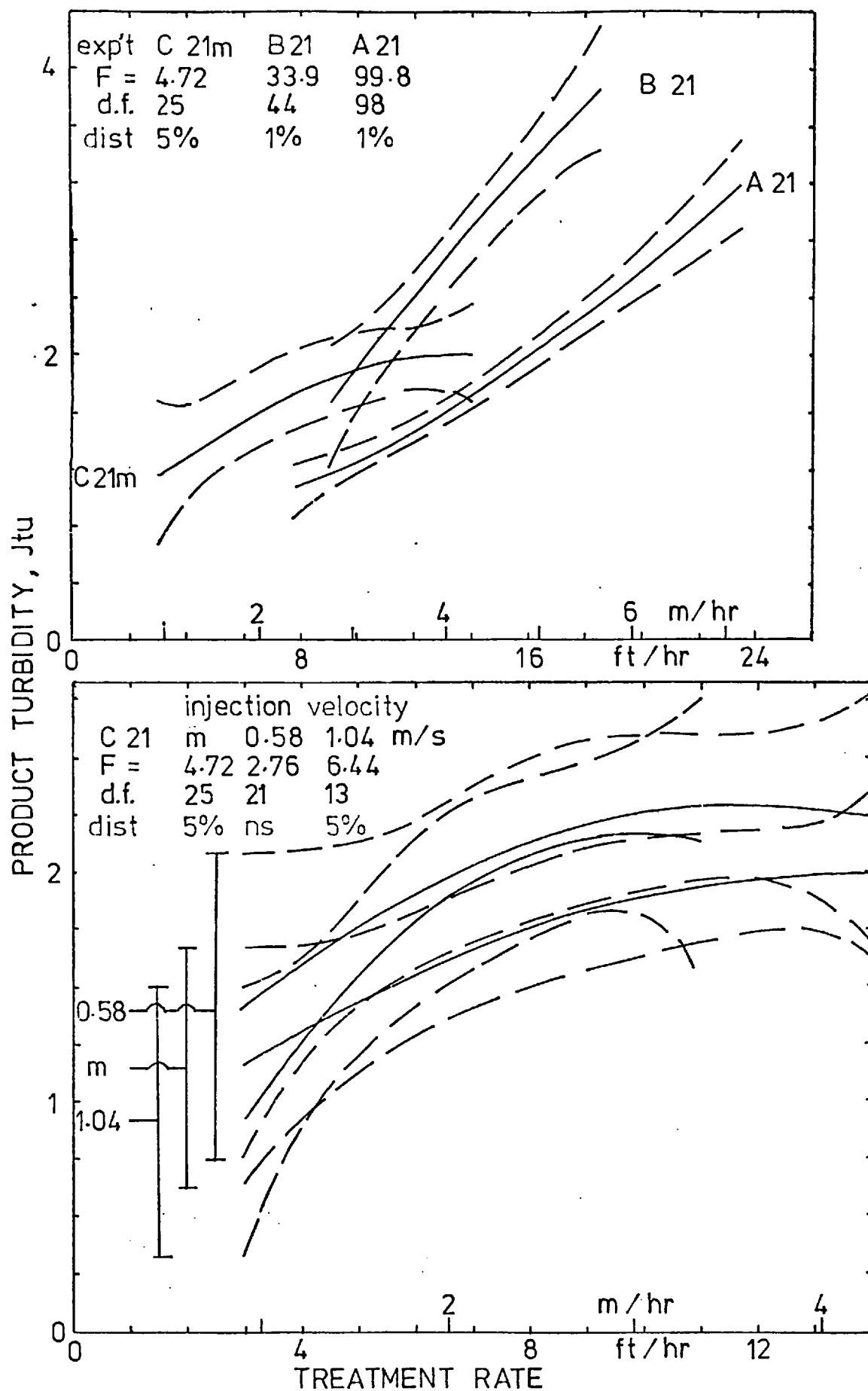


FIG 2.9 THE 95% CONFIDENCE LIMIT IN INTERPRETATION OF THE REGRESSIONS

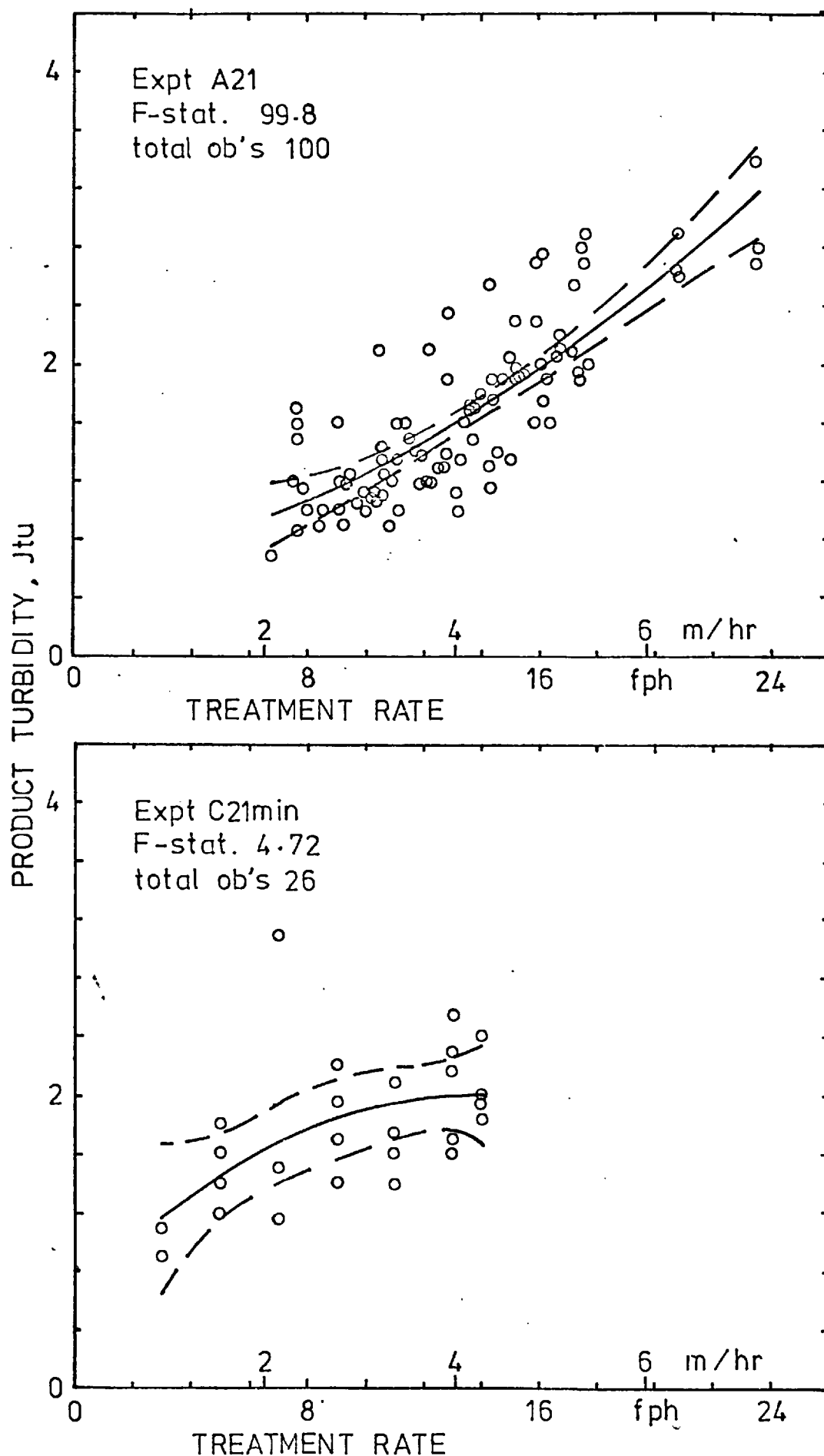


FIG 2.10 REPRESENTATION OF DATA BY REGRESSION ANALYSIS AND THE 95% CONFIDENCE LIMITS

Computing Services Ltd. The original facility was with the Atlas computer. In early 1972 this was changed to a CDC 200 User Terminal linked to a CDC 6500 computer. The section of the WRC which operates the computer facilities also provided assistance in the statistical analysis of the data.

2.3.2. Advantage of further refinement.

For some of the quadratic regressions, curve forms different from that expected were obtained such as extreme concavity, to give a minimum, or convex when concave is expected. Such forms represent the data as analyzed by the model and are due both to the empirical model and to the quality of the data although high confidence fits might still be obtained. They can nevertheless, with due allowances in their interpretation, be used for comparative purposes.

The examination of the various orientations of the quadratic which were obtained and examination of some of the distributions of residuals for these non-ideal orientations indicated that third order, cubic, regressions might have been more suitable. However, should such correlation be attempted caution would need to be taken in the interpretation of its success since a more complex model can improve the regression. c.f. concentration - velocity correlation, Sect. 4.1. Unless the more complex model is justified the simpler model should be preferred. Not only is the simpler model cheaper to use but is less likely to be misinterpreted. Some data sets were subjected to cubic regression. For those data sets examined no obvious improvement in regression could be obtained. The removal of one of the terms of the independent variable from the cubic model was often of little importance as the examples in Table 2.3. illustrate, by comparing the usually small value of the sum of squares due to that term with sum of squares due to the regression.

3. EXPERIMENTAL RESULTS

3.1. Effects of Uncontrolled Variables

Uncontrolled variables refers to the raw water quality parameters that were or were not measured, the experimental environment and other factors beyond the control of the experiments that could influence the results.

When the experimental work on the 3.5 m tank was initiated the first experiment was a 2-factorial-5 design test examining five controllable variables each at two levels. Ultimately the conclusions were not as firm as was hoped for with the factorial design approach causing certain operational problems. Similar comments have been made by Orcutt (1972) who used the same type of design of experiment in waste water floc-blanket sedimentation. The objective had been to determine the order of relative effects on the performance of the tank of the controlled variables considered. The variables were treatment rate, blanket level, injection velocity, recirculation rate and launder configuration. Blanket level was measured as the depth of the blanket surface below the surface of the water. Although this is the supernatant depth it is also a measurement by difference of the total depth of the blanket; different recirculation rates were obtained by the PCI variable velocity device; launder configuration was changed by blocking half the peripheral overflow holes.

Because this first experiment was not satisfactory a more elementary design of experiment was used. Treatment rate (upflow velocity), injection velocity and recirculation rate were examined more closely. The effects of blanket depth and supernatant depth have previously been demonstrated by Miller et al (1965) on small diameter units. Statistical evaluation of the results (experiments C3 and C4) demonstrated the relative importance of uncontrollable variables which include those which are monitored and unmonitored in the feed and the environment and also variations due to the experimental procedure, Table 3.1. For example in experiment C3, in the analysis of the Hach turbidity data, the uncontrollable variables caused a coefficient of variation of 15 per cent which could be reduced to 12.5 per cent by allowing for measured variations in the raw water quality.

To establish this more clearly the tank was operated under constant controllable conditions for three weeks (experiment C5) with about four sets of samples taken each day. Analysis of the results by regression confirmed that high levels of variability, due to uncontrollable and unmeasured variables, were possible in the settled water quality. The experiment was repeated two years later, as experiment ABC 20, with the three tanks in parallel. The results are summarized in Tables 3.2. and 3.3. Table 3.2. gives the correlation matrix analyses for the two experiments. The analysis shows the comparative importance of the parameters measured. The relative contribution of the parameters to the correlations is shown in Table 3.3. For example, for product turbidity, as given in the analysis of experiment C5 and illustrated by Sub-table 3.3, the temperature difference between the laboratory and the water accounted for 47.8 per cent of the total variance due to uncontrolled and unmeasured variables. Inclusion of other measured variables improved this to only

Observation	Tank	Uncontrolled variable						
		Water Temp 1	Air Temp 2	Temp Diff 3	Dose Al 4	Raw water		Mean sd
						580 OD 5	400 OD 6	
Product JTU	C5 (Hach)	- ns	59.7	47.8 22.8	58.2	57.2 4.2	53.4 5.7	1.640 0.407
Upper value		Per cent of coefficient of variance accounted for.						
Lower value		Per cent increase in the residual sum of squares if >2.0.						

Sub-table 3.3. ANALYSIS OF CONTRIBUTION BY UNCONTROLLED VARIABLES TO TANK PERFORMANCE

59.7 per cent. It was noticed that the air-water temperature difference had generally a significant contribution to the effect of the uncontrollable variables. The air-water temperature difference was then regarded as one of the important environmental factors acting upon the tanks, to which the 0.3 m tank was apparently particularly sensitive.

These results show that tank performance can be greatly affected by uncontrollable variables and that confident correlations of tank performance

can be difficult to obtain. The relative levels of variability of such parameters are seasonally dependent so that their contribution to tank performance will vary likewise.

The data indicates that the 1.2 m tank was the most stable, as shown by the comparison of the standard deviation of the performance parameter, with the mean value. Settled water quality was comparatively unaffected by environmental factors as it had the smallest coefficients of variance that could be accounted for. Also worth noting is that when the standard deviation of the performance parameter is small the coefficient of variance that can be accounted for is also small; that the raw 580 nm absorbance and dose aluminium figures were both prominent in accounting for the variances; and that the blanket floc volume and product turbidity are the more sensitive measurements of tank performance. This is shown by the larger values of the ratio of their mean value to the standard deviation, and the tendency for them to be able to account for a greater proportion of the variance.

3.2. Effects of Tank Shape and Size

From Table 3.4, giving comparative information of the three hopper tanks, 0.3 m, 1.2 m and 3.5 m, it can be seen there is, very approximately, a factor of ten difference in cross-sectional area between the tanks. One might therefore expect to distinguish a difference in performance between the tanks if a scale factor exists. It is important to note that for the level of each tank at which the blanket was normally kept all three tanks had approximately equal relative blanket volumes, i.e. total volume of blanket per unit maximum cross-sectional area. This means that for these blanket levels at equivalent treatment rates the mean residence time of the flow within the blankets can be equal. It is recognized that the relative proportions of the blanket contained by the hopper and parallel sections for each tank were substantially different.

Two sets of data, experiments 12 and 16, were obtained to provide an initial comparison of performance between the three tanks. For experiment 12 nothing intentional was done to cause the tanks to produce their best performance under the water conditions prevailing other than

providing the required attention to coagulant dosing. For experiment 16, the minimum injection velocity for the 3.5 m tank was used and the inlet of the 1.2 m tank had been modified, as explained in Sect. 3.4.2.

Experiment 12 was carried out under "summer conditions" and experiment 16 under "winter conditions". In both experiments flood periods were encountered and in each instance the peak flood imposed a temporary suspension of the experiment.

In experiment 12 the opportunity was taken during the flood period to clean out the 1.2 m tank. Upon recommencing the trial, the performance of this tank was not as good as it had been prior to the flood. This was identified by not being able to operate at the higher treatment rates and still maintain the blanket. It was necessary to extend the experimental period to obtain adequate data to identify the new performance as well as the original. The data for the other two tanks were found not to require divided analysis. However, for experiment 16 the flood period caused the data for all three tanks to require divided analysis.

In Figs. 3.1. to 3.6. various quadratics derived by regression analysis have been plotted, as described per Sect. 2.3.; the quadratics are also tabulated in Tables 3.5. and 3.6.

Figs. 3.1. and 3.2. show the relationship between product quality, in terms of aluminium concentration and/or turbidity, and blanket floc volume concentration. It is to be noted how little difference there was between the three tanks for all three experimental sets, i.e. 12, 16a and 16b, other than for B12a.

Figs. 3.3. and 3.4., which present the relationships of blanket floc volume concentration and blanket flux with treatment rate, show that there were obviously not only differences in hydraulic performance between the tanks but also that chemical conditions can influence these differences. Blanket flux has been calculated as the product of blanket floc volume concentration and treatment rate, where %fph is equivalent to $100 \text{ ft}^3/\text{ft}^2 \cdot \text{hr.}$

Figs. 3.5. and 3.6. present the conventional performance relationship of product quality with treatment rate. Product quality is expressed in terms of per cent aluminium residual of the dosed aluminium concentration

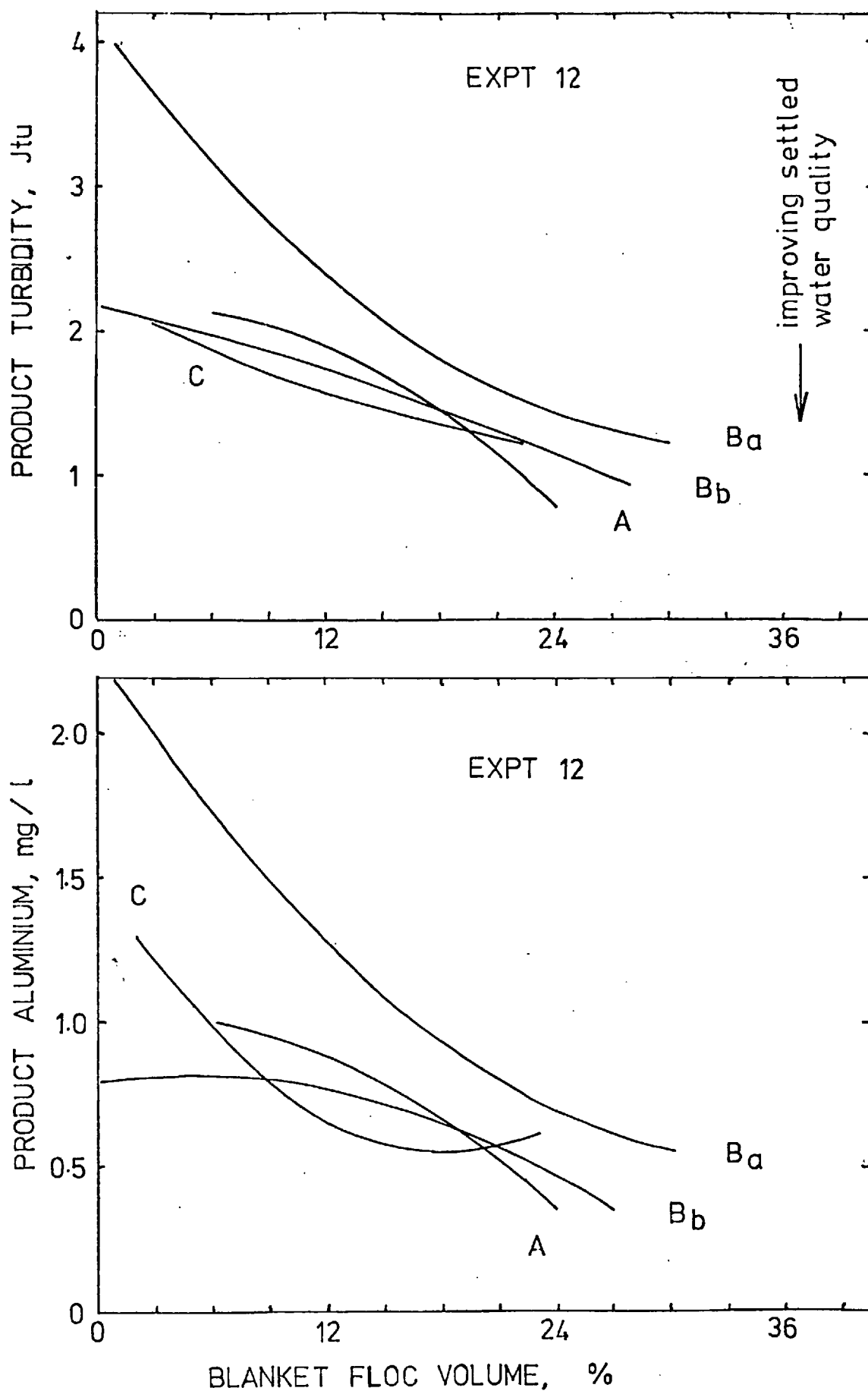


FIG 3.1 PRODUCT QUALITY — BLANKET FLOC VOLUME
RELATIONSHIP, EXPT 12 (table 3.5)

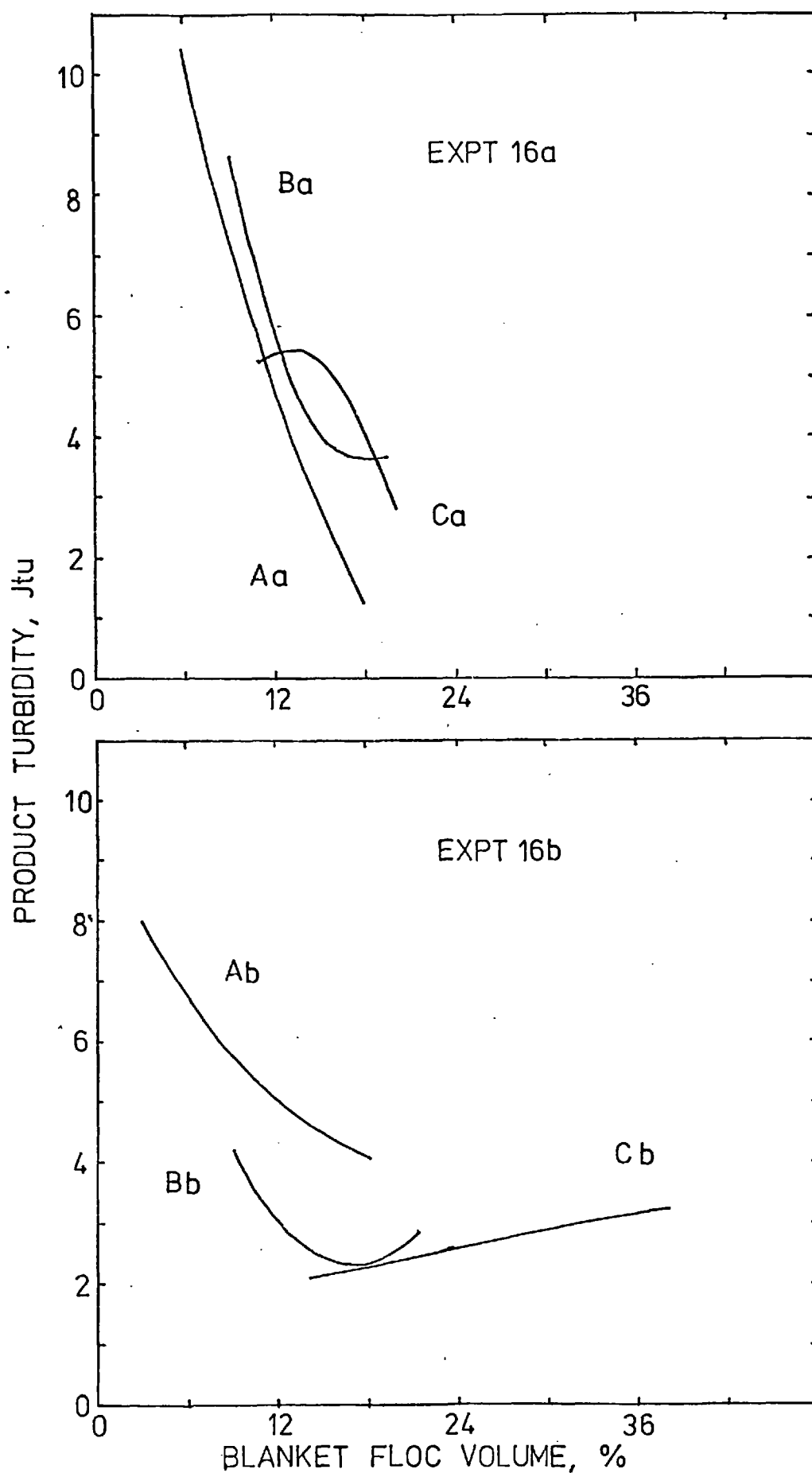


FIG 3.2 PRODUCT TURBIDITY — BLANKET FLOC VOLUME
RELATIONSHIP, EXPT 16 (table 3.6)

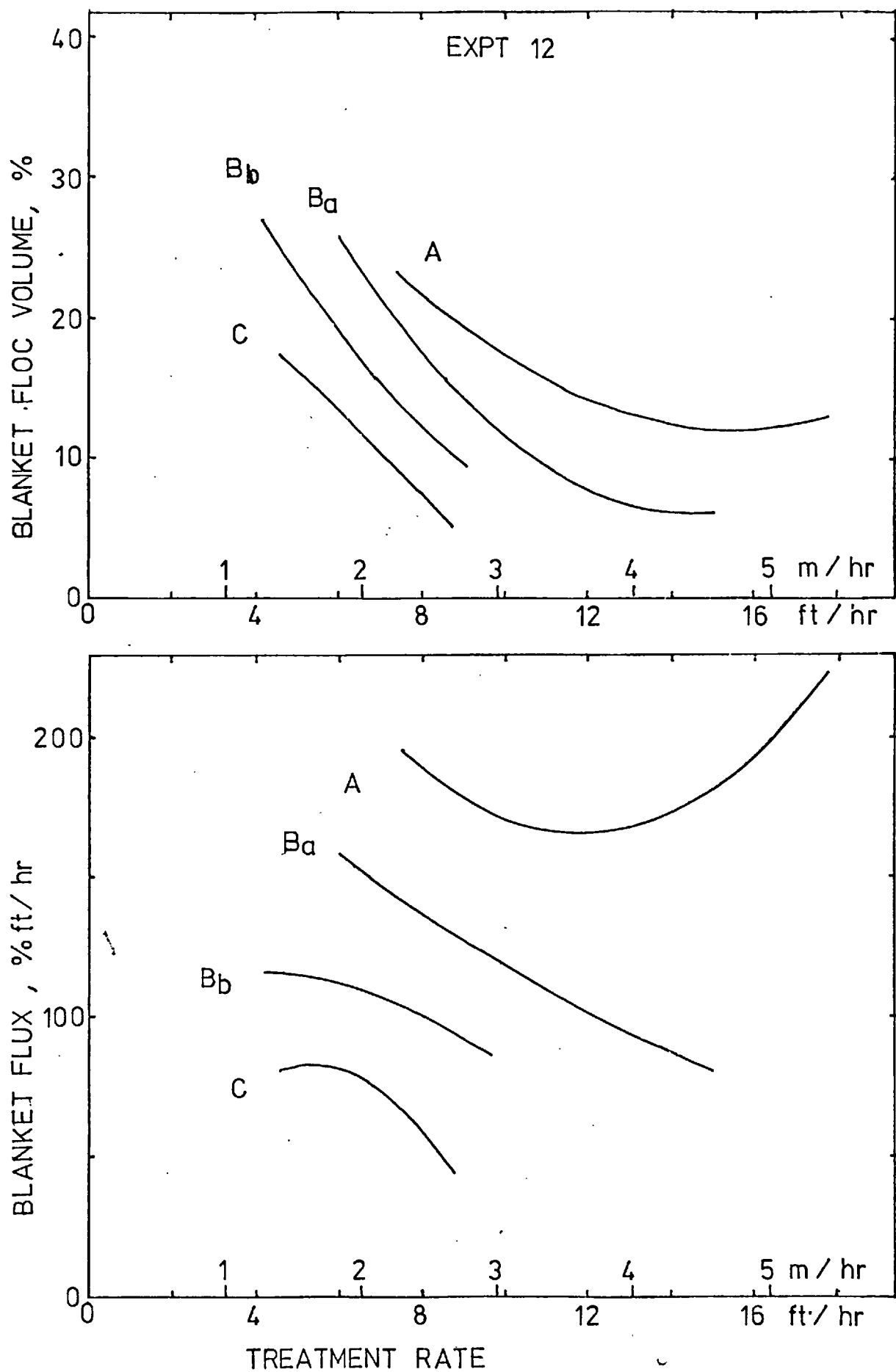


FIG 3.3 BLANKET QUALITY—TREATMENT RATE
RELATIONSHIP, EXPT 12 (table 3.5)

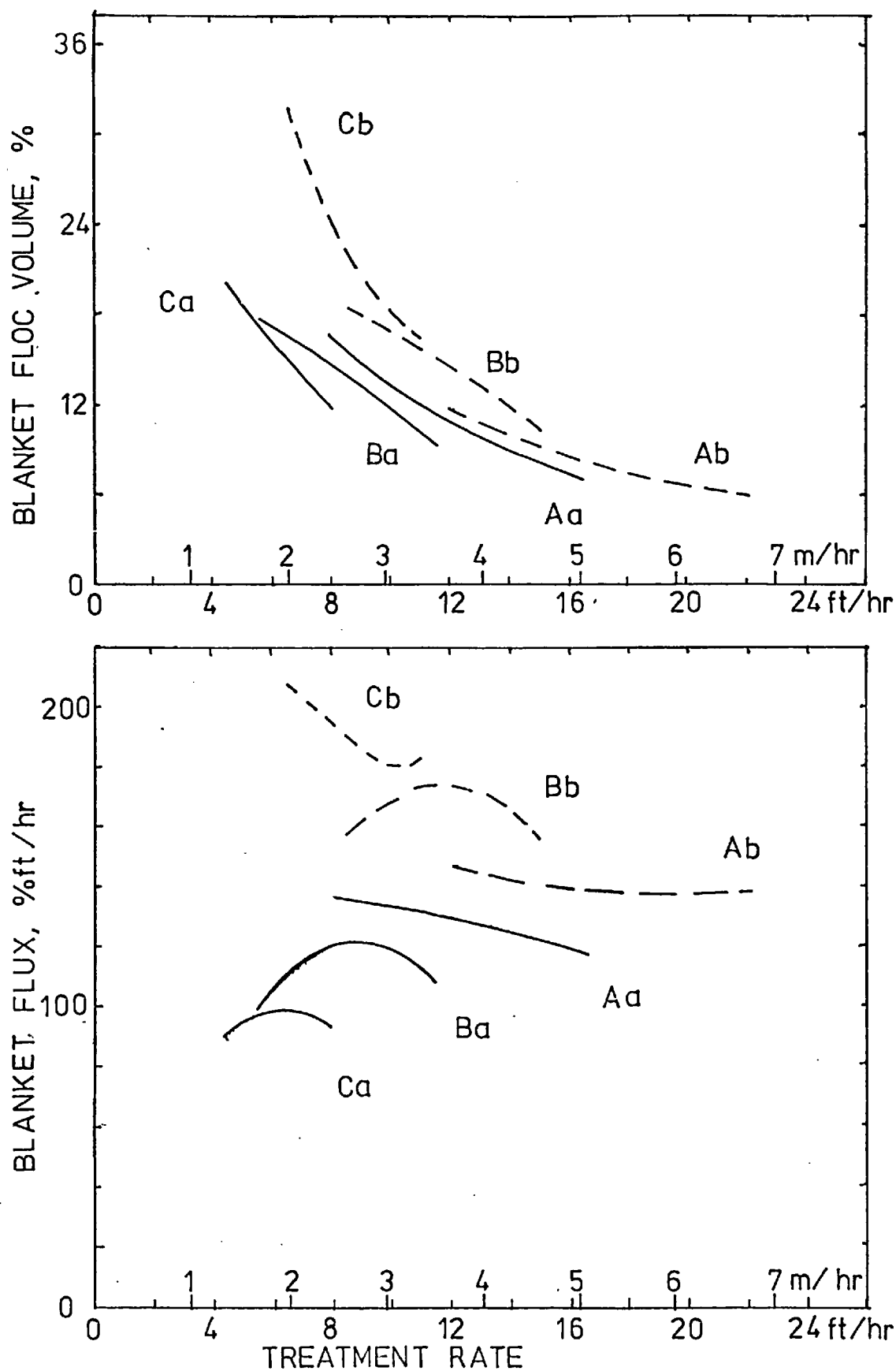


FIG 3.4 BLANKET QUALITY—TREATMENT RATE
RELATIONSHIP, EXPT 16 (table 3.6)

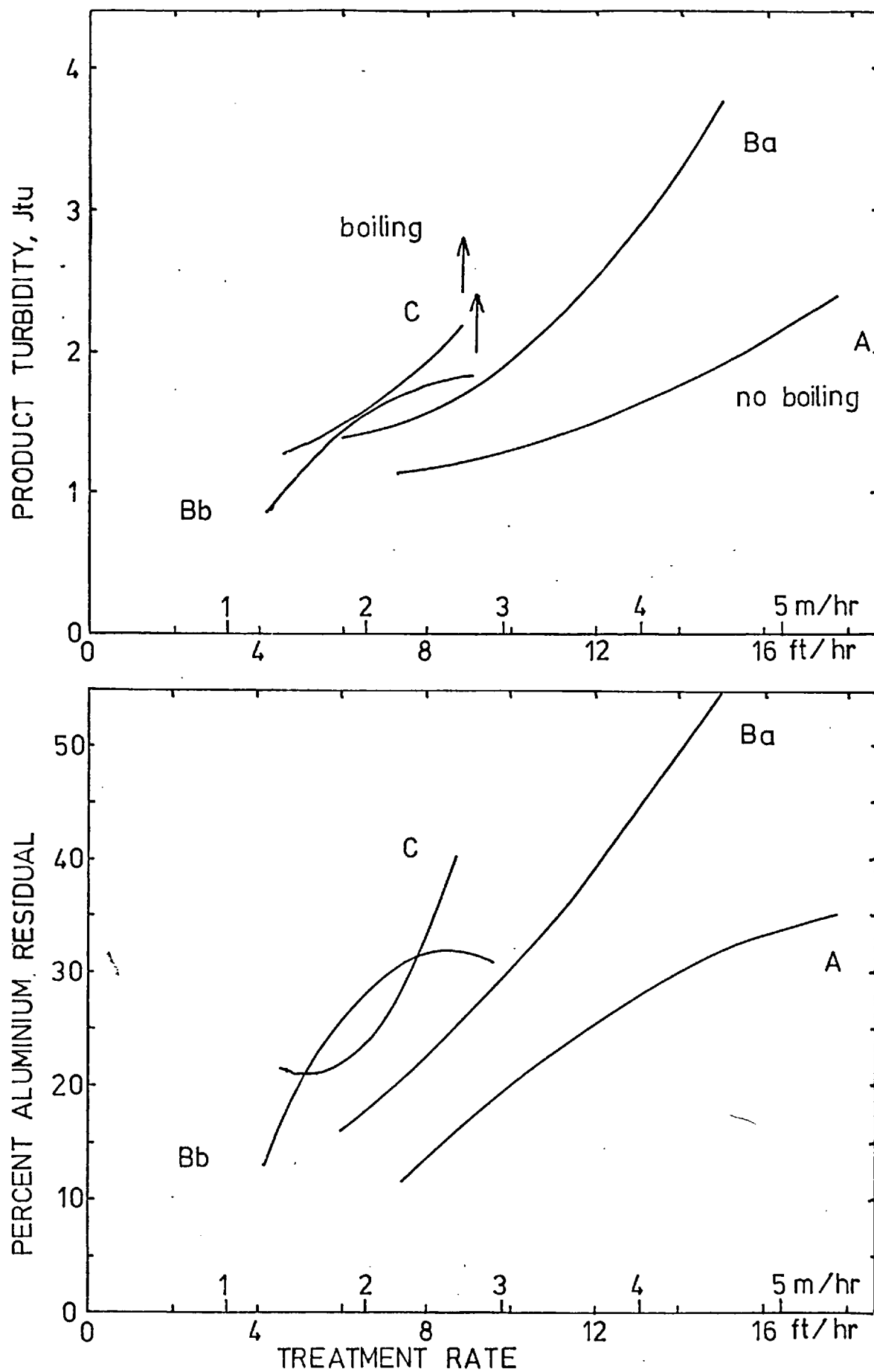


FIG 3.5 PRODUCT QUALITY—TREATMENT RATE RELATIONSHIP, EXPT 12 (table 3.5)

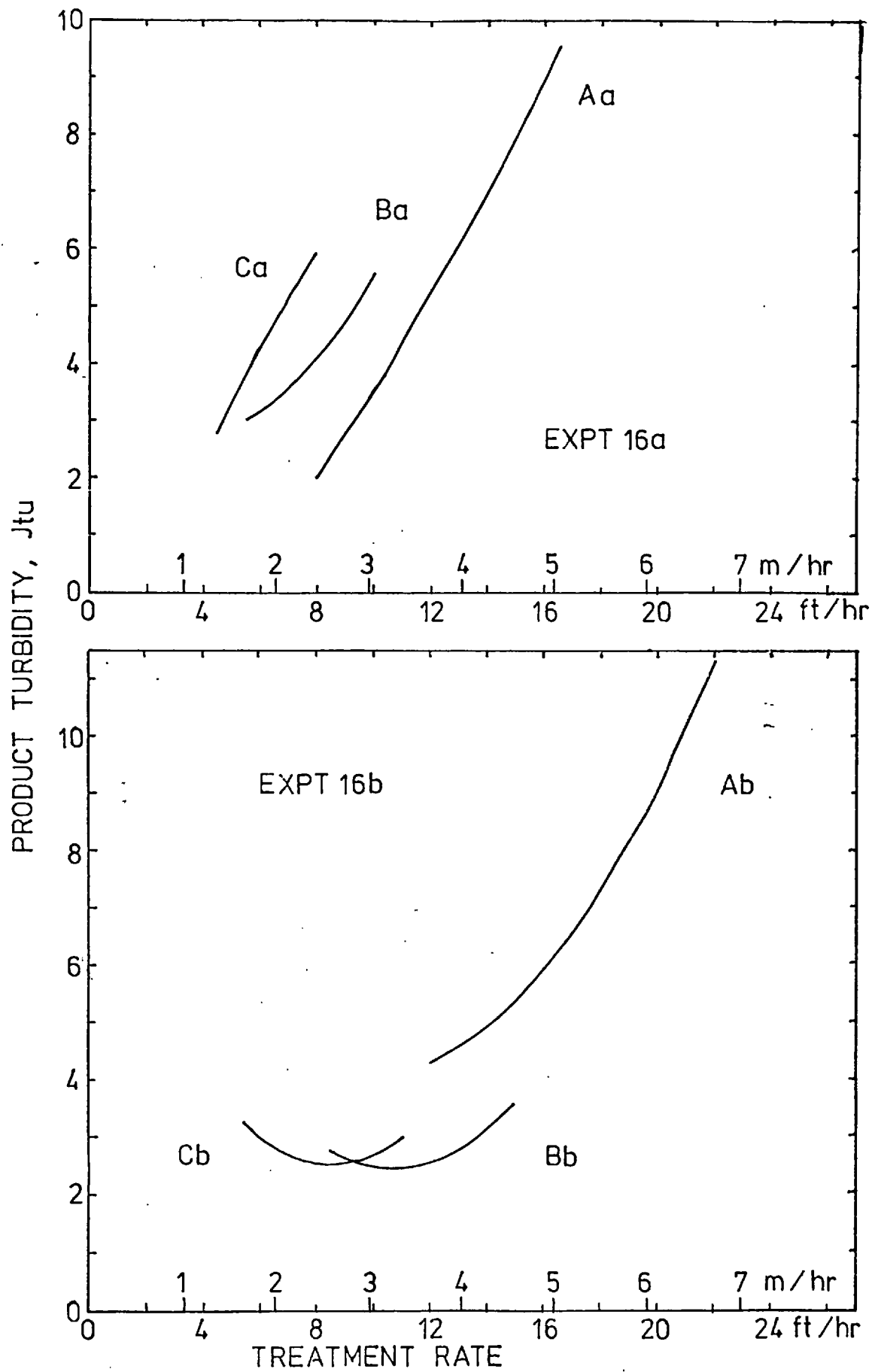


FIG 3.6 PRODUCT TURBIDITY—TREATMENT RATE
RELATIONSHIP, EXPT 16 (table 3.6)

and/or turbidity. These figures also show that there were obviously effects due both to the tanks and to the chemical conditions. The results of experiments 12 and 16a were consistent in as much as the 0.3 m tank gave a better performance than the 1.2 m tank which in turn was better than the 3.5 m tank. This was not evident for experiment 16b when there was some indication that the reverse was the case. This could have been associated with the quality of the blanket that had accumulated during the flood conditions that separated experiments 16a and 16b.

Particularly with regards to experiment 12, it was observed that the performances of the three tanks were associated with their hydraulic stabilities as indicated by boiling, where boiling indicates the appearance of localized but large-scale turbulent motion at the blanket surface. Boiling was not associated with the 0.3 m tank. For the 3.5 m tank treatment performance could not have been reported at higher treatment rates because of the extreme instability associated with the boiling that developed over the whole tank area. The ultimate criterion of stability was whether a definable blanket would remain overnight or be washed out by the boiling.

The results for experiment 12 show that the difference between before and after the flood for the 1.2 m tank might not only have been due to disturbance of inlet orientation but might also have been due to some chemical factor. It is thought that because the tank was not started with a freshly formed blanket, for the first part, but with sludge stored in the tank that this was contributive, but no data are available to substantiate this.

One of the conclusions from the review of the literature was that blanket floc volume concentration might be an important general clarification performance parameter, Sects. 1.4.1. and 1.4.2. These figures illustrate that product quality can be related to blanket quality, such as blanket floc volume concentration, Figs. 3.1. and 3.2, which in turn is dependent on the treatment rate and the tank hydraulic quality, Figs. 3.3. and 3.4. This results in the overall clarification performance variation with treatment rate, Figs. 3.5. and 3.6.

The operation and evaluation of these experiments indicated that the methods employed and approach taken appeared suitable for continued

application in subsequent investigations, the general results being summarized in the next section, and that there appeared to be factors related to tank size, and possibly shape, that could affect tank performance. Sects. 3.4. and 3.5. report the factors that were examined.

3.3. Effects of Seasonal Variations

As a result of the extensive investigations with the three laboratory upflow tanks examining the effect of various modifications in the two larger tanks, a considerable quantity of data accumulated. The data covered the period of raw water conditions encountered from May 1971 to October 1972, Table 2.2. It is therefore possible to examine the effect of seasonal variations in raw water quality on clarification performance, in general terms, and to examine the influence of these seasonal variations on the comparison of different tanks.

The overall comparison is made with Figs. 3.7. to 3.14. presenting each tank individually and distinguishing the 1.2 m tank fitted with and without inclined tube modules, Sect. 3.5.1. When injection velocity was examined the results for the 3.5 m tank represent the lowest injection velocity examined. Close comparison of these figures produces a number of observations of possible importance in the practical uprating of floc-blanket clarification.

The blanket floc volume concentration - treatment rate relationships for the 0.3 m tank were similar to those for the other two tanks, in most cases, Figs. 3.7. to 3.10. Exceptions were with the 1.2 m tank operated with the blanket within the tube modules, when higher concentrations occurred, and for the 3.5 m tank for experiments 6, 12 and 16a when lower concentrations occurred.

The per cent aluminium residual - treatment rate relationships of the 0.3 m tank were also similar to the results for the two other tanks, Figs. 3.11. to 3.14. These results did not appear to be affected substantially by the range of the quality of chemical treatment encountered.

The 0.3 m tank was also equivalent in general performance to the other two tanks as measured by the product turbidity - blanket floc volume concentration and the product turbidity - treatment rate relationships.

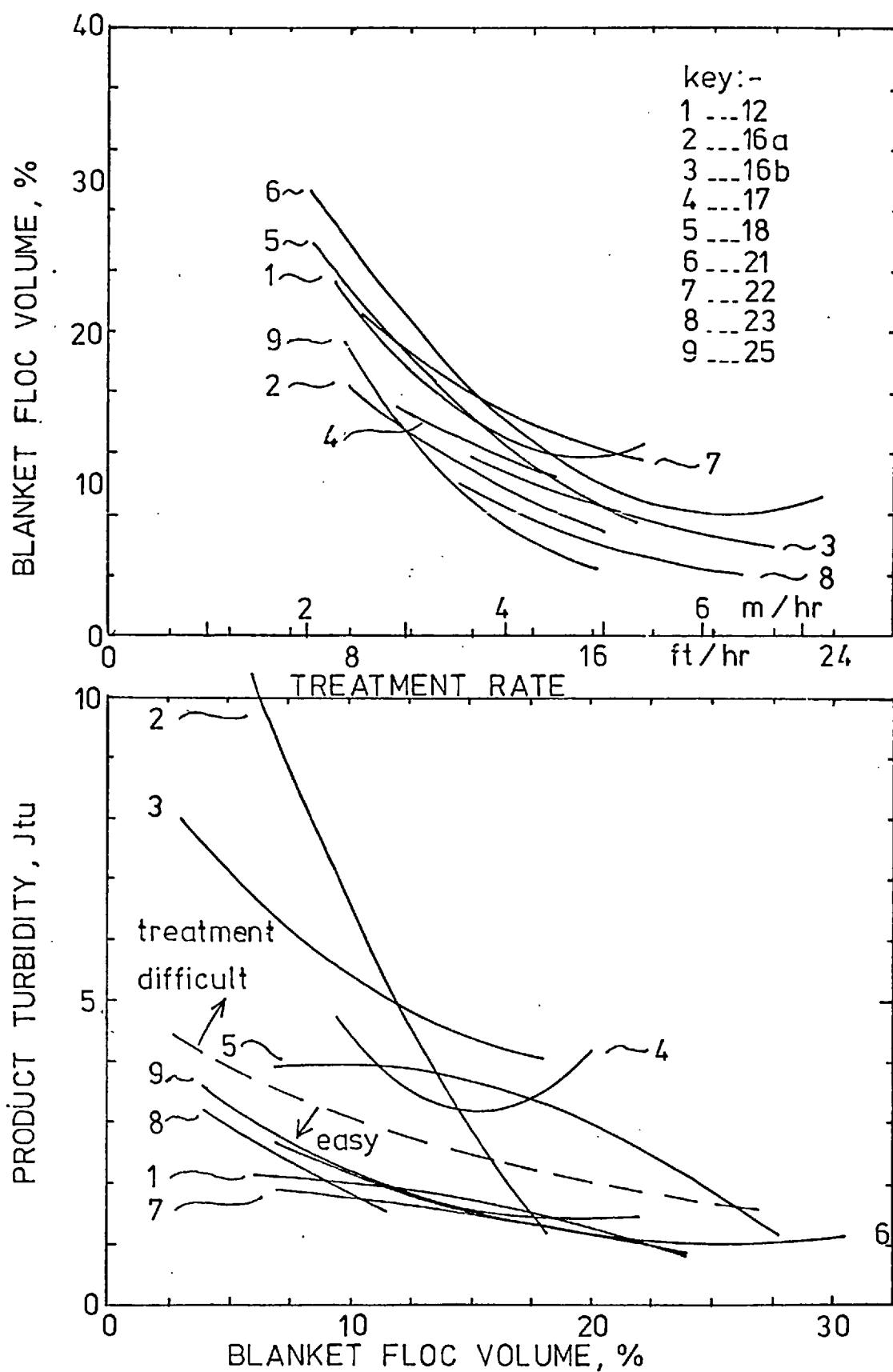


FIG 3.7 COMPARISON OF BLANKET QUALITY RELATIONSHIPS, 0.3 m TANK (table 3.7)

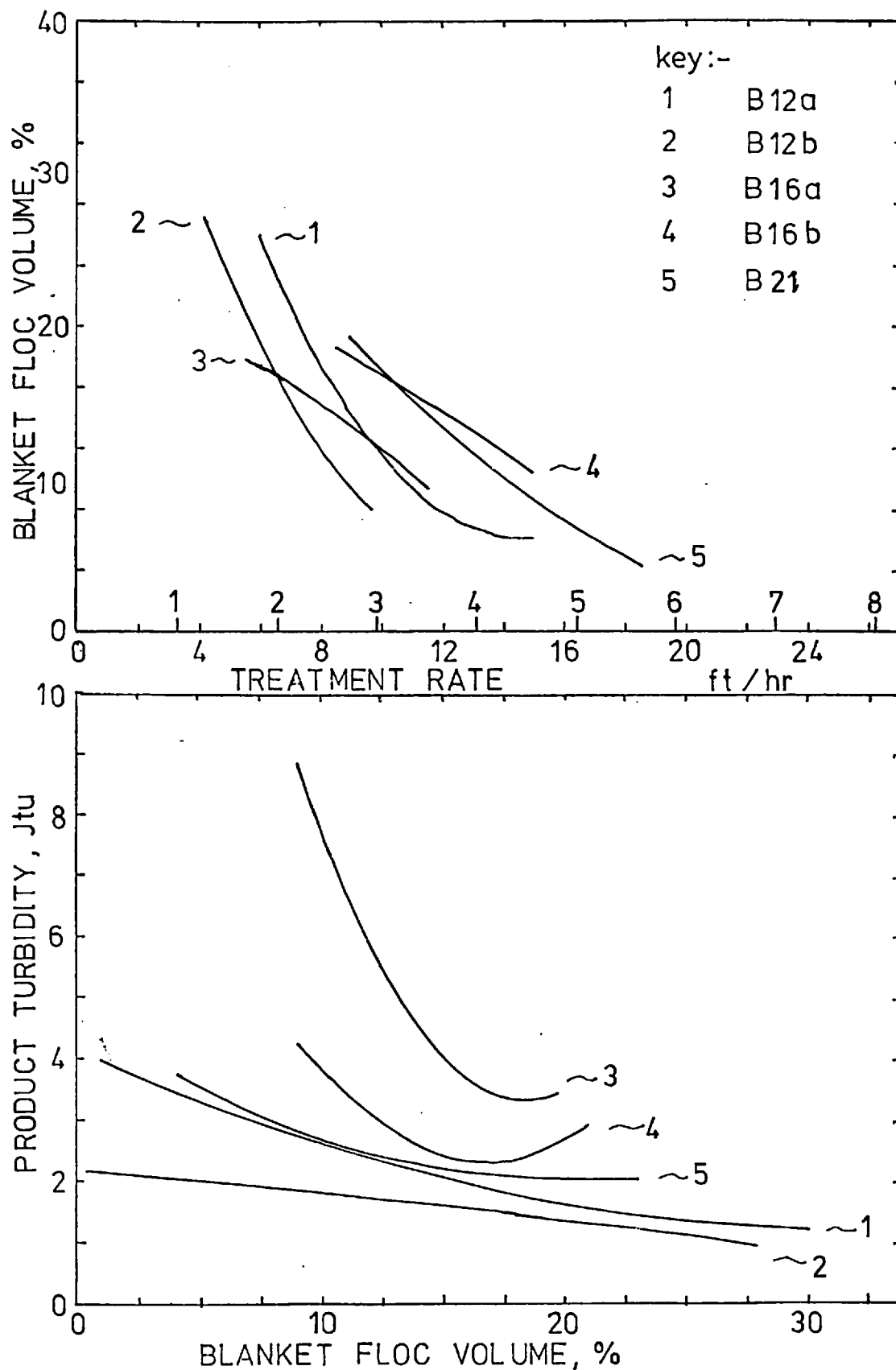


FIG 3.8 COMPARISON OF BLANKET QUALITY
 3.27 RELATIONSHIPS FOR THE 1.2m TANK
 WITHOUT TUBE MODULES (table 3.8)

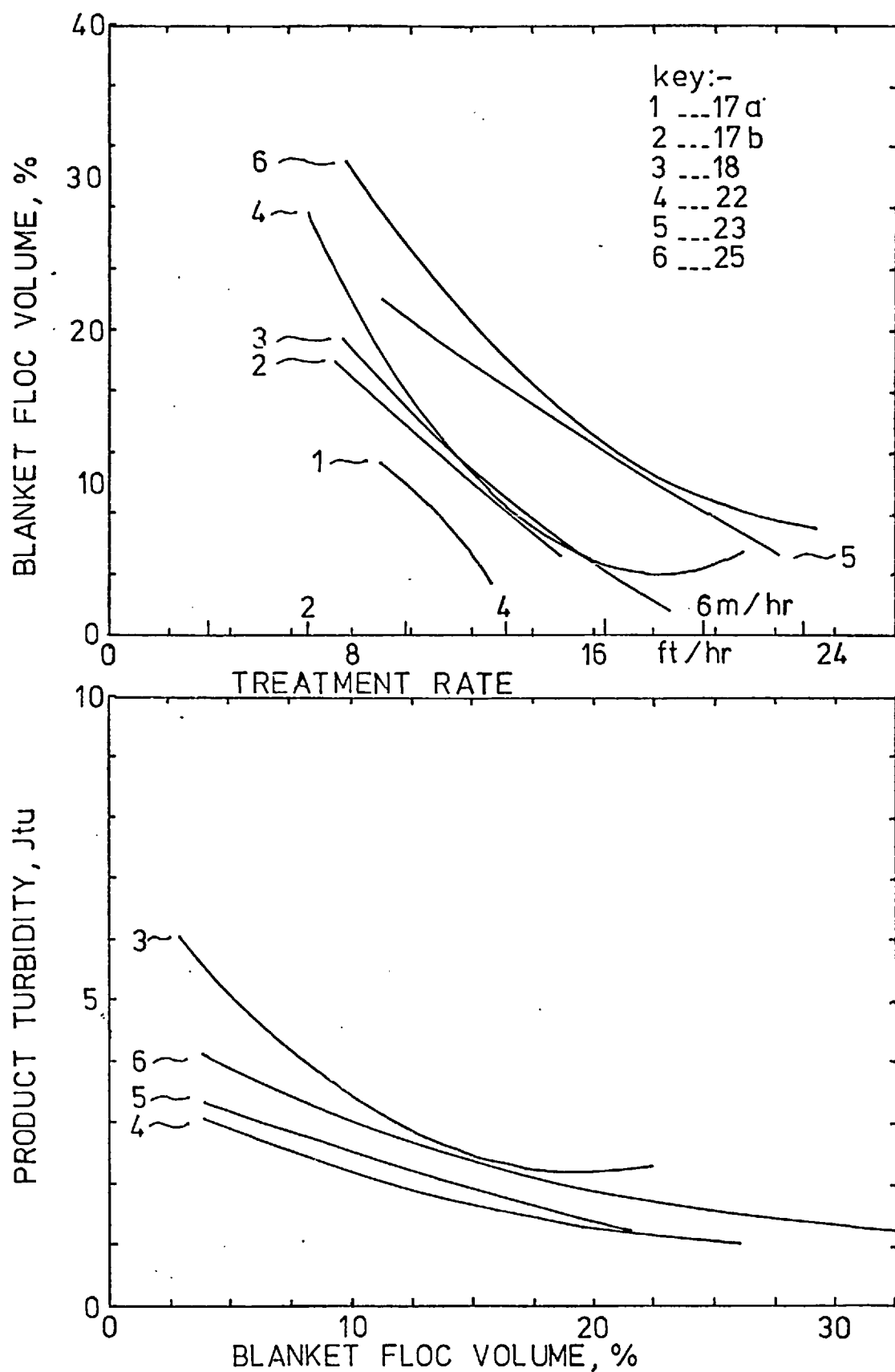


FIG 3.9 COMPARISON OF BLANKET QUALITY RELATIONSHIPS,
 3.28 1.2 m TANK WITH TUBE MODULES (table 3.9)

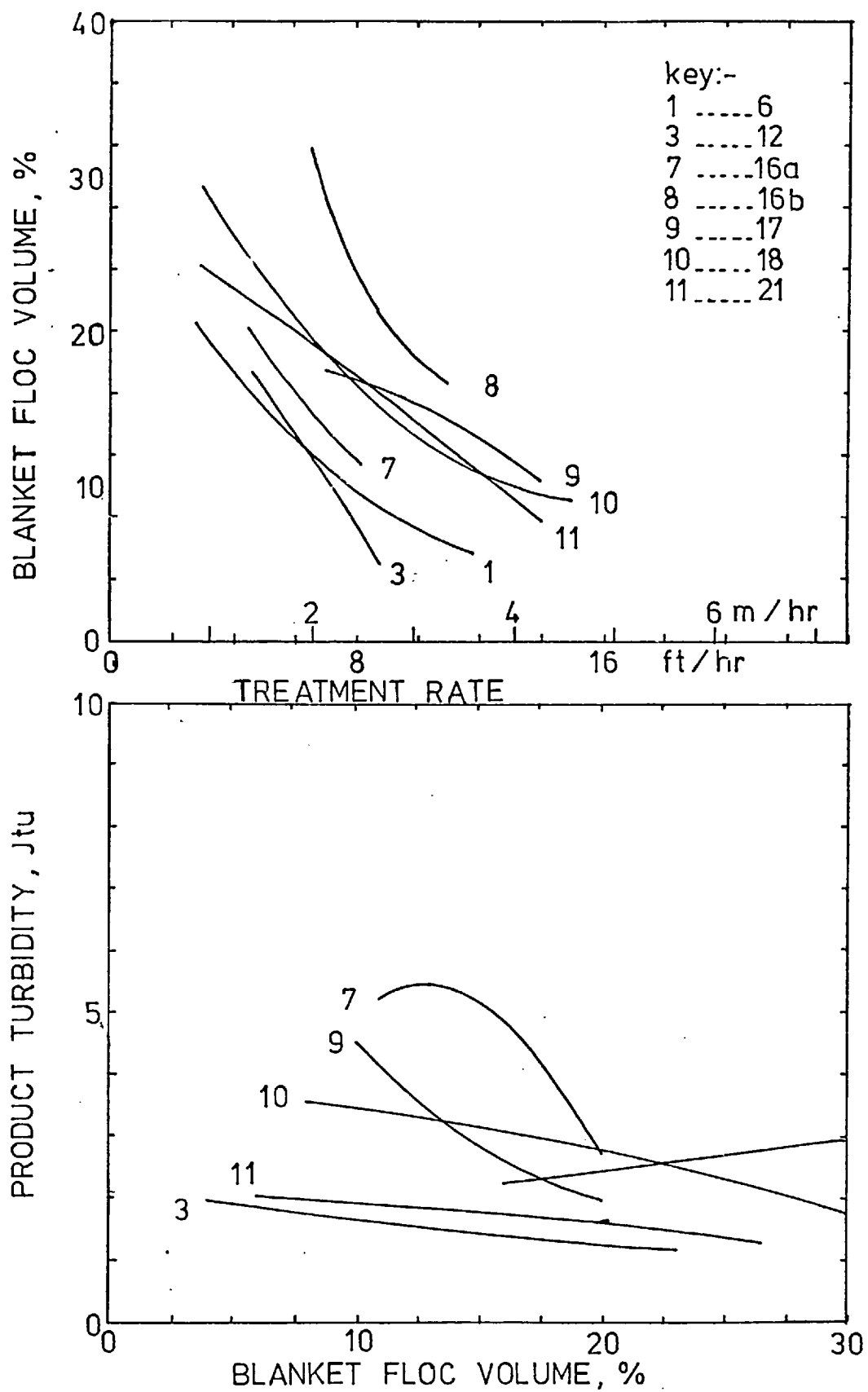


FIG 3.10 COMPARISON OF BLANKET QUALITY RELATIONSHIPS
3.5 m TANK (table 3.10)

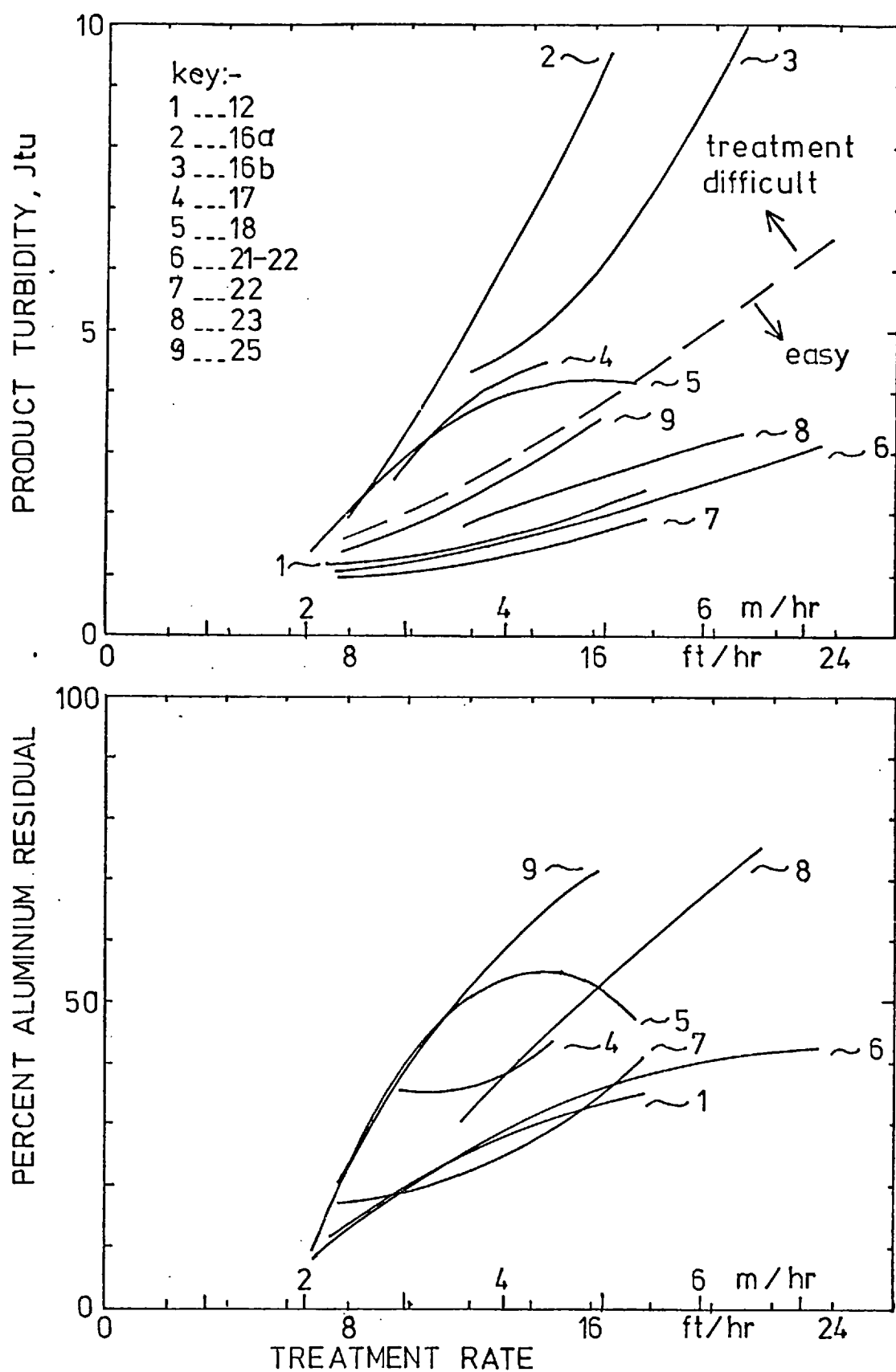


FIG 3.11 COMPARISON OF PRODUCT QUALITY—TREATMENT RATE RELATIONSHIPS, 0.3 m TANK (table 3.11)

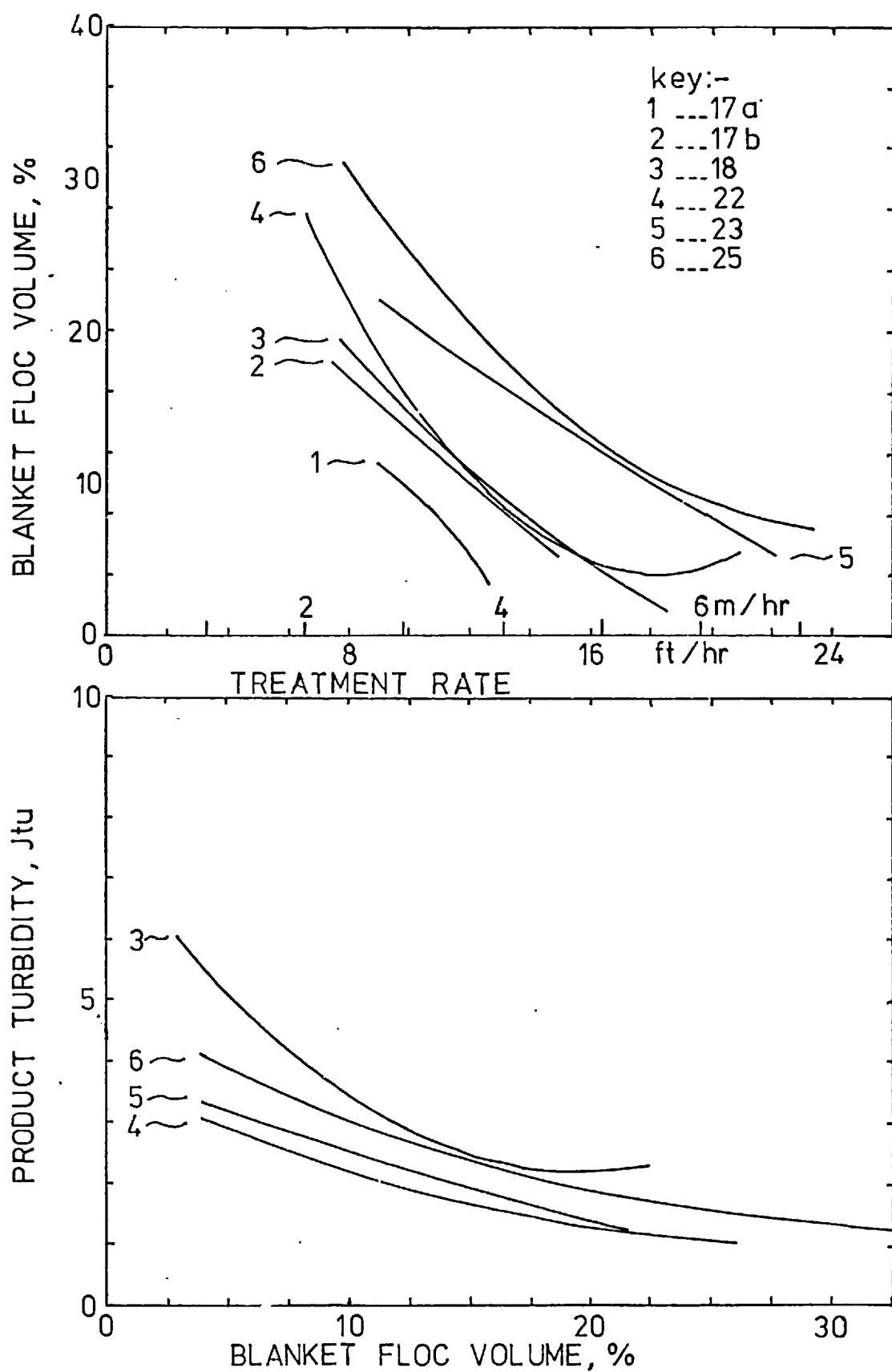


FIG 3.9 COMPARISON OF BLANKET QUALITY RELATIONSHIPS,
 3.28 1.2 m TANK WITH TUBE MODULES (table 3.9)

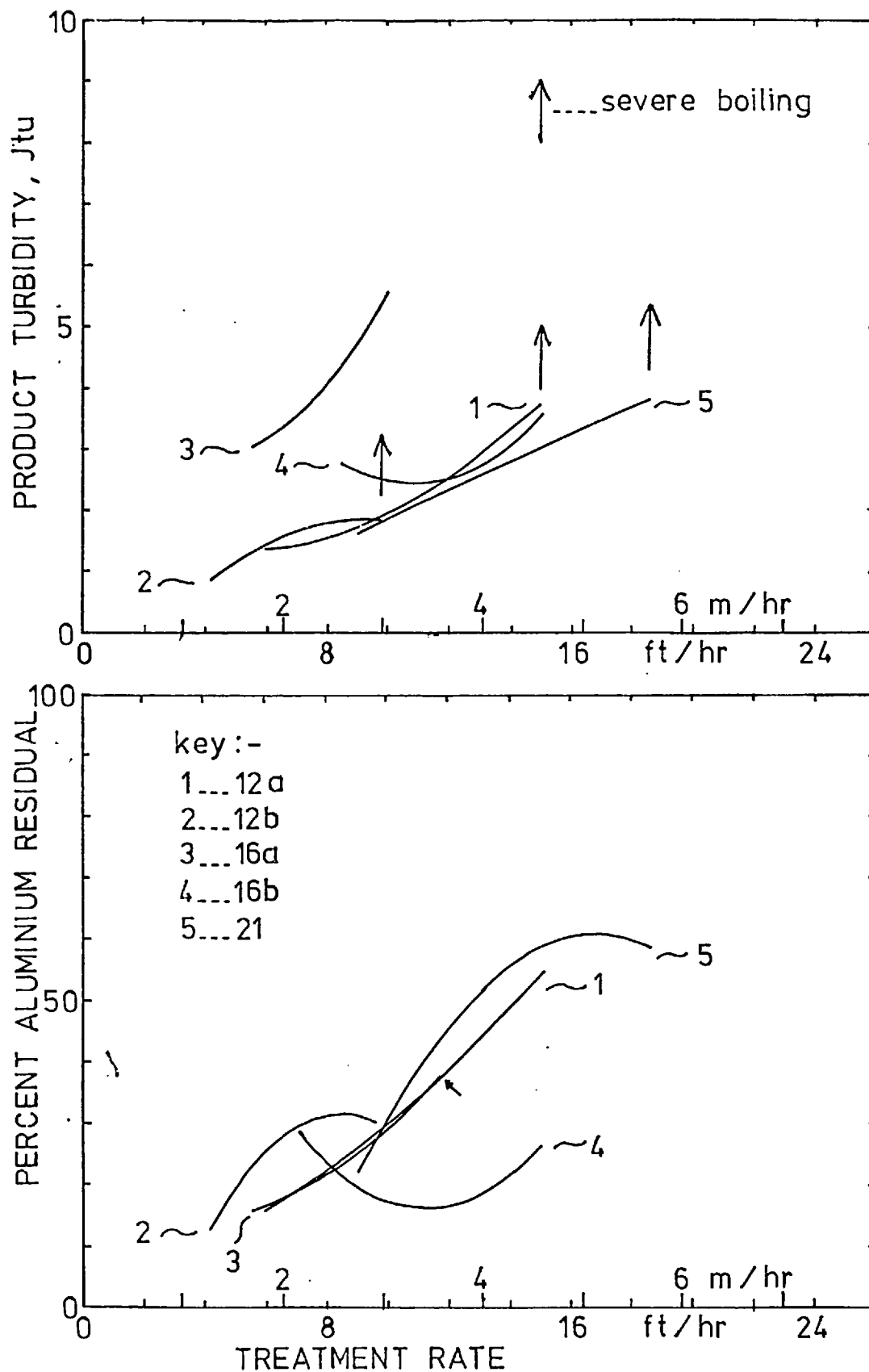


FIG 3.12 COMPARISON OF PRODUCT QUALITY—
 3.29 TREATMENT RATE RELATIONSHIPS, 1.2m TANK
 WITHOUT TUBE MODULES (table 3.12)

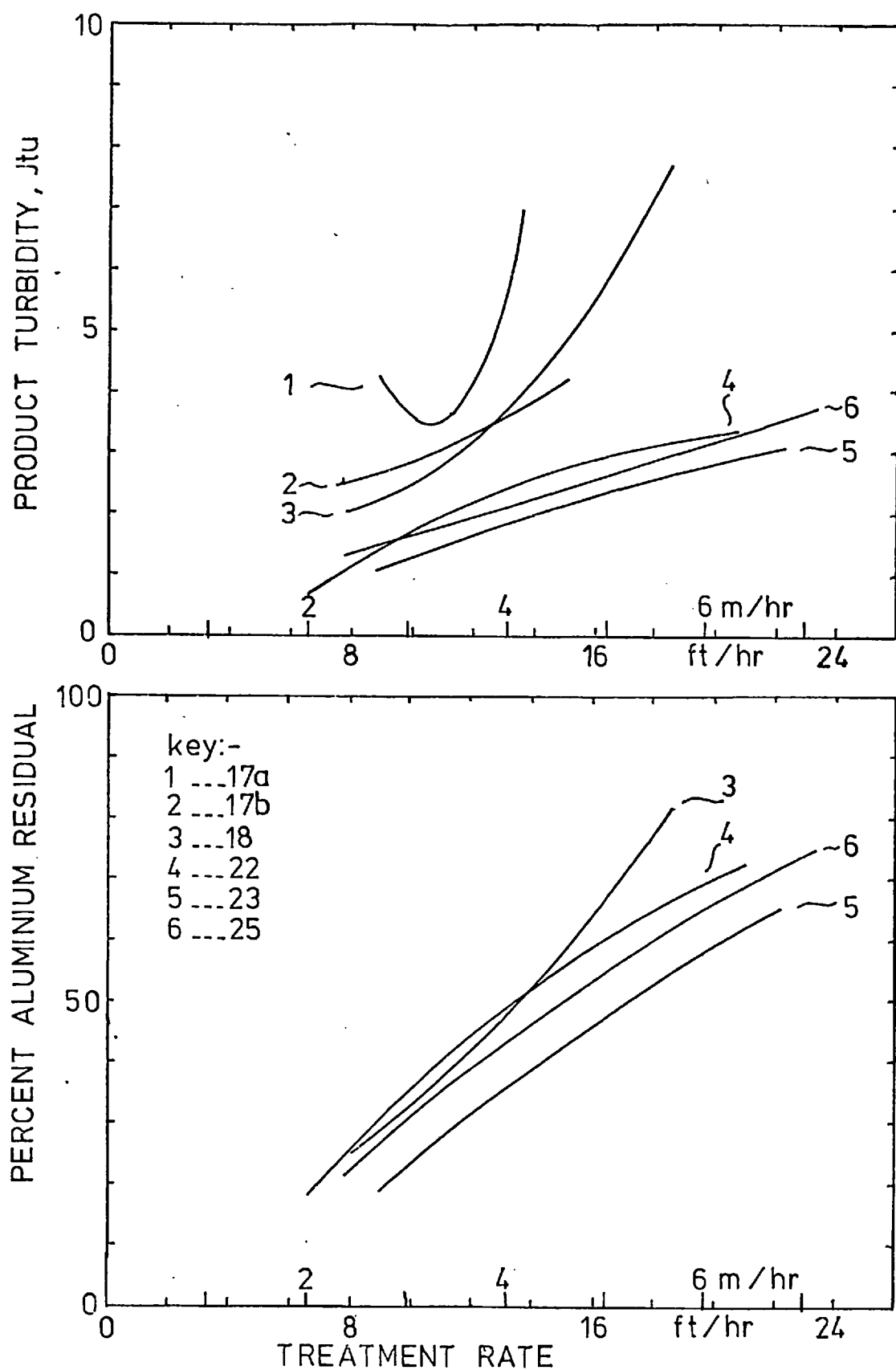


FIG 3.13 COMPARISON OF PRODUCT QUALITY—TREATMENT
3.30 RATE RELATIONSHIPS, 1.2m TANK WITH TUBE
MODULES (table 3.13)

due primarily to the mechanism of settling between close inclined surfaces. The improvement is not due to the separation efficiency itself within the modules but is related to the fact that the modules sustain and impose a greater solids concentration in the bulk of the blanket by returning solids to it. The concentration in the blanket is then greater than that which the treatment rate might support in the absence of the modules, even in completely stable conditions. This thickening of the blanket was also observed with the scale model.

It must be noted that at low treatment rates, even for a tank that would be unstable at higher treatment rates, tube modules do not cause a substantial improvement in tank performance. If at high treatment rates a tank can be stable then, even operating the modules within the blanket, the improvement in product quality or increase in treatment rate might still not justify their installation. However, the increased blanket density can permit greater confidence in operation at high rates and this additional factor might justify their installation.

3.5.1.2. Application: hydraulic model.

As part of the investigations a hydraulic model, scale 1 : 6, was constructed of the 1.2 m tank, Fig. 4.4, page 140, and a suitable rigid model sediment was selected. The selection of the model and sediment is presented in Appendix A.2.

Time was not available to confirm the limits of representation of the prototype by the model. Limited investigations were made with the model that strongly indicated the equivalence of operation and performance between the model and the prototype. Only 0.212 to 0.300 mm anthracite was used as the model sediment.

It was observed that the distribution of flow from injection through reversal and diffusion up the hopper was dependent on treatment rate. At low rates the solids against the hopper walls were stationary or almost stationary. At the middle of the range most of the solids would be sliding down into the apex with injected flow jetting a short way up the corners of the hopper. At high rates all sediment would be in full suspension and the jetting up the corners would project up into the parallel flow section.

The quality of flow distribution, particularly once jetting up the corners became substantial, was very dependent on the orientation of the inlet.

Two sampling points were fitted. The lower was made midway between the inlet and the adjacent left side, just above the flange. Although it was possible to draw a sample from wherever was required by attaching a suitable length of semi-rigid tubing, for Fig. 3.31, the sample was drawn from about 50 mm from the walls. The upper sampling point was made mid-centre of the same side, but just below the lower bracing, Fig. 2.5. For Figs. 3.32. and 3.33. the sample was drawn only a few millimeters from the wall.

The interrelationship of bed depth, treatment rate and solids concentration and the effect of tube modules on their interrelationship were investigated. Figs. 3.31. and 3.32. compare the interrelationship for the two sampling points. The relationship for the upper point is of a more regular nature. This is believed to be due to the position from which the lower sample is drawn such that the nature of the sample reflects the irregularities of flow in its vicinity. It was observed that the scatter of the points was greater for the lower sample point. Limited analysis indicated that the inflection of the results in Fig. 3.31. could be associated with the condition of maximum solids flux.

Scaled tube modules were also constructed with respect to tube size but not material thickness. Comparison of Figs. 3.32. and 3.33. demonstrates the effect of the tube modules on increasing the concentration once the surface of the bed enters them. It is noted that the greatest part of the concentration has been attained before the bed surface has passed through more than 40 per cent of the module depth. It is also noted that the greatest relative increase in concentration is obtained at the high treatment rates. The effect of the modules on elutriation was not examined with the model due to lack of time.

The effect of the modules on the concentration of the fluidized bed below the modules in the model supports the observation made for the floc blanket in the 1.2 m tank.

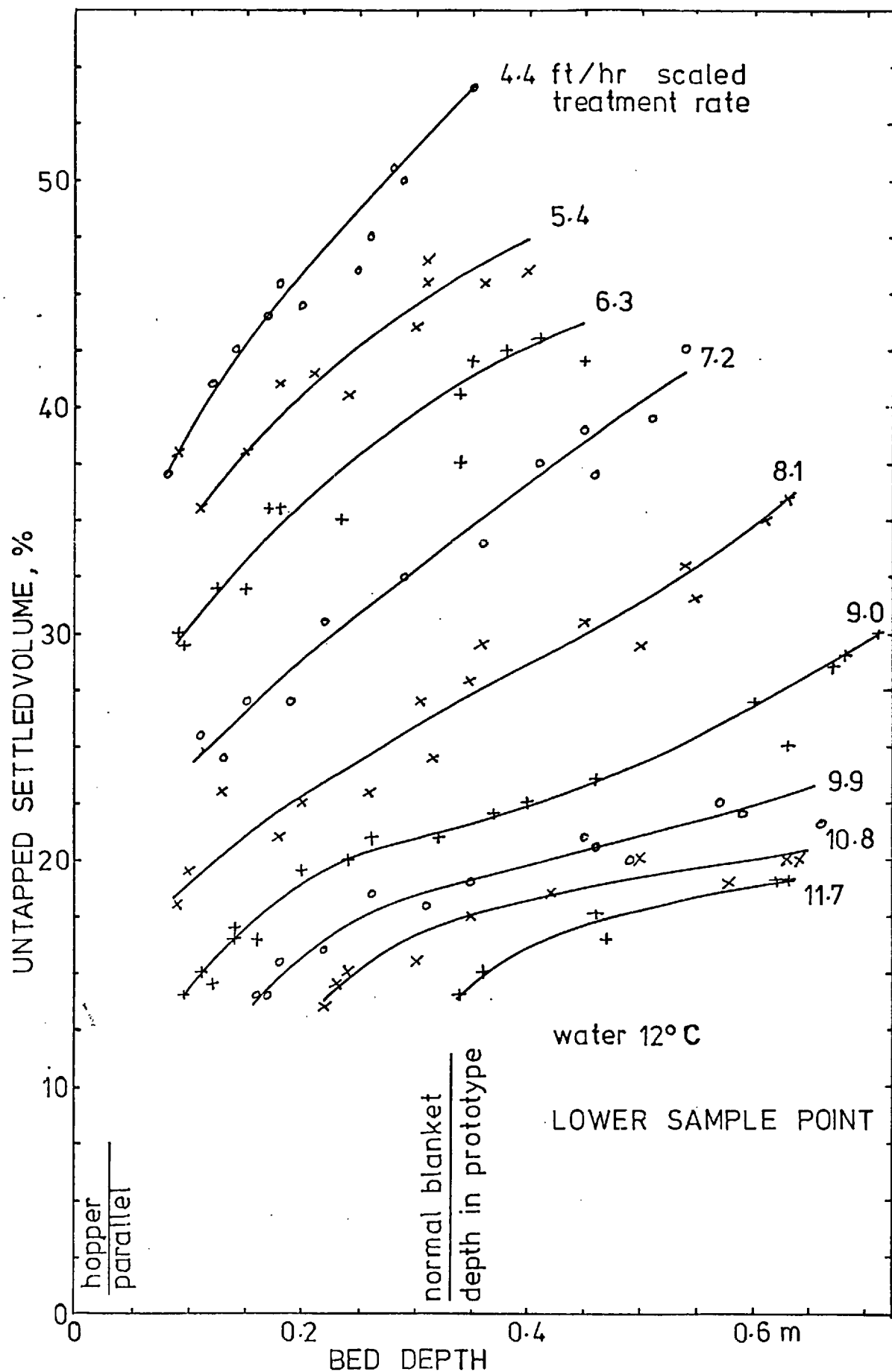


FIG 3.31 EFFECT OF BED DEPTH ON CONCENTRATION—TREATMENT RATE RELATIONSHIP IN THE MODEL

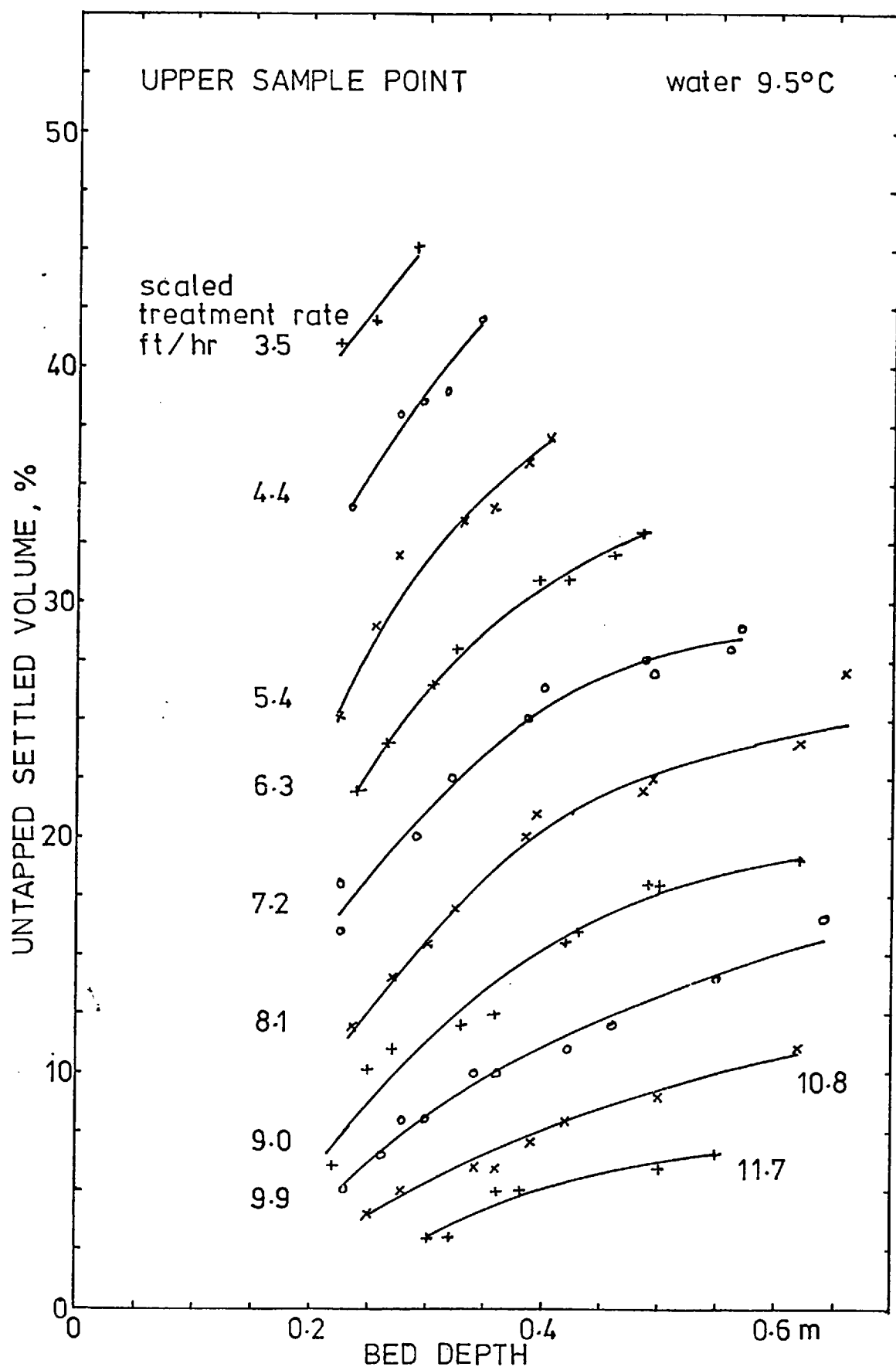


FIG 3.32 EFFECT OF BED DEPTH ON SOLIDS CONCENTRATION, WITHOUT MODULES

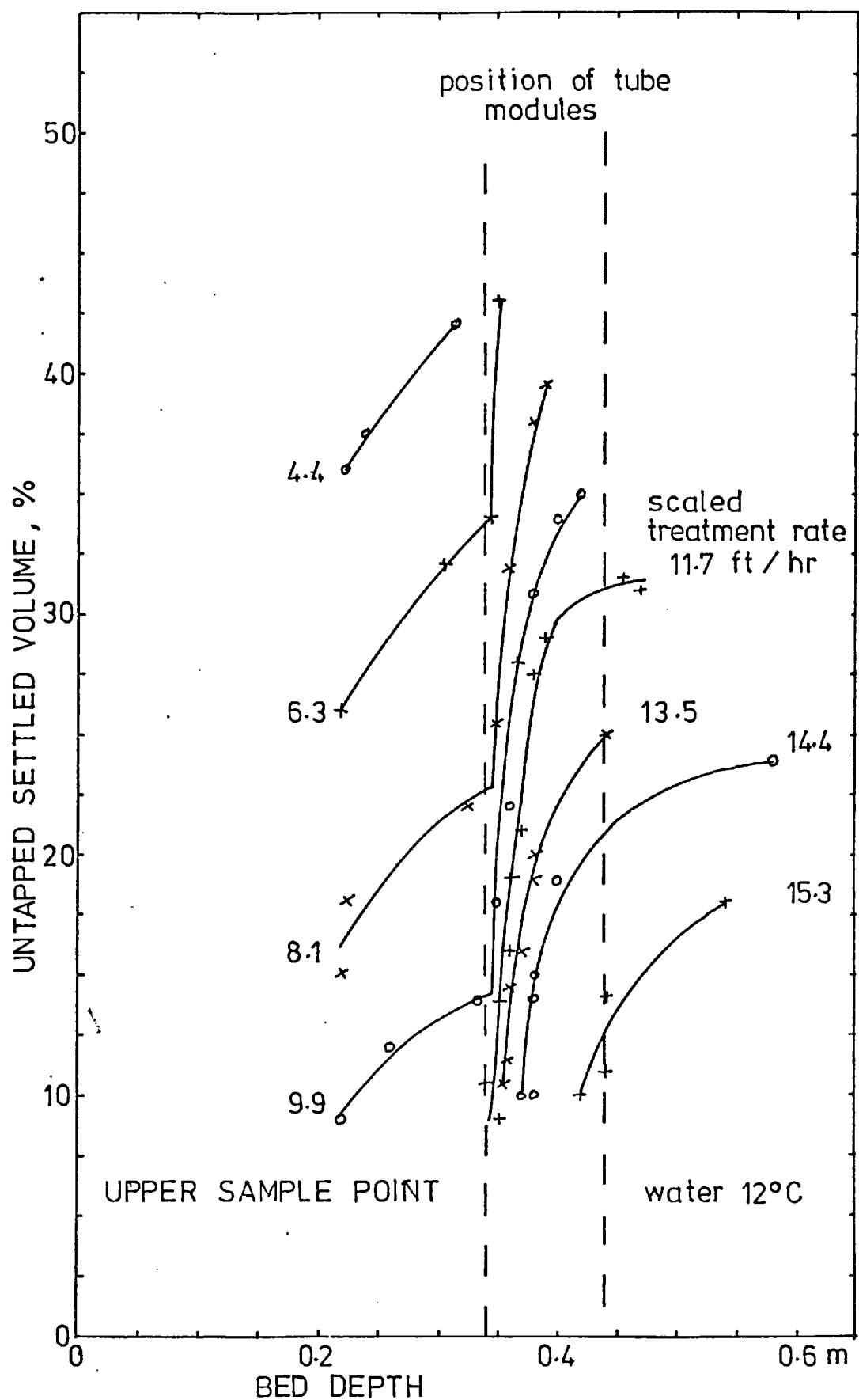


FIG 3.33 EFFECT OF TUBE MODULES ON THE BED DEPTH-SOLIDS CONCENTRATION RELATIONSHIP

3.5.2. Use of vertical baffles.

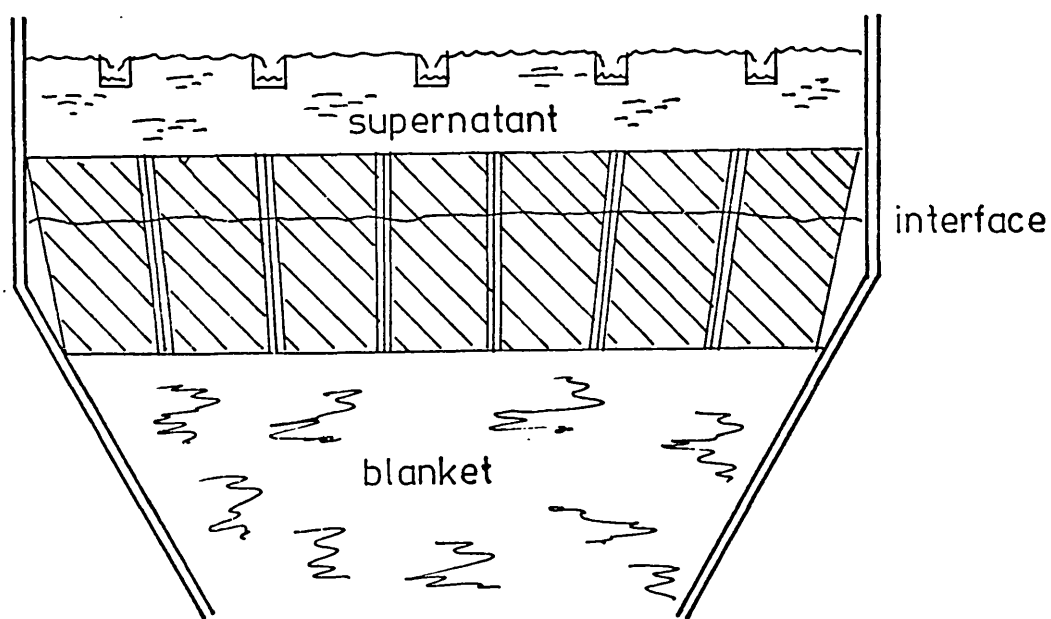
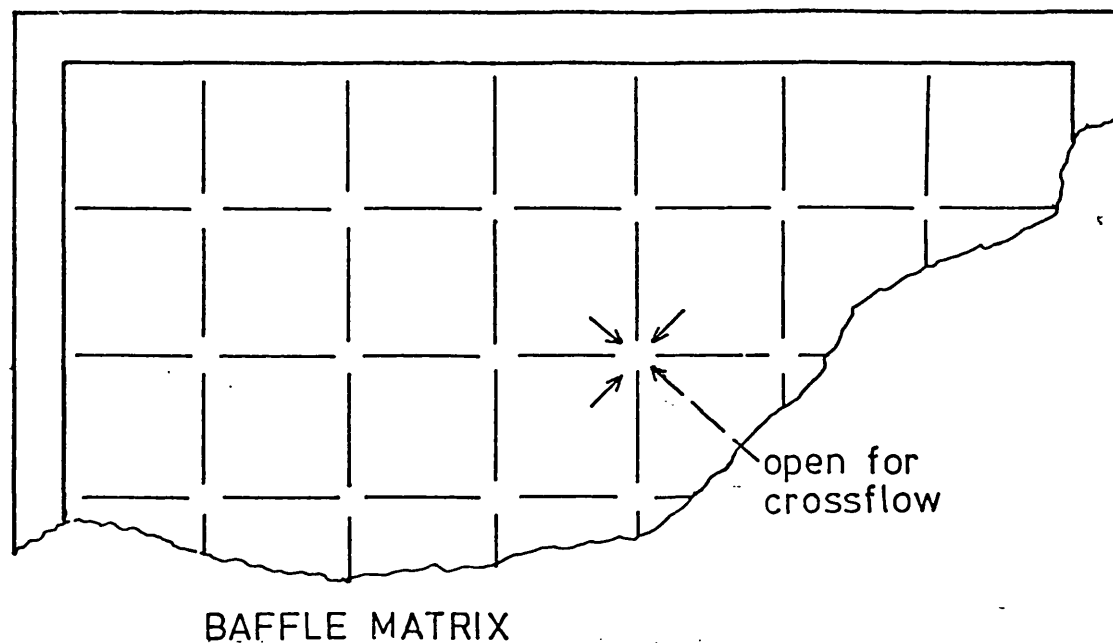
Moderately spaced deep vertical baffle systems placed across the blanket-supernatant interface have been shown capable of improving floc-blanket sedimentation performance. This work has been prepared in detail elsewhere; Gregory and Hyde (WRA 1973).

The use of baffles was investigated at three sites: Staines, South West Suburban Water Company; Trimpley, City of Birmingham Water Department; Mosswood, Sunderland and South Shields Water Company. Each site represents a different quality of raw water and hence different chemical treatment.

The purpose of a baffle system is to contain and control the dimensions of the large scale motion often present in floc blankets and so bring about an overall improvement in the blanket stability in the whole tank. The improved stability results in a better product quality which permits the tank to be operated at higher rates. In the trials the baffles were positioned in that part of the tank where it was believed they would have the greatest effect on the product quality. Since it is the control of the blanket-supernatant interface that is required the baffles should project into the supernatant.

The baffle systems, conceived as temporary structures, were constructed by fastening Rawl bolts into the tank walls and stretching fencing wire across the tank to form suitable upper and lower complementary grids. Heavy gauge polythene sheet 1.2 m wide was then strung between the two grids to form a matrix of columns. Each column was open to the adjacent columns at the corners, Fig.3.34, thus permitting crossflow of solids and satisfactory blanket level control. Because the 1.2 m tank in the WRC laboratory had been the largest size which could still give a reasonable stable performance, this size was chosen as the nominal dimension of the baffle grids. The dimension was also found suitable for construction within the large-scale tanks.

The conclusions drawn from the results have been confirmed by a full statistical examination made by Hilder and Brigham (WRA 1973). The results are summarized in Table 3.27. No results are presented for Staines since there was little firm numerical evidence of the behaviour of



POSITIONING OF BAFFLES

FIG 3.34 BLANKET-SUPERNATANT VERTICAL BAFFLE SYSTEM

the baffled tank producing a better product than the other tanks although there was visual evidence that this was the case. Additionally the investigations at Staines were not carried out by the writer and were prior to the work presented. They are best regarded as a feasibility study.

The designs of the experiments at Mosswood and Trimpley were different and so three separate analyses could be made for Trimpley and only two analyses for the Mosswood data.

The final column in Table 3.27. presents the estimates of the relative effect of the baffles in the baffled tank compared with the control tank. The confidence limits have been expressed as percentages of the corresponding mean product water quality from the control tank.

The results from Mosswood were also subjected to quadratic regression analysis, Fig. 3.35, Table 3.28. When the regressions are interpreted with the general experience of these investigations, giving due respect to the distribution of the points and range of treatment rates, the baffled tank is likely to show the better performance for treatment rates greater than $0.055 \text{ m}^3/\text{sec}$. The baffled tank might give as much as twenty per cent greater throughput with maintenance of product quality.

The overall conclusion from the baffle investigations is that, under similar conditions to those prevailing during the experiments, the use of baffles could be expected to improve the quality of the settled water and that this reduction would be of the order of twenty to thirty per cent lower than that produced by a similar tank without baffles.

The general experience of all the investigations suggests that the experiments on the baffled tanks were definitive. The general experience would also suggest that at low treatment rates when the blanket is naturally stable there will be no benefit from using baffles, and that this was possibly one of the reasons of the insignificance of the results from Staines.

The results for all three sites might have been more substantial if higher treatment rates could have been examined. However, the other investigations indicate that if at high treatment rates a tank can be stable then there is unlikely to be any benefit from installing such baffles.

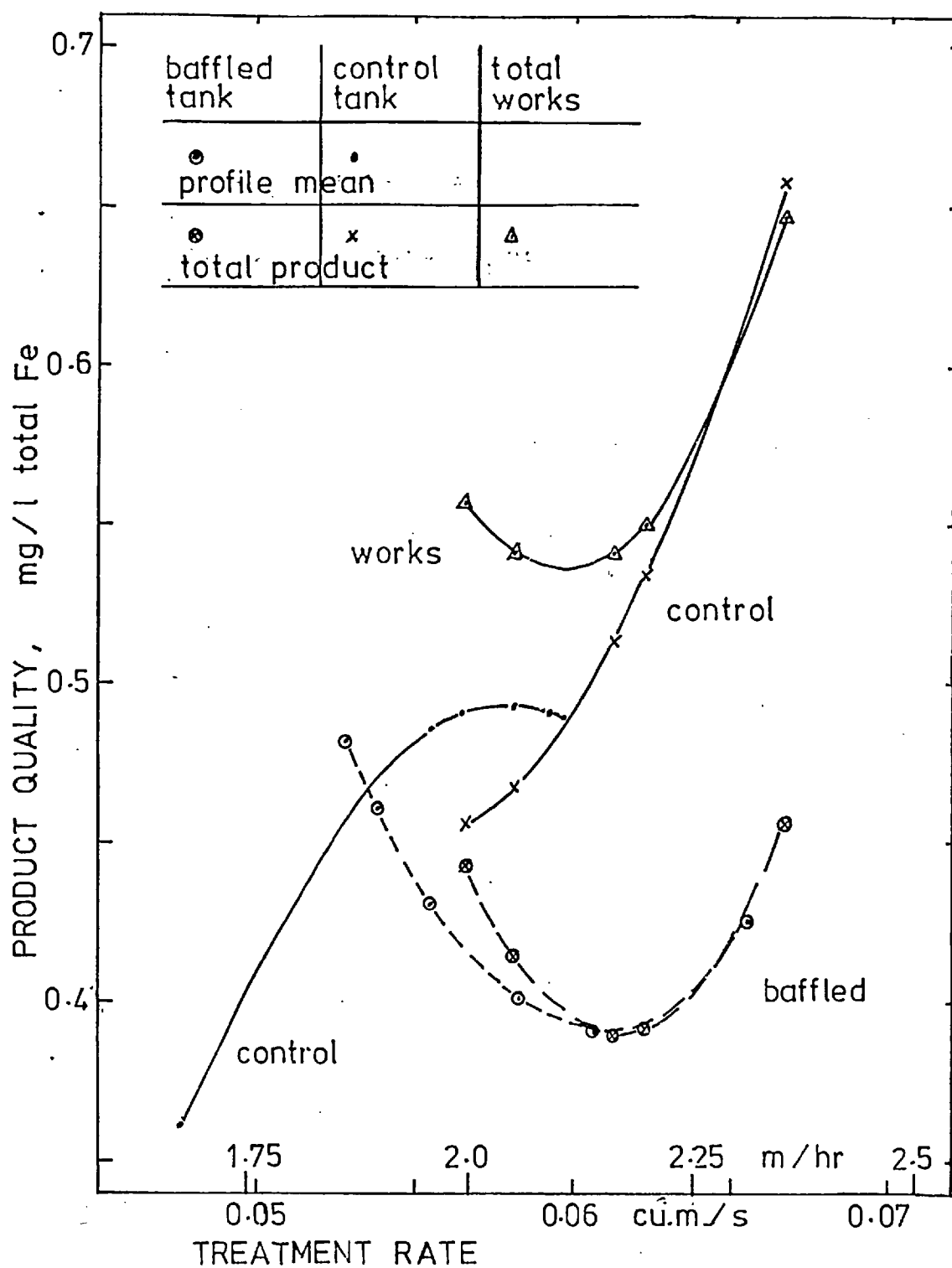


FIG 3.35 EVALUATION OF BAFFLED TANK AT MOSSWOOD, quadratic regression of data. (table 3.28)

3.6. Summary

(i) It was found that uncontrollable variables can greatly affect tank performance and that confident correlations between tank performance and uncontrollable variables can be difficult to obtain. The relative levels of variability of uncontrollable variables are seasonally dependent so that their contribution to the variation of tank performance will vary likewise.

(ii) Poor tank performance can be characterised by the boiling of the blanket surface in large tanks. Some of the factors related to tank size and shape that could affect tank performance were investigated. Boiling can be associated with poor flow distribution.

(iii) Extensive investigations were made with three upflow tanks of different dimensions. For the size range represented there was no conclusive evidence that tank dimension caused distinctive differences in clarification performance, providing the specific blanket volumes of the tanks are equal. However, comparison of tanks over the short period of one experiment could show differences between tanks.

(iv) High injection velocities created with an annular orifice cone valve could cause severe hydraulic instability of the floc blanket in the 3.5 m tank.

Various other inlet factors were also examined for their effects on the performances of the 3.5 m and 1.2 m tanks, but there were no substantial findings. However, problems of inlet flow centering in the 1.2 m tank showed that such a factor can cause severe hydraulic instability of a floc blanket.

(v) Tube modules placed above a floc blanket had no value for clarification with a stable blanket. Tube modules placed into the blanket surface caused substantial increase in the blanket concentration below the modules but no substantial improvement in clarification when compared with a stable blanket without tube modules.

Large vertical baffles placed at the blanket surface can also be used to maintain overall blanket stability. For tanks with poor blanket stability the use of baffles can result in improved clarification, at high treatment rates, or increase in treatment rate with maintenance of settled water quality.

4. ANALYSIS AND DISCUSSION OF THE RESULTS

4.1. Velocity - Concentration Analysis

4.1.1. Selection of mathematical models.

Velocity-concentration analysis was briefly considered in Sect. 1.4.5. The following presents the velocity-concentration relationships selected for the analysis of the experimental data obtained in the laboratory investigations.

Equation I

The most simple empirical relationship is given by equation 1.11 :

$$U = U_p \cdot \exp (- q_2 \cdot c) \quad \dots\dots\dots 4.1$$

Equation II

Landel et al (1965) and Happel and Brenner (1965) noted that many of the semi-empirical relationships for viscosity of suspensions can be expressed in the form of a power series. Thus, in the analysis of settling and fluidization the best general statement of the various relationships would appear to be the power series:

$$\frac{U}{U_p} = (q_4 \cdot c)^{k_3} \cdot (q_5 - c)^{k_4} \quad \dots\dots\dots 4.2$$

where q_4 , q_5 , k_3 and k_4 are dependent upon the data set. The simple form of this relationship is:

$$U = U_p \cdot c^{k_3} \cdot (1 - c)^{k_4} \quad \dots\dots\dots 4.3$$

Equation III

For even simpler purposes the following expression is usually preferred: (cf. equation 1.10)

$$U = U_p \cdot (1 - c)^{k_4} \quad \dots\dots\dots 4.4$$

Equation IV

Substituting for μ_s from equation 1.8 in the equation derived by Robinson (1926) from Stokes' equation of settling gives:

$$\frac{U}{U_o} = \left(1 - \frac{c}{c_m}\right)^{2.5} \quad \dots\dots\dots 4.5$$

which closely resembles equation 1.10 and can be represented by:

$$\frac{U}{U_q} = (1 - q_6 \cdot c)^{k_5} \dots\dots\dots 4.6$$

where U_q is equivalent to $U_o \cdot q_3$ in equation 1.12 and is distinguished from U_p in equation 1.10.,
 q_6 is a constant representing the fluid mechanical effects related to the floc concentration at incipient fluidization.

However, the value of q_6 needs to be established before equation 4.6 is easily used for regression analysis. Michaels and Bolger (1962), Thomas (1963a) and Scott (1966) have considered the use of a factor, equivalent to q_6 , to differentiate between the effective floc volume and the apparent floc volume, in that the irregular surface of floc particles will have a liquid hulk around it. Such a factor can also be used to adjust the concentration measured by the simple laboratory technique to the effective floc volume.

The effect of particle shape has also been accounted for in the value of k . Richardson and Zaki (1954) found that for large rigid particles in fluidization the value of k_4 for high values of Reynolds number could be given by: $2.7 \cdot Z^{0.16} \dots\dots\dots 4.7$
 where Z is called the volumetric shape factor, which implies a fluid mechanical correction. Richardson (1971) has considered this in detail. The value of 2.7 is noted to be close to the value of k in equation 4.5. If, however, a relative concentration based on the concentration at incipient fluidization could be used, accounted for by q_6 , such fluid mechanical effects of particle behaviour might well be automatically accounted for as appears possible in viscosity-concentration correlations.

Equations V and VI

A further approach is to consider the flux of the suspension; the product of velocity and concentration, which Kynch (1952) has analyzed with reference to thickening. In the concentration range of interest the flux, $U \cdot c$, m^3/m^2 hr, has a maximum value with respect to both U and c and can therefore be represented as the quadratic relationships:

$$U \cdot c = \alpha_u + \beta_u \cdot U + \gamma_u \cdot U^2 \dots\dots\dots 4.8$$

$$\text{and } U \cdot c = \alpha_c + \beta_c \cdot c + \gamma_c \cdot c^2 \dots\dots\dots 4.9$$

What maximum flux represents in fluidization is not clear. However, Pruden and Epstein (1964) have discussed the stratification by size in particulate fluidization and in hindered settling. They were particularly concerned in establishing the difference between three relationships involving k that define specific values of concentration: the porosity e_c at which the centre-to-centre distance between neighbouring particles is minimized by varying only particle diameter at constant velocity relative to the particles; the porosity e_m at which the velocity is maximized by varying only particle diameter at constant particle number concentration and, the porosity e_f at which mass sedimentation flux is maximum.

$$e_f = \frac{k_1 - 1}{k_1 + 1} \dots\dots\dots 4.10$$

$$e_c = e_m = \frac{3mk_1}{3 - m + 3mk_1}$$

where $1 < m < 2$ and k_1 are both dependent on particle Reynolds Number.

For spheres Davies and Kaye (1972) have shown that stratification does not occur for binary mixtures if particle volume concentration is greater than that concentration which represents the critical pipe radius effect, whereby the lattice of the larger particles entrap the smaller species. They found that for irregular shapes the entrapment is likely to occur at lower concentrations, e.g. 0.16, than for spheres, e.g. 0.38. Their results also showed that open cubic structures could represent concentrated slurries greater than 0.15 for angular particles and 0.20 for spheres. This is the range in which maximum flux is usually found to occur.

For regression analysis, the above equations were all transposed to the following forms:

$$\text{equation 4.1 : } \ln U = \ln U'_p - q'_2 \cdot s \dots\dots\dots 4.11$$

$$4.3 : \ln U = \ln U'_p + k'_3 \cdot \ln(s) + k'_4 \ln(1 - s) \dots\dots\dots 4.12$$

$$4.4 : \ln U = \ln U'_p + k'_4 \cdot \ln(1 - s) \dots\dots\dots 4.13$$

$$\text{equation 4.6 : } \ln U = \ln U'_q + k'_5 \ln (1 - q'_6 \cdot s) \dots\dots\dots 4.14$$

$$4.8 : s \cdot U = \alpha'_u + \beta'_u \cdot U + \gamma'_u \cdot U^2 \dots\dots\dots 4.15$$

$$4.9 : s \cdot U = \alpha'_s + \beta'_s \cdot s + \gamma'_s \cdot s^2 \dots\dots\dots 4.16$$

where s is the blanket floc volume concentration (the measured volume concentration of the floc in the blanket) as distinguished from c the actual or effective volume concentration, and where "prime" also denotes this difference.

4.1.2. Comparison of the models.

As well as equations 4.15 and 4.16, equations 4.11 and 4.13 were also examined in the quadratic form, e. g.:

$$\ln U = \ln U'_p - q'_2 \cdot s + q''_2 \cdot s^2 \dots\dots\dots 4.17$$

Although this was not necessary it did show the effect on the efficiency of regression of increasing the complexity of the model.

Other than for equation 4.12, the equations were examined with the general multiple regression program "Multireg", suitable for power series. Equation 4.12, since it consisted of two independent variables, was examined using the general multiple regression program, "Biomed". This program can in particular evaluate the relative contribution of the individual independent variables to the regression. Equation 4.12 can also be compared with the model proposed by Steinour (1944) which can be expressed as:

$$\frac{U}{U_p} = c^{-1} \cdot (1 - c)^3 \cdot F(c) \dots\dots\dots 4.18$$

where $F(c)$ is a function of c , and for Steinour:

$$F(c) = \frac{c}{1 - c} \cdot 10^{-1.825} \dots\dots\dots 4.19$$

Of note is that in the general analysis of clarification performance, the blanket floc concentration s was correlated as a function of treatment rate, $F(U)$, as compared with velocity-concentration analysis with U correlated as a function of concentration, $F(s)$.

To simplify the use of equation 4.14 a value of q'_6 was estimated. Its value represents the difference between the measured concentration, s ,

and the hydrodynamically effective volume concentration, which can only be represented by c for non-flocculated spherical particles. An estimate of 2.5 for the value of q'_6 was made and the method used to determine this is given in Appendix A.3.

Some of the results obtained from the regression analyses are presented in Table 4.1. This table compares the usefulness of the various equations on the basis of the magnitude of the F-statistic and illustrates that equation 4.14 tended to provide the best regressions of the data. Using the quadratic model there was little to choose between equations 4.11 and 4.13, with only a slight indication that 4.13 is better than 4.11. Table 4.2 gives further details of the comparison of equations 4.11 and 4.13 when used in the quadratic form. The value of including either the first or second order power term in the quadratic is tested on the basis of the magnitude of the F-statistic. Generally the second order term is of less value and often insignificant in the quadratic regression. The value of the first order term is marginally greater for equation 4.13 than 4.11.

Table 4.3 gives details of the comparisons of the three equations, 4.11, 4.12 and 4.14, for the linear models only. It can be seen that equations 4.11 and 4.14, respectively, produce the largest and smallest values of the treatment rate at zero concentration. This might distinguish the relative importance of these models.

The examination of equation 4.12 is presented in Table 4.4. In most cases $\ln(1-s)$ had only slight priority of selection over $\ln(s)$ for initial correlation. This is shown by the magnitude of the correlation matrix coefficients of these two terms with $\ln U$. For example, with experiment B25 the term $\ln(1-s)$ was selected as having the more substantial contribution to the model. However, inclusion of the term $\ln(s)$ caused only an increase in value of the R.S.Q., residual sum of squares expressed as the total fraction reduction by inclusion of that term, from 0.8975 to 0.9097. This would tend to justify the use of equation 4.13. This two-parameter model can be compared with the general results found by Steinour (1944), as in Table 4.4. Steinour's model can be written as equation 4.18, where $F(c)$ is the shape factor which is a function of porosity. He presented a figure of the variation in value of

the shape factor derived from data of sedimentation of tapioca in oil. For the specific values $c \sim 0.1, 0.2$ and 0.3 estimates of $F(c)$ are then $0.070, 0.105$ and 0.125 . It will be observed that in Table 4.4 the estimates for the shape factor from the regressions are the same order of magnitude as found by Steinour.

Table 4.1 also provides comparison with the two flux models and the performance model of concentration dependent on treatment rate.

The results show that a simple equation, 4.14, which can account for the hydrodynamically effective volume of the solids in suspension can have superiority in correlation over other empirical formulae.

4.1.3. Detailed evaluation of the regressions.

The values of the constants and coefficients derived in the regression analyses with the preceding equations can provide information and characterization of the floc quality and general properties of the suspensions.

4.1.3.1. Distribution of values of the regression coefficients.

The distribution of the value of β , the regression coefficient, for the first order correlations of $\ln(1 - s)$ and of (s) are given in Fig. 4.1. For $\ln(1 - s)$ the bulk of the distribution is within the values 2.5 to 5.7 . For (s) the value is evenly distributed in the range -3.0 to -7.0 . These values compare closely with previously published data for floc and irregular-shaped rigid particles. Although these values represent settled volumes, s , they would be little altered if corrected for a more realistic volume concentration, c , since estimates indicate a porosity of approximately 0.10 for the settled volumes. This point also holds for the determination of the velocities.

Examination of the improved regression using $\ln(1 - 2.5s)$ indicates that the values of the terminal velocity were slightly less than the other two models, Table 4.3. A notable feature was that the value of β was substantially reduced in value tending towards a value close to unity. However, this feature requires further testing.

The spread of these distributions illustrates the problem of examining the coagulation-flocculation of natural water.

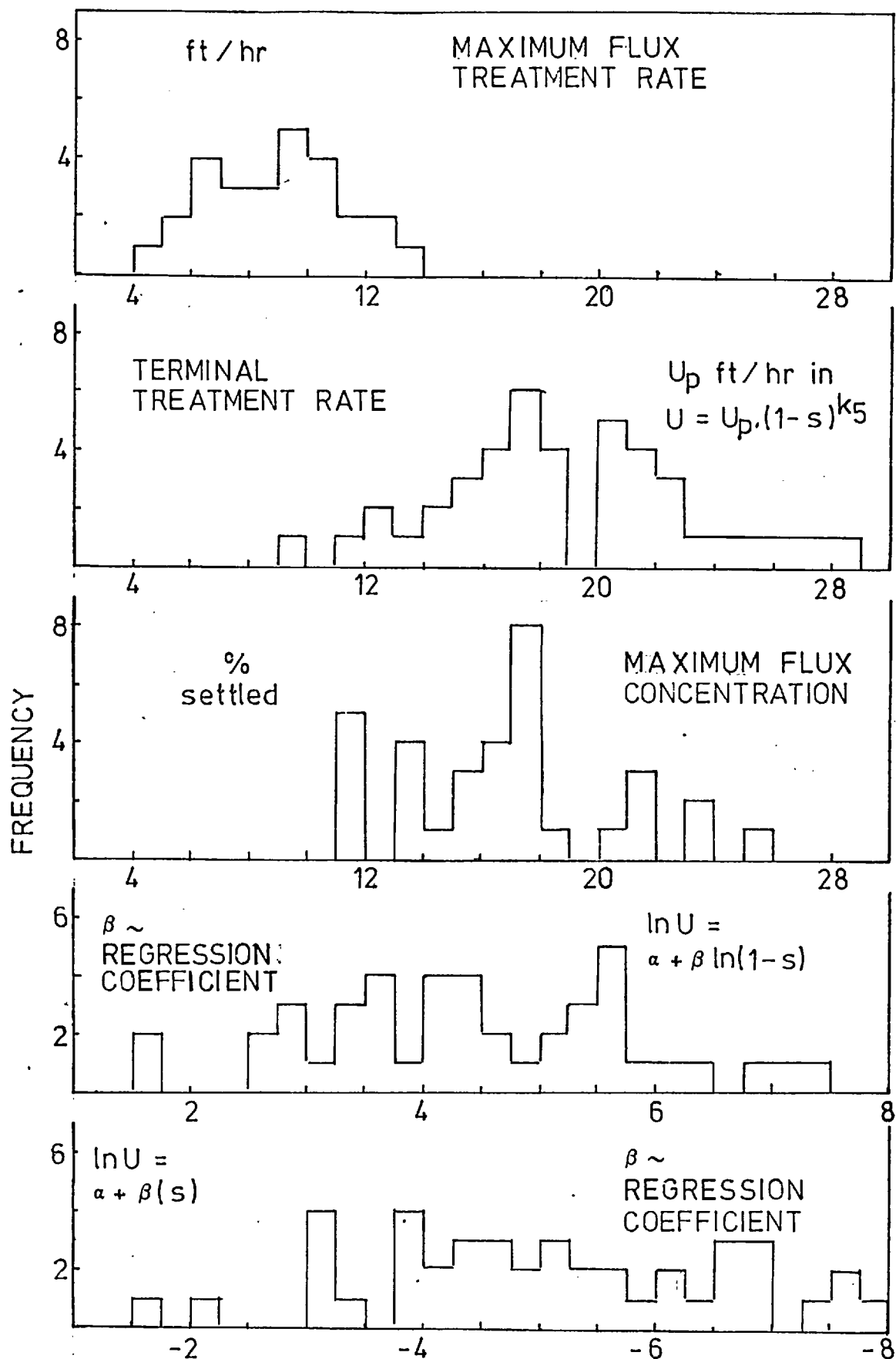


FIG 4.1 DISTRIBUTIONS OF VARIOUS VELOCITY-CONCENTRATION REGRESSION VALUES

4.1.3.2. Terminal velocity.

The constant α derived in the use of equation 4.11 to 4.14 can be evaluated as the terminal velocity of a single floc particle, but from the statistical analysis can only be interpreted as the velocity of the suspension extrapolated for zero solids concentration. Thus, for comparing suspensions of different materials, chemical treatment, temperature, hydraulic flow conditions, etc., comparison should strictly be made for the same concentration range and preferably the narrowest range possible. Similar restrictions are necessary on the interpretation of the other coefficients of the models, viz β and γ .

Characteristic values of the terminal velocity calculated from α are presented in Table 4.3. The distribution of the values for the terminal velocity for the correlation of $(1 - s)$ is shown in Fig. 4.1.

It is noted that the terminal velocity values appear substantially less ($1/2$ to $1/3$) than the values usually calculated using the Stokes equation and measured for single floc particles in free suspension as also noted by Kaye and Davies (1962). Kaye and Davies suggested that for flocculated suspensions the particle size calculated from the hindered settling equation is not the mean size of the individual particles but the effective size of the flocs. This, therefore, implies that the uprate potential of many sedimentation systems is much less than might have been anticipated.

Floc diameter:		0.5	1.0	1.5	2.0	2.5 mm
Floc density:	1.001	0.386	1.54	3.47	6.17	9.65
kg/litre	1.002	0.772	3.09	6.84	12.30	19.30
	1.004	1.55	6.18	13.80	24.70	38.60
	1.005	1.93	7.72	17.40	30.90	48.20
	1.010	3.86	15.40	34.70	61.70	96.50

Stokes velocity in m per hr for floc of various diameters and density at 10°C in water of viscosity 0.0131 poise. Water density assumed 1.000 kg per litre.

This table indicates that the experimental terminal settling velocities of 7 to 9 m per hr represent low floc density and/or small Stokes' diameter. It is considered that the terminal velocity estimated from the regressions defines more suitably the limit of operation, and hence uprate potential, of a blanket.

4.1.3.3. Effect of water temperature.

Adjustment of the terminal velocity values to a standard viscosity of 0.01 poise to account for temperature variations was found to make the distribution of the results less acceptable. However, Fig. 4.2. presents an examination of both the maximum flux velocity equation 4.15, and the terminal velocity, equation 4.13, for effect of temperature. The velocities have been plotted with respect to the viscosity of water for the temperature estimated as the average for the various experiments. To assist the evaluation of the data the lines A X B and A' X B' have been constructed. The point X was selected as mid-range for the viscosity and velocity. Points A and B were then determined as the end of range viscosities and velocity at X referred to these viscosities. Because changes in water density, due to change in water temperature, is also of a similar order of magnitude of the density for the quality of floc encountered, the points A' and B' represent A and B respectively for the effect of a change in water density on floc of density of about 0.006 kg per litre. For the maximum flux velocity the data are inadequate for a conclusion to be made. For the terminal velocity the data, particularly for the 0.3 m tank, indicates that the magnitude of the velocity was primarily dependent on the viscosity, or temperature, of the water. Accounting for a change in density difference is not so apparently valid. It might be that floc naturally became less dense with increase in temperature.

4.1.3.4. Maximum flux conditions.

For the two relationships of blanket flux the velocity and concentration at maximum flux can be considered as being special values in defining the quality of floc and properties of the suspensions. For conditions at Medmenham the distributions in these values are given in Fig. 4.1. From all the data, this maximum flux velocity was observed to equal approximately half the terminal velocity deduced from the linear correlation of $\ln(1 - s)$.

The value of either the maximum flux or terminal velocity was observed to be dependent on the hydraulic quality of the tank. The greatest values were generally obtained for the 0.3 m tank and the 1.2 m tank fitted with inclined tube modules.

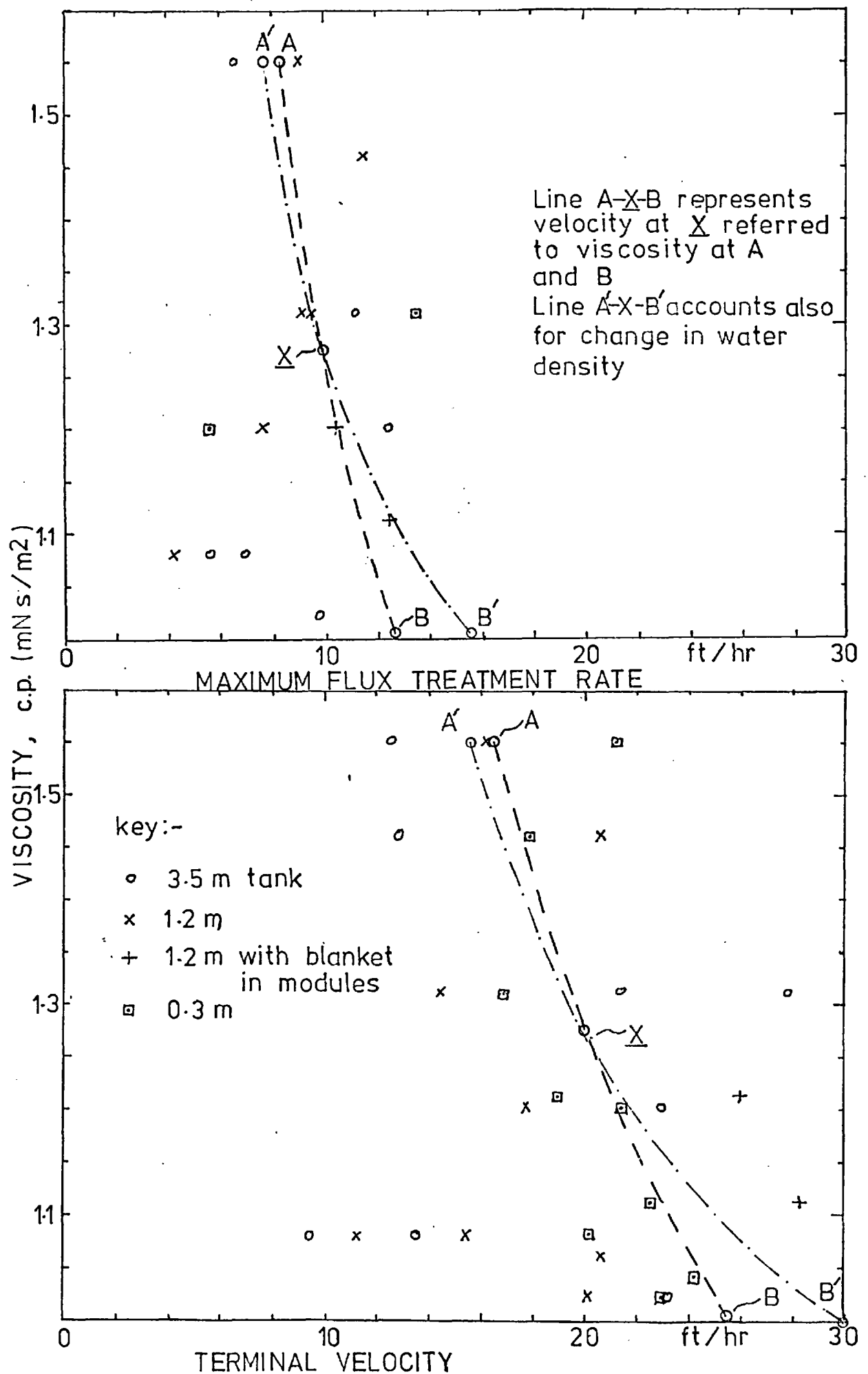


FIG 4.2 EXAMINATION OF SETTLING DATA FOR EFFECT OF WATER TEMPERATURE

Close examination of the general performance data of the tanks indicates that there is a strong relationship between the commencement of deterioration in product water quality and maximum flux concentration and velocity conditions. The practical interpretation of this maximum flux condition is that it represents conditions of operation likely to give the best tank performance with respect to quantity and quality only, operational cost and optimum relationship with following processes not being considered.

Davies and Kaye (1972) have examined the settling of suspensions of various shaped rigid particles. They defined a critical concentration for mixtures of particles as the concentration above which segregation was not observed. For spherical particles of equal density the critical volumetric concentration is in the range 0.35 to 0.40, and for mixtures of cubes and cylinders about 0.17. For a multiple size mixture, such as occurs with floc, the critical concentration is observed to represent the transition from the diffuse to the defined interface of their suspension. It has been mentioned that the packed point concentration could not be determined easily for a settled concentration of less than about 0.16. The concentration at maximum flux was in the range 0.13 to 0.18. It appears that the phenomena of maximum flux and defined interface transition and the critical concentration defined by Davies and Kaye are the same condition of a suspension.

Davies and Kaye explained that the critical concentration was due to the inter-particle orientations and resultant mechanical inter-locking of the smaller species. Thus, for a floc blanket, entrapment by straining will also be involved. Deterioration in product quality is then associated with the relaxation of the entrapment and straining as inter-particle distances increase with increase in treatment rate and the development of the diffuse interface. For concentrations greater than critical the product quality primarily represents material unsuccessfully coagulated and therefore not effectively flocculated which is small enough to pass through the mechanical structure of the blanket. If this mechanism of clarification is valid then product quality relationships should be more correctly correlated for conditions representing either greater or less than critical. To examine this mechanism further, Fig. 4.3. was prepared. The treatment rate associated with product quality deterioration has been estimated for the

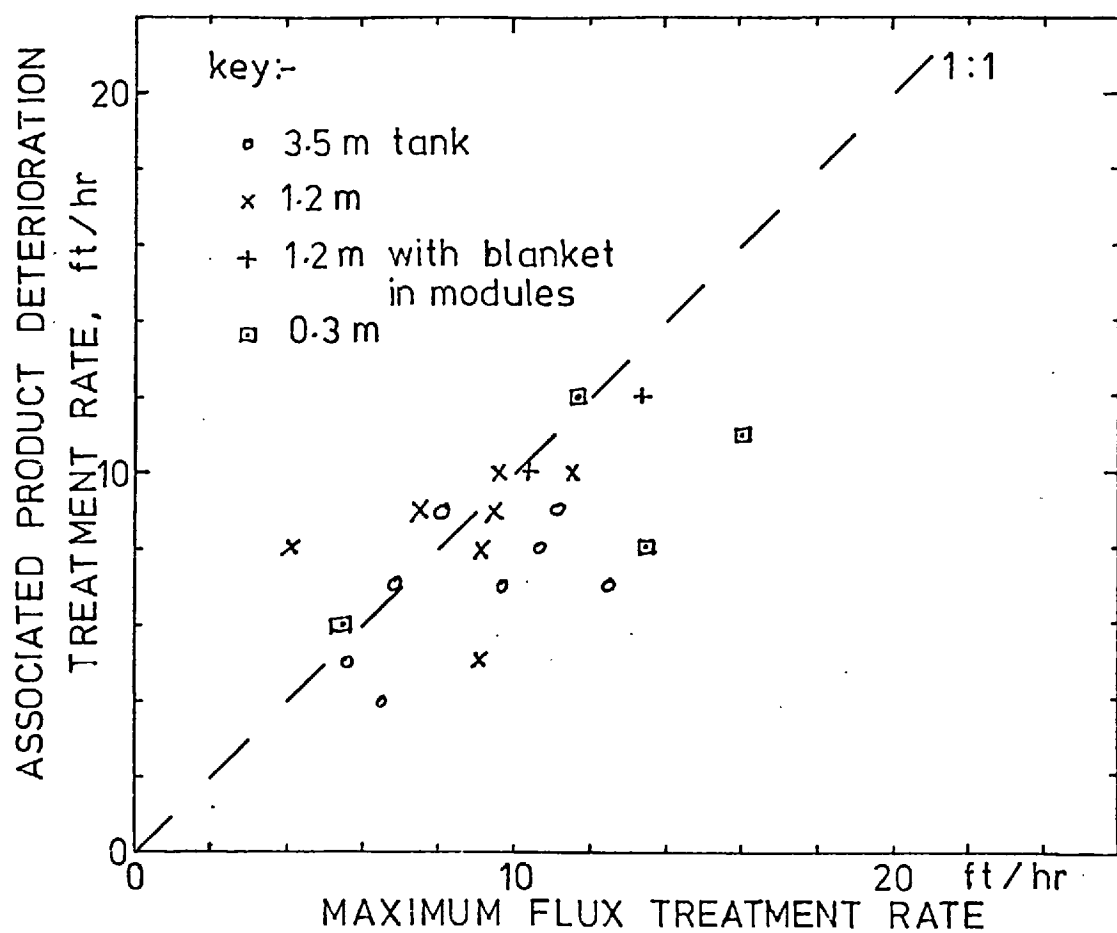


FIG 4.3 ASSOCIATION OF MAXIMUM FLUX TREATMENT RATE WITH PRODUCT QUALITY DETERIORATION

three tanks from their respective group presentations of product turbidity - treatment rate relationships. This value is plotted against the maximum flux treatment rate. The bias to one side of the equality line, indicates that the estimate of product deterioration was conservative. The maximum flux treatment rate otherwise appears to be closely related to deterioration in product quality.

4.2. Comparison With Other Work

4.2.1. Flocculation theories.

Ives (1968, 1969a and 1969b) has produced the most comprehensive quantitative examination of floc-blanket clarification known to exist. Ives (1968) attempted to apply the theory of orthokinetic flocculation then available to the case of a conical-shaped upflow clarifier. His objective was to produce some design considerations which relate the clarifier dimensions to the rate of flow and the characteristics of the floc. He examined the clarifier for its individual functions as a flocculator, as a retention tank for floc and as a balancing tank for the solids fed in. When these functions are put together they should specify the hydraulic requirements of the tank and lead to some design considerations. However, Ives had to make many simplifications which may not be justified in practice. These are discussed whilst reworking his design example:

Viz. Let us assume that we require a clarifier to treat

* 2 mgd ($Q = 3.7 \text{ cu ft/s}$); at 50°F , $\mu/\rho = 1.41 \cdot 10^{-5} \text{ sq ft/s}$.

(i) Although Argaman and Kaufman (1970) have recognised that orthokinetic flocculation is a balance between floc growth and breakup, the term G.c.t. used by Ives is a much easier expression of flocculation to employ and has found some general acceptance. Ives took G.c.t. = 100 as a typical value. Vostreil (1971) and Fair et al (1971) have proposed that a modified form of G.t. can represent clarification conditions in a floc blanket, where: (see Sect. 1.4.4.)

$$(\text{G.t.}) \text{ modified} = Ca = \sqrt{\frac{P}{\mu \cdot \bar{V}}} \cdot \frac{\bar{V}}{Q} \dots\dots\dots 4.20$$

* units as used in the original by Ives.

$$\text{where } P = \rho_b \cdot g \cdot h_f \cdot Q, \quad \text{N.m/sec,} \quad \dots\dots\dots 4.21a$$

in which ρ_b density of the blanket, kg/l,

h_f useful loss of head = weight in water
of the floc in the blanket,

$$= L \cdot c \cdot \Delta\sigma, \text{ m,} \quad \dots\dots\dots 4.21b$$

$\Delta\sigma$ specific gravity difference between floc and water.

$$Ca = \left[\rho_b \cdot g \cdot \frac{L \cdot c}{\mu} \Delta\sigma \cdot \frac{V}{Q} \right]^{\frac{1}{2}} \quad \dots\dots\dots 4.22$$

$$\text{but } \frac{V}{Q} \cong \frac{L}{U} \quad \text{hence } Ca = \left[\rho_b \cdot g \cdot \frac{L^2 \cdot c}{\mu \cdot U} \Delta\sigma \right]^{\frac{1}{2}} \quad \dots\dots\dots 4.23$$

It is believed that the value of c should be taken as $q_6 \cdot s$, the hydrodynamically effective volume concentration. The value of this equation, at Medmenham in the experimental tanks at maximum flux conditions, when $L = 2$ m effective depth, $U = 3$ m/hr, $s = 0.16$, $\Delta\sigma = 0.005$.

$$Ca = 8.6 \times 10^3$$

(which is of the same order of magnitude found by Vostreil)

$$\text{hence } \underline{G.c.t. = 3550}$$

(ii) The assumption of a single particle size, shape and density throughout the blanket is justified providing they are regarded as their effective values. However, the work reported has shown that the use of Stokes velocity as the terminal velocity in the velocity-concentration relationship is not acceptable. Using the apparent terminal velocity means the lower boundary of the blanket is unrealistically higher than calculated by Ives. From observation through a clear plastic column, the flow conditions at the lower boundary appear extremely turbulent. The terminal velocity in fully turbulent flow is given by:

$$U_o = \left[\frac{4}{3} \cdot \frac{d \cdot (\rho_f - \rho)}{0.44 \rho} \cdot g \right]^{\frac{1}{2}} \quad \dots\dots\dots 4.24$$

$$\text{and } = \frac{4 Q}{\pi \cdot L_1^2}$$

for the example $L_1 = 0.94$ m

this level is comparable with the levels found in practice.

(iii) From the investigations the velocity-concentration data is probably well represented by:

$$U = U_q \cdot (1 - q_6 \cdot s)^{1.0} \quad \dots\dots\dots 4.26$$

where U refers to the upflow velocity at the blanket surface.

Therefore the power dissipated per unit volume is given by

$$P_D = \frac{4 \cdot \Delta \rho \cdot g \cdot Q}{\pi \cdot L^2 \cdot q_6} \cdot \left[1 - \frac{U_s}{U_q} \right] \quad \dots\dots\dots 4.27$$

This should be compared with Ives who proposed that a concentration gradient existed through the depth of the blanket, which in general can be assumed not to be significant.

$$\text{Hence: G.c. } \delta t = \left[\frac{\Delta \rho \cdot g \cdot \pi}{4Q \cdot \mu} \right]^{1/2} c^{3/2} \cdot L \cdot \delta L \quad \dots\dots\dots 4.28$$

Then integrating between $L = L_1$ and $L = L_s$

$$\text{G.c.t.} = \left[\frac{\Delta \rho \cdot g \cdot \pi}{4Q \cdot \mu} \right]^{1/2} \cdot \left[1 - \frac{4Q}{\pi \cdot L_s^2 \cdot U_q} \right]^{3/2} (L_s^2 - 0.9) \cdot \frac{1}{2} \quad \dots\dots\dots 4.29$$

$$\text{hence: } 3550 = 542 \left[1 - \frac{66.7}{L_s^2} \right]^{3/2} (L_s^2 - 0.9) \cdot \frac{1}{2}$$

$$\text{and: } 13.1 = \left[1 - \frac{66.7}{L_s^2} \right]^{3/2} \cdot (L_s^2 - 0.9) \quad \dots\dots\dots 4.30$$

Solving by trial and error, for the R.H.S.:

if L_s	=	8.5	9.0	10.0	9.5	9.6
R.H.S.	=	1.37	6.0	18.8	11.6	13.2

The value of $L_s = 9.6$ m. This is about that found in practice; compared with 7.4 m calculated by Ives.

$$\left[\begin{array}{l} \text{Check } U_s = \frac{4Q}{\pi \cdot L_s^2} = 0.0014, \text{ m/sec} \\ \text{to give } s = 0.12 \end{array} \right]$$

Since the calculation was meant to arrive at maximum flux conditions, the method results in slight underdesign. However, the whole calculation is very sensitive to a small change in the value of L_s . Maximum flux is found at $L_s = 10.3$ m.

(iv) The maximum value of G will be at the lower boundary of the blanket:

$$G_1 = \left[\frac{c \cdot \Delta \rho \cdot g \cdot Q \cdot 4}{\pi \cdot \mu \cdot L_1^2} \right]^{1/2} \dots\dots\dots 4.31$$

$$= 41 \text{ sec}^{-1}$$

and $G_s = 4.1 \text{ sec}^{-1}$ at the blanket surface.

These values are clearly below most shearing values found for mechanical flocculation.

It appears that acceptable yet simplifying changes can be made to Ives' theory that lead to more acceptable answers to the calculations in the theoretical design of floc-blanket clarification. However, what is also important is prediction of separation/clarification efficiency by the blanket. Ives did not achieve this. Prediction can be achieved if the settled water quality - blanket concentration and - upflow velocity relationships are known, as established by these investigations.

4.2.2. Reaction theories.

The adsorbition approach followed by Cretu (1968) presupposes the presence of particles with non-terminated development of physical properties in addition to fully developed particles. The incompletely developed particles are the basis of the clarification mechanism whilst the fully developed particles provide the basic structure of the floc blanket. The incompletely developed particles exhibit an adsorbent character and completion of their development is a mass transfer process. The clarification process may then be represented at steady state by:

$$- \delta C \cdot Q = B \cdot S_z \cdot \delta z \cdot C \dots\dots\dots 4.32$$

for an incremental change in C of δC through an incremental depth of blanket δz at level z from the inlet,

where Q volumetric flow rate ,
 S_z cross section at level z ,
 B separation parameter = $b \cdot C_s$, sec.^{-1}
 C_s concentration in the blanket at steady state,
 at z , $U_z = Q/S_z$ and $b \sim$ adsorbition coefficient.

$$\text{Hence } \frac{dC}{C} = - \frac{B}{U_z} \cdot dz \quad \dots\dots\dots 4.33$$

Therefore for a parallel flow blanket zone and if $z_o = 0$:

$$C = C_o \cdot \exp \left(- b \cdot C_s \cdot \frac{z}{U_z} \right) \quad \dots\dots\dots 4.34$$

Since z/U_z is equivalent to time of contact, this relationship is equivalent to that proposed by Hudson (1965) for orthokinetic flocculation when $B = G \cdot C \cdot \text{sec}^{-1}$ and to that of a first order reaction if B is the specific rate constant.

Cretu has also developed his relationship for the case of an expanding flow blanket zone with the assumption of a homogeneous suspension. Cretu has found that if $C_s = 3600 \text{ mg/l}$ (nature not stated) and U_z in parallel flow = 0.75 mm/sec and z_o to $z_1 = 1.25 \text{ m}$ then $b = 0.55$ in parallel flow and = 0.83 in expanding flow, $\text{cm}^3/\text{gm sec}$. $0.28 \cdot \text{m}^3/\text{kg.hr}$.

Shogo (1971) took a similar approach but attempted to account for non-ideal flow conditions by introducing the distribution function $E\phi$ of detention time in the blanket.

$$\frac{C}{C_o} = \int_0^\infty \exp(-k_s \cdot T \cdot \phi) \cdot E\phi \cdot d\phi \quad \dots\dots\dots 4.35$$

where ϕ is the normalized detention time,

T is the theoretical mean residence time.

The solution of this relationship is given by:

$$\frac{C}{C_o} = 4\psi \cdot \exp\left(P_e \cdot \frac{B}{2}\right) \cdot \left[(1+\psi)^2 \cdot \exp\left(\psi \cdot \frac{P_e \cdot B}{2}\right) - (1-\psi)^2 \cdot \exp\left(-\psi \cdot \frac{P_e \cdot B}{2}\right) \right]^{-1} \quad \dots\dots\dots 4.36$$

where $\psi = \sqrt{1 + \frac{4k_s \cdot T}{P_e \cdot B}}$, and $P_e \cdot B = \frac{U \cdot L}{E_z}$

E_z = coefficient of diffusion, and $B = L/d$.

Shogo concluded that flocculation in a blanket is approximately a linear reaction, that the reaction can be represented by the above and that the reaction velocity k_s is approximately proportional to the coefficient of diffusion. He examined his data with the empirical formula:

$$k_s = K_s \cdot P_u^a \cdot T_c^b \cdot U^c \cdot C_s^d \cdot E_z^e \quad \dots\dots\dots 4.37$$

He found the best correlation was achieved with a highly turbid water, 1000 mg/l, coagulated with PAC (polyaluminium chloride) to give:

$$k_s = \frac{55.7 E_z^{0.943}}{U^{1.96} C_s^{0.069}} \dots\dots\dots 4.38$$

Shogo found that k_s ranged in value from 0.2 to 2.4 min^{-1} for alum and for PAC coagulated water. Comparison with Cretu gives:

$$b.C_s = 0.12 \text{ to } 0.18 \text{ min}^{-1}.$$

Some of the data obtained in these investigations were examined on the basis of Cretu's method. For experiments AC18 the characteristic range in value of $b.z$ was 0.03 to 0.42 mg Al. hr/ft.litre which is about 0.25 to 3.5 cm^3 per grm sec with a value of about 1.0 at maximum flux conditions. In the units used by Shogo, k_s was found to be in the range 0.10 to 0.50 min^{-1} and at maximum flux conditions about 0.15 min^{-1} . The value of k was found to decrease in value with increase in treatment rate, ie proportional to $U^{-1.5}$.

This comparison illustrates that the order of magnitude of the reaction velocity coefficient is of the same order of magnitude for different floc blanket systems but the precise value will be characteristic of the coagulation chemistry and the mixing conditions within the blanket.

4.2.3. Other comparisons.

Table 4.5. summarizes the pertinent details of results of similar work to that done on velocity-concentration correlation. This table illustrates that a wide variety of investigations have found a wide range of values for the various coefficients. Their values are to a great extent characteristic of the coagulation-flocculation system and hence the quality of the floc particles. Unfortunately their close comparison is limited by the different techniques used for the measurement of floc volume concentration.

In general the values of the coefficients found in this investigation are comparable with those already published. Although a value of 2.5 for q_6 was used, the value of q_6 was found to vary occasionally beyond the range 1.8 to 3.5. This variation was usually associated with raw water quality changes and unsatisfactory coagulant doses.

It has already been noted that the value of q_6 is similar to the Richardson and Zaki, Eqtn. 4.7, volumetric shape factor coefficient and the exponent in the viscosity relationship found by Landel et al, Eqtn. 1.8. The value of f in Bond's equation has been found to vary from 1.6 to 3.25 ; it is also noted that $2.5^{2/3}$ equals 1.6. However, Michaels and Bolger (1962) found for flocculated kaolinite that the ratio of aggregate volume concentration to floc volume concentration could have a value in the range 3.5 to 4.0 , where an aggregate was defined as a cluster of flocs that could form at low shear rates during settling measurements.

The range in value found for the exponent in Richardson and Zaki's equation, being greater than generally found for uniform rigid particles, illustrates that some other factor, closely associated with the measurement of concentration, must be included to account for wide ranging particle properties. Such a factor must be capable of easy, empirical or theoretical determination for such difficult systems as floc suspensions.

This investigation found that the treatment rate at maximum flux was about half the treatment rate at zero floc concentration. Bond (1959) noted that the blanket surface remained clearly defined up to a treatment rate of about half his terminal settling rate, U_p , that slight boiling occurred above $0.55 U_p$ and clarification deteriorated noticeably at about $0.65 U_p$. Tambo et al (1969) have found a floc blanket is stable for treatment rates less than about $0.7 U_p$. For greater than $0.8 U_p$ they found the blanket very unstable with the coefficient of diffusion becoming exceedingly large. From the experience of these investigations, treatment rates greater than about 0.75 of the treatment rate at zero floc concentration would not be recommended.

4.2.4. Inclined settling.

The investigations showed that in a floc blanket between inclined parallel surfaces 50 mm apart the floc concentration can be 50 per cent greater than for a blanket with simple upward flow. However, the mechanism of clarification proposed for simple upflow conditions does not account for the lack of improvement in clarification with the greater floc concentration between inclined surfaces.

Most of the work published related to this subject has been concerned either with the clarification-sedimentation of dilute suspensions, with primarily discrete settling conditions, or with the batch settling of concentrated suspensions. No useful reference was found related to fluidization in inclined vessels with the maintenance of a constant level surface to the fluidized bed.

Zahavi and Rubin (1975) have studied the batch settling of clay suspensions in vertical, right-angled trapezoid and parallelogram shaped vessels. Within the range of variables they studied, 2 to 10% volume concentration, 35 to 65° inclination, base length 9.5 to 98 cm, settling rates could be as great as three times that in a vertical settling vessel. They developed a theoretical model which gave good agreement with their experimental data. However, they commented that the theoretical model may fail because of mixing and turbulence effects when the distance between planes becomes relatively small, and in their investigations, less than about 10 cms. They also made the same qualitative observations as Kinoshita (1949) and Pearce (1962) that a circulation of the particles occurs under the downward facing surface. McMichael (1972) made particular reference to a theorem by Bjerknes (Prandtl (1952)):

'If the tube is vertical, the suspension settles with its surfaces of constant density parallel to surfaces of constant pressure, assuming the pressure distribution in the fluid is hydrostatic. If a suspension settles in an inclined tube, and the pressure distribution is hydrostatic, surfaces of constant density will intersect at some angle with surfaces of constant pressure. This crossing of the surfaces of constant pressure and constant density generates a circulation within the fluid body. The rate at which circulation is generated within the fluid body depends on the angle of intersection of the local density and pressure gradients.'

In addition Zahavi and Rubin introduced the concept that the settling velocity of the suspension between inclined surfaces, V_{in} , is the sum of the settling rate at the liquid-suspension surface, V_s , which depends on suspension concentration and can be obtained from settling experiments in vertical vessels in the regular manner, and V_d which is the contribution of clear liquid from under the downward facing surface.

$$V_{in} = V_s + V_d \quad \dots\dots\dots 4.39$$

From this is developed for the settling velocity at height λ from the top:

$$(V_{in})_x = (V_s)_x + \frac{\bar{q} \cdot (h_o - \lambda)}{\sin \theta \cdot r} \quad \dots\dots\dots 4.40$$

where $\bar{q}$ is defined as the average flow rate of clear liquid per unit area of inclined plane, and r is the horizontal distance between planes.

They found the average value of $\bar{q}$ was $0.751 \text{ cm}^3 \text{ per cm}^2 \cdot \text{min}^*$ and could be assumed to be constant for the range of variables they examined.

With reference to Fig. 3.33, the effect of tube modules in the hydraulic model, it cannot be accepted that $\bar{q}$ in these results was constant for all levels in the tube modules.

From equation 4.40:

$$\frac{d(V_{in} - V_s)}{dh} = \frac{\bar{q}}{\sin \theta \cdot r} \quad \dots\dots\dots 4.41$$

but if: $V_s = U_q(1 - q_6 \cdot \lambda)^{1.0}$

then: $\frac{dV_s}{dh} = \frac{U_q \cdot q_6 \cdot d\lambda}{dh} \quad \dots\dots\dots 4.42$

In Fig. 3.33, after the first small increment of tube, the value of $\frac{d\lambda}{dh}$ appears constant for about the next 0.05 m of tube and equal to about 7.0 per m. The values of U_q and q_6 were not determined for the anthracite used in the model. For equal solids concentration, $\frac{dV_{in}}{dh}$

appears to be constant, equal to about 177 ft per hr.m.⁺⁺ It is assumed these values are applicable to the prototype; then:

$$\bar{q} = 13.4 \text{ cm}^3 \text{ per cm}^2 \cdot \text{min.}^{**}$$

This gives:

$$V_{in} - V_s = 5.3 \text{ ft per hr}^{\$}$$

This can be compared with the results given in Fig. 3.9 of flocculation versus treatment rate. The difference between the blanket surface being within and below or without tube modules, for equal floc concentration is about 5 ft per hr.^{\$\$} Similarly for constant concentration in Fig. 3.33 the

* 0.451 m per hr

++ 54 hr⁻¹

** 8.04 m per hr

\$ 1.62 m per hr.

\$\$ 1.53 m per hr.

maximum increase in velocity that could be obtained tended to be about 5.4 ft per hr.^{\$}

It therefore appears that initially efficient use of the inclined surfaces occurs but as the inclined column increases in length the inclined surfaces become less efficiently involved until some equilibrium condition is reached associated with the velocity contribution from the downward facing surface.

Yao (1970) has proposed the relationship:

$$S_c = \frac{V_o}{V_{in}} \left(\sin \theta + \frac{L}{d} \cos \theta \right) \dots\dots\dots 4.43$$

for dilute suspensions which might be applicable at the entrance to the tubes only. Where S_c is a factor whose magnitude depends on the shape of the settler. For square settlers,

$$S_c = 11/8 \cong 1.375$$

With reference to Fig. 3.33 for thickening in the initial useful length of tube, for example, increase in treatment rate from 6.3 to 8.1 ft/hr.^{\$\$}

$$S_c = \frac{6.3}{8.1} \left(0.866 + 6 \cdot \frac{0.025}{0.05} \cdot 0.50 \right) = 0.78 (0.866 + 1.5) \\ = 1.85$$

Other estimates of S_c also tend to be as large. This suggests that the velocity increase per length of tube should be much greater.

For further comparison, the Degremont "Super Pulsator" clarifier recently introduced, Richard (1974), uses parallel plates spaced 300 mm horizontally apart with projecting edges on their downward facing surfaces to provide rigidity to the plate and affect the circulation patterns at the blanket surface. Substantial increases in treatment rate, with acceptable clarification, are apparently claimed.

Examination of maximum flux conditions for the blanket within the tube modules indicated that maximum flux concentration for inclined flow was greater, about 0.24 to 0.30, than for vertical flow, about 0.15 to 0.18, for aluminium floc.

It would appear that, especially for close inclined parallel surfaces, the circulation predicted by Bjerknes at the surface of the suspension assists entrainment and breaks down the mechanical entrapment mechanism. This infers that under inclined flow conditions the mechanical entrapment

\$ 1.65 m/hr.

\$\$ 1.92 to 2.47 m/hr.

mechanism does not become efficient until higher concentrations, for example, for inclined flow the product quality per blanket concentration was worse than in upward flow.

Fig. 4.4. is a reproduction of a close-up photograph taken of the model with the anthracite surface in the tube module at an upflow velocity at the lower end of the range over which the interface became diffuse. The magnification is slightly greater than two. The module was made with half-width inclined planes on the outside vertical planes. The photograph therefore represents the profiles existing between the tank wall and first vertical plane. The development of a relatively clear liquid zone beneath the downward facing surfaces is evident. The origin of the clear zone appears to be at least twice the width of a tube below the upper limit of the interface of the suspension.

4.3. Implications of the Work

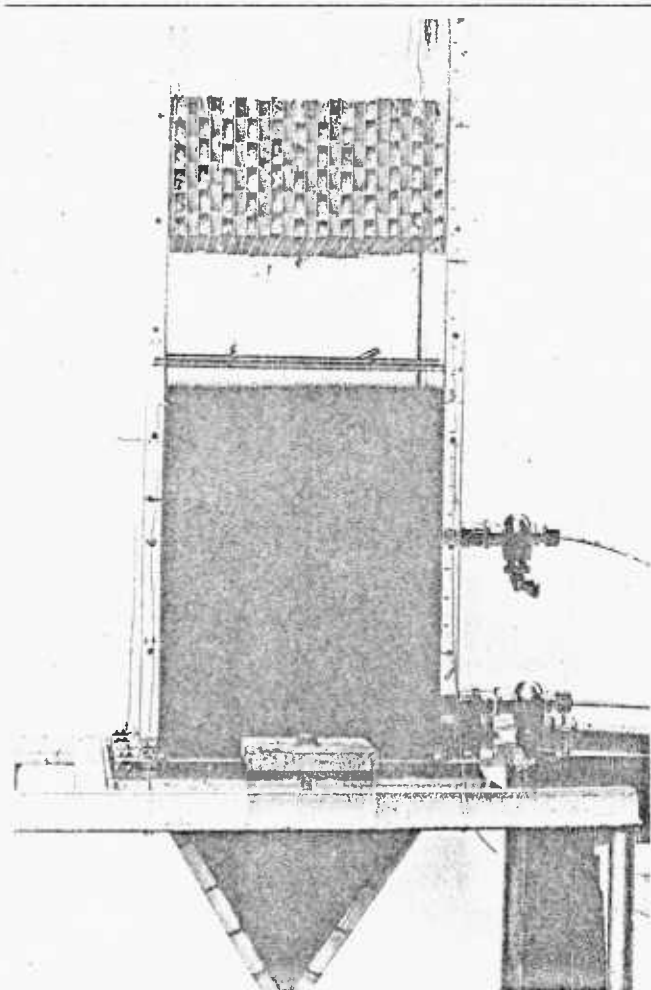
4.3.1. Floc blanket theory.

The practical investigations and the review of the literature have produced a greater understanding of the process of floc-blanket clarification. This should result in greater confidence and efficiency in the design and operation of the process.

The investigations have shown the nature of the clarification mechanism of a floc blanket. Proposals have been made as to how floc blanket data might be analysed and interpreted and what other factors, besides normal operational parameters, might need to be considered, namely factors representing raw water quality and environmental variations. The results of the investigations show that designing for the treatment of new sources must involve pilot plant trials.

A substantial part of the investigations were concerned with the examination of various design features, in particular tank size. The design features were generally of importance in respect to the hydraulic stability of the floc blanket and included the control of injection velocity and bulk flow control devices.

From the overall experience the approach in the operation of the process can be defined. This can include the control of chemical treatment



General view of the model



Anthracite fluidized in model tube modules to show clear zone under inclined surface

FIG 4.4 SCALE MODEL WITH TUBE MODULES

and blanket level and the parameters that should be measured to maintain performance. However, most important of all is appreciation of those factors that influence the mechanism of clarification.

It has been demonstrated that product quality is dependent on the blanket floc volume concentration, which is in turn dependent on the treatment rate and the tank hydraulics. This results in the variation of overall clarification performance with treatment rate. The deterioration in product water quality with increase in treatment rate is related to the maximum flux floc concentration and treatment rate. The maximum flux condition can be explained by the clarification of a floc blanket being primarily a mechanism of mechanical particle entrapment, at the maximum flux or greater concentration. For smaller concentrations, flocculation and sedimentation become increasingly more prominent contributions to the clarification mechanism. The maximum flux condition represents the condition of operation likely to give the best tank performance with respect to quantity and quality only, operational cost and optimum relationship with following processes not being considered. The maximum flux condition also represents the ease of treatment of the water for the chemical treatment applied, and hence can be used as a measurement of floc quality, raw water quality and tank efficiency for the water temperature and the operational and environmental conditions prevailing.

This mechanism of clarification does not account for the incommensurate improvement in product quality with the substantial increase in blanket concentration below tube modules when the blanket surface is operated within the tube modules. A qualitative model has, however, been proposed for the settling of concentrated suspensions between close inclined surfaces.

4.3.2. Application of the work.

4.3.2.1. Approach to design.

The investigations have shown that complete dependence on mathematics for the design of floc-blanket clarification is not possible. This is not because the mathematics do not exist but because the values of certain constants and coefficients cannot be obtained from books or simple laboratory analysis but must be obtained from continuous flow plant. Particularly important is that these values are subject to seasonal variation.

Further, unless considerable experience is available, the successful chemical treatment and the optimization with associated treatment processes can be more confidently established by pilot plant operation. Pilot plant on a new source can provide the basis of a training for new personnel for the intended new works.

Whenever possible the pilot plant should be operated over a long enough period such that the full range of water treatment situations is experienced. Frequent change of treatment rate over a wide enough range should be practised, thereby a complete performance band will be identified with seasonal variations, with the possibility of estimating a statistical confidence. Of particular interest are the maximum flux conditions for worst and best treatability of the raw water and how their difference in treatment rate compares with the projected annual demand variation for the plant. This information then defines the design capacity of the tanks giving due allowance for hydraulic inefficiency and increase in demand on the plant at some later date.

However, the use of the available mathematics; velocity-concentration relationship for suspensions and the flocculation and reaction clarification theories; should be developed further. Their use in the meantime should greatly benefit the comparison of floc-blanket clarification of different waters and with different coagulants.

4.3.2.2. Design features.

(i) Shape: The choice of basic tanks structure, whether hopper or flat bottomed, whether circular or square, whether premix or simple upflow, is primarily based on economics. These investigations have not shown that a simple hopper tank can perform better than any other type of floc blanket tank. What the investigations have shown is that if one tank does not perform as well as another, when operated in parallel, then the difference might well be due to the hydraulic stability of the blankets in the two tanks. Thus some proprietary designs may have advantages over others resulting from size and quality of flow distribution. However, the conclusions suggest that a flat bottomed tank will not function as well as a single hopper tank because of the need for good inlet and diffusion.

(ii) Size: Size, in floc blanket tanks, refers primarily to cross-sectional area and not the depth of operation. Increasing the area in a hopper tank will, however, increase the depth as required by the dimension of the constituent hopper or hoppers. If it is assumed that the effect of blanket depth on performance is due to the contact with the suspended solids then the potential performance might be represented by the parameter of relative blanket volume. For example, a 10 m diameter hopper of 60° included angle is equivalent to 2.9 m of parallel flow. Thus the greater the size of tank the greater the tank depth necessary to provide equivalence of contact with the blanket. This aspect does not apply for flat bottomed tanks.

Miller et al (1965) have demonstrated the effect of increasing blanket depth on separation efficiency for a small diameter system. This effect can be expected to hold for large tanks providing hydraulic stability exists. It has been suggested that hydraulic instability as a dilution mechanism decreases the blanket solids concentration which contributes to the reduction in separation efficiency. Achievement of the required efficiency can be obtained by suitable reduction of treatment rate and increase of blanket depth. However, the indications are that, although blanket depth assists in producing hydraulic stability, its contribution to clarification efficiency is not in providing contact time for coagulation and flocculation but by causing increased blanket concentration. The dependence of blanket concentration on total depth was found with the hydraulic model as well as with the three tanks. The variation of concentration with depth and treatment rate is still being investigated.

(iii) Inlet conditions: The investigations have shown that the injection velocity should not exceed a certain or limiting value that decreases with treatment rate for large tanks. It appears that the limiting injection velocity is also dependent on the floc density and water temperature.

It was observed that a simple factor such as inlet alignment can influence the performance but the magnitude of the effect of such a geometric factor is likely to be dependent on the total tank geometry. A square tank is likely to be more vulnerable to poor inlet alignment than a circular tank.

As to the general comparability of circular and square plan tanks it is accepted that square tanks are likely to deteriorate before circular tanks

with boiling appearing initially up the corners unless suitable modifications are made. If suitable modifications are made there need be little difference in performance between the two shapes of tanks of equivalent dimensions. Various modifications have been proposed in the literature and examined in these investigations, but a logical approach should be taken for the adoption, if necessary, of such modifications.

(iv) Blanket stability: Blanket stability, as identified by the stability of the blanket surface, can affect product quality. The degree of instability might be identified from the difference between the treatment rate with instability and the treatment rate for stable flow that gives the solids concentration obtained for unstable conditions. If boiling is observed not to be selectively distributed over the tank extreme bulk circulation is unlikely to exist.

The investigations have illustrated that if blanket instability occurs, attention should first be given to the inlet conditions. Further, modification to the inlet conditions is likely to be far cheaper than modifications to flow conditions in the blanket, particularly at the blanket surface. The feasibility of the simpler and cheaper modifications should always be examined first.

Blanket level control should be considered as an aspect of blanket stability. It is recommended that careful attention be given to the sizing and positioning of suitable in-situ sludge concentrators that function as level control weirs. The dimensions of such concentrators are determined by mass balance and from the time necessary for a preliminary thickening of the solids collected. Only for certain situations should it be necessary to consider regular solids removal from the apex of a hopper.

(v) Water collection: Providing the supernatant depth allows for the dimensions of any boiling that might occur, the launders should be constructed for an even collection. Normal practice has been for the supernatant depth to be more than about 2.0 m. It is suggested that if boiling is minimal, if blanket expansion rates can be controlled by balancing flow increases with the capacity of the sludge concentrators, and if wind effects can be avoided, supernatant depth could be controlled easily at depths of less than 2.0 m.

4.3.2.3. Uprating and general operation.

The investigations have shown that if uprating of floc blanket tanks by hydraulic modifications can be achieved without modification of the chemical treatment, then the plant was originally inadequately designed or constructed, or underrated. It has been shown that hydraulic improvements might be possible on some tanks which would improve treatment rate by 30 to 60 per cent with maintenance of product quality. If hydraulic uprate is sought that will cause the blanket concentration to be less than that at maximum flux, then the laboratory experience indicates that difficulty in operation is likely to become extreme for blanket concentrations of alum floc less than 10 per cent. Further, the results show that decreasing the blanket concentration from maximum flux to 10 per cent will only provide an increase in treatment rate, for alum, regardless of product quality, of about 40 per cent.

Difficulties in treatment can be remedied by suitable use of coagulant aids, which will only be necessary for that period of difficult treatment. However, it should be added that difficult treatment might only be due to poor chemical treatment. Hydraulic modifications will not compensate for poor chemical treatment. If the best clarification without severe problems is being sought then the treatment rate which represents maximum flux concentration for the worst treatment situation is recommended. To operate below this critical condition should be regarded in most circumstances as wasteful, especially if the concentration is so great that the packed point concentration is greater than 100 per cent, but to operate above, the probability of encountering operational difficulties will rapidly increase. The choice of operating level is dependent on the optimization of the total treatment system.

4.3.3. Future investigations.

The investigations have not included the use of polyelectrolytes or other coagulants other than alum. With other chemical treatment it is extremely likely that the majority of the conclusions will remain unaltered, only the magnitude of the results and pertinent values might differ. Investigations now in hand using ferric sulphate as coagulant indicate that the maximum flux concentration for iron floc is in the range of 20 to 25 per cent.

The investigations have indicated that the floc normally produced at Medmenham, using alum, is of reasonably consistent quality. It would be extremely useful to generate equivalent information for other types of water so that comparisons of ease of treatment can be made more effectively.

It is clear that adequate appreciation of the variables outside experimental control is required. Knowledge of the full variation of each important variable through the seasons permits the extreme seasonal coagulation performance to be estimated. Knowledge of short term variations, diurnal and weekly, allows the variability of short term performance to be assessed. More recent examination of raw water analysis data has indicated the possible importance of orthophosphate concentrations in the raw water in accounting for the variability of clarification efficiency.

The effects due to diurnal and weekly variations could, to a greatly significant extent, be dampened out by adequate short term storage. At Medmenham, feed water is taken directly from the River Thames, the quality of which is therefore immediately sensitive to any local activity in or on the River. Obviously, the ultimate response is related to the capability of the clarification system to absorb any variation with due respect to its relative magnitude and duration. It could be useful to consider the capacity of the blanket to absorb variations in input quality and relate this to tracer responses.

The dynamics of a fluidized floc system might be worthy of further investigation. The validity of the mechanical energy balance and hydraulic analysis approaches to tank stability require further substantiation. In the analysis of stability the contribution of density gradients could be examined closely, together with greater elucidation of the contribution of temperature, solids concentration and viscosity.

It could be useful to extend flocculation theory to the application of concentrated suspensions. Appreciation of the precise contribution of time in the flocculation of concentrated suspensions might be of great assistance in the evolution of new tank designs.

The velocity-concentration analysis has indicated that the approach taken of using the relative concentration should be extended to other types of floc and both rigid and various shaped particles in both vertical and inclined settling.

The use of parallel inclined surfaces should be examined further, particularly on the effect of distance between the surfaces.

The investigations have only been with hopper bottomed tanks. Substantial economic advantage might be available if the hopper design can be replaced by a simple vertical sides flat bottom tank if a very similar performance rating can be produced. Similarly, multi-hopper tanks in a large installation might be viable if a hopper is such a size to present savings by facilitating quick modular construction. It would be useful to examine further the feasibility of examining tank design using hydraulic scale models in conjunction with rigid model sediments.

5. CONCLUSIONS

- (i) The performance of floc blanket tanks has been shown to be affected by various factors related to both the water quality and the hydraulic design of the tanks.
- (ii) There appears to be no fundamental factor that governs the comparative behaviour between tanks of different size. The investigations indicated that the larger is the tank the more dependent the performance becomes on the hydraulic design and accuracy of construction. The effect of inlet design and accuracy of construction can be easily demonstrated with a Perspex scale sedimentation model.
- (iii) A small diameter (e.g. 0.3 m) column can be regarded as hydraulically ideal such that its performance only represents the limitations in treatment due to the quality of the floc in the blanket. Such a unit can be regarded as capable of demonstrating the best possible performance of stable vertical flow of an otherwise hydraulically poor large scale tank.
- (iv) Excessive injection velocity in large single hopper tanks can cause deterioration in tank performance. The influence of injection velocity becomes more critical with increase in treatment rate and increase in water temperature.
- (v) Depending on the treatment rate and the hydraulic quality of the blanket, moderately spaced large vertical baffles at the blanket-supernatant interface can improve tank performance.
- (vi) Inclined tube modules placed above the blanket cannot improve tank performance better than that representative of best stable vertical flow. When the blanket-supernatant interface is within the tube modules blanket density is increased but there is not a commensurate improvement in clarification. For the chemical conditions of the investigations the clarification was only marginally better than for best stable vertical flow.
- (vii) Blanket concentration data have been examined by methods similar to other workers. The results are in close agreement with other reported results. An improvement in the method of analysis of such data is suggested.

(viii) Blanket concentration, when used together with treatment rate and product quality, has been found to be a useful parameter in evaluating tank performance. The treatability of a floc is characterised by these three parameters at the condition of maximum blanket floc flux.

(ix) The method of evaluating and presenting tank performance data by quadratic models obtained by linear regression analysis using the method of least squares, was found useful.

APPENDIX

A.1. Diffusion Control, Selection of Grids

A.1.1. Introduction.

The objective of diffusion control is to counteract streaming flow and to prevent it from existing. The jets of streaming flow must be dispersed efficiently to approach the creation of the ideal of a homogeneous flow front of isotropic turbulence. Such dispersion might be achieved by the presence of secondary surfaces to cause additional impingement and expansion after flow reversal.

It is known that suitable design, choice of level of the inlet and use of baffles can considerably influence the quality of flow diffusion, e.g. Hale-Ives frustrum conical baffle, Hale (1971), Daer inlet diffuser, Webster (1966). In trying to improve the quality of inlet flow in the 1.2 m square tank, without the extreme complication of the accurate centering that was apparently needed, two extensions were tried. The first was 0.23 m long with 0.012 m dia holes evenly distributed around and along it and open ended into the apex of the hopper. The intention was that flow diffusion would come from the holes as well as the open end ^{so minimizing} streaming. Improvement was not apparent. The second was with a similar extension with a slightly higher density of holes and with the end blocked such that all flow was diffused. Improvement was apparent but could not be contributed to the diffuser inlet.

Hale (1971) in his model tests, besides examining plate and conical baffles, also examined the potential of fine wire mesh horizontal baffles but did not use a model suspension. Hale concluded that the headloss imposed by the wire mesh, with the help of corner baffles, was able to cause an even distribution of flow through that plan section, but all in the vertical direction; some directional assistance was required in a diverging section. To fulfil the requirements of an even upflow throughout any plan section of the tank would necessitate some directional characteristic of the headloss device, so Hale attempted to provide this by placing baffles directly on to the mesh. However, he found that any baffling superimposed on the uniform flow distribution produced by the headloss caused instability.

It is believed that Hale who experimented with water only overlooked the benefit of the solids in suspension in the blanket. The blanket itself

with its micro-turbulent structure can provide the necessary directional influence. The degree of influence is dependent on the floc concentration and other floc quality parameters.

In practice fine mesh grids cannot be used. A fine mesh will trap solids in the feed. If the mesh size is increased enough to allow the solids in the feed to pass it is still possible for partial blocking to occur by the accumulation of sludge settling from the blanket as experienced by the Russians, Mackrle and Mackrle (1960).

The simple baffles examined by Hale (1971) and Gould (1967b), in their model tests, deflect the streaming flow. A degree of diffusion of the streaming occurs from the deflection, so improving the quality of the flow front. A deflection system is suggested, therefore, that causes maximum redistribution of the streaming flow. Such a system can be regarded as a median between simple deflection baffles and a mesh grid.

The blind area of a diffusion grid should face the streaming flow. It can be considered that a two or even three-layer system might well be necessary to impose complete redistribution of streaming flow. The level of the top grid in a hopper tank must be suitable to maximize the directional influence of the blanket and to conveniently design for suitable hydraulic conditions across the grid.

Suitable hydraulic conditions are those which minimize jet formation through the orifices of the grid yet cause sufficient headloss to assist flow distribution. The degree of jet formation is represented by the value of the discharge coefficient which is the degree of flow concentration through the orifice. For a sharp-edged orifice, Coulson and Richardson (1963), the maximum value of the coefficient of discharge, C_d , occurs between:

$$10^2 < N_{Re}, \text{ Reynolds Number, } < 2 \times 10^3 \dots\dots\dots A.1$$

dependent on the fractional free area of the orifice. This relationship, however, is for flow in a straight pipe and must therefore be used with care in the present context. Excessive headloss can be generated by an orifice plate for fractional free areas less than 0.35, B.S.I. (1964). The value of C_d becomes very sensitive to the value of N_{Re} for fractional free areas greater than 0.60 and less than 0.40. It is therefore suggested that diffusion grids should be designed for this range of free area.

At this stage of the investigations experience indicated that the maximum operational rate of a tank was likely to be that which supports a blanket floc concentration of 10 per cent. At Medmenham the equivalent treatment rate using alum as coagulant was also estimated as likely to be 3.7 m per hr. Since this is the rate at which the diffusion grids would be required to operate most effectively, the design conditions are then defined.

Double-layer grid systems were installed in both the 3.5 m and 1.2 m tanks before an understanding of some of the possible implications of diffusion grid design was developed. However, both the practical experience and subsequent theoretical analysis indicated that grids could be of value in some applications and that temperature of the water affects their value.

A.1.2. Application, 3.5 m tank.

A two-layer system was tried in the 3.5 m tank. The lower and upper grids respectively had free area fractions of 0.52 and 0.58 and were placed at the 1.52 m and 1.88 m diameter levels. The levels were selected because of the existence of suitable means of retaining the grids in position. The grids were constructed of planks of 150 mm width profile cut from scrap 200 mm and 250 mm diameter PVC piping and installed with the concave face downwards. The concave nature of the baffle surface was considered to improve the deflection function. The geometry of the grids is shown in Fig. 3.20.

For retrospective analysis, if:

$$N_{Re} = \frac{\rho v d}{\mu} \leq 2 \times 10^3 \quad \dots\dots\dots A.2$$

where

v velocity of fluid through the orifice, m/sec

d diameter of an individual orifice of the grid, m

taking $\rho = 1.00 \text{ kg/litre}$ and $\mu = 1.0 \text{ mN.s/m}^2$

and at 3.7 m per hr, $v = \frac{3.7}{3600} \cdot \frac{3.5^2}{D \cdot a} \text{ m per sec}$

where

D hopper diameter at grid level, m

a grid fractional free area

and if n is the number of orifices in the grid,

then $n.d^2 = a.D^2$ A.3
 from equation A.2:

$$D^2 > 6.3 \frac{d}{a}$$

and substituting this in equation A.3:

$$D > \frac{6.3}{\sqrt{a.n}}, \text{ m}$$

For the upper grid, $n = 12$ and $a = 0.58$,
 therefore $D > 2.39$, m.

Increasing the value of the viscosity, such as for lower temperatures and increased solids concentrations, can reduce this value in direct proportion. Similarly, the diameter is in direct proportion to the value of Reynolds number. If $\mu = 1.5 \text{ mN.s/m}^2$, then $D > 1.59$ m, and the level of the upper grid might be then justified. For a level of 1.88 m good flow quality might be expected for temperatures below 11°C to give stability of the blanket.

If the grid is lower than these calculations could justify, the treatment rate at the onset of instability due to inefficient flow distribution is predicted from the design treatment rate proportional to the square of both the viscosity value and the grid diameter.

A.1.3. Application, 1.2 m tank.

A double-layer grid system was installed in the 1.2 m tank also prior to the theoretical approach proposed. The grids were constructed for a free area fraction of 0.55 and placed at the 0.37 m and 0.51 m levels. These grids were also constructed from strips cut from scrap PVC piping. The grid geometries are given in Fig. 3.21. Since in a square tank streaming is known to occur up the corners, the orientation of the grid geometry was to baffle the corners. In a circular tank such selective orientation is difficult to apply.

Utilizing the same design conditions:

$$D > \frac{0.74}{\sqrt{a.n}}, \text{ m}$$

for the upper grid $n = 10$ and $a = 0.60$

$$D > 0.30 \text{ m}$$

for the lower grid $n = 12$, and $a = 0.55$ to give $D > 0.29$ m.

This analysis indicates that stability is likely to exist. The level of the upper grid is likely to support stability for all treatment rates capable of maintaining a suspension of suitable floc concentration, unless the critical value of Reynolds number is substantially reduced.

A.2. Hydraulic Models

A.2.1. General.

The investigations have shown that the hydraulic efficiency of a tank is an important criterion in floc-blanket sedimentation performance. It would be extremely useful to be able to test a design of tank as a hydraulic model constructed in clear plastic rather than to go to the greater expense of constructing a prototype and to laboriously test its performance.

It is necessary not only to correctly model the hydraulic design of the tank but also to suitably represent the sediment. It is assumed impossible to model the flocculation mechanism, but with perseverance a suitable precipitation reaction might be found. However, the performance of a tank has been shown to be primarily dependent on the hydraulic flow condition as well as on the concentration of the solids in suspension for hindered settling concentrations. The importance of flocculation in the modelling can be assumed negligible, although in reality flocculation does contribute to the separation process.

When examining the settling of dilute suspensions, such as with horizontal or radial flow sedimentation, the contribution of the flocculation is likely to be of significance. The use of a rigid model sediment is still likely to be of considerable value, for although not influencing the hydraulic flow whilst in suspension, it will, however, aid the prediction of the settlement zones and modify the flow patterns according to the settlement profiles.

A.2.2. Sedimentation models.

Gould (1969) has considered the use of sedimentation models for the hydraulic design of clarifiers. The model requirements imposed by Gould are that:

- (a) The ratio of the resultant forces on any representative particle in the model, to the forces on a corresponding particle in the

prototype, should be the same for all particles or elements of volume. This condition will be attained if the component forces also have the same proportionality.

- (b) The flow pattern should be similar in model and prototype, after making allowance for time and scale effects.

It can be demonstrated that these two requirements satisfy the elements of the phenomena being examined.

The Richardson Number, N_R , is used to satisfy the first requirement of similarity:

$$N_R = \frac{\Delta\rho \cdot g \cdot d}{\rho \cdot U^2} \dots\dots\dots A.4$$

where

- $\Delta\rho$ density difference between particles and fluid
- ρ density of particle
- U velocity of particle
- d diameter of particle.

Similarity of flow pattern is obtained by consideration of velocity ratios.

Gould also showed that in this case, when the same fluid is used in the model and the prototype, the Reynolds Number, N_{Re} , based on fluid velocity and tank dimensions will be the same in both model and prototype.

Table A.1 refers to the requirements for hydraulic symmetry. When studying flocculation phenomena important parameters are reaction time and velocity shear gradients. The table shows that these cannot be the same in model and prototype for hydraulic similarity. A satisfactory model sediment for the hydraulic model is required to produce reasonable similarity in sedimentation, in inducing density currents, in turbulent intermixing and in concentration-velocity relationships.

A.2.3. Selection of model.

Gould (1969) has shown that, if the same liquid is used then the sediment particles in the model should be n^{-1} times the particle size in the prototype and that the settling velocity should be n times greater. These conditions imply that the apparent density in water should be n^3 times greater in the model than the prototype if the particles are of such a size and density to obey Stokes's Law.

$$n^3 = \frac{\rho_s - 1}{\rho_f - 1} \quad \dots\dots\dots A.5$$

where

ρ_s density of model sediment, kg/litre
 ρ_f density of prototype floc. kg/litre

Floc-density calculations for treatment conditions encountered at the WRC give a value in the range 1.0015 to 1.015. For what can be regarded as normal water conditions and chemical treatment with alum the range is 1.002 to 1.005, kg/litre.

Gould (1967a, 1969) considered sand to be a suitable model sediment. However, the model sediment must closely satisfy size as well as settling velocity to maintain solids volumetric concentrations and the suspension viscosity as well as satisfying the conditions for similarity. Although Gould used a value for floc density of 1.002 his value for floc size of 1.0 mm is not entirely satisfactory.

In estimating what size of floc particle to use it is important to distinguish between the size of flocs that contribute to the bulk of a blanket and the size that separates from the blanket and contributes to the product quality. Good product quality can be recognized by the narrow floc size range of small floc. The range is of the order 0.1 to 1.0 mm. Once the blanket interface deteriorates and product quality deteriorates from increased carryover a further range of particles can be considered superimposed upon the first. It can be assumed that the secondary range represents that of the bulk of the blanket, viz Davies and Kaye (1972), Sect.4.1.3.4. The range might be of the order 0.5 mm to 2.5 mm. Under certain chemical treatment conditions floc sizes up to 10 mm can be created.

Table A.2 sets out the model sizes for both sand and anthracite for a range of floc density. It will be noticed that because the model size is proportional to a cube root the interrelationship of model size and sediment density is not very sensitive. To validate the use of either sand or anthracite limited settling data was obtained for various size ranges and compared with data obtained for alum floc of various quality, Fig.A.1. As the figure indicates some consideration was given to the comparability of

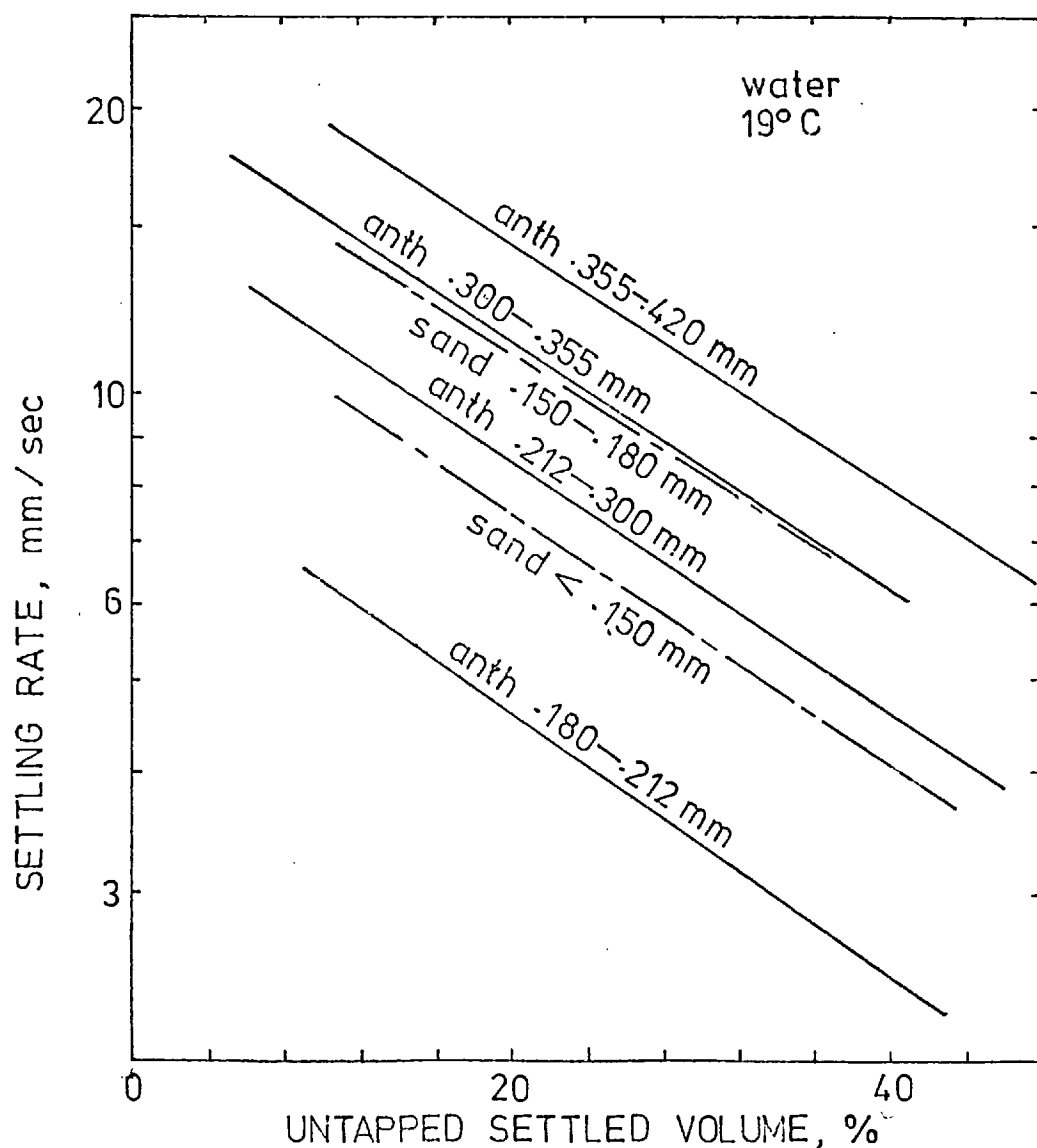
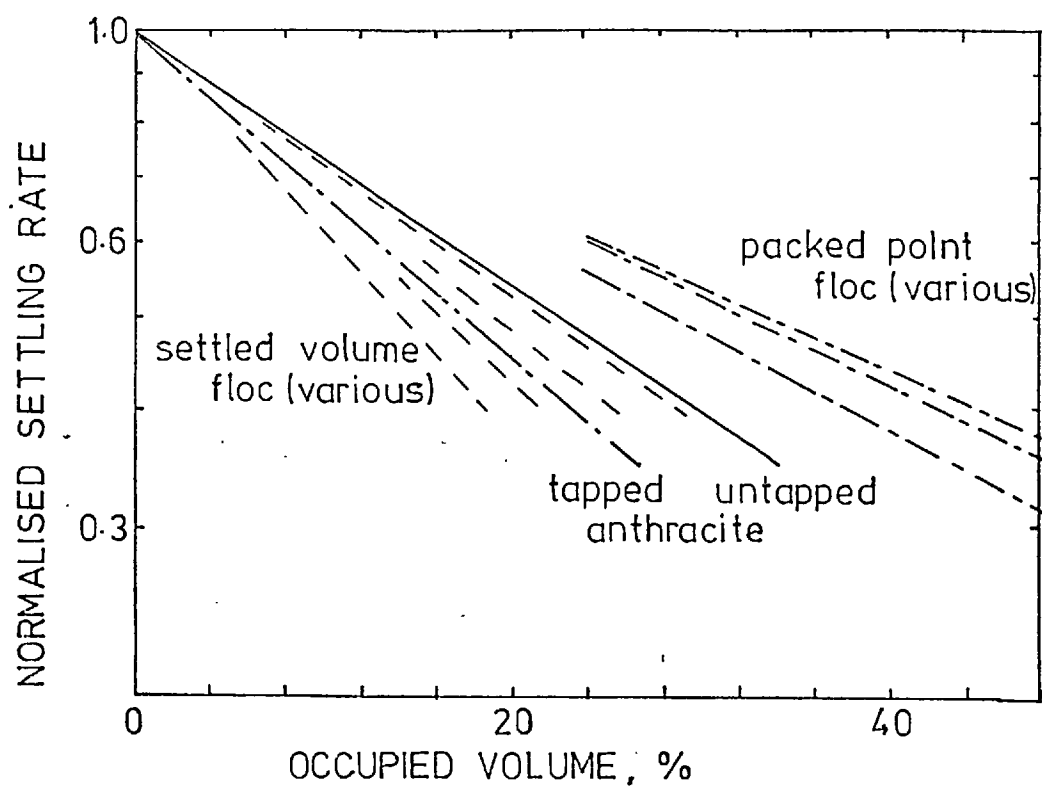


FIG A.1. SETTLING RATE-CONCENTRATION COMPARISON
FOR MODEL SEDIMENT SELECTION

the settled and packed point concentrations for floc with the untapped and tapped volumes for the rigid sediment. (The comparison of settled and packed point concentrations is made in Sect.A.3.) This aspect was not pursued further and for the purpose of the modelling the settled floc concentration was compared with the untapped rigid sediment volume. This showed that if a model scale of 6 is used then anthracite in the size range 0.212 to 0.422 mm can be used for low density floc, 1.002 to 1.004, and sand in the range 0.120 to 0.212 mm for floc of a higher density, 1.006 to 1.010. A compromise with respect to the modelling of sediment size is made; the sand size range represents floc sizes of 0.7 to 1.2 mm and the anthracite represents 1.2 to 2.5 mm. By choosing a scale of 9 the sand can then be used to model the low density floc. The choice of scale is limited by the availability of a model sediment of appropriate density and settling characteristics. The volumetric concentration of the rigid sediment are expressed in terms of the untapped settled volume fraction. Detailed analysis of the model results are likely to involve evaluating this measurement, and the tapped settled volume, in comparison with the settled and packed point measurements for floc.

A 1 : 6 scale model was constructed to be representative of the 1.2 m square tank. Due allowance had to be made to the inlet and outlet of the model for their adequate hydraulic capacity and that they were constructed for easy removal and replacement. For ease of construction, maintenance and access to the inlet the hopper was flanged and bolted to the parallel flow section. The model was constructed from 12 mm thick clear Perspex sheet.

The model was operated either by using water direct from the mains and leading to waste after a sediment trap to collect carryover, or recycled water by direct pumping. The former was preferred since the water temperature then remained constant and discolouration of the water did not occur due to accumulation of fines by attrition.

The limited investigations made with the model are reported in Sect.3.5.1.2.

A.3 Floc Concentration Measurement

Analysis of the behaviour of floc suspensions is dependent on the satisfactory measurement of floc volumetric concentration. Unfortunately, aluminium and iron hydroxide flocs are not rigid particles and their shape and density are dependent on various chemical and hydromechanical factors of the treatment process. As such no method of volumetric measurement will be rigorous and explicit.

The easiest measurement of a volumetric concentration is that obtained from a settling test usually standardised as thirty minutes settling of a sample in a 100 ml measuring cylinder. Another measurement can be obtained by determining the 'packed point'. The packed point is defined as the point of transition from the constant settling rate period to the initial part of the falling rate period in the settling profile of a suspension. In practice the transition between the two periods for floc is not sharp and so the packed point is estimated. The determination of the packed point was made with a 1 litre graduated measuring cylinder. It is appreciated that the dimensions of the cylinder can influence the measurement of settling velocity and final concentration. This might have been particularly important if the current investigations had been concerned with rigid particles. However, with the inherent inaccuracies associated with the measurement of floc of inconsistent quality it is unlikely the dimensions of the cylinders used would have greatly influenced the measurements obtained.

Fig.A.2 shows the equivalence of the two measurements of concentration for normal river water quality and coagulation with aluminium sulphate at Medmenham. The relationship can be regarded as linear for the concentration range presented. It is to be noted that with the alum floc the packed point could only be easily determined for a settled concentration, i.e. blanket floc volume, greater than 0.16 to 0.20. The constant of proportionality is approximately 2.5. This implies the packed point cannot be determined for a settled concentration greater than 0.40. It is appreciated that these measurements are highly dependent on floc quality, concentration and temperature. However, the quality and value of the settled concentration is illustrated by Fig.A.3 of data from experiments 13 and 21. This figure indicates that within the concentration ranges

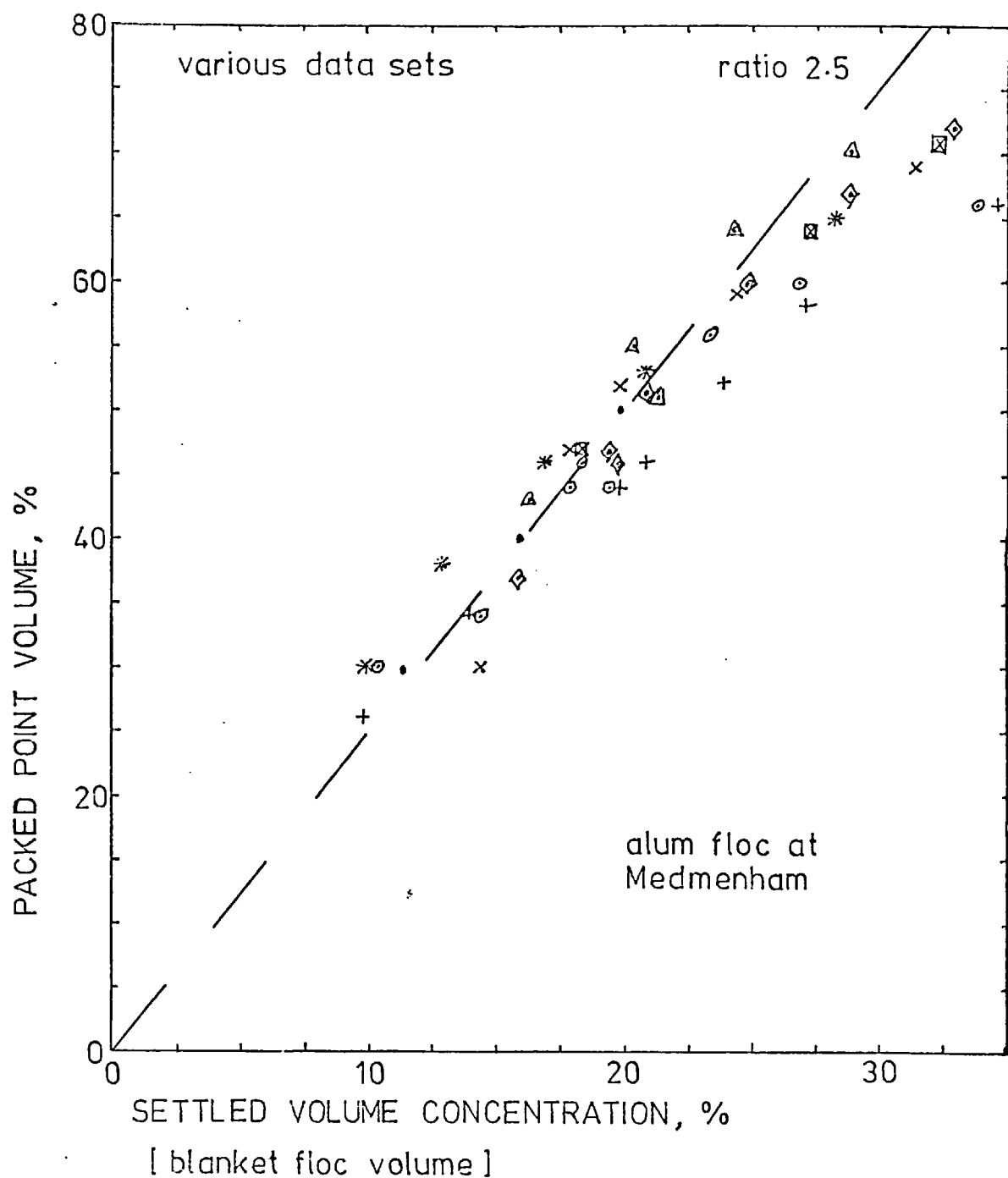


FIG A.2 EQUIVALENCE OF THE PACKED POINT AND THE SETTLED VOLUME CONCENTRATIONS OF FLOC

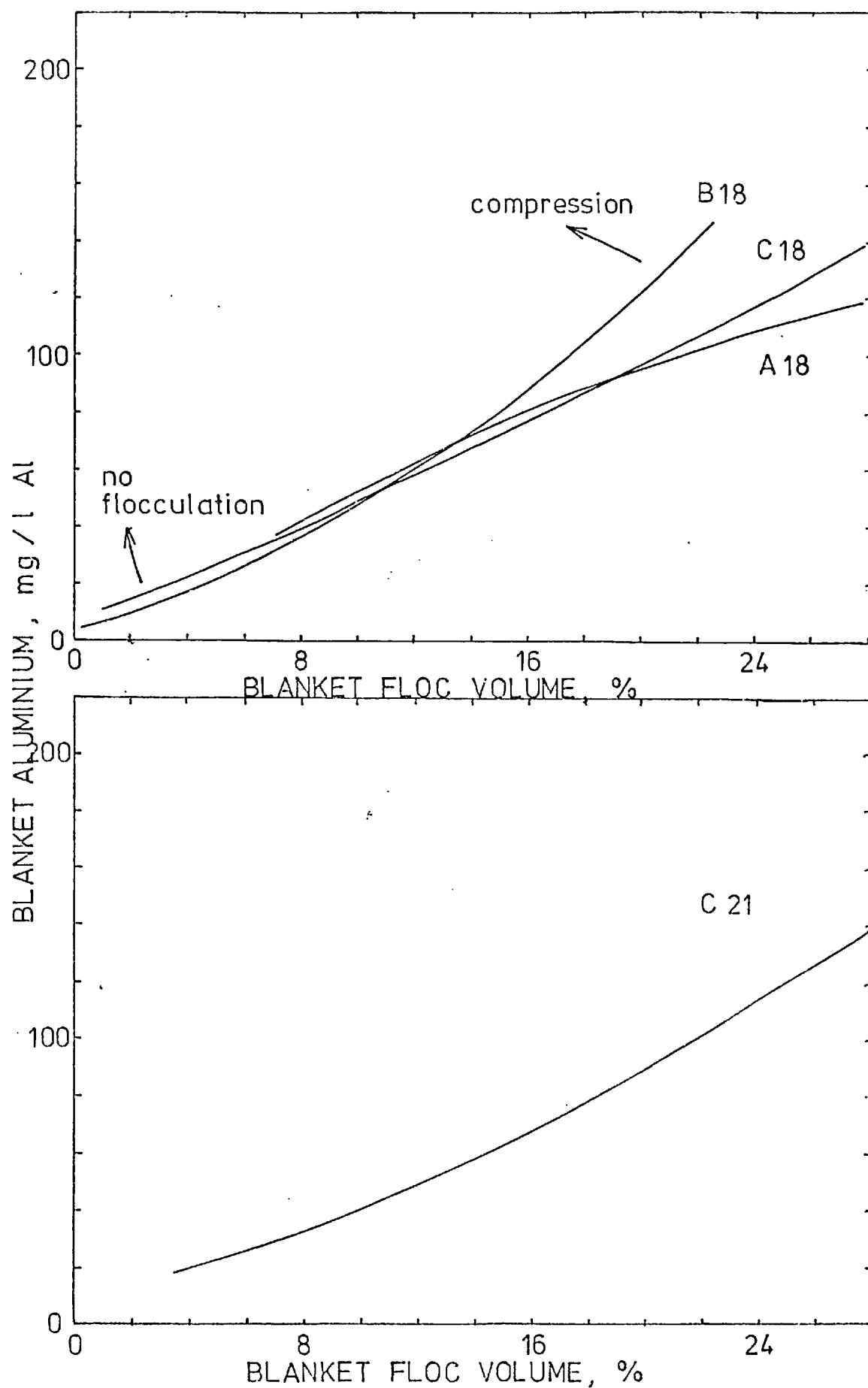


FIG A.3 COMPARISON OF BLANKET FLOC VOLUME WITH BLANKET ALUMINIUM

investigated , the settled concentration does not deviate substantially at the higher concentrations due to compaction at the bottom of the settled floc. Concentrations greater than those presented are of no interest in the present context since they represent conditions of incipient fluidization, packed beds and thickening. The difference between the two measurements is that they measure different particle - particle orientation.

The settled and packed point concentrations are measurements uncorrected for the porosity between the particles. For rigid particles it can be easy to determine the porosity of a settled volume, but for floc only a crude estimate can be made. It would be useful if such a correction was unnecessary particularly for the comparison of settling data of one kind of particulate material with another. However, it is the intention to use the packed point concentration as a measurement that has hydrodynamic significance and could thus dispense with the need to consider porosity.

NOMENCLATURE

a	fractional area; orifice area, m^2
b	absorption coefficient (Cretu), $m^3/kg.hr$
B	separation parameter (Cretu), sec^{-1}
c	volumetric concentration, m^3/m^3
C	mass concentration of particles or of coagulant cation, mg/litre
C_a	Camp Number (Vostrcil)
C_d	coefficient of discharge,
d	diameter of particle, orifice, m
D	diameter of vessel, m
e	porosity or voidage, m^3/m^3
E_z	coefficient of diffusion
E_ϕ	distribution function of detention time in the blanket
f	particle shape constant (Bond)
$F()$	function of
g	gravitational constant, m/sec^2
G	velocity gradient, sec^{-1}
h	useful loss of head, expressed as metres head of water
k_1 , etc	power indices in velocity-concentration analysis
k_s	flocculation coefficient, Shogo, sec^{-1} .
K	flocculation constant, dim.
K_A	aggregation constant in flocculation, dim
K_B	breakup constant in flocculation, sec.
K_s	flocculation constant (Shogo)
L	Total vertical depth of blanket, m
m	index of hydrodynamic regime
n	number concentration, of orifices, or scale
N	dimensionless number
P	mechanical power, N.m/sec.
q_1 , etc.	arithmetical constants in velocity-concentration analysis
$\bar{q}$	average flow rate of clear liquid per unit area of inclined plane, $m/hr.$
Q	volumetric flow rate, m^3/sec
r	horizontal distance between inclined planes, m.

s	settled volume concentration, floc, m^3/m^3
S_c	shape factor of inclined settler (Yao)
t	flocculation time, sec
T	Theoretical mean residence time, sec.
U	superficial upflow velocity, m/hr
U_o	terminal velocity of a single particle, m/hr
U_p, U_q	modified terminal velocities determined by correlation, m/hr.
v	injection velocity, m/sec.
$\frac{V}{\bar{V}}$	settling/fluidizing velocity between inclined surfaces, m/hr volume, m^3
x	independent variable (abscissa)
y	dependent variable (ordinate)
z	height or length, m
Z	volumetric shape factor (Richardson and Zaki)

α	regression constant
β, γ	regression coefficients
δ	differential of
Δ	difference of
ϵ	standard deviation
θ	angle, degrees
λ	distance, settled, m.
μ	viscosity, N.sec/ m^2
ρ	density, kg/m^3
σ	specific gravity
φ	dimensionless detention time, t/T
ψ	factor defined by Shogo, eqtn. 4.36

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QUALITY PARAMETER	MAX	AVE	MIN	S. D.
Ammonia mg. N/l	0.469	0.125	0.02	-
Nitrate mg. N/l	8.36	6.13	3.39	1.02
K. MnO ₄ value mg. O ₂ /l	19.1	6.05	3.33	2.88
CHLLA (Acetone) mg/m ³	157.2	18.1	2.2	30.2
Total phosphorous mg. P/l	1.070	0.583	0.284	0.176
Reactive silica mg. SiO ₂ /l	14.60	10.80	4.20	2.27
Absorbance, 400 nm (40 mm cell, filtered)	0.145	0.042	0.013	0.025
Absorbance, 580 nm (40 mm cell)	0.368	0.092	0.011	0.092
Conductivity mhos/cm, 20°C	700	583	443	44.5
pH value	8.60	8.00	7.55	0.215
Total hardness mg. CaCO ₃ /l	340	303	269	-
Alkalinity mg. CaCO ₃ /l	253	212	147	21.4
Temperature °C	21.5	11.6	2.8	4.72

TABLE 2.1 QUALITY OF RIVER THAMES AT MEDMENHAM 1971

Experiment	Date	Description	Parallel Experiment	Description
C1	8/68 to 12/68	factorial design, 5 controlled variables each at 2 levels	P1	similar factorial to C1
C2a	1/69 to 2/69	non-statistical, recirculation rate	none	
C2b	2/69 to 3/69	non-statistical, injection velocity	none	
C3	4/69 to 5/69	factorial, 5 levels recirculation rate and 2 levels treatment rate	none	
C4	5/69 to 7/69	factorial, as C3, injection velocity and treatment rate	P3	factorial, treatment rate and recirculation rate
C5	7/69	constant controlled variables	P3	" " " "
C6	8/69 to 9/69	non-statistical, treatment rate	P4	non-statistical, treatment rate
no experiments				
C11	10/70 to 1/71	statistical, injection velocity and treatment rate	none	
C12	5/71 to 8/71	treatment rate, regression analysis r.a.	A, B12	parallel common dosed C12
C13	6/71 to 9/71	preinjection high shear rate, r.a.	none	
C14	9/71 to 11/71	injection velocity and treatment rate, r.a.	none	
C15	11/71 to 1/72	injection velocity and treatment rate, salt tracing	none	

TABLE 2.2 (first side) SUMMARY OF INVESTIGATIONS WITH THE TANKS

Experiment	Date	Description	Parallel Experiment	Description
C16	1/72 to 2/72	treatment rate, r. a.	A, B. 16	parallel common dosed (p. d.)
C17	3/72 to 4/72	diffusion grid, injection velocity and treatment rate r. a.	A, B. 17	p. d., B with tube modules and blanket below
C18	5/72	- ditto -	A. B. 18	- ditto -
C19	6/72	ditto but for salt tracing	A. 19	p. d.
C20	6/72	constant controlled variables, diffusion grid	A, B. 20	p. d., B with tube modules and blanket below.
C21	7/72 to 8/72	grid removed, injection velocity and treatment rate, r. a.	A, B. 21	p. d., B with diffusion grid and modules removed.
			B. 22	p. d. tube modules and grid and blanket below
B23	9/72	blanket in modules, treatment rate, r. a.	A. 23	p. d.
B25	10/72	- ditto -	A. 25	p. d.

TABLE 2.2. (Cont'd) SUMMARY OF INVESTIGATIONS WITH THE TANKS

Expt. no.	y Variables x	$y = a + \beta x^1 + \gamma x^2 + \delta x^3$			test of x^1		test of x^2		test of x^3		
		Regres- sion ss	F of regres- sion	Total d.f.	ss due to x^1	F of test	ss due to x^2	F of test	ss due to x^3	F of test	F of quadratic
A23	product Jtu; treatment rate g. p. h.	8.271	15.52	45	0.329	1.85	0.291	1.64	0.280	1.58	22.19
A23	" blanket floc %	10.284	26.43	45	0.006	0.05	0.003	0.02	0.005	0.04	40.53
B23	" treatment rate g. p. h.	16.883	81.52	47	0.225	3.26**	0.143	2.07	0.125	1.82	119.2
B23	" blanket floc %	17.267	95.47	47	0.477	7.91**	0.259	4.30***	0.245	4.06**	132.2
B22	" treatment rate g. p. h.	25.817	94.47	49	0.378	4.15**	0.722	7.92***	0.842	9.25*	116.6
B22	" blanket floc %	15.248	31.15	42	0.110	0.67	0.004	0.03	0.001	0.00	47.91
B21	" treatment rate g. p. h.	20.005	22.35	44	0.152	0.51	0.109	0.37	0.105	0.35	33.86
B21	" blanket floc %	14.449	10.71	42	0.121	0.27	0.000	0.00	0.024	0.05	16.42

* coefficient < 0.1%; ** < 5%.

TABLE 2.3 TEST OF POWER TERMS IN REGRESSIONS USING CUBIC MODELS

EXPERIMENT	C3	C4
PRODUCT QUALITY PARAMETER	COEFFICIENT OF VARIATION.	
Hach Turbidity	15%	25%
Hach (adjusted for water temperature)	-	19.3%
Hach (adjusted for raw 580nm OD)	14.2%	22.5%
Hach (adjusted for raw 400nm OD)	13.7%	22.5%
Hach (adjusted for raw 300nm OD)	13.2%	-
Hach (for raw 580 and 300 nm OD)	12.5%	-
Hach (for raw 580, 400 and 300nm OD)	12.5%	-
SED Al	16.5%	23.4%
SED Al (adjusted for water temperature)	-	23.4%
SED Al (adjusted for raw 580nm OD)	-	23.7%
SED Al (adjusted for raw 400nm OD)	-	23.1%
SED Al (adjusted for dosed Al)	-	23.3%
Water Temperature Range, °C	10.5 to 15.5	14.2 to 20.0
Raw 580nm OD	0.033 to 0.157	0.021 to 0.097
Raw 400nm OD	0.013 to 0.051	0.018 to 0.071
Hach Turbidity, Jtu	1.30 to 2.70	0.85 to 2.80
SED Al, mg/l as Al.	0.51 to 1.24	0.37 to 1.04

TABLE 3.1 IMPORTANCE OF UNCONTROLLABLE VARIABLES
IN THE EVALUATION OF TANK PERFORMANCE,
EXPERIMENTS C3 and C4.

EXPERIMENT 5 (C only)						
Uncontrolled Variable (Table 3.3)	1	2	3	4	5	6
1	1.0	0.660	0.486	-0.403	0.141	0.121
2		1.0	0.977	-0.077	0.119	0.250
3			1.0	0.024	0.098	0.256
4				1.0	0.332	-0.090
5					1.0	0.050
6						1.0
mean	21.31	26.30	4.99	3.54	0.093	0.039
s.d.	0.73	3.01	2.59	0.25	0.023	0.005

EXPERIMENT 20 (A, B and C)						
Uncontrolled Variable (Table 3.8)	1	2	3	4	5	6
1	1.0	0.624	0.336	-0.532	0.103	-0.461
2		1.0	0.946	-0.190	0.301	-0.399
3			1.0	-0.008	0.320	-0.289
4				1.0	0.080	0.467
5					1.0	-0.108
6						1.0
mean	15.60	20.31	4.72	3.26	0.053	0.035
s.d.	0.55	1.59	1.32	0.11	0.019	0.003

TABLE 3.2 CORRELATION MATRIX ANALYSIS OF
UNCONTROLLED VARIABLES

Observation	Tank	Uncontrolled variable						
		Water Temp 1	Air Temp 2	Temp Diff 3	Dose Al 4	580 OD Raw 5	400 OD water 6	Mean sd
Product 580nm OD 1	A20	60.2	59.6 2.9	ns	60.1	57.1 10.6	46.9 22.0	0.01125 0.0042
	B20	- ns	47.2 4.2	- ns	42.6 9.2	29.8 8.9	- ns	0.0060 0.0027
	C20	31.5	- ns	- ns	28.6 8.2	31.1	31.7	0.0085 0.0030
	C5	- ns	70.1	59.9 35.9	69.9	68.8 5.1	65.0 6.4	0.0124 0.0054
Product Al 2	A20	- ns	61.4 37.7	69.5 4.0	70.3	66.5 6.5	70.2	0.741 0.172
	B20	34.4	- ns	34.0	34.2	30.9 9.5	33.5	0.396 0.082
	C20	- ns	47.9 3.7	42.3 2.7	43.8	39.0 15.2	- ns	0.648 0.147
	C5	- ns	68.6	66.4 44.0	70.0	69.2	68.1 2.3	0.572 0.138
Product Jtu 3	A20	- ns	71.0 50.5	77.6 9.8	81.1	81.0	80.0 3.7	1.676 0.401
	B20	- ns	38.1	- ns	32.8	30.6 9.4	36.4 2.5	1.108 0.183
	C20 Bowser	- ns	40.3 16.2	46.2	46.2	42.3	44.0	1.390 0.235
	C5 Hach	- ns	59.7	47.8 22.8	58.2	57.2 4.2	53.4 5.7	1.640 0.407
Blanket Floc Volume 4	A20	46.3 21.5	- ns	54.8	52.6 6.2	54.2	55.1	22.01 1.16
	B20	57.4 2.3	- ns	39.2 15.4	55.3 5.9	58.0	49.7 9.3	22.79 2.53
	C20	- ns	- ns	51.9 3.6	42.2 3.1	38.4 14.7	48.3 5.5	19.44 2.13
Product 400 OD	C5	48.5 7.6	- ns	48.9	48.7	48.9	39.9 15.9	0.0247 0.0057

Upper value	Percent of coefficient of variance accounted for
Lower value	Percent increase in residual sum of squares if >2.0
Treatment Rates: A20... 10 g.p.h, B20... 10 g.p.h, C20.... 7 g.p.h. C5 5.5 g.p.h.	

TABLE 3.3 ANALYSIS OF CONTRIBUTION BY UNCONTROLLED VARIABLES TO TANK PERFORMANCE

Tank	A	B	C
Size	0.31 m dia	1.22 m Sq	3.51 m dia
Maximum Plan Area	0.073 m ²	1.49 m ²	9.66 m ²
Relative Area	1.00	20.4	132
Parallel Depth	2.75 m	4.58 m	2.44 m
Hopper Depth	0.46 m	1.07 m	2.74 m
Angle of Hopper	22°	60°	60°
Supernatant Depth	0.90 m	2.75 to 3.05 m	1.25 m
Hopper Volume	0.0126 m ³	0.525 m ³	9.75 m ³
Parallel Volume	0.1225 m ³	2.73 m ³	8.98 m ³
Total Blanket Volume	0.1351 m ³	3.26 m ³	18.73 m ³
Specific Blanket Volume	1.85 m ³ /m ²	2.19 m ³ /m ²	1.94 m ³ /m ²
Hopper Blanket	9.3%	16.1%	52.0%

TABLE 3.4 COMPARISON OF TANK DIMENSIONS

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d. f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
A12	3.1	Product turbidity, Jtu; Blanket floc volume, %	1.738	0.0214	-0.0032	13.925	214.8	16.61	2,77	1%
B12a	"	" "	2.547	-0.179	+0.0027	12.015	200.6	9.80	2,30	1%
B12b	"	" "	1.516	-0.032	-0.0004	16.228	312.5	47.18	2,54	1%
C12	"	" "	1.635	-0.063	+0.0008	11.376	150.2	9.32	2,94	1%
A12	"	Product Aluminium, mg/l "	0.793	0.0051	-0.0014	14.000	214.1	22.85	2,78	1%
B12a	"	" "	1.365	-0.0996	0.0014	11.956	197.6	49.18	2,31	1%
B12b	"	" "	0.650	0.0095	-0.0010	16.228	312.5	69.43	2,54	1%
C12	"	" "	0.747	-0.103	0.0028	11.376	150.2	33.05	2,94	1%
A12	3.3	Blanket floc volume, %; Treatment rate, fph	14.09	-5.27	0.168	13.64	193.9	27.17	2,77	1%
B12a	"	" "	11.96	-7.83	0.268	10.98	129.8	52.39	2,31	1%
B12b	"	" "	16.27	-6.50	0.219	6.98	51.4	66.31	2,54	1%
C12	"	" "	11.35	-1.85	-0.0845	6.73	46.7	73.14	2,93	1%
A12	"	Blanket flux, gph %; treatment rate, fph	185.6	-37.5	1.60	13.64	193.89	6.20	2,77	1%
B12a	"	" "	112.5	-13.9	0.25	10.98	129.76	8.52	2,31	1%
B12b	"	" "	105.8	7.51	-0.94	6.943	50.89	2.59	2,53	NS
C12	"	" "	72.07	43.49	-3.89	6.728	46.70	18.02	2,93	1%
A12	3.5	Product turbidity, Jtu; treatment rate, fph	1.677	-0.073	0.0077	12.90	175.1	57.36	2,113	1%
B12a	"	" "	2.206	-0.258	0.0248	10.17	112.1	45.84	2,56	1%

TABLE 3.5 REGRESSION ANALYSIS RESULTS, EXPERIMENT 12

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma(x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
B12b	3.5	Product turbidity, Jtu; treatment rate, fph	1.540	0.729	-0.0399	7.01	51.9	36.34	2,55	1%
C12	"	" "	1.672	-0.100	0.0234	6.74	46.8	26.95	2,117	1%
A12	"	Product aluminium percent; "	26.58	5.750	-0.138	12.91	175.2	66.34	2,113	1%
B12a	"	" "	32.11	1.413	0.136	10.12	111.1	120.24	2,55	1%
B12b	"	" "	26.56	17.89	-1.063	7.02	52.1	100.86	2,55	1%
C12	"	" "	26.36	-17.12	1.624	6.71	46.5	36.66	2,115	1%

TABLE 3.5 (CONT'D) REGRESSION ANALYSIS RESULTS, EXPERIMENT 12

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
A16a	3.2	Product turbidity, Jtu; Blanket floc volume, %	5.320	-1.271	0.0211	12.05	159.0	26.08	2,17	1%
B16a	"	" "	5.182	-2.296	0.0625	14.14	211.6	14.63	2,19	1%
C16a	"	" "	4.442	1.413	-0.0544	15.83	261.0	14.08	2,21	1%
A16b	"	" "	5.859	-0.513	0.0118	9.27	98.6	4.83	2,29	5%
B16b	"	" "	2.764	-1.029	0.0305	14.60	222.1	11.70	2,37	1%
C16b	"	" "	2.589	0.067	-0.0003	22.86	555.7	2.23	2,37	NS
A16a	3.4	Blanket floc volume, %; Treatment rate, fph	12.05	-2.51	0.0564	11.48	139.6	25.17	2,17	1%
B16a	"	" "	14.14	-0.368	-0.0603	8.36	73.6	14.13	2,19	1%
C16a	"	" "	15.84	-2.97	0.0475	6.22	39.9	27.07	2,22	1%
A16b	"	" "	9.27	-1.64	0.0312	15.56	247.7	3.10	2,29	NS
B16b	"	" "	14.60	-0.419	-0.0352	11.80	142.8	29.67	2,37	1%
C16b	"	" "	22.86	-12.76	0.537	8.60	75.7	30.61	2,37	1%
A16a	"	Blanket flux, % fph; Treatment rate fph	129.3	-0.01	-0.09	11.475	139.64	0.62	2,17	NS
B16a	"	" "	113.2	27.09	-1.48	8.364	73.61	1.41	2,19	NS
C16a	"	" "	95.56	15.58	-1.17	6.220	39.93	0.32	2,22	NS
A16b	"	" "	140.7	-6.26	0.16	15.56	247.72	0.04	2,29	NS
B16b	"	" "	167.9	34.53	-1.47	11.80	142.78	1.27	2,37	NS
C16b	"	" "	190.8	-34.18	1.60	8.60	75.69	1.59	2,37	NS

TABLE 3.6 REGRESSION ANALYSIS RESULTS, EXPERIMENT 16

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
A16a	3.6	Product turbidity, Jtu; Treatment rate, fph	4.824	0.536	0.0143	11.38	135.5	34.99	2,18	1%
B16a	"	" "	4.157	-0.465	0.0660	7.85	63.9	11.94	2,20	1%
C16a	"	" "	4.396	1.580	-0.0550	6.17	39.1	15.25	2,24	1%
A16b	"	" "	5.883	-0.947	0.0484	15.39	242.5	21.10	2,32	1%
B16b	"	" "	2.765	-1.228	0.0574	11.80	142.8	4.32	2,37	5%
C16b	"	" "	2.637	-1.440	0.0844	8.52	74.6	0.79	2,38	NS

TABLE 3.6 (CONT'D) REGRESSION ANALYSIS RESULTS, EXPERIMENT 16

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma(x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
A	3.7	Blanket Floc Volume, %; Treatment Rate, fph								
12	"		14.09	-5.271	0.1677	13.64	193.9	27.17	2:77	1%
16a	"		12.05	-2.506	0.0564	11.48	139.6	25.17	2:17	1%
16b	"		9.266	-1.637	0.0312	15.56	247.7	3.10	2:29	NS
17	"		12.78	-1.128	0.0116	11.99	145.8	5.38	2:24	5%
18	"		13.84	-3.884	0.0889	12.95	179.6	208.4	2:65	1%
21	"		15.08	-4.529	0.1106	13.77	204.9	195.1	2:94	1%
22	"		15.31	-2.710	0.0644	13.39	187.6	39.79	2:60	1%
23	"		6.63	-1.956	0.0405	16.11	266.1	27.22	2:43	1%
25	"		8.90	-5.70	0.160	13.27	187.5	321.4	2:51	1%
	3.7	Product Turbidity; Blanket Floc Volume, %								
12	"		1.738	0.0211	-0.0032	13.93	211.8	16.61	2:77	1%
16a	"		5.320	-1.271	0.0211	12.05	159.0	26.08	2:17	1%
16b	"		5.859	-0.513	0.0118	9.27	98.6	4.83	2:29	5%
17	"		3.758	-1.300	0.0423	12.78	168.5	1.99	2:22	NS
18	"		3.501	0.1471	-0.0080	13.36	216.8	15.24	2:65	1%
21	"		1.722	-0.2373	0.0047	15.08	264.9	63.04	2:94	1%
22	"		1.424	-0.0358	-0.0009	15.31	250.6	27.84	2:60	1%
23	"		2.563	-0.2885	0.0052	6.630	48.70	40.53	2:43	1%
25	"		2.742	-0.3381	0.0084	8.87	110.0	84.79	2:52	1%

TABLE 3.7. COMPARISON OF BLANKET QUALITY RELATIONSHIPS FOR THE 0.3m TANK

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
B12a	3.8	Blanket Floc Volume, %; Treatment Rate, fph	11.956	-7.826	0.2677	10.984	129.8	52.39	2:31	1%
B12b			16.272	-6.499	0.2187	6.979	51.4	66.31	2:54	1%
B16a			14.136	-0.368	0.0603	8.364	73.6	14.13	2:19	1%
B16b			14.600	-0.419	-0.0353	11.800	142.8	29.67	2:37	1%
B21			11.047	-3.080	0.0545	13.744	197.5	88.19	2:40	1%
B12a	3.8	Product Turbidity, Jtu; Blanket Floc Volume, %	2.547	-0.179	0.0027	12.015	200.6	9.80	2:30	1%
B12b			1.516	-0.0323	-0.0004	16.228	312.5	47.18	2:54	1%
B16a			5.182	-2.296	0.0625	14.136	211.6	14.63	2:19	1%
B16b			2.764	-1.029	0.0305	14.600	222.1	11.70	2:37	1%
B21			2.737	-0.2598	0.0064	11.047	148.3	16.42	2:40	1%

TABLE 3.8. COMPARISON OF BLANKET QUALITY RELATIONSHIPS FOR THE 1.2m TANK
WITHOUT TUBE MODULES

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
B	3.9	Blanket Floc Volume, %; Treatment Rate, fph								
17a	"		7.292	3.031	-0.2402	11.00	122.8	247.76	2:9	1%
17b	"		12.393	-1.559	-0.0062	10.81	121.6	66.90	2:25	1%
18	"		11.60	-2.994	-0.0510	11.94	151.2	112.4	2:57	1%
22	"		9.473	-6.372	0.1751	14.15	214.4	192.1	2:52	1%
23	"		11.69	-1.656	0.0127	16.93	302.3	430.5	2:45	1%
25	"		15.96	-4.13	0.08	15.74	274.0	312.2	2:62	1%
	3.9	Product Turbidity, Jtu; Blanket Floc Volume, %								
18	"		3.498	-0.5499	0.0141	11.60	166.1	81.26	2:57	1%
22	"		2.454	-0.1767	0.0028	9.473	140.2	84.27	2:52	1%
23	"		2.357	-0.1420	0.0010	11.69	162.9	132.2	2:45	1%
25	"		2.552	-0.1980	0.0028	15.96	332.0	230.5	2:62	1%

TABLE 3.9 COMPARISON OF BLANKET QUALITY RELATIONSHIPS FOR THE 1.2M TANK
FITTED WITH TUBE MODULES

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
C	3.10	Blanket Floc Volume, %; Treatment Rate, fph								
6	"		13.145	-3.461	0.1212	6.348	45.93	43.64	2:28	1%
12	"		11.35	-1.849	-0.0845	6.728	46.70	73.14	2:93	1%
16a	"		15.84	-1.974	0.0475	6.220	39.93	27.07	2:72	1%
16b	"		22.86	-12.76	0.5369	8.600	75.69	30.61	2:37	1%
17	"		15.22	0.6221	-0.0783	9.759	100.17	41.11	2:26	1%
18	"		16.55	-3.946	0.1256	9.046	96.77	125.85	2:19	1%
21	"		14.58	-1.406	-0.0047	9.539	103.9	75.58	2:23	1%
	3.10	Product Turbidity, Jtu; Blanket Floc Volume, %								
12	"		1.635	-0.0627	0.0008	11.38	150.2	9.32	2:94	1%
16a	"		4.442	1.413	-0.0544	15.83	261.0	14.08	2:21	1%
16b	"		2.589	0.067	-0.003	22.86	555.7	2.23	2:37	NS
17	"		3.496	-0.9685	0.0230	13.30	185.4	129.79	2:75	1%
15	"		3.387	-0.1958	0.0029	13.81	243.3	33.78	2:88	1%
21	"		1.779	-0.0105	-0.0007	14.58	245.6	2.11	1:23	NS

TABLE 3.10 COMPARISON OF BLANKET QUALITY RELATIONSHIPS FOR THE 3.5m TANK
(Lowest injection velocity when applicable).

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
A	3.11	Product Turbidity; Jtu; Treatment Rate, fph								
12	"		1.677	-0.0731	0.0077	12.90	175.1	57.36	2:113	1%
16a	"		4.824	0.5364	0.0143	11.38	135.5	34.99	2:18	1%
16b	"		5.883	-0.9474	0.0484	15.39	242.5	21.10	2:32	1%
17	"		3.724	2.013	-0.0677	11.83	141.8	8.92	2:31	1%
18	"		3.573	1.052	-0.0327	13.21	186.2	35.39	2:72	1%
21	"		1.717	0.0367	0.0031	13.67	202.2	99.80	2:96	1%
22	"		1.423	-0.1112	0.0082	13.41	188.0	78.08	2:61	1%
23	"		2.563	0.2963	-0.0040	16.11	266.1	22.19	2:43	1%
25	"		2.734	0.0452	0.0090	13.24	186.8	300.3	2:53	1%
	3.11	Percent Aluminium, %; Treatment Rate, fph								
12	"		26.58	5.75	-0.1381	12.91	175.2	66.34	2:113	1%
17	"		37.43	-8.684	0.4167	11.94	144.7	1.06	2:21	NS
18	"		45.11	23.32	-0.8163	13.20	185.2	41.58	2:63	1%
21	"		28.99	5.79	-0.12	13.67	202.2	25.48	2:96	1%
22	"		27.58	-2.51	0.19	13.41	188.0	56.04	2:61	1%
23	"		51.64	6.67	-0.06	16.13	266.7	34.12	2:42	1%
25	"		55.27	15.19	-0.38	13.19	185.5	164.1	2:52	1%

TABLE 3.11 COMPARISON OF PRODUCT QUALITY - TREATMENT RATE RELATIONSHIPS FOR THE 0.3m TANK

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
B12a	3.12	Product Turbidity, Jtu; Treatment Rate, fph	2.206	-0.2596	0.0248	10.166	112.1	45.84	2:56	1%
B12b			1.540	0.7288	-0.0399	7.014	51.9	36.34	2:55	1%
B16a			4.157	-0.465	0.0660	7.848	63.9	11.94	2:20	1%
B16b			2.765	-1.228	0.0574	11.800	142.8	4.32	2:37	5%
B21			2.738	0.2797	-0.0019	13.640	194.5	33.86	2:42	1%
B12a	3.12	Percent Aluminium, %; Treatment Rate, fph	32.109	1.413	0.1364	10.124	111.1	120.24	2:55	1%
B12b			26.560	17.885	-1.063	7.024	52.1	100.86	2:55	1%
B16a			23.56	-1.46	0.295	8.222	70.9	7.11	2:24	1%
B16b			19.35	-15.19	0.672	11.731	141.7	2.12	2:36	1%
B21			48.77	20.96	-0.62	13.640	194.5	8.37	2:42	1%

TABLE 3.12 COMPARISON OF PRODUCT QUALITY - TREATMENT RATE RELATIONSHIPS
FOR 1.2M TANK, WITHOUT TUBE MODULES

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
B	3.13	Product Turbidity, Jtu; Treatment Rate, fph								
17a	"		4.647	-7.052	0.3341	11.56	136.3	288.4	2:12	1%
17b	"		3.069	-0.0782	0.0138	10.57	116.8	15.43	2:24	1%
18	"		3.493	-0.4538	0.0372	11.95	157.3	258.3	2:58	1%
22	"		2.453	0.4559	-0.0098	14.16	214.6	57.42	2:53	1%
23	"		2.357	0.2500	-0.0032	16.93	302.3	119.2	2:45	1%
25	"		2.539	0.1696	-0.0004	15.64	271.0	170.7	2:63	1%
	3.13	Percent Aluminium, %; Treatment Rate, fph								
18	"		43.12	1.042	0.1599	11.90	150.1	67.89	2:57	1%
22	"		50.92	6.95	-0.12	14.16	214.6	58.76	2:53	1%
23	"		47.91	5.74	-0.07	16.81	298.3	153.2	2:44	1%
25	"		49.64	5.35	-0.06	15.49	166.5	352.4	2:61	1%

TABLE 3.13: COMPARISON OF PRODUCT QUALITY - TREATMENT RATE RELATIONSHIPS
FOR THE 1.2m TANK FITTED WITH TUBE MODULES

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
C 6	3.14	Product Turbidity, Jtu; Treatment Rate, fph	1.496	-0.0837	0.0134	6.557	48.33	14.37	2:26	1%
11	"		4.092	-0.4147	0.0725	7.100	54.00	3.70	2:22	5%
12	"		1.672	-0.1000	0.0234	6.735	46.81	26.95	2:117	1%
14	"		2.267	-16.32	0.9614	8.725	76.66	2.93	2:9	NS
15a	"		2.540	-1.454	0.0689	8.450	72.60	1.34	2:2	NS
15b	"		3.314	3.868	-0.1659	8.018	64.98	130.62	2:8	1%
16a	"		4.396	1.580	-0.0550	6.167	39.10	15.25	2:24	1%
16b	"		2.637	-1.440	0.0844	8.524	74.58	0.79	2:38	NS
17	"		2.871	-1.098	0.0683	9.581	96.87	13.53	2:28	1%
18	"		2.952	0.2395	-0.0054	9.046	96.77	7.08	2:19	1%
21	"	Percent Aluminium, %; Treatment Rate, fph	1.779	0.1972	-0.0071	9.539	103.9	4.72	2:23	5%
12	3.14		26.36	-17.12	1.624	6.714	46.47	36.66	2:115	1%
17	"		29.29	-5.038	0.3638	9.633	97.97	6.81	2:27	1%
18	"		37.53	7.634	-0.3281	9.050	97.95	7.66	2:17	1%
21	"		34.29	6.14	-0.18	9.539	103.9	36.65	2:23	1%

TABLE 3.14. COMPARISON OF PRODUCT QUALITY - TREATMENT RATE RELATIONSHIPS FOR THE 3.5 m TANK
(Lowest injection velocity when applicable)

HACH TURBIDITY, Jtu								
f_0	± 0.246	r_0	r_1	r_2	r_3	r_4	mean	± 0.110
		1.58	1.68	1.90	2.05	1.55	1.75	
f_1		1.70	1.50	1.98	1.92	1.22	1.66	
mean	± 0.174	1.64	1.59	1.94	1.98	1.38	confidence F < 5%	

SED Al mg/litre								
f_0	± 0.0969	r_0	r_1	r_2	r_3	r_4	mean	± 0.0433
		0.663	0.657	0.687	0.800	0.743	0.710	
f_1		0.643	0.750	0.710	0.813	0.687	0.721	
mean	± 0.0685	0.653	0.703	0.698	0.807	0.715		

SED 580 nm OD $\times 10^3$								
f_0	± 2.7	r_0	r_1	r_2	r_3	r_4	mean	± 1.2
f_1		11.3	6.0	12.7	12.3	10.7	10.6	
		9.7	7.3	6.3	10.7	15.0	9.8	
mean	± 1.9	10.5	6.7	9.5	11.5	12.8		
<u>Notation</u>								
Treatment rate		f_0 1.40 m/hr f_1 1.92 m/hr						
Injection velocity		r_0 to r_4 ...0.18, 0.24, 0.30, 0.37, 0.43m/s						

TABLE 3.15 PRODUCT QUALITY INTERACTION WITH TREATMENT RATE AND INJECTION VELOCITY, EXPT. C4.

	TREATMENT RATE, m per hr				
Injection velocity m per sec	1.40	1.66	2.16	2.67	2.92
	HACH TURBIDITY, Jtu				
0.15	2.96	2.67	4.00	5.09	5.76
0.31	2.58	2.58	3.44	4.80	5.90
0.46	2.77	2.64	3.72	4.65	5.20
0.61	2.59	2.70	3.74	4.06	5.61
mean (4 × 5)	2.72	2.65	3.73	4.65	5.57

	SED AL mg/litre				
mean, 4 × 5	0.605	0.674	0.872	0.842	0.923

	SED 580 nm OD				
mean, 4 × 5	0.0158	0.0140	0.0191	0.0251	0.0330

ANALYSIS OF MODEL: $x_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + Z_{ijk}$			
	TURBIDITY	AL	580 nm OD
μ	3.86	0.783	0.0214
	F-STATISTIC only α_i significant, confidence <1%		
α_i : treatment rate	6.78; 4/80;	10.69; 4/80	7.20; 4/80
β_j : injection velocity	0.15; 3/80;	1.77; 3/80	0.26; 3/80
$(\alpha\beta)_{ij}$ their interaction	0.063; 12/80	0.218; 12/80	0.042; 12/80

TABLE 3.16 PRODUCT QUALITY INTERACTION WITH TREATMENT RATE AND INJECTION VELOCITY EXPT. C11

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
C14	3.15	Product turbidity, Jtu; Treatment rate fph for injection velocity 0.27 mps	2.267	-16.32	0.961	8.725	76.67	2.93	2:9	NS
"	"	0.43 mps	2.246	- 6.08	0.379	8.700	76.28	1.04	2:10	NS
"	"	0.58 mps	2.519	- 1.51	0.119	8.506	72.88	0.85	2:14	NS
"	"	0.73 mps	2.533	-24.36	1.534	8.461	72.26	21.26	2:15	1%
"	"	0.88 mps	4.714	-34.40	2.255	8.682	75.94	8.11	2:11	1%
"	"	1.04 mps	5.459	-13.36	1.013	8.323	69.80	1.89	2:8	NS

TABLE 3.17 EFFECT OF INJECTION VELOCITY ON TANK PERFORMANCE EXPT. C14

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
C15a	3.16	Product turbidity, Jtu; Treatment rate, fph for injection velocity 0.27 mps	2.540	1.454	-0.069	8.450	72.60	1.34	2:2	NS
"	"	0.43 "	2.560	2.205	-0.117	8.450	72.60	1.84	2:2	NS
"	"	0.58	2.440	-0.183	0.023	8.450	72.60	10.80	2:2	NS
"	"	0.73	2.670	1.496	-0.077	8.450	72.60	3.85	2:2	NS
"	"	0.88	2.780	1.869	-0.095	8.450	72.60	11.22	2:2	NS
"	"	1.04	4.550	21.84	-1.333	8.063	65.76	0.553	2:1	NS
C15b	3.16	0.27	3.314	3.868	-0.166	8.018	64.98	130.62	2:8	1%
"	"	0.43	3.106	-20.27	1.408	7.911	62.96	192.84	2:6	1%
"	"	0.58	2.975	-35.47	2.432	7.667	59.15	120.37	2:3	1%
"	"	0.73	3.406	-48.48	3.277	7.850	62.01	142.68	2:5	1%
"	"	0.88	3.115	-12.62	0.915	7.750	60.33	32.36	2:7	1%
"	"	1.04	3.975	19.09	-1.182	7.667	59.15	2.69	2:3	NS

TABLE 3.18. EFFECT OF INJECTION VELOCITY ON TANK PERFORMANCE EXPT. C15.

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
C21	3.17	Product Turbidity Jtu; Treatment Rate, fph								
"	"	minimum injection velocity	1.779	0.197	-0.0071	9.539	103.9	4.72	2:23	5%
"	"	injection velocity 0.43 mps	1.950	0.163	-0.0078	10.667	121.6	0.32	2:12	NS
"	"	0.58	2.077	0.265	-0.0111	9.091	94.7	2.76	2:19	NS
"	"	0.73	1.917	0.400	-0.0217	7.167	57.7	1.94	2:9	NS
"	"	0.88	1.796	0.437	-0.0212	7.286	60.4	10.80	2:11	1%
"	"	1.04	1.779	0.511	-0.0254	7.000	55.9	6.44	2:11	5%
C21	3.17	Percent Aluminium; Treatment Rate								
"	"	minimum injection velocity	0.343	0.0614	-0.0018	9.539	103.9	36.65	2:23	1%
"	"	injection velocity 0.43 mps	0.388	0.0504	-0.0017	10.667	121.6	2.75	2:12	NS
"	"	0.58	0.363	0.0070	0.0011	9.091	94.7	7.19	2:19	1%
"	"	0.73	0.189	-0.0733	0.0049	7.167	57.7	0.044	1:9	NS
"	"	0.88	0.299	0.1105	-0.0054	7.286	60.4	23.56	2:11	1%
"	"	1.04	0.190	0.2217	-0.0159	7.000	55.9	0.708	2:11	NS

TABLE 3.19 EFFECT OF INJECTION VELOCITY ON TANK PERFORMANCE, EXPT. C21

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
C21	3.18	Blanket Floc Volume %; Treatment Rate, fph								
"	"	minimum injection velocity	14.58	-1.406	-0.0047	9.539	103.9	75.58	2:23	1%
"	"	injection velocity 0.43	11.20	-3.684	0.1163	10.667	121.6	12.00	2:12	1%
"	"	0.58	12.82	-3.161	0.0803	9.091	94.7	86.90	2:19	1%
"	"	0.73	15.50	-2.794	0.0548	7.167	57.7	40.58	2:9	1%
"	"	0.88	14.50	-4.419	0.1509	7.286	60.4	142.41	2:11	1%
"	"	1.04 m/s	16.69	-4.173	0.1085	6.846	53.9	40.43	2:10	1%
C21	3.18	Percent Aluminium, %; Blanket Floc Volume%								
"	"	minimum injection velocity	0.343	-0.0155	-0.000	14.577	245.6	21.30	2:23	1%
"	"	injection velocity 0.43	0.388	-0.0064	-0.0001	11.200	147.8	1.98	2:12	NS
"	"	0.58	0.363	-0.0354	0.0007	12.818	206.6	7.47	2:19	1%
"	"	0.73	0.189	-0.1563	0.0049	15.500	268.3	0.567	2:9	NS
"	"	0.88	0.299	0.0011	-0.0005	14.500	250.1	19.19	2:11	1%
"	"	1.04 m/s	0.189	0.0319	-0.0009	16.692	334.6	0.202	2:10	NS

TABLE 3.20 EFFECT OF INJECTION VELOCITY ON BLANKET QUALITY EXPT. C21

Experiment number 3.5 m tank	Lowest unstable injection velocity	Associated treatment rate with unstable injection velocity	Temperature range	Viscosity range	Associated blanket concentration	Blanket aluminium concentration	Product turbidity at 2.4 m/hr	Treatment rate giving 10.0 percent blanket concentration at low injection
C	m/s	m/hr	°C	poise	percent volume	mg/l Al per percent	Jtu	m/hr
without diffusion grids								
14	0.73	2.8	10 to 15	0.0131 to 0.0114	est. 11.0	-	2.0	est. 2.7
15a	1.04	est. 1.8	7 to 8.5	0.0143 to 0.0137	est. 12.0	-	2.5	est. 2.8
15b	1.04	est. 1.8	5 to 9	0.0152 to 0.0135	est. 12.0	-	3.0	est. 2.7
21	0.73	3.4	17 to 20.5	0.0108 to 0.0104	9.5	4.5	2.0	3.5
with diffusion grids								
17	1.04 not observed	est 3.0	95 to 11.5	0.0133 to 0.0126	10.0	6.0	2.5	4.2
18	0.88	3.4	11.5 to 15.0	0.0126 to 0.0114	9.0	5.0	3.0	4.0

TABLE 3.21 ANALYSIS OF INJECTION VELOCITY INVESTIGATIONS,
3.5 m TANK

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
C17	3.22	Product Turbidity, Jtu; Treatment Rate, fph								
		minimum and 0.27 m.p.s.	2.871	-1.098	0.0683	9.581	96.9	13.53	2:28	1%
		injection velocity 0.58	3.447	-0.603	0.0522	10.800	120.4	13.48	2:12	1%
		" 0.73	4.018	-1.030	0.0776	11.214	129.2	28.32	2:11	1%
C17	3.22	" 0.88 m/s	4.186	-0.298	0.0418	11.286	130.9	18.50	2:11	1%
		Percent Aluminium, %; Treatment Rate, fph								
		minimum and 0.27 m/s	29.29	-5.038	0.364	9.633	98.0	6.81	2:27	1%
		injection velocity 0.58	31.82	-3.200	0.253	10.786	120.4	6.04	2:11	5%
		0.73	32.81	-4.660	0.383	11.231	129.8	12.36	2:10	1%
		0.88 m/s	34.94	-9.941	0.597	11.133	127.5	9.24	2:12	1%

TABLE 3.22 EFFECT OF INJECTION VELOCITY ON PRODUCT QUALITY EXPT. C17

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
C17	3.23	Blanket Floc Volume, %; Treatment Rate, fph minimum and 0.27 m/s	15.224	0.622	-0.0783	9.759	100.2	41.11	2:26	1%
"	"	injection velocity 0.58	12.941	0.434	-0.0730	10.706	118.4	36.06	2:14	1%
"	"	0.73	11.714	-0.538	-0.0334	11.214	129.2	20.01	2:11	1%
"	"	0.88 m/s	11.313	0.165	-0.0650	11.125	127.1	27.01	2:13	1%
C17	3.23	Product Turbidity, Jtu; Blanket Floc Volume % minimum and 0.27 m/s	2.871	-0.725	0.0156	15.232	237.9	14.72	2:25	1%
"	"	injection velocity 0.58	3.447	-0.721	0.0116	12.967	173.3	20.27	2:12	1%
"	"	0.73	4.018	-1.039	0.0230	11.714	144.2	62.49	2:11	1%
"	"	0.88 m/s	4.179	-1.060	0.0255	11.071	129.3	37.62	2:11	1%
"	"	all injection velocities	3.497	-1.969	0.0230	13.301	185.4	129.79	2:75	1%

TABLE 3.23 EFFECT OF INJECTION VELOCITY ON BLANKET QUALITY · EXPT. C17

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
C18	3.24	Product Turbidity, Jtu; Treatment Rate fph minimum injection velocity	2.952	0.2395	-0.0054	9.046	96.8	7.08	2:19	1%
"	"	injection velocity 0.43	3.522	-0.7461	0.0375	10.778	123.7	0.47	2:6	NS
"	"	0.58	3.507	-0.3188	0.0236	10.267	114.8	5.19	2:12	5%
"	"	0.73	3.337	0.2530	-0.0031	9.200	101.5	6.85	2:12	5%
"	"	0.88	3.809	-0.6978	0.0484	10.188	112.7	5.00	2:13	5%
"	"	1.04 m/s	3.644	0.1026	0.0151	8.118	78.8	5.99	2:14	5%
C18	3.24	Percent Aluminium, %; Treatment Rate fph minimum injection velocity	37.53	7.634	-0.3281	9.050	98.0	7.66	2:17	1%
"	"	injection velocity 0.43	47.07	19.410	-0.8348	10.778	123.7	1.74	2:6	NS
"	"	0.58	45.95	-0.758	0.0561	10.267	114.8	0.07	2:12	NS
"	"	0.73	42.37	10.577	-0.4824	9.071	100.1	4.35	2:11	5%
"	"	0.88	48.52	1.761	-0.0381	10.071	111.5	0.36	2:11	NS
"	"	1.04 m/s	36.57	10.624	-0.4673	7.929	74.4	9.88	2:11	1%

TABLE 3.24 EFFECT OF INJECTION VELOCITY ON PRODUCT QUALITY EXPT.C18

Exp't	Fig	y Regression Variables x	$y = \alpha + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			α	β	γ	$\bar{x}$	$\bar{x}^2$			
C18	3.25	Blanket Floc Volume, %; Treatment Rate, fph								
		minimum injection velocity	16.545	-3.946	0.1256	9.046	96.8	125.85	2:19	1%
"	"	injection velocity 0.43	11.333	-6.763	0.2356	10.778	123.7	24.18	2:6	1%
"	"	0.58	11.800	-3.297	0.1049	10.267	114.8	21.92	2:12	1%
"	"	0.73	14.400	-5.282	0.1985	9.200	101.5	54.15	2:12	1%
"	"	0.88	11.233	-4.624	0.1504	10.000	108.9	27.19	2:12	1%
"	"	1.04 m/s	15.786	-5.705	0.2232	7.929	76.1	38.76	2:11	1%
C18	3.25	Product Turbidity, Jtu; Blanket Floc Volume, %								
		minimum injection velocity	2.933	-0.0213	-0.0015	17.225	346.8	5.24	2:17	5%
"	"	injection velocity 0.43	3.522	0.2176	-0.0091	11.333	155.6	0.46	2:6	NS
"	"	0.58	3.507	-0.4068	0.0122	11.800	159.0	7.10	2:12	1%
"	"	0.73	3.418	-0.1334	0.0014	13.929	269.3	4.64	2:11	5%
"	"	0.88	3.725	-0.5476	0.0166	11.500	166.7	7.44	2:11	1%
"	"	1.04 m/s	3.089	-0.2163	0.0032	16.54	346.7	6.71	2:10	5%
"	"	all velocities	3.387	-0.1958	0.0029	13.813	243.3	33.78	2:88	1%

TABLE 3.25 EFFECT OF INJECTION VELOCITY ON BLANKET QUALITY
EXPT. C18

Exp't B	Parallel Tanks	Objective	Observation	Water °C	Viscosity c'poise	Blanket Al per volume	Product Jtu at 2.4 m/hr	Treatment rate for blanke concentration 0.10 m/hr
12	A, C	simple comparison	between A and C	15 to 19	1.14 to 1.03	-	1.5 and 1.8	3.2 and 2.6
16a	A, C	simple comparison	between A and C	2.5 to 6.5	1.64 to 1.45	6.0	4.0	3.4
16b	A, C	inlet modified	all same	5.5 to 7.5	1.50 to 1.41	6.0	-	est 4.6
17	A, C	tube modules, low blanket	all same with best C	9.5 to 11.5	1.36 to 1.26	6.0	2.5	3.0 and 3.7
18	A, C	tube modules	as A and best C	11.5 to 15	1.26 to 1.14	5.0	2.0	3.8
20	A, C	tube modules, constant treatment	B > C > A for stability	15 to 16.5	1.14 to 1.10	4.5	n.a.	n.a.
21	A, C	modified diffusion	as best C, worse than A	18.5 to 20.5	1.04 to 1.00	4.5	est 1.4	4.4
22	A	modified diffusion, tube modules	worse than A	17 to 19	1.08 to 1.03	est 4.0	1.1	3.8
23	A	tube modules, high blanket	better than A	14 to 18	1.17 to 1.05	4.0	est 1.0	5.5
25	A	tube modules	better than A	11.5 to 14.5	1.26 to 1.16	4.0	1.3	5.7

TABLE 3.26 SUMMARY OF INVESTIGATIONS WITH 1.2 m TANK

Data	Mean Baffled Control	Diff. of Means	D.F.	Estimated Variance	95% Confidence interval c.f. control tank
<u>TRIMPLEY</u>					percent
Laundry	0.348 0.511 mg/l Fe	0.163	70	0.000178	30.38 to 33.76
Central	0.457 0.656 mg/l Fe	0.199	13	0.00158	17.20 to 43.40
Turbidity	26.56 33.44 mg/l FE	6.88	8	5.78	13.38 to 27.77
<u>MOSSWOOD</u>					
Profiles	0.432 0.469 mg/l Fe	0.037	99	0.0028	0.85 to 14.93
Product	0.417 0.503 mg/l Fe (mean of works 0.557)	0.042	16	0.00026	8.75 to 25.45

TABLE 3.27 EXAMINATION OF TANK DIFFERENCES

Exp't	Fig	y Regression Variables x	$y = a + \beta (x - \bar{x}) + \gamma (x^2 - \bar{x}^2)$					F-statistic	d.f.	Dist.
			a	β	γ	$\bar{x}$	$\bar{x}^2$			
Mosswood	3.35	Product Quality vs Treatment Rate mg/l Fe m^3/s								
		Baffled Tank, profile mean	0.4357	-177.2	1460.1	0.0572	0.0033	0.994	2:4	NS
		Control Tank, profile mean	0.4683	142.2	-1227.3	0.0561	0.0032	3.663	2:3	NS
		Baffled Tank, total product	0.4167	-287.8	2345.1	0.0599	0.0036	1.519	2:6	NS
		Control Tank, total product	0.5033	-157.7	1440.6	0.0599	0.0036	19.289	2:6	1%
		Total Works, total product	0.5567	-273.9	2294.1	0.0599	0.0036	3.194	2:6	NS

TABLE 3.28 QUADRATIC REGRESSION ANALYSIS OF MOSSWOOD DATA

Experiment	Total number of observations	F - statistic of the regression between					
		ln U			c	U.c	
		quadratic of s	quadratic of ln(1 - s)	ln (1-2.5s)	quadratic of U	quadratic of U	quadratic of s
B25	64	365	382	197	312	30	81
A25	53	286	292	380	321	71	338
B23	47	408	408	838	430	57	194
A23	45	27	27	55	27	3.1	91
B22	43	133	133	251	192	22	125
A21-22	62	49	49	90	40	1.2	23
B21	42	88	88	155	88	-	-
A21	96	195	195	169	195	6.6	43
C21min	25	53	54	109	76	11	4.4

TABLE 4.1 REPRESENTATIVE RESULTS FROM THE REGRESSION ANALYSES COMPARING THE USEFULNESS OF THE EQUATIONS.

Experiment	regression between ln U and x =	Total d.f.	F - Statistic		
			of the model $a + \beta x + \gamma x^2$	test to include	
				βx	γx^2
			all *		
B25	ln(1 - s)	64	381.7	124.5*	22.58*
	s	64	365.2	77.14*	7.70
A25	ln(1 - s)	53	292.3	66.85*	13.36*
	s	53	285.9	51.97*	8.51
B23	ln(1 - s)	47	408.2	10.03	3.56
	s	47	407.9	5.04	7.00
A23	ln(1 - s)	45	27.23	0.71	0.27
	s	45	27.03	0.53	0.33
B22	ln(1 - s)	43	133.3	13.45*	0.08
	s	43	133.4	8.59	0.08
A21-22	ln(1 - s)	62	48.75	0.89	6.89
	s	62	49.23	1.94	8.71
B21	ln(1 - s)	42	87.80	17.56*	1.70
	s	42	87.90	12.66*	0.69
A21	ln(1 - s)	96	194.7	91.95*	26.58*
	s	96	194.7	67.69*	17.49*
C21(min)	ln(1 - s)	25	53.57	2.08	0.16
	s	25	53.32	0.94	0.58

* signifies confidence 0.1%

TABLE 4.2 VALUE OF THE POWER TERMS IN THE QUADRATIC MODELS.

Exp't	Regression of $\ln U = \alpha + \beta \cdot F(s)$					
	β			$\alpha \ln a$, ft/hr i.e. terminal velocity		
	$F(s) = s$	$\ln(1 - s)$	$\ln(1 - 2.5s)$	$F(s) = s$	$\ln(1 - s)$	$\ln(1 - 2.5s)$
B25	-3.961	3.128	0.565	27.8	25.9	21.1
A25	-4.722	4.155	1.287	19.5	19.0	18.1
B23	-4.983	4.327	1.308	29.4	28.3	26.3
A23	-5.432	5.065	1.793	22.8	22.6	22.2
B22	-4.431	3.778	1.068	21.4	20.6	19.2
A21-22	-4.328	3.700	1.078	25.3	24.2	22.3
B21	-3.858	3.391	1.046	20.6	20.1	19.2
A21	-4.141	3.313	0.699	24.7	22.9	19.0
C21(min)	-7.282	6.124	1.680	25.1	23.2	19.6

TABLE 4.3 RESULTS OF THE REGRESSIONS WITH THE LINEAR MODELS.

Exp't	Model: $\ln u = \alpha + \beta \ln(s) + \gamma \ln(1-s)$								For Steinour: $\gamma = +3, \beta = -1$		For Steinour: $F(s) = \frac{s}{1-s} \cdot 10^{-1.825}$ if: $s=0.1$ 0.2 0.3 then $F(s) =$ 0.070 0.105 0.125		
	correlation matrix coeffs for the pairs			coefficients			R. S. Q.		$\gamma - 3$	$\beta + 1$			
	$\ln u$ $\ln(s)$	$\ln u$ $\ln(1-s)$	$\ln(1-s)$ $\ln(s)$	α	β	γ	$\ln(s)$	$\ln(1-s)$					
B25	-0.929	0.947	-0.941	2.6590	-0.2093	2.1159	0.9097	0.8975	-0.8841	0.7907	0.175	0.354	0.533
A25	-0.948	0.948	-0.974	2.1439	-0.2311	2.0749	0.8994	0.9111	-0.9251	0.7689	0.184	0.362	0.555
B23	-0.929	0.971	-0.972	3.8528	0.1613	5.5107	0.9478	0.9436	2.5107	1.1613	0.054	0.045	0.034
A23	-0.728	0.746	-0.981	3.2604	0.0381	5.6208	0.5563	0.5560	2.6208	1.0381	0.069	0.106	0.113
B22	-0.910	+0.931	-0.965	2.9736	-0.0162	3.6655	0.8665	0.8664	0.6655	0.9838	0.135	0.228	0.290
A21- 22	-0.700	0.758	-0.980	5.7011	0.8612	8.8624	0.6217	0.5753	5.8624	1.8612	0.007	0.007	0.005
B21	-0.887	0.898	-0.971	2.6144	-0.1152	2.4016	0.8108	0.8066	-0.5984	0.8848	0.135	0.282	0.427
A21	-0.895	0.866	-0.965	1.3346	-0.6466	0.1496	0.8008	0.8009	-2.8504	0.3534	0.598	1.12	1.90
C21 min	-0.871	0.907	-0.975	3.9531	-0.2767	7.7257	0.8251	0.8221	4.7257	1.2767	0.032	0.023	0.013

TABLE 4.4 CORRELATION OF VELOCITY - CONCENTRATION DATA AND COMPARISON WITH STEINOUR'S RELATIONSHIP

Reference	System	Concentration measurement	Values found for q and k
Maude and Whitmore (1958)	settling: various non-flocculated	-	$k_5 = 4.15 \text{ to } 9.35$
Bond (1959)	settling; alum, lime fluidization; alum lime	24 hrs occasionally stirred settled volume	$f = 2.78$ 3.25 2.4
Thomas (1963)	settling; various solids size 0.4 to 17.0 μ .	-	$q_2 = 5.9$
Tesarik (1967)	fluidization; alum + silica, alum, iron flocs	2 hr settled vol.	$k_5 = 4$
Edeline et al (1968)	fluidization; FeCl_3 + poly, activated sludge	2 hr settled vol.	$k_5 = 3.3$ 12 to 27
Brown and La Motta (1971)	fluidization; alum, alum + poly, iron.	?	$k_5 = 1.75 \text{ to } 6.40$
Merkel (1971) C < thickening C > thickening	{ settling fluidization settling fluidization	30 min settled vol activated sludge	$q_6 = 1.7; k_5 = 4.8$ 1.7 7.7 1.2 1.4 2.2 0.7
Hale (1971)	settling and fluidization alum and silica	3 hrs settled vol.	$f = 1.6 \text{ to } 2.5$
Vostrcil (1971)	settling; fluidization; FeCl_3 + various polys	?	$f = 1.4 \text{ to } 2.8$ $k_5 = 3.0 \text{ to } 10.8$
Sen (1972)	settling; iron alum	60 mins settled vol.	$q_2 = 7.44$ 2.94
Stevenson (1972)	Bond's data		$q_2 = 10$

TABLE 4.5 SUMMARY OF PUBLISHED RESULTS OBTAINED FOR FLOC SUSPENSIONS.

Property	Prototype	Model
Size	L	L/n
Suspension particle size	d	d/n
Velocity	U	nU
Particle settling velocity	U_p	nU_p
Particle specific gravity	ρ_s	$\rho_f + n^3 [\rho_s - \rho_f]$
Detention period	T	T/n^3
Flow	Q	Q/n
Shear Gradient	G	$n^2 G$

TABLE A.1 REQUIREMENTS FOR HYDRAULIC SIMILARITY

Floc ρ_s	1.001	1.002	1.003	1.004	1.006	1.010	1.020
Sand $\rho_s = 2.65$							
n	11.8	9.37	8.18	7.44	6.50	5.48	4.35
1/n	0.0848	0.107	0.122	0.134	0.154	0.182	0.230
Anthracite $\rho_s = 1.60$							
n	8.43	6.70	5.85	5.33	4.64	3.91	3.11
1/n	0.118	0.149	0.171	0.188	0.215	0.255	0.322

TABLE A.2 SELECTION OF MODEL SIZE