EXPLORATORY STUDY ON ACTIVATED SLUDGE BULKING AND FOAMING PROBLEMS IN SOUTHERN AFRICA

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FINAL REPORT TO THE WATER RESEARCH COMMISSION ON A TWO YEAR EXPLORATORY STUDY ON ACTIVATED SLUDGE BULKING AND FOAMING PROBLEMS IN SOUTHERN AFRICA (1983 - 1984)

Project tasks

1. **Survey on the extent and severity of bulking and foaming problems**
2. **Identification of filamentous micro-organisms**
3. **Sludge settleability and secondary settling tank behaviour**

by

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114|1|85

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SYNOPSIS

1. Objectives

In a memorandum to the Water Research Commission (WRC), the Institute for Water Pollution Control (IWPC) indicated that sludge bulking was a problem of considerable concern in South Africa. Consideration of the problem led the WRC to contract the University of CapeTown to undertake an exploratory study into the problem. The objectives of the study were

i) survey the extent and severity of activated sludge bulking and foaming problems,

ii) identify the filamentous micro-organisms that are the principal cause of bulking and foaming,

(iii) identify research needs and directions for controlling bulking and foaming problems to serve as a basis for possible future research.

(iv) review the literature on bulking control with the view of compiling an information document on bulking identification and preventaive and remedial measures,

(v) review the literature on sludge settleability and secondary settling tank design criteria and procedures with the view of updating current techniques.

Conclusions and Recommendations

A survey of 111 Southern African activated sludge plants treating a total flow of 1515Mℓ/d indicates the following breakdown in problems at a level worse than minor (figure in brackets represents percentage of total flow): 44%(47%) either bulking or foaming or both; 32%(43%) bulking; 40%(38%) foaming, 27%(34%) bulking and foaming; 5%(9%) bulking only; 12%(4%) foaming only; and 56%(53%) neither bulking nor foaming.

Identification of filamentous micro-organisms in 96 mixed liquor and 37 foam samples indicates that the eight principal dominant filaments in descending order of frequency in the mixed liquor are Type 0092, M.parvicella, Types 1851, 0675, 0914, 0041, Nocardia spp. and Type 0803, and the three in the foam are Type 0092, M.parvicella and Nocardia spp. All these filaments sort into the low F/M group. Some of these filaments are also the principal dominant ones in the mixed liquor in U.S.A. plants i.e. Nocardia spp. (ranked 1st), Types 0041 (5th), 0675 (6th) and 0803 (7th) and in European plants i.e. M.parvicella (1st), Types 0092 (4th) and 0041 (6th). The highly ranked dominance of M.parvicella and Nocardia spp. in foam samples is not unusual as these two are notorious for foaming problems.

The review of the bulking control literature was undertaken by Professor D Jenkins of the University of Berkeley, California and the information document prepared by him is due to be published by the Water Research Commission soon.

On the basis of the exploratory study on bulking, it is recommended to undertake research into preventative and remedial measures for foaming and bulking control. Towards this end the WRC has concluded two contracts, one with the University of Pretoria to investigate foaming and the other with the University of Cape Town to investigate bulking. In the bulking research, the high incidence of low F/M filament types indicates the appropriate remedial action to be the application of selector reactors. Consequently, research should focus on the following aspects owing to their particular relevance to South Africa's biological nutrient removal technology:

(i) aerobic selectors, and their effects on readily biodegradable (soluble) COD utilization and oxygen consumption rates and integrating these into the general kinetic activated sludge model to serve as a basis for research into anoxic selectors,

(ii) anoxic selectors for application in full scale denitrification plants

(iii) the feasibility of anaerobic, anoxic and aerobic selectors for incorporation in nutrient removal plants.

Is is recommended also to investigate chlorination as a bulking control measure and its effect on biological nitrogen and phosphorus removal plants.

In the review of sludge settleability and secondary settling tank design procedures, relationships between the different sludge settleability measures viz. the flux theory constants V_0/n, Stirred specific Volume Index at 3,5g/ℓ ($SSVI_{3,5}$) and Diluted Sludge Volume Index (DSVI), were investigated and verified with data reported in the literature. With the aid of these relationships, the predictions of four secondary settling tank design procedures, viz. (i) the flux, (ii) the Water Research Centre (WRC), (iii) Abwasser Technik Verband (ATV) and (iv) Stichting Toegepost Onderzoek Reiniging Afvalwater (STORA) procedures, are verified against full scale data measured by STORA (1981). The verification shows that the flux and WRC procedures ovepredict the permissible solids loading, and hence the permissible maximum overflow rate by about 20%. A comparison of the flux, WRC, ATV and STORA procedures shows that for average to poor sludge settleability (DSVI > 120 mℓ/g, $SSVI_{3,5}$ > 80 mℓ/g), all predict similar maximum overflow rates. A comparison of the flux and WRC procedures with the empirical hydraulic overflow rate criterion of 1 m/h at Peak Wet Weather Flow (set by the IWPC SA branch)indicates that this criterion is adequate only for non-bulking sludges (DSVI < 150 mℓ/g, $SSVI_{3,5}$ < 100 mℓ/g) provided the reactor concentration is less than 3,5g/ℓ.

The review indicates that a large body of research information is available on the behaviour of secondary settling tanks. A significant portion of this work was conducted at full scale and directed specifically at developing design procedures but recognize sludge settleability. Although these procedures give good correlation with observed behaviour, they have not been widely adopted in South Africa. Consequently, at present attention should be focussed on upgrading currently used empirical design criteria by making available the design procedures and full scale experience (appropriately modified where required) rather than conduct further full scale research. It is recommended to meet this need by

(i) writing an information document on sludge settleability and secondary settling tank design for publication by the Water Research Commission,

(ii) writing a series of technology transfer papers for publication in "IMIESA" or "Water, Sewage and Effluent" highlighting important aspects for design and operation,

(iii) writing a series of scientific papers for Water SA detailing original contributions by the author of the review.

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INTRODUCTION

Bulking may be described as a phenomenon in activated sludge plants in which the sludge settles so slowly that the volume occupied by the settled sludge in the secondary settling tank becomes excessive; the sludge volume builds up eventually to spill over with the clarifier overflow resulting in high suspended solids concentrations in the effluent.

The micro-organisms in activated sludge, broadly speaking, can be divided into two basic groups, i.e. filamentous micro-organisms and floc-forming micro-organisms. The filamentous micro-organisms form an essential part of the activated sludge floc because they form the backbone to which the floc-forming organisms adhere. If there are insufficient filaments, the floc is weak and subject to break-up into smaller particles in the turbulent zones of the activated sludge plant; when this happens, fine floc particles remain suspended in the supernatant after a period of settling and this condition is called pin-point floc. If the filaments are present in too great numbers, the sludge flocs are bound up together by the filaments in a weblike structure resulting in a very clear supernatant but also in a very poor settling sludge, and this condition is known as filamentous bulking. Clearly, a balance between floc-formers and filaments is desirable to yield a sludge with good settling and clarification properties.

In March 1981 the Water Research Commission (WRC) was approached by the Institute for Water Pollution Control (IWPC) (Southern African Branch) in connection with the problem of sludge bulking. The IWPC indicated that a survey which it had undertaken had shown that sludge bulking was a problem of considerable proportion in South Africa. It expressed its concern that this problem was currently not receiving high priority by any of the water research organizations in South Africa and therefore requested that the matter receive urgent attention.

Thorough consideration of the problem highlighted by the IWPC, led the Commission to provide funds for a short term exploratory study to establish the extent and nature of the sludge bulking problem in South Africa. More specifically, the objectives of the study were:

(i) Survey the extent and severity of activated sludge bulking and foaming problems;

(ii) Identify the filamentous micro-organisms that are the principal cause of the bulking and foaming;

(iii) Identify research needs and directions aimed at controlling bulking and foaming problems to serve as a basis for possible future research contracts;

(iv) Review the literature on bulking control with the aim of drawing up an information document on bulking identification, remedial preventative measures.

(v) Review the literature on sludge settleability and secondary settling tank design criteria and procedures with the aim of updating techniques presently in use.

Over the past two years the University of Cape Town undertook the exploratory study and investigated the five aspects set out above. The results have been reported in detail in a number of reports and scientific papers (see Section 7). This report summarizes the findings of this research work.

1. EXTENT AND SEVERITY OF SLUDGE BULKING AND FOAMING

In order to obtain information on bulking and foaming problems in activated sludge plants in South Africa, a short two page questionnaire requesting information on bulking and foaming was (i) distributed to all local authorities (± 400) and members of the IWPC (S A Branch) during early 1983 and (ii) published in IMIESA (1983, 8, 7, 59) and S A Water Bulletin (Aug 1983, 15-16). Information requested included the size and type of the plant, and the extent to which bulking and foaming was a problem.

The response to the survey was excellent; 220 returns were received. Of these, 109 reported not having activated sludge plants, 111 supplied the necessary information on activated sludge plants with design flows from 0,5 to 150 Mℓ/d. The results of the survey, in terms of plant number and design flows are summarized in Fig 1. The results have been analysed in detail by Blackbeard and Ekama (1984). In summary, of the 111 plants, 78% experienced either bulking or foaming, or both problems together, in various degrees of severity ranging from minor to impossible. This number of plants represented 80% of the total design flow. Bulking was reported to take place in 56%(68%)* of the plants, foaming in 68%(65%) and neither bulking nor foaming in 22%(20%). Sorting the plants with minor problems in the group of plants with no problems and accepting the plants reporting difficult, manageable or impossible problems as the problem plants requiring bulking and foaming remedial attention, the breakdown of the problem plants is as follows: 44%(47%) of the plants have either bulking or foaming or both problems, 32%(43%) have bulking, 40%(38%) have foaming and 56%(53%) have neither bulking nor foaming problems.

With regard to bulking, only the larger plants (> 40 Mℓ/d) reported the problem as impossible; all the smaller plants reported the problem at worst to be manageable. A possible explanation for this is that large plants are likely to have a greater industrial waste content, some fractions of which may stimulate the growth of filamentous organisms. Similarly, foaming appears to be more severe in large than in small plants. A reason for this may be the same as that cited above for bulking but additionally, some of the large plants have diffused air aeration which tends to exacerbate an inherent foaming problem. However, this assessment is a purely subjective one and no direct cause/effect relationships could be deduced.

The survey confirmed that bulking and foaming problems were sufficiently widespread, and severe, to merit proceeding with the remaining objectives of the research programme i.e. addressing objectives (ii) to (v) listed above.

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*The first figure is the percentage of plants and the second (in brackets) is the percentage of the total design flow.

TABLE I

DOMINANT FILAMENT TYPES INDICATIVE OF CERTAIN ACTIVATED SLUDGE OPERATIONAL PROBLEMS

(Jenkins et al., 1985)

Suggested Causative Conditions	Indicative Filament Types
low F/M ratio	M.parvicella, Types 0041, 0675, 0092, 0581, 0961, 0803, H.hydrossis, Nocardia spp.
low dissolved oxygen	Type 1701, S.natans, H.hydrossis
presence of sulphide	Thiothrix spp., Beggiatoa spp.; Type 021N
low pH	fungi
nutrient deficiencies	H.hydrossis, S.natans, Thiothrix spp., Types 021N, 0041 and 0675

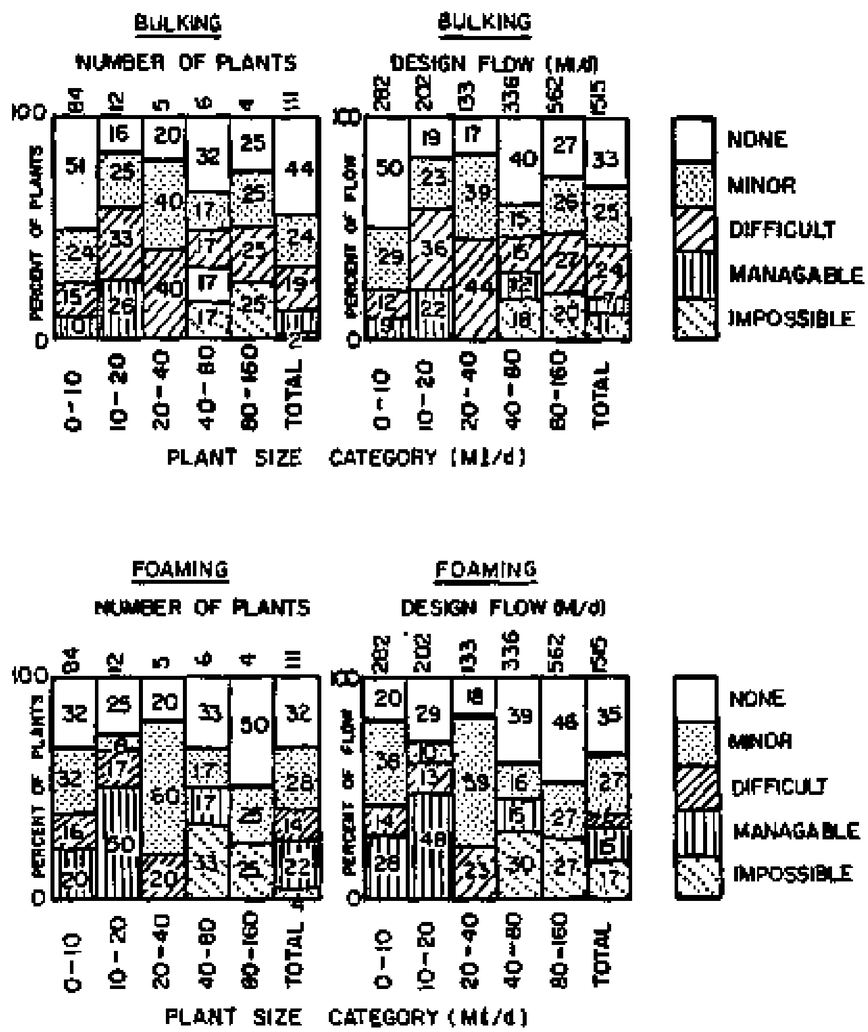

Figure 1 *Severity of bulking (top) and foaming (bottom) in different plant size categories and in the total number of plants. The percentage of the total number of plants in each category (left) and the percentage of the total design flow in each category (right) with impossible, manageable, difficult, minor and no problems is given. The total number of plants (left) and total design flow (right) in each category is given at the top of the figures. The breakdown of all the plants together is shown in the Total column in each figure.*

2. IDENTIFICATION OF FILAMENTOUS MICRO-ORGANISMS

2.1 Causes of filamentous bulking

Each type of filamentous micro-organism is likely to prefer a specific set of environmental conditions for its proliferation. Hence predominance of one type over another will depend on environmental conditions in the activated sludge plant. At present, it is only possible to suggest tentatively which process operational conditions favour the proliferation of some filamentous micro-organisms; these conditions and the corresponding filaments which favour them are listed in Table 1. Using this Table possible problematic operational conditions can be identified from the types of filamentous micro-organisms present. It may then be possible to change the conditions to prevent the proliferation of the filaments and so to ameliorate the bulking problem.

2.2 Acquisition and analysis of samples

Mixed liquor and foam samples (if present) were obtained for filament identification from most plants that participated in the questionnaire survey irrespective of whether the plant reported bulking or non-bulking conditions. The filaments were identified by the internationally accepted microscopic analysis technique of Eikelboom and van Buijsen (1981). In this technique the following terms are used to express the results:

(i) Overall abundance - a semi-quantitative assessment of the abundance of all the filament types present in the sample.

(ii) Occurrence - the presence of a particular filament type.

(iii) Dominance and secondary - the most abundant filament type present The microscopic analysis allows distinction between bulking and non-bulking sludges on the basis of the filament abundance in the samples. The results of the identification of the filaments in bulking and non-bulking mixed liquor samples (judged in the microscopic analyses from overall filament abundance level) and foam samples are set out below.

2.3 Filaments in bulking samples

The frequency of occurrence and frequency of dominance of the different filaments in the bulking sludges are given in Table 2. The eight most frequently occurring and dominant filament types are ranked 1 to 8 in descending order in Table 2 and this ranking number is shown in brackets. The results in Table 2 are shown graphically in Fig 2 in which the filaments are ranked from left to right in descending order of frequency of dominance.

From Fig 2 and Table 2 the eight most frequently occurring filament types in bulking sludges, in descending order are: Type 0041 present in 94%, Type 0092 in 79%, Type 0675 in 64%, Type 0914 in 53%, *Microthrix parvicella* in 51%, *Nocardia* spp. in 42%, *Haliscomenobacter hydrossis* in 30% and type 0803 in 26% of those plants having filamentous bulking sludges. The eight most frequently dominant filaments are Type 0092 in 43% of the plants, *M.parvicella* in 28%, Type 1851 in 23%, Type 0675 in 21%, Type 0914 in 17%, Type 0041 and *Nocardia* spp. each in 15%, and Type 0803 in 11% of plants. All these types apparently favour low Food/Micro-organism (F/M) ratio conditions although Types 0041 and 0675 also apparently have a selective advantage with nutrient deficient conditions (Table 1). However, in South African plants the low F/M conditions are the most likely cause as most activated sludge plants are operated at long sludge ages.

Frequency of occurrence and frequency of dominance of filament types in bulking sludges in the U.S.A. also are listed in Table 2. Comparing the South African and U.S.A. results, Type 0041 is the most frequently occurring filament in both countries; similarly in both countries *Nocardia* spp. and *H.hydrossis* are frequently occurring filaments (6th and 7th in S.A. respectively and 4th and 3rd in U.S.A. respectively) is termed dominant while the remainder are termed secondary. If the overall abundance is high it is possible to have 2 or more dominant filament types.

With regard to the frequency of dominance of filaments in U.S.A. plants, from Table 2 the six principal ones are, in descending order, *Nocardia* spp., Type 1701, Type 021N, *Thiothrix* spp. and *S.natans* and Type 0675. Proliferation of these apparently can be ascribed to all the possible causes listed in Table 2, except low pH; the probable reason for

Table 2

FREQUENCY OF OCCURRENCE AND FREQUENCY OF DOMINANCE OF FILAMENT TYPES IN SOUTH AFRICAN AND UNITED STATES BULKING SLUDGES

Filamentous micro-organism	SOUTH AFRICA This study *Occurrence		@Dominance		U.S.A. Richard *et al.* (1981) *Occurrence		Jenkins *et al.* (1985) @Dominance	
Type 0092	79	(2)	43	(1)	18	(7)	3	(11)
H.parvicella	51	(5)	28	(2)	10	(10)	9	(7)
Type 1851	53	(4)	23	(3)	10	(10)	6	(9)
Type 0675	64	(3)	21	(4)	-		10	(6)
Type 0914	53	(4)	17	(5)	-		0	-
Type 0041	94	(1)	15	(6)	64	(1)	12	(5)
Nocardia spp.	42	(6)	15	(6)	45	(4)	30	(1)
Type 0803	26	(8)	11	(7)	9	(11)	9	(7)
Type 1701	21		4		60	(2)	27	(2)
N.limicola.	21		4		18	(7)	8	(8)
Type 1702	4		4		-		0	-
H.hydrossis	30	(7)	2		47	(3)	6	(9)
Type 021N	19		2		38	(5)	16	(3)
Type 0961	9		2		6	(13)	5	(10)
Thiothrix spp.	6		2		17	(8)	15	(4)
Type 0581	4		2		8	(12)	1	(12)
Flexibacter	4		0		-		0	-
Unknown	4		0		18	(7)	< 1	(13)
Type 1863	2		0		11	(9)	0	-
Type 1852	2		0		-		0	-
S.natans.	0		0		27	(6)	10	(6)
fungi	0		0		8	(12)	< 1	(13)
Beggiatoa spp.	0		0		3	(15)	1	(12)
Bacillus spp.	0		0		5	(14)	0	-
Number of samples	56				-		300	
Number of plants	36				167		190	

* Percentage of treatment plants in which the particular filament was observed to be present.

@ Percentage of treatment plants in which the particular filament was dominant.

() The figure in brackets denotes the rank in descending order.

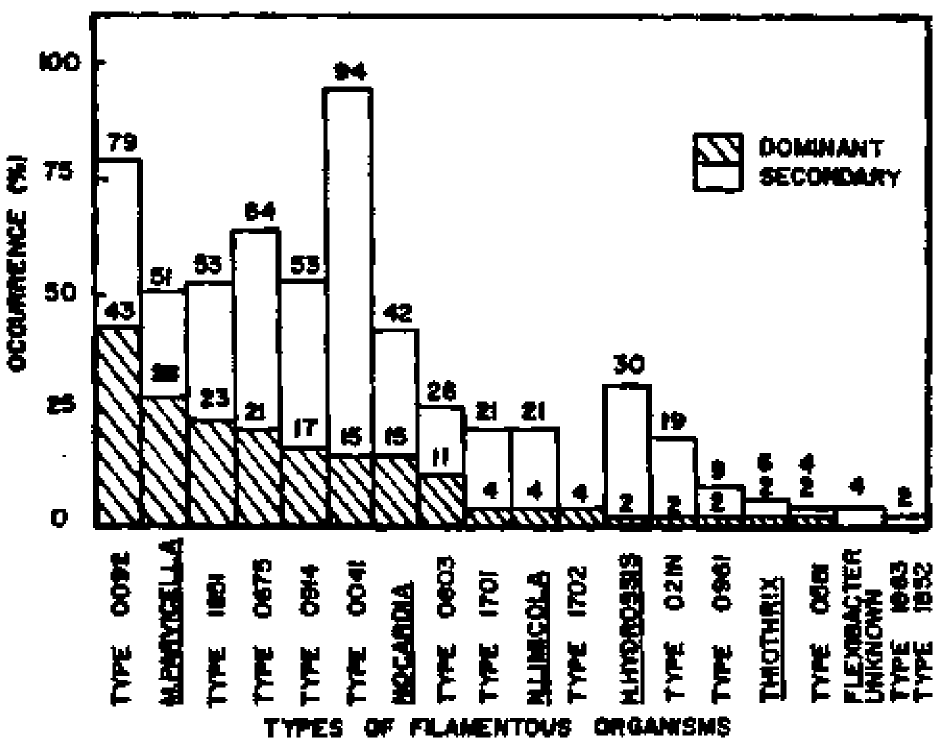

Figure 2 *Filamentous micro-organisms in bulking mixed liquor samples ranked in descending order of dominance.*

this is that in the U.S.A. activated sludge processes are operated under a wide range of conditions, from high rate (short sludge age, high F/M, possibly low Dissolved Oxygen, D.O.) to low rate (long sludge age, low F/M,). Comparing the principal dominant filaments in South African and U.S.A. bulking sludges, the three types that are common are (i) Nocardia spp. - 7th in S.A. and 1st in U.S.A., (ii) Type 0041 - 6th in S.A. and 5th in U.S.A. and (iii) Type 0675 - 4th in S.A. and 6th in U.S.A. Clearly, there is similarity with the U.S.A. only where the filaments are low F/M types.

The principal dominant filament types causing bulking in Europe and Germany have been identified in independent surveys by Eikelboom (1977) and Wagner (1982) respectively. In Table 3 the principal dominant filaments for South Africa are ranked in descending order plus the corresponding ranking number for that filament found in Europe, Germany and U.S.A., as reported by the different investigators. Both Eikelboom's and Wagner's surveys show that bulking in Europe and Germany may be caused by one or more of the different causative operating conditions (except low pH) (Table 1). This is perhaps not unexpected because in Europe activated sludge processes are operated at both high rate, in which the low D.O. filaments may develop and low rate, in which the low F/M filaments may develop.

Comparing the surveys in Europe with that in South Africa, again there is some similarity but, as in the U.S.A., only in so far as the causative filaments are the low F/M types: M.parvicella, Type 0041 and Nocardia spp. are in the top six in both countries. The major differences are (i) in Europe the filaments Type 021N, S.natans, Type 1701 and H.hydrossis often are the cause of bulking whereas in South Africa these seldom are, and (ii) filaments Types 0675 and 0914 are not listed in the European surveys, whereas these are the 4th and 5th most frequently dominant filaments in South Africa.

Assessing the situation in South Africa, with respect to the suggested causes in Table 1, the low F/M ratio (long sludge age) filamentous micro-organisms (Type 0092, M.parvicella, Types 1851, 0675 and 0914) abound in bulking sludges. These types also cause a large proportion of the bulking problems in Europe and the U.S.A. so that the low F/M condition is one that is of greatest practical importance.

Table 3

RANKING OF DOMINANT FILAMENT TYPES IN SOUTH AFRICAN, EUROPEAN AND NORTH AMERICAN PLANTS

Filamentous microorganisms	South Africa this study	U S A Jenkins *et al.*, (1985)	Europe Eikelboom (1977)	Germany Wagner (1982)
Type 0092	1	11	4	-
M.parvicella	2	7	1	2
Type 1851	3	9	12	-
Type 0675	4	6	-	-
Type 0914	5	-	-	-
Type 0041	6	5	6	3
Nocardia spp.	6	1	14	5
Type 0803	7	7	9	10
Type 1701	8	2	5	8
N.limicola	8	8	11	7
Type 021N	-	3	2	1
H.hydrossis	9	9	3	6
S.natans	-	6	7	4
Thiothrix spp.	9	4	17	-
Type 0581	9	12	8	-
Type 0961	-	10	10	9
Beggiatoa spp.	-	12	-	-
Number of Plants	56	190	200	315
Number of samples	56	300	1100	3500

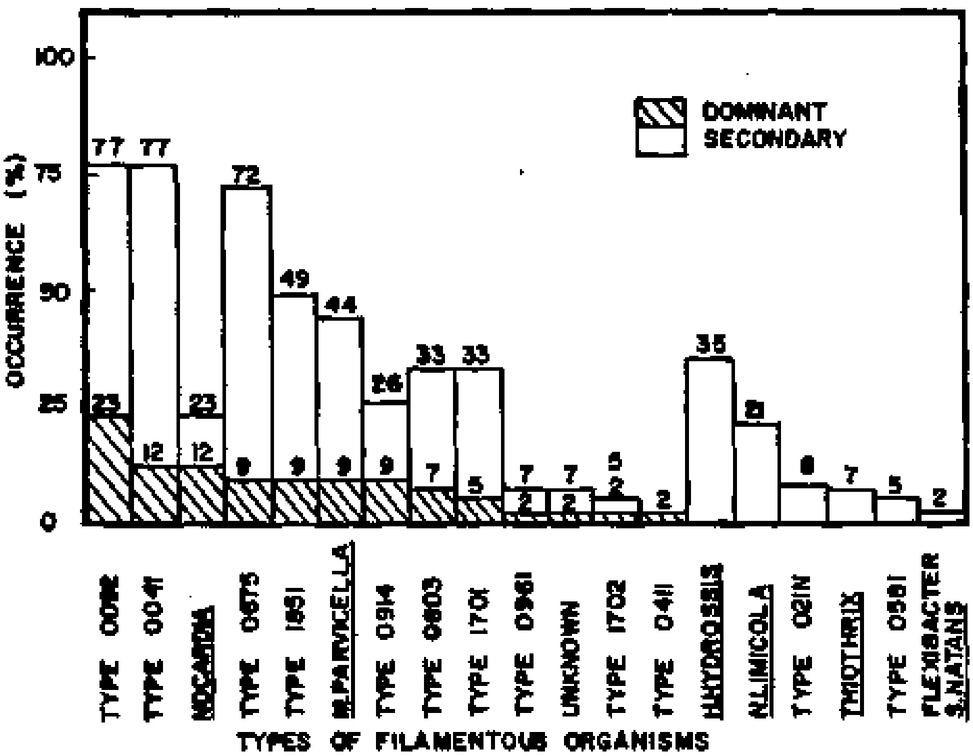

Figure 3 *Filamentous micro-organisms in non-bulking mixed liquor samples ranked in descending order of dominance.*

2.4 Filaments in non-bulking sludges

The filament types in non-bulking sludges are set out in Fig 3 which shows that the five most frequently occurring filaments in descending order of frequency, are Types 0092 and 0041 in 77% of samples, Type 0675 in 72%, Type 1851 in 49% and *M.parvicella* in 44% and the seven most frequently dominant filaments, in descending order of frequency, are Type 0092 in 23%, Type 0041 and *Nocardia* spp. each in 12% and Types 0675, 1851, 0914 and *M.parvicella* each in 9%.

Table 4

FILAMENTOUS ORGANISMS IN FOAM SAMPLES FROM PLANTS IN SOUTHERN AFRICA

Filamentous Micro-organism	Foam Sample *Occurrence	Foam Sample @Dominant	Rank
Type 0092	73	46	1
M.parvicella	59	46	1
Nocardia spp.	41	30	2
Type 0041	73	14	3
Type 0803	27	11	4
Type 0914	46	11	4
Type 0675	51	8	5
Type 1841	43	5	6
H.hydrossis	14	3	7
Type 021N	22	0	-
Type 1701	22	0	-
N.limicola	11	0	-
Type 0961	8	0	-
Thiothrix spp.	5	0	-
Type 1702	5	0	-
Type 1852	5	0	-
Type 1863	5	0	-
Type 0581	3	0	-
Beggiatoa	3	0	-
Unknown	3	0	-

Number of samples = 37
Number of plants = 37

* Percentage of plants in which each filament was observed to occur
@ Percentage of plants in which each filament was observed to be dominant

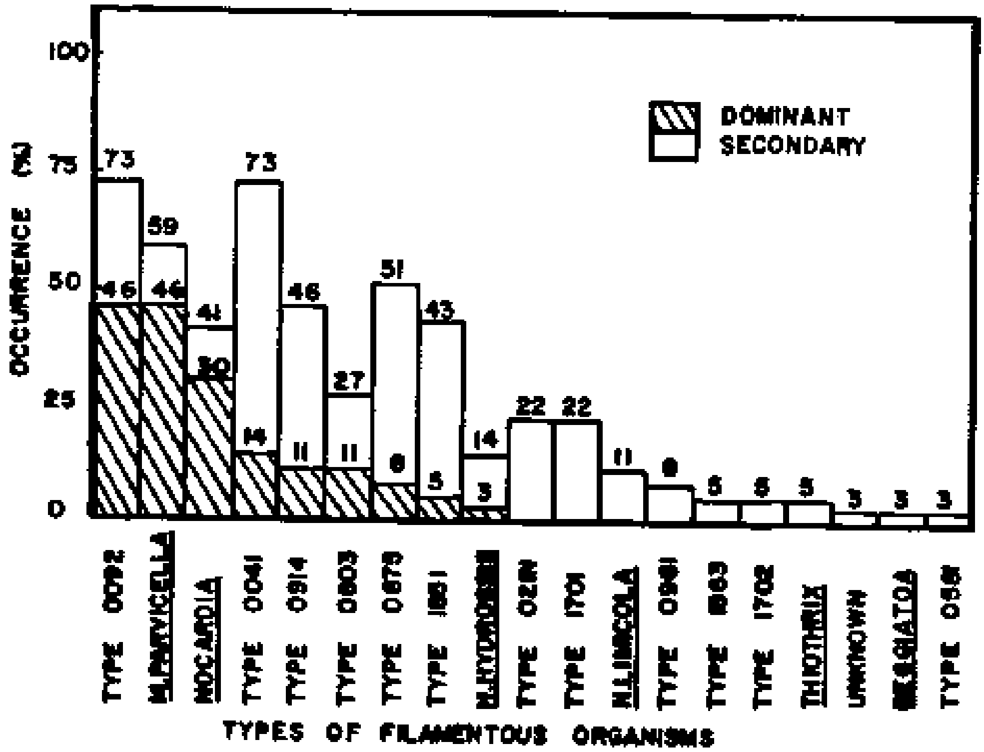

Figure 4 Filamentous micro-organisms in foam samples ranked in descending order of dominance.

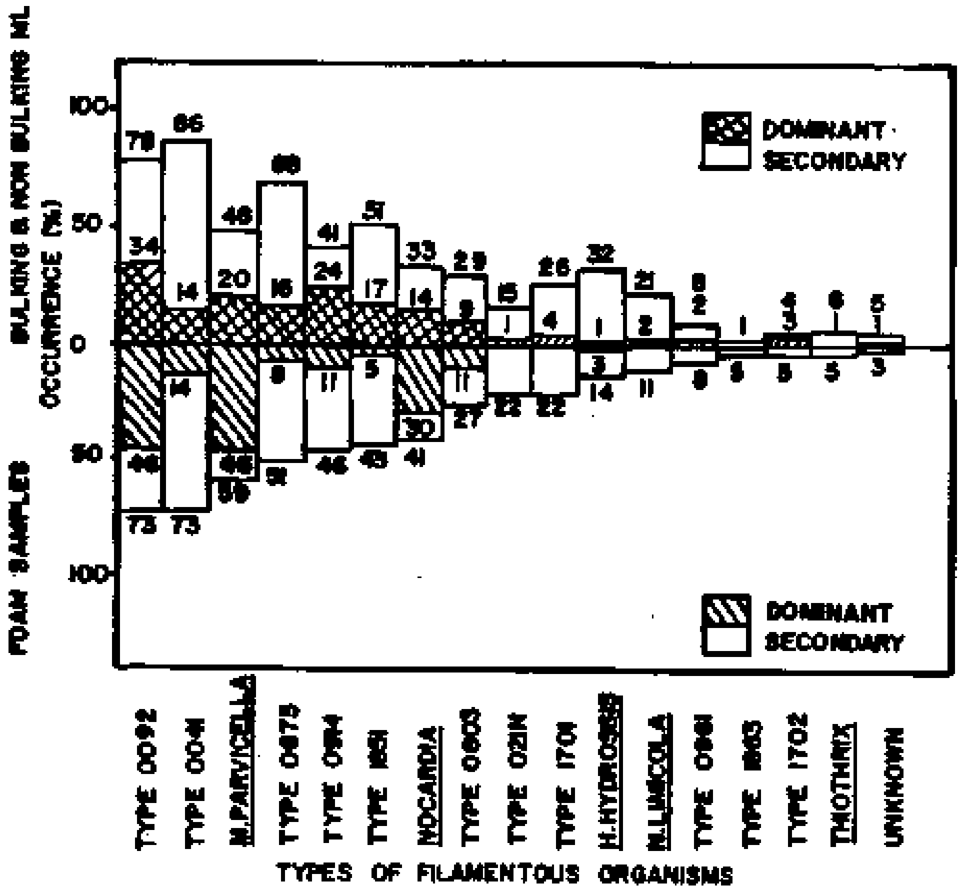

Figure 5 Comparison of filamentous micro-organisms in foam samples (bottom) with those in both bulking and non-bulking mixed liquor samples (top) ranked in descending order of frequency of occurrence in foam samples. The filaments that are dominant in the foam samples with a significantly higher frequency than in the mixed liquor samples, selectively accumulate in the foam and can be said to be foaming filaments i.e. Type 0092, *M.parvicella* and *Nocardia* spp. The filaments that are dominant in the foam samples with approximately the same frequency as in the mixed liquor samples, are present in the foam due to incidental entrapment from the mixed liquor.

Comparing the seven most frequently dominant filaments in non-bulking samples with those in the bulking ones, it appears that they are the same types except the order of ranking is slightly different. Hence bulking and non-bulking sludges are essentially similar with regard to the types of filaments present in them, the difference lies only in the abundance level of the filaments. This seems to indicate that under certain conditions, the principal causative agents increase in abundance to cause the bulking problem but the conditions that stimulate this are at present unknown.

2.5 Filaments in foam samples

The frequency of occurrence and frequency of dominance of filamentous organisms in the foam samples are set out in Table 4 and shown graphically in Fig 4, in which the filaments are arranged in descending frequency of dominance. From Fig 4, the six most frequently dominant filaments are Type 0092, M.parvicella, Nocardia spp., Types 0041, 0914 and 0803. However, it cannot be concluded from this that these filaments are the main causative agents for foaming because they are present also in the mixed liquor from which the foam originates. This difficulty can be resolved by comparing the frequency of dominance of filaments in foam samples with that in mixed liquor samples (see Fig 5). From Fig 5, those filaments which are found with approximately equal frequency of dominance in the foam and the mixed liquor can be said to be present in the foam due to incidental entrapment from the mixed liquor; the first five of these, are Types 0041, 0675, 0914, 1851 and 0803. Those filaments which dominate with a considerably higher frequency in the foam compared with the mixed liquor, can be said to be specific foaming organisms due to their selective accumulation in the foam; the principal three of these are, in descending order, Type 0092, M.parvicella and Nocardia spp. The finding that M.parvicella and Nocardia spp. are two of the principal filaments causing foaming in South Africa is not surprising; these two are notorious internationally for causing this problem. The finding that Type 0092 perhaps causes foaming is unexpected because, to the knowledge of the writers, this is not recorded in the literature. However, the implication that Type 0092 is a possible foaming filament is tentative at best: M.parvicella and Nocardia spp. are dominant in foam samples 2,3 and 2,1 times more frequently than in mixed liquor samples respectively, but for Type 0092 this ratio is 1,35.

3. RECOMMENDATIONS FOR BULKING AND FOAMING RESEARCH

The exploratory study described above (for details see Blackbeard et al., 1985) as well as visits to a number of local sewage works indicates that bulking and foaming give rise to considerable problems in activated sludge plants in South Africa. A considerable information base already exists on the control of sludge bulking and foaming, as set out in the review of Jenkins et al. (1985) (see Section 4 below). However, a number of research needs related to bulking and foaming control and remedial measures in activated sludge plants have been identified and are detailed below.

(1) Investigate bulking, its causes, control and preventative measures at activated sludge plants.

(2) Investigate foaming, its causes, control and preventative measures at activated sludge plants.

3.1 Bulking control measures

With regard to bulking control and preventative measures, considerable advances have already been made internationally, but these measures need to be investigated more closely to evaluate their application in South Africa. Bulking remedial and preventative measures can be divided into two groups viz:

i) Non-specific bulking control methods

ii) Specific bulking control methods.

3.1.1 Non-specific bulking control measures

The non-specific bulking control methods involve dosing the plant experiencing the problem with a bacteriacide such as chlorine or hydrogen peroxide. The principle behind non-specific bulking control is that the filaments extending outside the sludge flocs expose a much larger surface area than the floc formers within the sludge flocs, with the result that the former are more susceptible to toxicity: The bacteriacides kill the filaments outside the sludge flocs thereby controlling their growth. The dosing has to be done in a specific and very controlled manner so as to affect the filamentous organisms only and not the other bacteria in the process, in particular the nitrifying organisms which effect nitrification. Chlorine dosing involves two aspects (i) a total dose of between 1 and 10g chlorine per kgMLSS per day and (ii) an exposure rate of at least 2 to 3 times per day to keep the actual dosing concentration low (5-20 mg/ℓ). The most common dosage point in the plant is in the return sludge stream because here the MLSS concentration is high and soluble COD low. With this method, considerable success in controlling bulking has been achieved in the U.S.A. (Jenkins and Richard, 1985). In response to a short course on activated sludge bulking control presented by Professor D Jenkins, the method has been applied with some success at a few extended aeration plants in South Africa e.g. Heidelberg and Daspoort (S.A. Waterbulletin, Aug., 1983).

To apply chlorination in South Africa, the following needs attention (for details see Blackbeard et al., 1985).

- To investigate the effects of chlorination on the specific micro-organisms implicated in the biological phosphorus removal, such as Acinetobacter. This is important for South Africas's nutrient removal plants. No experience of this has been reported to date.

- To adapt where necessary the chlorination technique for use at South African plants and engender confidence and reliability in its application by bulking control demonstrations and publication in trade and technical journals.

In the South African context chlorination should not be viewed as an emergency control measure only - although its expense will limit its extensive use in South Africa some municipalities have found regular chlorination to improve sludge settleability (thereby allowing higher overflow rates) more economical than the cost of interest rates on capital investments required for additional settling tanks. However, it must be remembered that in many instances, specific bulking control measures can be applied for permanent prevention of bulking, in particular the selector approach.

3.1.2 Specific bulking control measures

The most important reason for knowing the different filamentous micro-organism types is that it assists identifying possible specific operating conditions that lead to their proliferation. The principal filaments causing bulking in South African plants are the low F/M (long sludge age) types. The indicated measure for their control is the "selector" reactor approach; with this approach, a small aerobic (or anoxic) reactor is placed ahead of the main biological reactor. The principle of the "selector" reactor is that the readily biodegradable COD (or dissolved COD) is at a relatively high concentration and hence is utilized at a high rate in the selector, a condition which reputedly gives the floc-forming types of micro-organisms a growth advantage over the filamentous micro-organism types. By the suppression of the filamentous growth, good settling sludges are obtained.

Considerable success has been recorded in the U.S.A. and Europe in controlling and curing low F/M filamentous bulking with the selector approach (for U.S.A. experience see Jenkins and Richard, 1985). In the main, this research describes situations where the selector reactors or zones are aerobic. Recently, work by the Berkeley group, has indicated that the selector effect also can be induced if the reactor or zone is anoxic (i.e. in the presence of nitrate and absence of dissolved oxygen), but this development has not yet been adopted at full scale. Anoxic selectors are of particular relevance to South Africa where nitrification is obligatory - indeed it is unlikely that aerobic selectors, as applied to extended aeration plants, will find wide application here because of the advantage of denitrification once nitrification is included in the design. Furthermore, biological nutrient removal plants have anaerobic reactors as their first zone and this raises the question of the applicability of the selector approach for bulking control in these plants.

Noting the above, it is recommended to investigate the following aspects due to their particular relevance to biological nitrogen and phosphorus removal technology in South Africa (for detailed background, see Blackbeard et al., (1985);

- aerobic selectors and their effects on the readily biodegradable (soluble) COD utilization and oxygen consumption rates with the view to integrating these in a general kinetic theory and thereby assist in developing a rational design procedure for aerobic selectors.

- anoxic selectors for application in full scale denitrification plants

- the feasibility of anaerobic, anoxic or aerobic selectors for incorporation in nutrient removal plants for bulking control.

3.1.3 Bulking control research contract

The recommendations on bulking control research set out above have been incorporated in a 3 year research contract between the Water Research Commission and the University of Cape Town. The research program is to be executed in collaboration with Dr Jenkins of the University of California, Berkeley.

3.2 Research into foaming control

With regard to foaming, it would appear best to adopt two approaches in this research: (i) to investigate different design features in activated sludge plants and secondary settling tanks that will lead to efficient and effective foam removal and to investigate alternatives for ultimate disposal of the collected foam. This approach is likely to yield the most cost-effective relief to foaming problems in the short term (ii) to investigate the causes for the proliferation of the foaming micro-organisms Nocardia spp. and M.parvicella; a knowledge of the causes will allow development of control measures that will lead to the decline of these organisms in the activated sludge plant.

Research on the two approaches has been initiated: At the Department of Water Utilization of the University of Pretoria under Prof W Pretorius with funding from the Water Research Commission, both approaches are being investigated, although the first approach is at present emphasized; at the Sanitary Engineering Research Laboratory of the University of California, under Prof D Jenkins, research attention is focussed on the second approach. Some interesting advances in combating foaming problems are likely to flow from these investigations in the not too distant future.

3.3 Closure

The survey summarized in this report has stimulated interest in bulking and foaming control methods in the municipal wastewater treatment field in South Africa, an interest that has existed for many years in Europe and the U.S.A. With the keen research interest at the international level in solving bulking and foaming problems, and the two Water Research Commission contracts focussing attention on the problems locally, it is envisaged that significant progress in dealing with these problems will be made in the not too distant future.

4. REVIEW OF BULKING AND FOAMING CONTROL LITERATURE

This aspect of the exploratory study was not covered by the Cape Town group. The Water Research Commission commissioned Professor D Jenkins of the University of California, Berkeley, U.S.A. who has wide experience in bulking control at full scale, using chlorination and aerobic selectors, to review the literature. The review is currently being finalized and will be published as a Water Research Commission publication entitled: "Manual on the causes and control of Activated Sludge Bulking and Foaming", by D Jenkins, M Richard and G T Daigger (1985).

5. SLUDGE SETTLEABILITY AND SECONDARY SETTLING TANK DESIGN

In addition to the research into the extent and severity of bulking and foaming, and identification of the filaments that cause these problems, the exploratory study also envisaged a review of research on sludge settleability and secondary settling tank behaviour, with the aim of possibly updating current secondary settling tank design theories or procedures.

5.1 Filamentous organisms and settleability

To obtain a quantitative measure of the effect of filamentous organisms on sludge settleability, efforts have been directed at relating the sludge settleability to the number or the total length of filaments. Sezgin et al., (1978) and Pipes (1979) found the most widely used settleability measure, the Sludge Volume Index (SVI), to be poorly related to the filament number (millions/mg). This is because (i) the filament number fails to account for filament length and (ii) the SVI test is a poor settleability measure. Sezgin et al., (1978) and Lee et al., (1983) investigated the effect of filament length, (denoted Total Extended Filament Length TEFL, km/g) on the SVI, but plots of SVI versus log TEFL showed such a wide scatter that an SVI of 150 mℓ/g could have a TEFL ranging between 5 and 70 km/g (see Fig 6). This work demonstrated the inadequacy of the SVI as an indicator of filament number or length. Work by Lee et al., (1983) shows that the Diluted Sludge Volume Index (DSVI), is an improved settleability measure over the SVI, and does give a consistent relationship with log TEFL (Fig 6): for TEFL below 30 km/g, corresponding to a DSVI of 150 mℓ/g, the filaments do not influence the DSVI significantly; however for TEFL above 30 km/g, the filaments rapidly commence to dominate the settling behaviour, indicated by the marked progressive increase in DSVI. Evidently the DSVI can serve as an indirect quantitative assessment of the filament length and can be used to identify bulking sludges. As a guide, one can accept that sludges with DSVI above 150 mℓ/g, are bulking sludges. With regard to the SVI this consistency of behaviour is absent; the reported SVI values at which bulking is implicated differ widely - from as low as 100 mℓ/g to as high as 200 mℓ/g; from Fig 6 this is not unexpected. However in the absence of DSVI experience one is forced in the interim to use the SVI to identify bulking sludges in the field. Taking note of the above range, one can accept, rather arbitrarily, that sludges with SVI's above 150 mℓ/g are bulking sludges.

5.2 Sludge settleability and secondary settling tank design procedures

5.2.1 Empirical design criteria

The conventional measure for determining sludge settleability is the Sludge Volume Index (SVI). Despite many attempts, it has not been

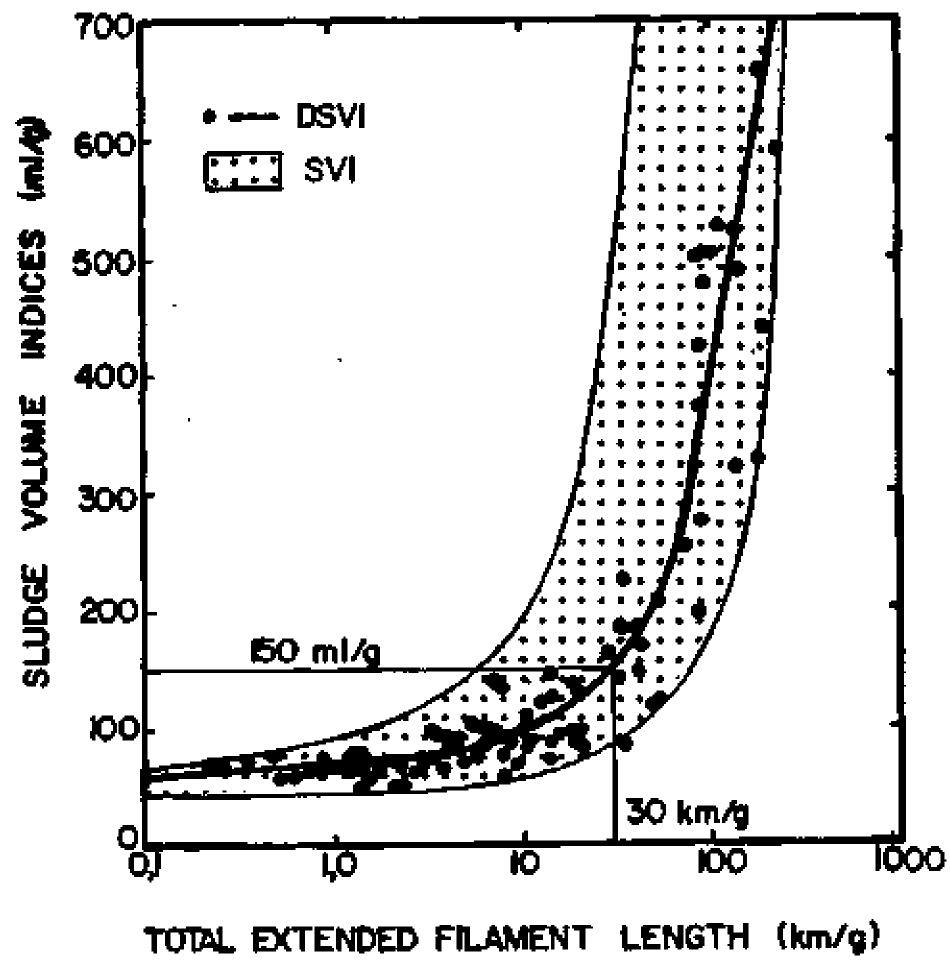

Figure 6 Relationship between Total Extended Filament Length (TEFL) and the Sludge Volume Index (SVI) and the Diluted Sludge Volume Index (DSVI). The SVI is inconsistently related to the TEFL such that a sludge with an SVI of 150 ml/g may have a TEFL ranging between 6 to 70 km/g. In contrast, the DSVI is consistently related to the TEFL in that a sludge with a DSVI of 150 ml/g has a TEFL of approximately 30 km/g (Lee *et al.*, 1983).

possible to incorporate the SVI successfully into a rational settling tank design procedure. The principal reason for this is the inadequacy of the SVI as a settleability measure - it has been criticized on the following aspects: the SVI (1) is not independent of sludge concentration (2) is not independent of cylinder diameter and depth (3) is affected by gentle stirring (4) has no observable relation to rheological properties of sludge (5) has no relation to the zone settling velocity.

Because of these inadequacies, sludge settleability has not featured directly in design criteria for settling tanks but enters in an indirect and often quite empirical fashion: For the various process types, design criteria have been set down which experience has shown to provide, usually, for adequate functioning of the settling tank over a range of settling behaviour that can arise. These rules do not incorporate directly the settleability of the sludge - this is "hidden" in the hydraulic and solids loading design criteria; examples of such criteria are those recommended by (i) the Institute for Water Pollution Control (IWPC, SA Branch) (Table 5), (ii) the United States Environmental Protection Agency (USEPA) (Table 6), and (iii) the Great Lakes - Upper Mississippi River Board of State Sanitary Engineers (GLUMRB, or Ten States) (Table 7). All these criteria in effect implicitly accept that settleability will not fall below a certain minimum quality, a quality unknown but in conformity with past experience of similar sludges.

Since 1950, considerable research effort has been directed to developing improved measures for sludge settleability and incorporating these into rational theories or design criteria or procedure for settling tanks. Three such settleability measures have been developed i.e. (i) The stirred Zone Settling Velocity (ZSV) test with its associated flux theory (ii) the Dilute Sludge Volume Index (DSVI) test with its associated ATV* and STORA* design procedures and (iii) the Stirred Specific Volume Index (SSVI) test with its associated WRC* theory.

5.2.2 Zone Settling Velocity (ZSV) test and the flux theory

The Zone Settling Velocity test is conducted in a gently stirred (1 rpm) column of about 100 mm diameter and 600 mm deep. About 2 to 3 minutes after the column has been filled with sludge of a certain concentration and stirring commenced, the solid/liquid interface begins to subside and zone settling commences. During stirred zone settling, the subsidence rate of the interface is called the Zone Settling Velocity (ZSV) and is measured from the slope of the straight line portion of an interface height - time plot. Because the sludge concentration of the zone settling region remains constant during zone settling and is equal to the concentration with which the column was originally filled, the ZSV is associated with the original sludge concentration. By repeating the test

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*Research organizations i.e.
ATV - Abwasser Technik Verband, Germany.
STORA - Stichting Toegepast Onderzoek Reiniging Afvalwater, Ryswijk, Holland.
WRC - Water Research Centre, Stevenage, England.

at different concentrations a set of ZSV concentration data can be collected.

The origin of the flux theory can be traced as far back as 1916 with the work of Coe and Clevanger. Since that time it has received considerable research attention: notable contributions towards its development have been by Kynch, (1952), Yoshioka et al., (1957), Vesilind (1968), Dick and co-workers (1967, 1970, 1972), Alkema (1971), Keinath and co-workers (1973, 1977, 1983), Pitman (1980, 1984) and Ekama et al., (1984). To facilitate analytical solutions from the flux theory (as opposed to the graphical ones developed by Yoshioka et al., 1957), Vesilind (1968) and Dick and Young (1972) proposed mathematical expressions linking the ZSV and the solids concentration; the former proposed a semi-log one i.e. $V_s = V_o e^{-nX_t}$ whereas the latter a log-log one i.e. $V_s = V_o X t^{-n}$ (where V_s is the ZSV in m/h and X_t the MLSS concentration and V_o and n are constants that describe the settleability of the sludge called the flux theory constants). In reviewing these expressions in the flux theory, Smollen and Ekama (1984) found the semi-log expression yielded a more consistent flux model and also gave closer correlation with their measured ZSV - concentration data at laboratory, pilot and full scale and also with data reported in the literature.

Today, the flux theory is probably the most rational model available for secondary settling tanks, its value and usefulness well attested in the quoted references. However, it has not been widely adopted for design and operation principally for three reasons: (i) it requires multiple batch stirred settling tests (6 to 10) over a range of concentrations from about 2 to 12 g/ℓ to obtain the ZSV - concentration data, a tedious undertaking, (ii) measurement of ZSV-concentration data is uncommon in practice and the test has not acquired familiarity as a sludge settleability measure with the result that no data base relating this measure to full scale settling tank behaviour has developed and (iii) to the knowledge of the writers the flux theory per se has not been verified on full scale settling tanks. These problems with the flux theory, in particular the tedious ZSV-concentration measurement, has prompted the development of other simpler settleability measures.

Table 5: Secondary settling tank design criteria for activated sludge plants set out by the IWPC (S A Branch) (1973)

1. Maximum overflow rate at Peak Wet Weather Flow	1,0 m/h
2. Minimum retention time at Peak Dry Weather Flow	1,5 h
3. Maximum weir loading rate at Peak Dry Weather Flow	8,3 $m^3/h/m$

Table 6: Secondary settling tank design criteria for activated sludge plants set out by the EPA (1975)

Type of Process	Hydraulic loading (m/h)		Solids loading ($kg/m^2/h$)		Sidewall depth (m)
	Average	Peak	Average	Peak	
Air activated sludge	0,68-1,36	1,70-2,04	4,08-6,08	10,17	3,66-4,57
Extended aeration	0,34-0,68	1,36	4,08-6,08	10,17	3,66-4,57
Oxygen act. sludge	0,68-1,36	1,70-2,04	5,08-7,13	10,17	3,66-4,57

Table 7: Secondary settling tank design criteria for activated sludge plants set out by GLUMRB (1978)

Type of Process	Hydraulic Loading (m/h)		Solids loading ($kg/m^2/h$)		Weir overflow rate ($m^3/h/m$)	
	Average	Peak	Average	Peak	Average	Peak
Conventional, step aeration contact - stab.	-	2,04	-	10,17	-	7,75

5.2.3 The Diluted Sludge Volume Index (DSVI) design procedures

The simplicity of the SVI test has been a major factor contributing to its popularity. Accordingly there were endeavours at modifying the test such that it retains its simplicity but improves its usefulness. One of the main deficiencies of the SVI is its dependency on the Total Settleable Solids concentration (TSS). Stobbe (1964) investigated this dependence and showed that the test result is largely independent of concentration if in the 1 litre cylinder the 30 minute Settled Volume (SV_{30}) is less than 250 mℓ. In consequence, he proposed the Diluted Sludge Volume Index (DSVI) in which the sludge is diluted such that the SV_{30} is less than 200 mℓ in the 1ℓ cylinder; the DSVI is given by the SV_{30} divided by the diluted sludge concentration in the cylinder.

5.2.3.1 *The ATV and STORA design procedure*

The DSVI's insensitivity to sludge concentration makes it a consistent basis for comparison of sludge settleability in different activated sludge plants. The DSVI has been integrated into two settling tank design procedures proposed by the ATV (1973, 1976) and STORA (1981) groups respectively. These two procedures are identical in principle and operate as follows: Using STORA's symbols, the product of the biological reactor sludge concentration (G_a, g/ℓ) and the DSVI (I_{SV}, mℓ/g) is called the Sludge Volume (VS_v, mℓ/ℓ). The Sludge Volume VS_v is empirically linked to the permissible overflow rate (q_A, m/h) found from experience to give safe designs i.e.

for ATV : $q_A = 2400\ (VS_v)^{-1,34}$ subject to $q_A < 1,6$ m/h (1)

for STORA: $q_A = \frac{1}{3} + 200/VS_v$ subject to $300 < q_A.VS_v < 400$ and $q_A < 2,0$ m/h (2)

The permissible overflow rate function for the ATV procedure is not based on settling tank failure per se (i.e. gross solids overflow witheffluent solids concentrations of several hundred mg/ℓ) but on limiting the effluent solids concentration below 30 mg/ℓ. In developing their function, STORA (1981) found that there is only a small difference in permissible overflow rate for an effluent solids concentration of 30 mg/ℓ and settling tank failure because when failure occurs the effluent solids concentration increases suddenly from very low (< 30 mg/ℓ) to several hundred mg/ℓ. STORA (1981) therefore based their function on settling tank failure.

Extensive research at full scale, (STORA, 1981) has indicated that the ATV and STORA procedures predict with reasonable accuracy the permissible overflow rates from DSVI measurements (Stofkoper and Trentelman, 1982). (see section 5.5.4. below).

5.2.3.2. *The Koopman and Cadee design procedure*

A third design procedure based on DSVI measurement is proposed by Koopman and Cadee (1983) in the U.S.A. In this procedure the DSVI measurement is used to estimate the flux theory constants V_o and n in the semi-log ZSV - concentration expression from a set of corresponding DSVI and V_o and n data that Koopman and Cadee collected. Once V_o and n are known, the permissible solids loading is calculated via the flux theory. This approach has not yet been tested at fullscale but clearly its success will largely depend on the success of the flux theory (see 5.5.3 below) and how general their set of data are for converting DSVI to V_o and n (see 5.4.1 below).

5.2.4 <u>The Stirred Specific Volume Index and the Water Research Centre design procedure</u>

White (1975) modified the SVI by introducing gentle stirring (1 rpm) during settling. He found that this improved flocculation and reduced short-circuiting and bridge formation effects, thereby creating conditions more in keeping with those in the settling tank. But more importantly, gentle stirring induces a linear relationship between the 30 minute Settled Volume (SV_{30}) and sludge concentration. He called this test the <u>S</u>tirred <u>Sp</u>ecific <u>V</u>olume <u>I</u>ndex (SSVI). For most sludges White investigated, the SSVI was independent of the initial sludge concentration. However, for some sludges this was not the case, hence to impart a generality to theSSVI as a comparative measure for sludge settleability, he proposed a standard concentration of 3,5 g/ℓ for reporting the SSVI data, denoting it the $SSVI_{3,5}$.

In terms of the $SSVI_{3,5}$, one empirical theory is available. This theory, known as the <u>W</u>ater <u>R</u>esearch <u>C</u>entre (WRC) theory is based on the flux theory for predicting the maximum solids handling capacity of settling tanks. Research at full scale has indicated that the WRC theory predicts within 20% the maximum solids handling capacity of a settling tank based on the $SSVI_{3,5}$ as the sludge settleability measure (White, 1975; STORA, 1981; Rachwal et al., 1982). The $SSVI_{3,5}$ has been widely adopted in England as the routine sludge settleability measure and, together with the WRC theory is extensively used for design and control of secondary settling tanks.

5.3 Scope of the research

In the UCT research program, the problems with the flux theory set out above were addressed with a view to making it more attractive for design and operation of settling tanks. This was largely successful because with settleability data measured and reported in the literature, it can be shown that it is no longer necessary to do the tedious multiple batch tests to measure the ZSV-concentration data to obtain the flux constants V_o and n because these can be estimated from relationships that can be established between V_o and n and the $SSVI_{3,5}$ measure. Furthermore data was measured and obtained showing that a relationship between the DSVI and $SSVI_{3,5}$ also can be established. With the aid of these relationships the flux theory could be checked against full scale settling tank data reported by Stofkoper and Trentelman (1982). The same data also could be used to check the theory of Koopman and Cadee (1983) mentioned above and to verify the WRC theory developed by White (1975). Finally, having verified the settling tank theories, the predictions of the WRC and flux theories could be compared to the ATV and STORA design procedures and the empirical design criteria set out in Tables 5 to 7. From a comparison with the empirical design criteria the "hidden" sludge settleabilities in the criteria could be estimated. The remainder of this report discusses the more important results of this research.

5.4 Relationship between sludge settleability measures

5.4.1 Relationship between flux theory constants V_o/n and $SSVI_{3,5}$

Accepting the semi-log expression for the ZSV-concentration data i.e. $V_s = V_o \exp(-nX_t)$, Pitman (1984) found that the flux theory constants V_o and n, when expressed as V_o divided by n, i.e. V_o/n, correlated well with the $SSVI_{3,5}$ (see Fig 7). The relationship he obtained is

$$V_o/n = 67{,}9 \exp(-0{,}016\ SSVI_{3,5}) \qquad (r^2 = 0{,}968) \qquad (3)$$

To verify the generality of Pitman's data, these are compared with data reported in the literature in Fig 7. In Fig 7, the data of Rachwal <u>et al.</u> (1982) are averages of a number of years full scale operation; White's data (on which the WRC theory is based), which were calculated by equating the WRC and flux theory and finding paired data for V_o and n and $SSVI_{3,5}$, show a remarkably close correlation to Pitman's. The data that deviate significantly are those of Koopman and Cadee; However, they did not measure the $SSVI_{3,5}$ directly, this was estimated from the DSVI accepting that $SSVI_{3,5} = 0,67$ DSVI (see 5.4.2 below); apart from the deviation that may arise from the conversion, the principal cause for the deviation is that in Koopman and Cadee's the ZSV batch tests, to obtain V_o and n, the concentration range was only 0,7 to 4,8 g/ℓ, a range that is much too narrow for reliable V_o and n values and also much narrower than that of the other researchers (1 to 12g/ℓ).

Knowing V_o/n from the $SSVI_{3,5}$ does not unambiguously define V_o and n individually. This problem can be overcome because White's, Pitman's and Rachwal's data indicate that as V_o/n increases (i.e. settleability improves) so n decreases; all three data sets correlate well when plotted n versus log (V_o/n). Pitman's data yield

$$n = 0,88 - 0,393 \log (V_o/n) \quad (r^2 = 0,976) \tag{4}$$

Once n is known, V_o is found from Eq 5 i.e.

$$V_o = (V_o/n)n \tag{5}$$

The importance of Pitman's data is that they confirm White's original work and firmly establishes the relationship between V_o/n and $SSVI_{3,5}$, and n and V_o/n. Pitman's work consolidates the WRC and Flux theories into a single theory so that with only $SSVI_{3,5}$ data, the design engineer and plant operator has at his disposal both the WRC and flux theories and can utilize aspects of both in his work. Both these theories are verified against full scale data, (section 5.5.2 below). In the interests of brevity, detailed comparison of the WRC and flux theories is not presented in this report; such a comparison shows that the WRC theory requires a small modification to make it identical to the flux theory. This modification introduces the critical underflow rate which

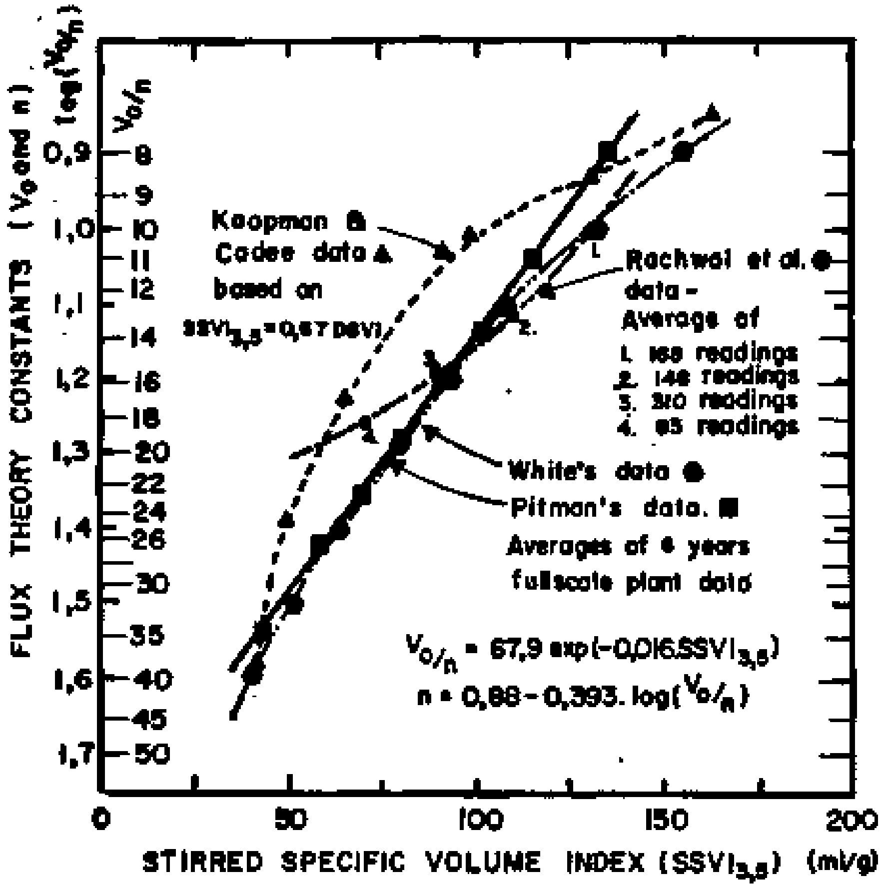

Figure 7 *Relationship between sludge settleability parameters V_o/n and $SSVI_{3,5}$ showing data from Pitman (1985), White (1975), Rachwal et al. (1982) and Koopman and Cadee (1983). With the exception of the last, there appears to be a consistent relationship between V_o/n and $SSVI_{3,5}$.*

sets an upper limit to the underflow rate beyond which settling tank overload cannot be ameliorated by further increases in underflow rate.

5.4.2. Relationship between DSVI and $SSVI_{3,5}$

Stofkoper and Trentelman (1982) report DSVI and $SSVI_{3,5}$ data pairs measured on 25 activated sludge plants (with and without primary settling) in Holland. Their data are shown plotted in Fig 8. Although there is a fairly wide scatter, it seems that the DSVI and $SSVI_{3,5}$ are linearly related i.e.

$$SSVI_{3,5} = k.\ DSVI \qquad (6)$$

where k = constant of proportionality = 0,65.

Data on 13 plants in the Western Cape over a wide range of settleability confirm Eq (6). However a slightly higher k value was found i.e. 0,68 instead of 0,65 (see Fig 9).

The spread of data in Figs 8 and 9 is such that there is little to choose between the two k values. Consequently, until the k value is more precisely fixed, or an improved relationship found with the aid of more data, it seems reasonable to assume that the $SSVI_{3,5}$ is approximately 2/3 of the DSVI i.e.

$$SSVI_{3,5} = 0{,}67\ DSVI \qquad (7)$$

The relationship between $SSVI_{3,5}$ and DSVI allows a comparison to be made between the DSVI based ATV and STORA design procedures and WRC and flux theories. This comparison is discussed briefly below (Section 5.6).

If it is possible to establish a firm relationship between the $SSVI_{3,5}$ and DSVI, it will become possible to use the WRC and flux theories and their associated design and operating charts with DSVI measurements which is a simpler and hence more appropriate measure for settleability in the field. However, it seems from the scatter of data collected to date that, from a design point of view, such an approach may not be sufficiently accurate and that it will have to stand over until more data are available. For this reason it is recommended that wherever possible, the $SSVI_{3,5}$ or DSVI, but preferably both, are measured routinely on full scale plants so that a data base for these measurements can be established. Such a data base will be of great value for design of secondary settling tanks.

5.4.3 Relationship between SVI and flux V_o/n

Owing to the general acceptance of the SVI in practise, one may ask if it is not possible to establish a relationship between the SVI and the flux theory constants V_o/n and so side-step the problem of encouraging operators and engineers to adopt the DSVI and/or $SSVI_{3,5}$. In his paper, Pitman (1984) presents a relationship between the SVI and the flux constants V_o/n and suggests that with this relationship, the flux theory,

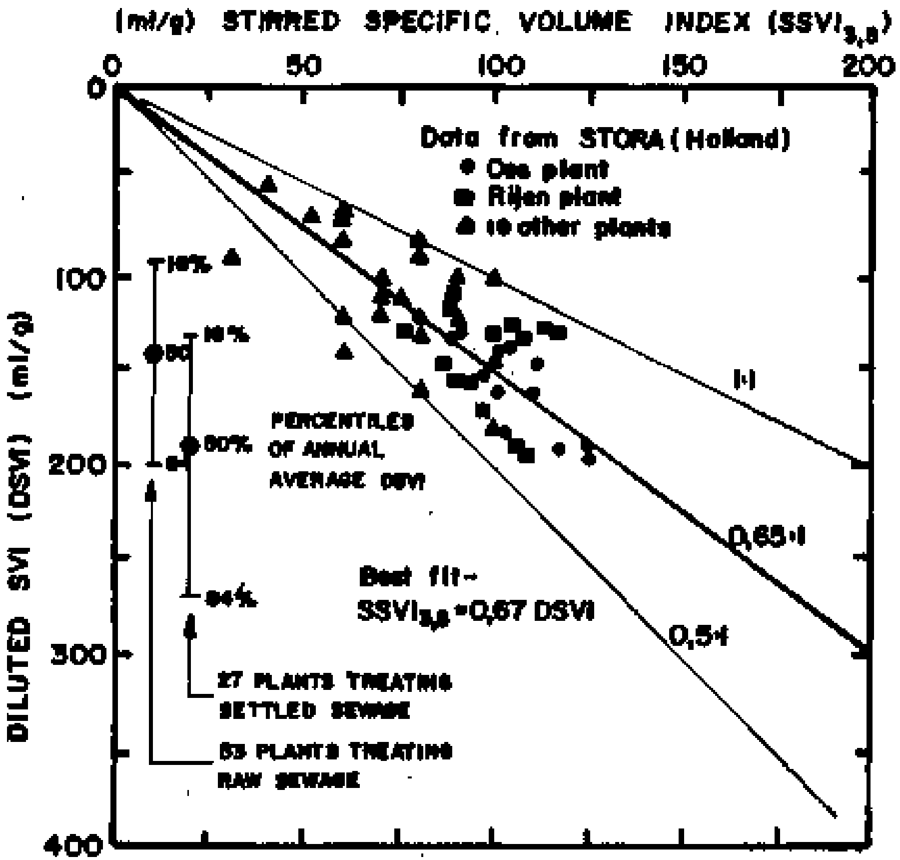

Figure 8 Relationship between sludge settleability parameters DSVI and $SSVI_{3,5}$; data from STORA (1981) on 25 plants in Holland. Data show some scatter, but best fit yields $SSVI_{3,5}$ = 0,65 DSVI. Distributions of annual average DSVI measured on 53 raw and 27 settled sewage plants in Holland are shown on DSVI axis (left).

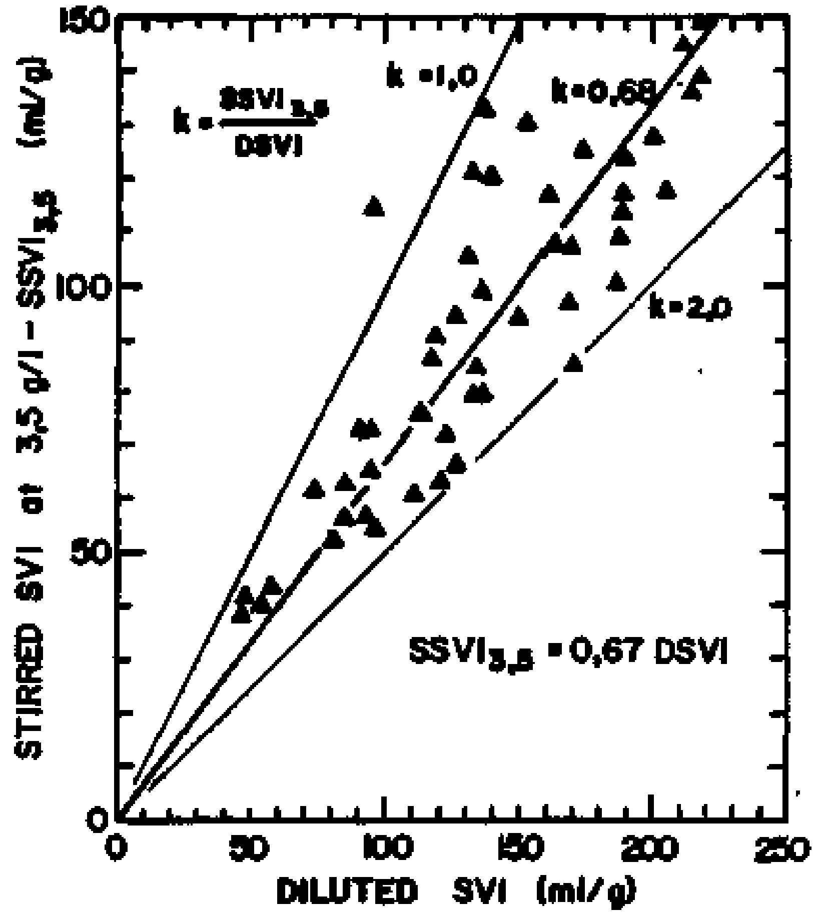

Figure 9 Relationship between sludge settleability parameters DSVI and $SSVI_{3,5}$ from 13 plants in the Western Cape. Data show some scatter but best fit yields $SSVI_{3,5}$ = 0,67 DSVI.

and its associated design and operating chart proposed by Ekama et al., (1984), can be used with the SVI measurement. Although the relationship correlates reasonably well ($r^2 = 0,913$), the writers are of the opinion that it should not be used because of the SVI's dependence on sludge concentration at high 30 minute settled volumes ($SV_{30} > 400$ mℓ/ℓ) and other problems associated with it (see 5.1 and 5.2.1 above). It is possible that from the settleabilities and concentrations measured by Pitman, the SVI was not strongly affected by concentration (which may be why he obtained the reasonable correlation), but this concentration effect may be substantial with other sludges. Indeed it is because of the unpredictable behaviour of the SVI at different concentrations between different sludges, that the more reliable $SSVI_{3,5}$ (or the DSVI, with the necessary caution, see 5.4.2 above) is preferred for estimating the flux constants V_o/n.

5.5 Verification of the settling tank theories

5.5.1 Data source

STORA (1981) undertook an extensive investigation into full scale secondary settling tank behaviour in which they analysed 45 cases of solids loading on 23 plants. The settling tanks investigated were circular and had

i) diameters larger than 30 m
ii) side wall depths of 1,5 to 2,5 m
iii) conical bottoms with a slope of 1 in 12 towards the centre
iv) scraper sludge collection systems to central sludge collection hoppers
v) peripheral overflow effluent weirs.

Each test was conducted as follows: Influent to the plant was shut off and accumulated in the sewer. At the same time the underflow recycle was set to the required rate and, while the influent was withheld, the settling tank emptied itself of sludge. The test commenced at the moment the influent pumps were started and set at the required flow rate to give a preselected overflow rate. The flows were kept constant until the test led to (i) sludge loss over the effluent weirs in which case the test ended in a solids overloaded state, (ii) a steady state in which the sludge blanket remained at a constant level in the settling tank, in which case the test ended in a solids underloaded state and (iii) an inability to maintain the influent flow at the specified rate due to a shortage of sewage, in which case the final over- or underload state was inferred from the measurements stated above - if this was not possible with reasonable accuracy, the test was deemed inconclusive. During each test the following were measured at regular intervals (i) influent and recycle flows (ii) sludge settleability with the $SSVI_{3,5}$, DSVI and batch ZSV*.

5.5.2 Comparison of predicted and measured maximum solids loading for the Flux, WRC and K & C theories.

For the 45 tests, the applied solids loading (G_{ap}) was calculated from the influent and underflow rates and the solids concentration in the feed flow to the settling tank at (i) the onset of failure for the overloaded cases and (ii) equilibrium for the underloaded cases. For the (i) flux (ii) WRC and (iii) Koopman and Cadee (K & C) theories, the predicted solids loading was calculated from the measured influent and underflow rates, the settler feed flow concentration and sludge settleability: for the flux theory the V_o and n were estimated from the measured $SSVI_{3,5}$ withthe aid of Eqs (3 to 5); for the WRC theory the measured $SSVI_{3,5}$ was used directly and for the K & C theory, the V_o and n were calculated from the measured DSVI with the aid of the equations given in their paper. A comparison of the predicted and applied solids loading for the Flux, WRC and K & C theories is given in Figs 10 to 12 respectively. In Figs 10 to 12, the different settling tank loading cases are marked as follows: solids overload i.e. failure X; solids underload i.e. safe O and

* This data unfortunately cannot be used because these, like those of Koopman and Cadee, were measured over too narrow a concentration range (1 to 4,5 g/ℓ). Because of this, STORA (1981) incorrectly concluded that the flux theory, although providing a good conceptual model for secondary settling tanks, is unsatisfactory for predicting settling tank failure. This comment is not intended to disparage their work; on the contrary the scope and detail of the work is very impressive and their experimental data are the most valuable and comprehensive available in the literature. In the opinion of the writers this research obviates the need for doing full scale settling tank experimentation until the wealth of information contained in all the data has been carefully evaluated.

inconclusive Δ; for perfect prediction, all the X's should fall below the diagonal and all the O's above. Because many data fall near the diagonal, the data are sufficiently discerning to locate the onset of solids overload.

For the flux and WRC theories, 6 overload cases fall incorrectly above the diagonal, but no underload cases fall incorrectly below the diagonal. This indicates that the theories tend to overpredict the maximum solids loading; if the predicted solids loading is reduced by 20% (which is shown in Figs 10 and 11 by the line Applied = 0,80.Predicted) all except one solids overload cases are correctly placed. The reason for this reduced loading rate is ascribed to the differences in the direction of the flux flow patterns in the settling test on which the predictions are based and in the full scale tank; in the former these are vertical only whereas in the latter these are horizontal and vertical. For the K & C theory (Fig 12) all the data points generally fall lower in the diagram indicating that this theory generally predicts lower solids loadings compared to flux and WRC theories. This is because generally lower V_o and n values are estimated from the STORA measured DSVI data with K & C's relationships; this is indirectly reflected in Fig 7 in which the K & C data fall above the other researchers (on the basis that $SSVI_{3,5}$ = 0,67 DSVI; the K & C data conform best in Fig 7 when $SSVI_{3,5}$ = 0,80 DSVI, but a constant of proportionality of 0,80 seems too high compared to the data in Figs 8 and 9). Despite the generally lower prediction of the solids loading with the K & C theory, 5 overload cases fall incorrectly above the diagonal and 2 underload cases fall incorrectly below the diagonal (Fig 12). In order to estimate the approximate solids loading it seems that with this theory also the predicted solids loading should be reduced by 20% (see Applied = 0,80 Predicted line in Fig 12). On the basis of this reduction, all except one (the same one found in the flux and WRC theories) overload cases are correctly placed, but the exception is not misplaced very far as for the WRC and flux theories.

5.5.3 <u>Qualitative verification of the flux theory</u>

The observations made during the different loading cases can be used to verify the fundamental principle of the flux theory. It was found that a distinct sludge blanket level exists between the sludge on the

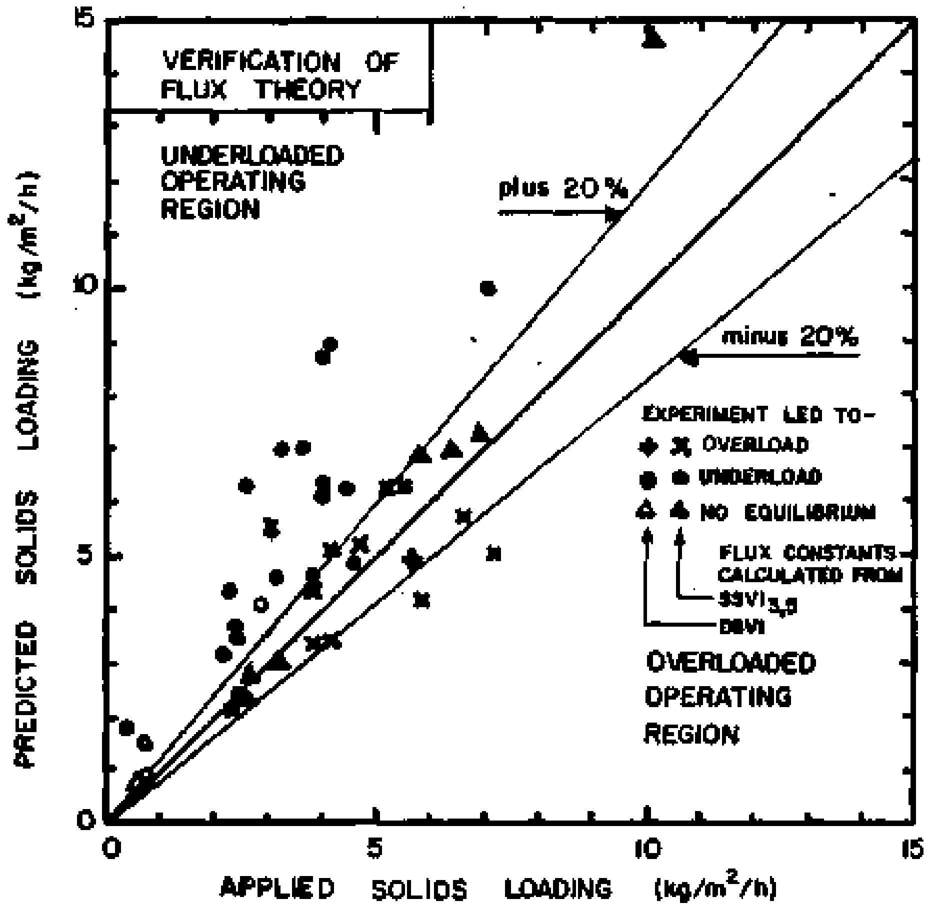

Figure 10 Verification of the flux theory; predicted solids loading versus applied solids loading observed during 45 full scale settling tank experiments by STORA (1981). The theory overpredicts the solids loading by about 20%.

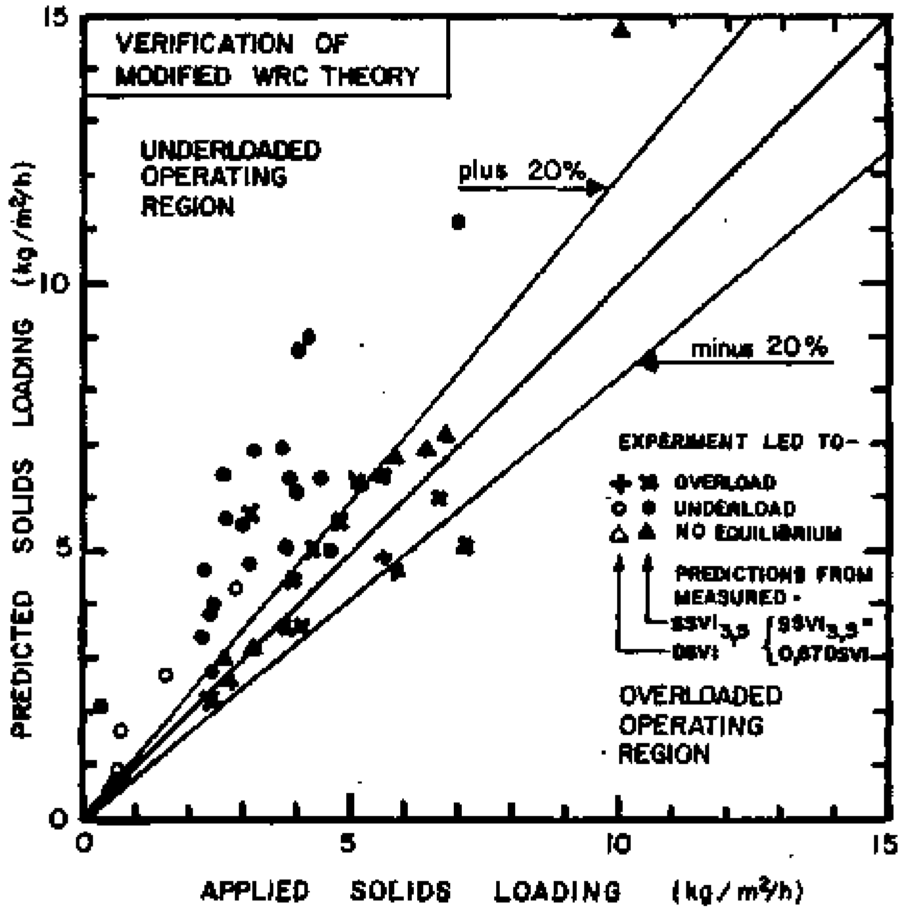

Figure 11 Verification of the modified WRC theory; predicted solids loading versus applied solids loading observed during 46 full scale settling tank experiments by STORA (1981). The theory overpredicts the solids loading by about 20%.

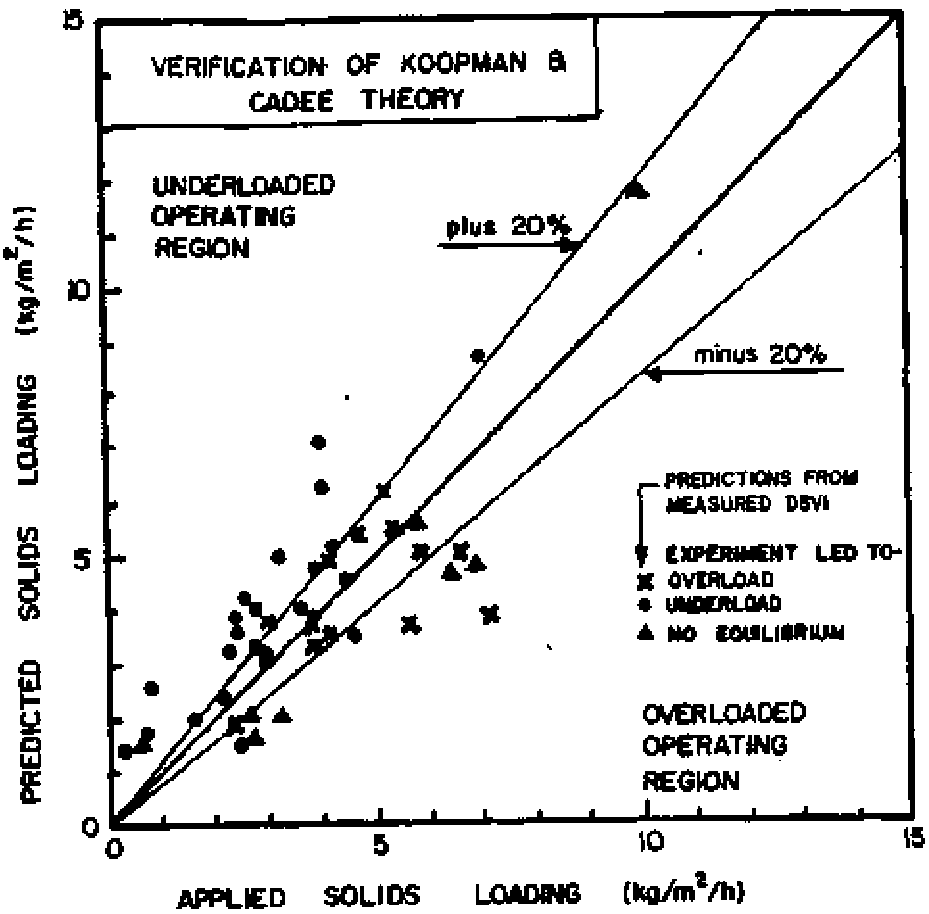

Figure 15 *Verification of the Koopman and Cadee theory; predicted solids loading versus applied solids loading observed during 46 full scale settling tank experiments by STORA (1983). The theory overpredicts the solids loading by about 20%.*

bottom of the tank and the clear supernatant above. At the start of the test, there is sludge only in the cone near the centre of the tank. As the test proceeds and more sludge enters the tank than is removed, first the bottom cone fills with sludge. When the cone is full, the sludge blanket level becomes horizontal and remains so throughout the remainder of the test irrespective of the outcome. In the underloaded cases, the sludge blanket level rises only to a certain height which is less than 0,3m above the bottom of the side wall. When this occurs the feed and underflow concentrations remain constant and the sludge concentration in the blanket increases towards the bottom in horizontal layers except near the inlet construction. The concentration in the bottom of the tank always is greater than in the underflow. In the overloaded cases, the sludge blanket level continues to rise until it reaches the overflow weir, its rate of rise depending on the severity of the overload. While the blanket is rising, the effluent solids concentration is low and remains constant. As soon as the blanket level is above 0,2m below the weir, sludge loss in the effluent commences and the effluent solids concentration increases suddenly by several hundred mg/ℓ. Under these conditions, a sludge layer of constant concentration and thickness ranging from 0,5m (near the middle of the tank) to 0,3m (near the periphery) exists in the sludge blanket over the whole area of the tank. Its position, thickness and concentration do not change with time. Below it, a zone of increasing concentration exists having a depth of about 0,5m parallel to the sloping bottom.

The essence of the flux theory is that it predicts that under overloaded conditions there is a critical zone settling layer of sludge which limits the solids transport to the bottom of the tank. This layer builds up and causes the sludge blanket level to increase. The observations cited above indicate that this behaviour indeed occurs under overloaded conditions thereby providing support for the fundamental principle on which the flux theory is based. The other aspects of the flux theory can be developed from this fundamental principle and it can be shown that these also agree with the full scale observations cited above (except that the concentration in the bottom of the tank is greater than in the underflow, but this is caused by the sludge collection systems rather than a theoretical inadequacy).

5.5.4 Verification of the ATV and STORA procedures

The ATV and STORA design procedures in essence are the same. Both provide a means to calculate the surface area and depth of the settling tank. With regard to the surface area, this is estimated from the permissible overflow rate (q_A) and the Peak Wet Weather Flow (PWWF), where q_A at PWWF is calculated from the empirical expressions (Eqs 1 and 2) linking q_A to the Sludge Volume (VS_v) by an iterative process: During PWWF, sludge is transferred from the biological reactor to the settling tank and needs to be stored there to avoid solids overload. This causes the biological reactor concentration (G_a) at WWF to be less than that at Dry Weather Flow (DWF). The lower G_a at WWF reduces the VS_v which in turn allows a higher q_A. An iterative procedure is followed by successively reducing G_a and continued until (i) the permissible sludge storage and required sludge storage are equal, (ii) the G_a at WWF is reduced to a minimum of 2 kg/m^3 or (iii) a maximum of 30% of the sludge mass is stored in the settling tank. Methods and equations for calculating the concentration at which the sludge is stored and volume available in the tank for sludge storage are given by the two design procedures.

With regard to the depth design in the two procedures, these also are similar and are based on the research of Merkel (1971a, 1971b, 1974) and Billmeier (1976). Four distinct zones are recognized in the tank i.e. from the bottom (i) thickening zone (ii) buffer or sludge storage zone (iii) separation zone and (iv) clear water zone. Methods for estimating the depths of the four zones and the concentrations in them are given. The required average depth (side wall + centre depths divided by 2) is the sum of the depths of the four zones but may not be less than 2 m.

STORA used their full scale data to check the ATV q_A-VS_v expression for estimating the overflow rate (Eq 1). For each loading case the VS_v was calculated from the measured DSVI and reactor concentration G_a at the end of the loading test i.e. to take account of the G_a reduction as required by the ATV procedure. The applied overflow rate q_A was plotted versus the VS_v in Fig 13 where the following symbols denote the outcome of the loading test - X failure i.e. solids overload, ● equilibrium i.e. safe and no solids overload, and ▲ inconclusive (see Fig 13). The ATV guide line (Eq 1) also is plotted in Fig 13. For perfect prediction, all the X's should fall above the line and all the ● below. Figure 13 shows this to be the case generally for $VS_v < 500$ mℓ/ℓ. However, for $VS_v > 500$ mℓ/ℓ (which are the usual design conditions) there are a group of safe loading cases that fall above the line indicating that for these VS_v values, the ATV theory tends to be too conservative. This conservativeness of the ATV guide line prompted STORA to modify the empirical ATV guide line distinguishing between safe and failure load cases (see Fig 13).

In their experimental work STORA also measured concentration profiles in the settling tanks in order to check the depth design of the ATV procedure. The most important aspect in the design of the depth is the estimate of the concentration in the sludge storage zone (G_c) during WWF. The estimate of G_c was adopted from Merkel's (1971a, 1971b, 1974) work and is given by $G_c = 500/I_{sv}$ kg/m^3 (where I_{sv} is the DSVI). STORA's measured concentrations in the storage zone were consistently 1,2 kg/m^3 higher than the estimated values, but they did not modify the equation because a slight underestimate of the sludge storage concentration introduces a factor of safety against solids overload having PWWF.

5.5.5 Discussion on the ATV and STORA procedures

With regard to the estimate of the overflow rate, considering the simplicity and apparent highly empirical nature of the guideline expressions (Eqs 1 and 2) the ATV and STORA guidelines can be seen to give remakably close boundary lines between settling tank overload and underload cases. Surprisingly, when tracing the development of the ATV procedure, it can be shown that the ATV expression (and hence the STORA also, though more indirectly) has its roots in the concepts of the flux theory: Merkel (1971a, 1971b, 1974), from a set of sludge settleability data (including paired data of ZSV (m/h) and 30 minute settled volume SV_{30} (mℓ/ℓ), which he accepted to be numerically equal to the Sludge Volume VS_v) developed an equation based on flux principles from which the overflow rate can be calculated from given DSVI, reactor concentration G_a and underflow recycle ratio R (Fig 14a). Furthermore, from a set of sludge thickening time - concentration data, he developed also a procedure for calculating the depth requirement of the settling tank from given DSVI, G_a and R (Figs 14b and c). From Fig 14a, the recycle ratio R only affects the overflow rate at good sludge settleability and/or low reactor concentration (i.e. VS_v < 500 mℓ/ℓ), situations for which one would not normally design. Noting this, Kalbskopf (1972) simplified Merkel's overflow rate equation by suggesting that the product of the overflow rate q_A, reactor concentration G_a and DSVI, a parameter which he called the <u>S</u>ludge <u>V</u>olume <u>L</u>oading (VS_A), can be assumed constant i.e.

$$\begin{aligned} VS_A &= q_A\, G_a.DSVI. \qquad [\ell/(m^2h) \text{ or } m^3/(m^2h)] \qquad (8) \\ &= q_A\, VS_v \end{aligned}$$

However he does not specifically recommend what VS_A value should be adopted. From his graphs it appears VS_A can range between 0,2 and 0,6, which is a very wide range and consequently a little counter-productive to his suggestion that VS_A can be assumed constant. Nevertheless his approach seems to be sound because both the ATV and STORA expressions have an almost constant VS_A i.e. > 0,3 for low VS_v and < 0,4 for high VS_v.

The approach of Kalbskopf eventually led to the ATV overflow rate versus VS_v expression set out in Eq (1), by trial and error relocation of the line to fit experimental data. The data that appear to have been

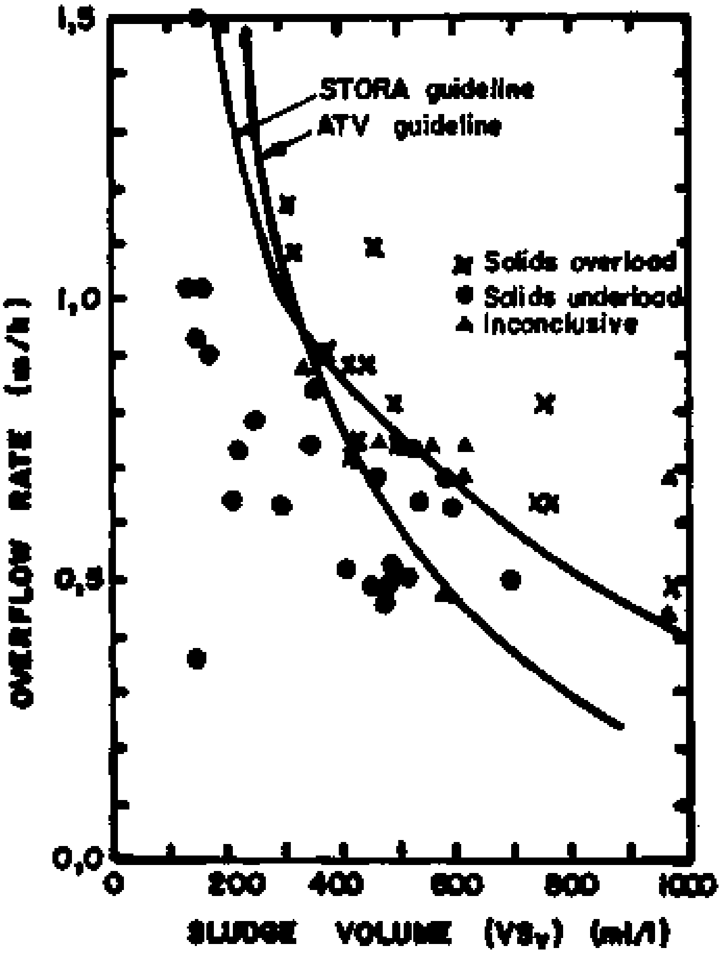

Figure 13 Verification of the ATV and STORA guidelines; comparison of the overflow rate (q_A) versus sludge volume (VS_v) expressions recommended by ATV and STORA with that measured on 45 full scale settling tanks by STORA (1981). The ATV guideline tends to be too conservative for sludge volume > 500 mℓ/ℓ, which led to the relocation of the guideline by STORA to give a closer correspondence between prediction and observation.

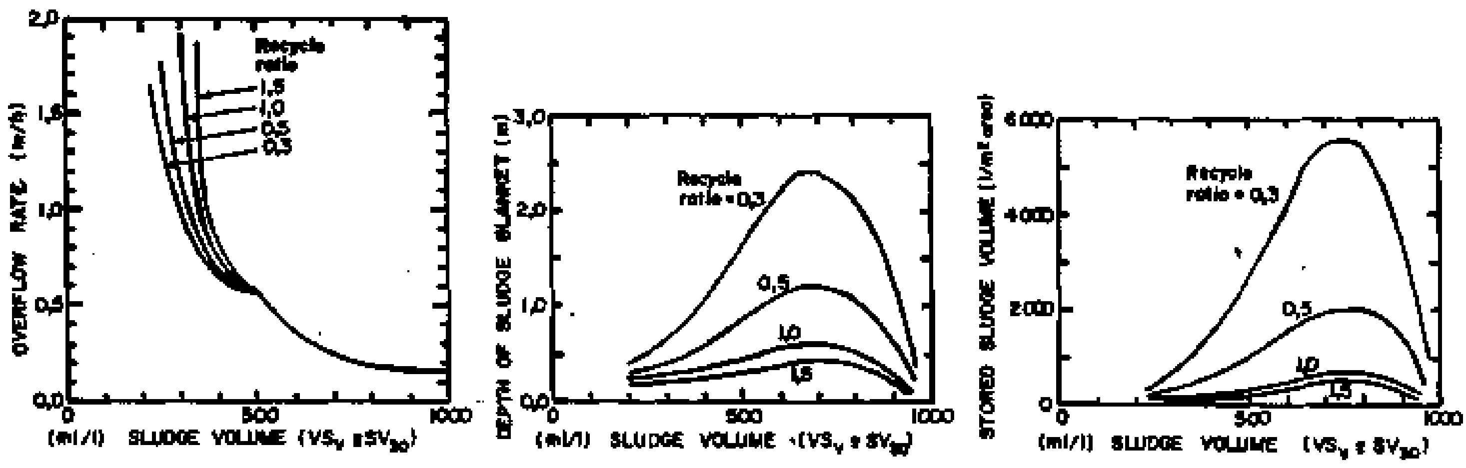

Figure 14 Permissible overflow rate (q_A) (Fig 14a, left), sludge blanket depth (h_{gem}) (Fig 14b, centre) and stored sludge volume in tank/unit area ($S_\pi I_{gu}/A$) (Fig 14c, right) versus sludge volume (VS_v) (vertical axis) from Merkel's flux based settling and thickening theory. Note (i) low recycle ratio (R) and poor settleability (VS_v > 500 mℓ/ℓ) causes low overflow rates, deep sludge blankets and large stored sludge volumes and (ii) recycle ratio affects overflow rate only for average to good settle-ability (VS_v < 500 mℓ/ℓ).

accepted by the ATV to fix the q_A - VS_v line are those measured by Pflantz (1969) on two full scale treatment plants in Germany: in Figs 15a and b effluent suspended solids concentration contours are plotted in the q_A - VS_v diagram; also shown is the ATV guideline expression, Eq (1). In Fig 15a the guideline accepted by the ATV falls very close to the 30 mg/ℓ effluent TSS contour; in Fig 15b, the guideline does not conform so well to the 30 mg/ℓ effluent TSS when $VS_v < 450$ mℓ/ℓ but the correlation for $VS_v > 450$ mℓ/ℓ (which are the normal design situations) nevertheless is reasonable. The differences between effluent TSS contours in Figs 15a and 15b arise apparently due to differences in DSVI of the sludge at the two plants; at Celle (Fig 15a), this was 80 mℓ/g and at Fallingsbostel (Fig 15b), this was 155, 201 and 306 mℓ/g.

The overflow rate (q_A) - Sludge Volume (VS_v) expression of the STORA procedure can be viewed as a further relocation of the guideline in the q_A - VS_v diagram but in this instance it is positioned so as to distinguish between solids underload and overload conditions rather than a specific effluent TSS concentration. Although this is a difference in principle (and is the only significant one between the two procedures), in practice it leads to only relatively small differences in overflow rate. The reason for this is that the settling tank operates safely with increasing overflow rate, except for small increases in effluent TSS concentration, until solids overload takes place, when precipitously, the effluent TSS increases from low values (30 - 60 mg/ℓ) to several hundred mg/ℓ.

5.6 Comparison of the Flux and WRC procedures and the ATV and STORA procedures

The major differences between the Flux and WRC design procedures and the ones set down by the ATV and STORA are that (i) the ATV and STORA do not recognize the underflow recycle ratio as important in the estimation of the permissible overflow rate whereas the WRC and Flux procedures do recognize this, and (ii) the ATV and STORA procedures include criteria with which the depth of the settling tank can be estimated whereas no methods are provided for this in the Flux and WRC procedures.

A direct comparison of the overflow rate estimates by the Flux, ATV and STORA procedures is given in Fig 16. The WRC predictions are

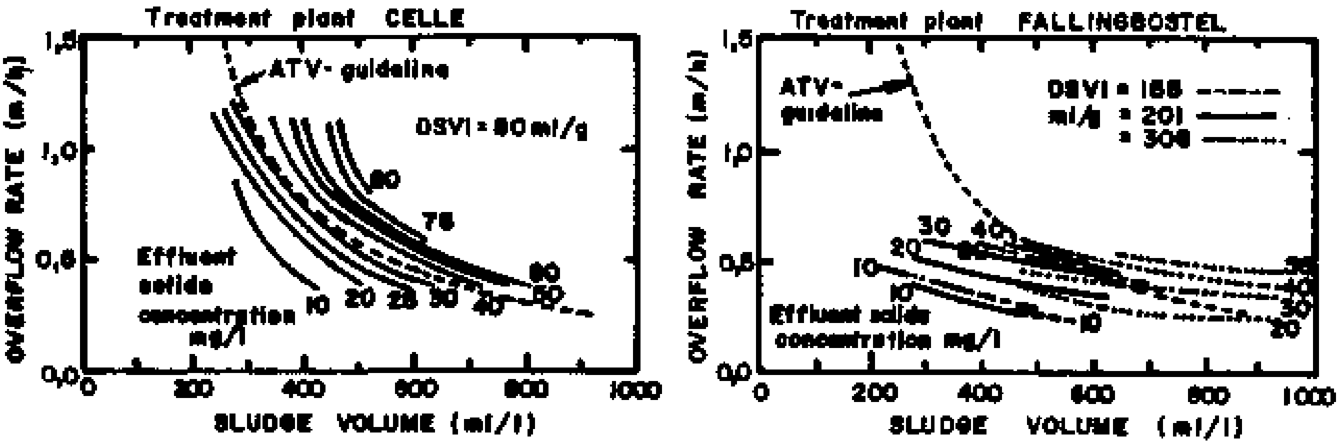

Figure 15 *Effluent suspended solids (C_e, mg/ℓ) contours for overflow rate (q_A) versus sludge volume (VS_v) for treatment plants Celle (left) and Fallingsbostel (right) (data from Pflantz, 1969). ATV guideline also shown and seems to indicate that the guideline is set to give 30 mg/ℓ effluent solids.*

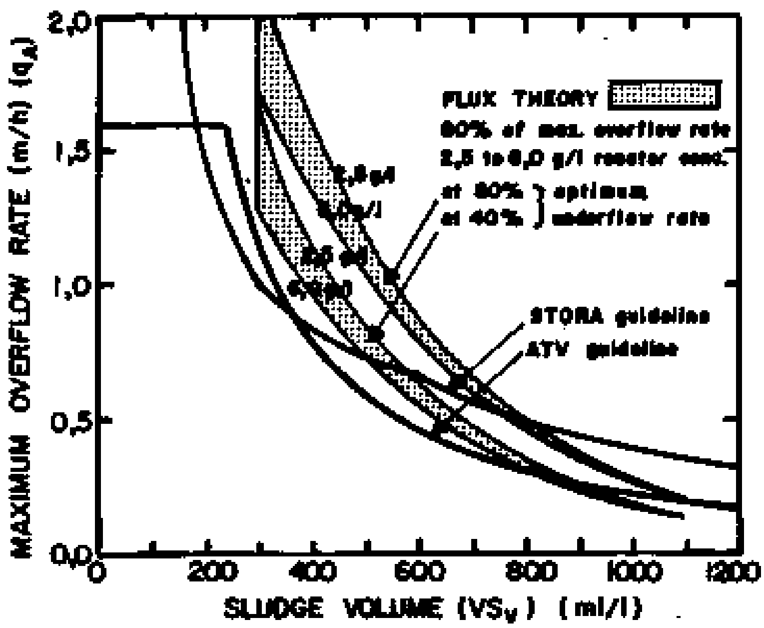

Figure 16 *Comparison of predicted maximum overflow rate (q_A) for different sludge volumes (VS_v) for the ATV, STORA and flux procedures. Flux theory overflow rates (reduced to 80% in conformity with verification) at 80% and 40% optimum underflow rates for 2,5 to 6,0 g/ℓ reactor concentration.*

omitted because these are virtually the same as those from the Flux procedure. The comparison is based on the following: (i) because the flux theory tends to overpredict the applied solids load by 20%, the predicted solids loading was reduced by 20% by reducing the applied fluxes attributable to both the influent and underflows by 20%. (ii) Pitman's data were used to convert the V_o and n to $SSVI_{3,5}$ which in turn was converted to DSVI on the basis of DSVI = 1,5 $SSVI_{3,5}$, (iii) Flux theory predictions are shown for recycle ratios set at 80% and 40% of the optimum values giving the maximum permissible overflow rate (actually, 100% and 50% of the optimum recycle ratio was chosen but because of the 20% reduction in accordance with (i) above, this is reduced to 80% and 40%). (iv) for the flux procedure, the overflow rate is sensitive to the feed concentration so that a range of concentrations from 2,5 (top of band) to 6 g/ℓ (bottom of band) are presented in Fig 16.

The following conclusions can be drawn from Fig 16:

(i) According to the flux procedure (and hence also the WRC), doubling the underflow rate from 40% to 80% of the optimum increases the overflow rate by about a third. This beneficial influence on the overflow rate of increasing the underflow rate is absent in the ATV and STORA procedures.

(ii) For good sludge settleability (VS_v < 500 mℓ/ℓ) the ATV and STORA design procedures are considerably more conservative than the flux procedure whereas for average to bad settling sludges (VS_v > 500 mℓ/ℓ), which would be the normal design situation, the different procedures yield approximately the same permissible overflow rates. This seems perplexing on first sight since all the procedures have been verified against the same set of data so that some degree of uniformity is expected. However the differences can be explained and are attributable to (a) variations in sludge settleability parameter conversion factors - these factors do show some variability between different sludges (see Figs 7 to 9) and different factors would lead to relative relocation of the lines and (b) one third of the solids loading experiments by STORA have recycle ratios less than half of the optimum for the maximum permissible overflow rate. Such low underflow rates significantly reduce the permissible overflow rate below the maximum, an effect that occurs to a far greater degree at the good sludge settleability and/or low feed concentration (low VS_v) than at poor settleability and/or high feed concentrations.

(iii) for the normal design conditions i.e. average to poor sludge settleability (VS_v > 500 mℓ/ℓ) the flux, WRC, ATV and STORA design procedures give approximately similar permissible overflow rates and differences in the procedures such as the influence of underflow rate, do have an effect but are of no major consequence.

5.7 Comparison of flux and WRC theories with empirical design criteria

Having established the qualitative and quantitative validity of the flux theory, the predicted maximum overflow rates and associated maximum solids loading can be compared to the empirical design criteria set out in Tables 5 to 7. This was done as follows: For a selected $SSVI_{3,5}$, the V_o and n values were calculated from Eqs (3 to 5). From V_o, the optimum underflow rate, (which gives the maximum permissible overflow rate) $(Q_r/A)_o$, is calculated from $(Q_r/A)_o = V_o/e^2$. The maximum permissible overflow rate, $(Q_i/A)_m$, is given by $(Q_i/A)_m = V_o e^{-nX_o}$, where X_o is the biological reactor sludge concentration. Now, the associated maximum solids loading, G_{apm}, is calculated from $G_{apm} = X_o \{(Q_i/A)_m + (Q_r/A)_o\}$, but to conform to observations this needs to be reduced by 20%. In making the 20% reduction to G_{apm}, it was accepted that the fluxes contributed by the influent and recycle flows are each reduced by 20%. In Figs 17 and 18, the reduced maximum overflow rate and solids loading respectively are plotted versus the $SSVI_{3,5}$ settleability measure. For convenience, the flux V_o/n and DSVI settleability measures calculated from Eqs (3 to 7) are shown also. To show the similarity between the modified WRC and flux theories the maximum solids loading for the modified WRC theory are plotted also in Fig 18. In Fig 18 the Modified WRC line is calculated as follows; from a selected $SSVI_{3,5}$ the optimum underflow rate is calculated (this calculation is the essence of the modification); knowing the underflow rate, the applied flux is calculated with the usual WRC equation; the applied flux is reduced by 20% and is independent of reactor concentration which is why there is only one line for applied flux in Fig 18. Superimposed on Figs 17 and 18 are the recommended design criteria set out in Tables 5 to 7. Because these criteria are independent of sludge concentration and settleability, each plots as a single horizontal line.

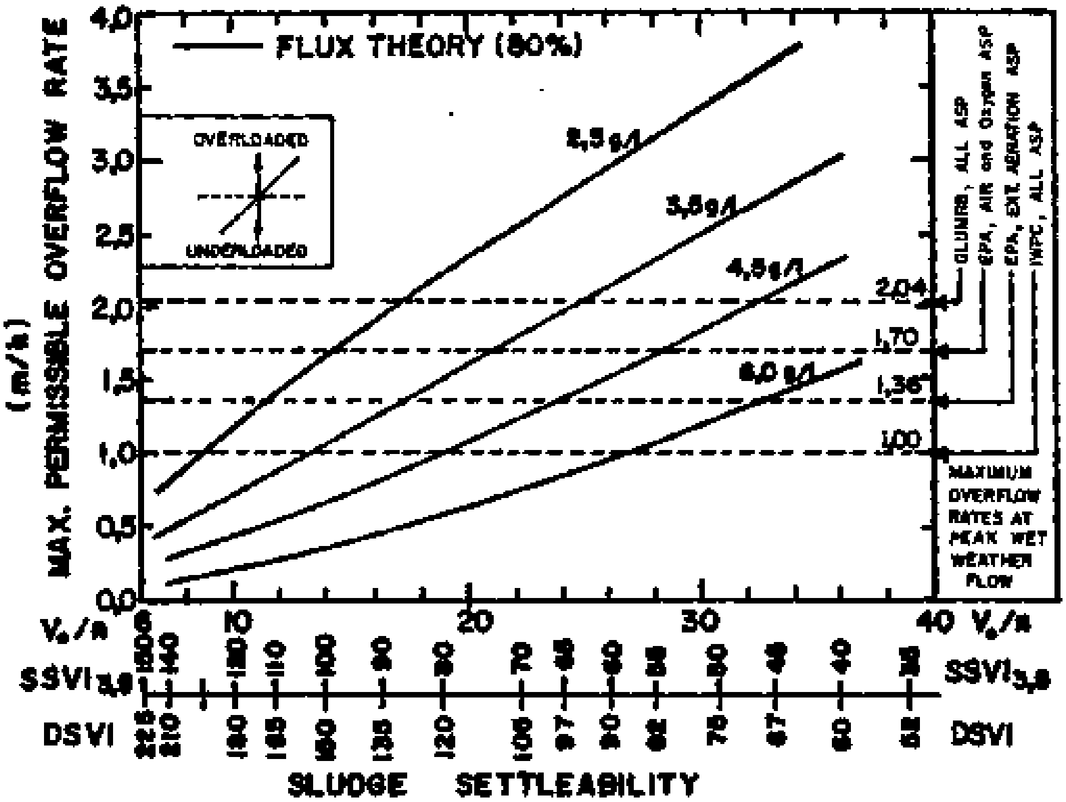

Figure 17 *Maximum permissible overflow rate (reduced to 80%) versus sludge settleability in terms of DSVI, $SSVI_{3,5}$ and V_o/n (related through Eqs 3 to 7) for the flux theory at 80% optimum underflow rate for 2,5; 3,5; 4,5 and 6,0 g/ℓ reactor concentration. Also shown are the hydraulic overflow rate criteria of the EPA, GLURMB and IWPC: Criteria give safe designs for settleabilities better than that given by the intersection point of the flux predictions and criteria lines (i.e. left of intersection point) e.g. 1 m/h IWPC criteria safe for DSVI < 150 mℓ/g at 3,5 g/ℓ.*

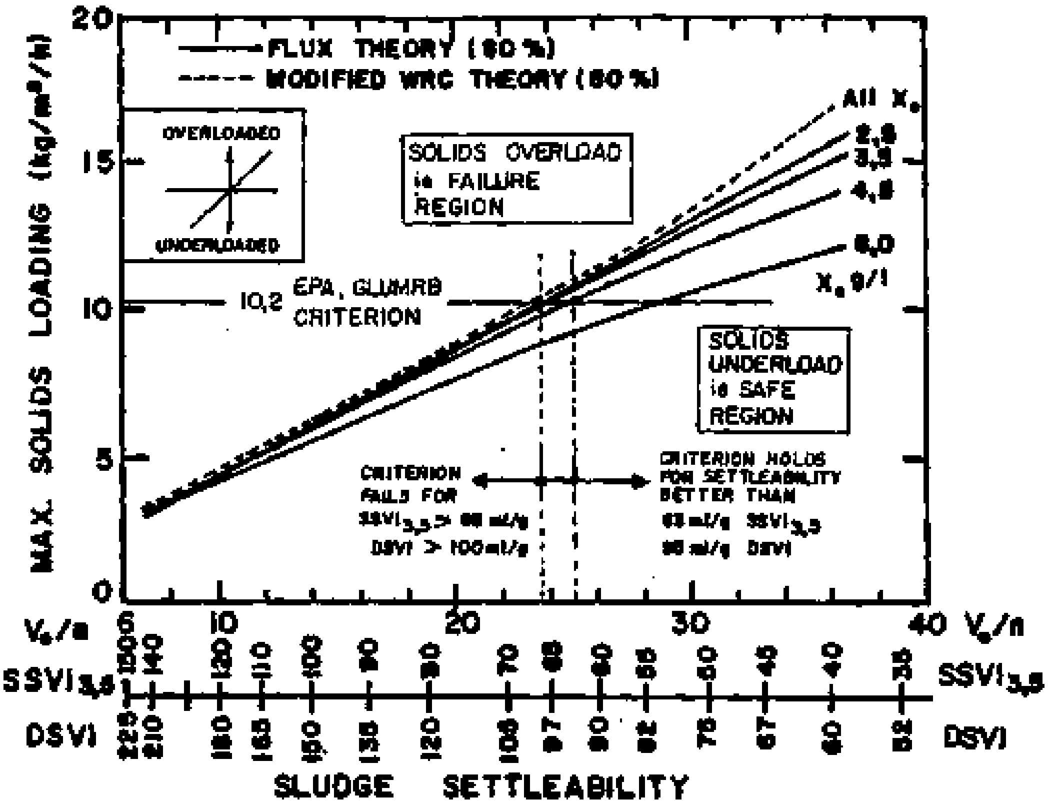

Figure 18 *Maximum solids loading (reduced to 80%) versus sludge settleability in terms of DSVI, $SSVI_{3,5}$ and V_o/n (related throgh Eqs 3 to 7) for flux and WRC theory at 80% optimum underflow rate for 2,5; 3,5; 4,5 and 6,0 g/ℓ reactor concentration (X_o). Also shown are the EPA and GLUMRB maximum solids loading criterion, which gives safe designs for settleabilities better than that given by the intersection point of the flux (and WRC) predictions and criterion lines, e.g. criterion safe for DSVI < 100 mℓ/g at 3,5 g/ℓ.*

The approximate sludge settleability that is "hidden" in the criteria is given at the intersection point of the horizontal lines and the calculated lines for the flux and modified WRC theories. From Fig 17, it appears that for a reactor concentration of 3,5 g/ℓ (an approximate average for S A plants), the IWPC 1 m/h overflow rate will yield safe settling tank designs for sludges with $SSVI_{3,5}$ below about 100 mℓ/g or DSVI below about 150 mℓ/g. The higher overflow rate criteria set by the GLUMRB and EPA require better sludge settleability for safe designs than that set by the IWPC i.e. for a reactor concentration of 3,5 g/ℓ, GLUMRB requires an $SSVI_{3,5}$ below about 63 mℓ/g (DSVI $<$ 95mℓ/g) and the EPA an $SSVI_{3,5} < 85$ mℓ/g (DSVI $<$ 130 mℓ/g) for extended aeration and an $SSVI_{3,5} <$ 75 mℓ/g (DSVI $<$ 110 mℓ/g) for air and oxygen activated sludge. The maximum solids loading criterion set by the GLUMRB and EPA (Fig 18) will lead to safe designs if the $SSVI_{3,5}$ is below about 65 mℓ/g (DSVI $<$ 100 mℓ/g): For the GLUMRB this settleability is consistent with that which leads to safe designs on the basis of overflow rate provided the underflow rate is set at the optimum; for the EPA, this settleability is better than that which leads to safe designs on the basis of overflow rate, indicating that the solids loading criterion is the limiting one if the settling tank is operated at the optimum underflow recycle rate.

5.8 Conclusions

The review above indicates the following:

1. The flux theory forms the basis for describing secondary settling tank behaviour. The origin of all the design procedures i.e., the flux, WRC, ATV and STORA, can be traced to the flux theory. The differences between the different design procedures are more apparent than real and arise from different settleability parameters and simplifications incorporated in them for practical convenience.

2. The DSVI and/or $SSVI_{3,5}$ should be adopted as the new sludge settleability parameters. The multiple batch tests to estimate the V_o and n flux constants may be abandoned (except for research purposes) because these constants can be estimated with reasonable accuracy from the $SSVI_{3,5}$. Although still of some practical value, the SVI is an inferior settleability test and its replacement by the DSVI or $SSVI_{3,5}$ should be strongly promoted.

3. With the aid of the relationships between the flux constants V_0 and n, DSVI and $SSVI_{3,5}$, the different settling tank design procedures and theories were verified against full scale settling tank operational data. The modified WRC and flux procedures overpredict the permissible solids loading by about 20%. For average to poor settling sludges (the usual design situation) the ATV guideline gives a good estimate of the permissible overflow rate for a maximum effluent solids concentration of 30 mg/ℓ, but tends to be conservative for estimating the overflow rates for the onset of solids overload. The STORA guideline is a minor relocation of the ATV guideline so that it yields overflow rates for the onset of solids overload rather than a specific effluent TSS concentration.

4. It is recommended that the Flux or modified WRC and ATV or STORA procedures are adopted for a more rational approach to design that include sludge settleability. For average to poor sludge settleability all these procedures yield approximately similar permissible overflow rates.

5. Both the $SSVI_{3,5}$ based flux and modified WRC procedures and the DSVI based ATV and STORA procedures have deficiencies. The former two include the effects of the underflow recycle, but exclude a means for estimating depth whereas the latter two exclude the effects of the underflow reycle but include a means for estimating depth. However, knowing the relationship between $SSVI_{3,5}$ and DSVI the positive aspects of the different approaches can be used in design.

6. Design criteria based on hydraulic overflow rates do not overtly recognize sludge settleability although in them a settleability is implicitly included; if in practice, a sludge has a settleability worse than that implied, the settling tank has a reduced maximum permissible overflow rate. At a biological reactor concentration of 3,5 g/ℓ, the IWPC 1 m/h overflow rate at PWWF will yield safe designs for sludges of settleability lower than a DSVI of 150 mℓ/g. A DSVI of 150 mℓ/g also is the upper limit for non-bulking sludges (see Blackbeard <u>et al.</u>, 1985). Consequently, the 1 m/h IWPC hydraulic criterion appears adequate for non-bulking sludges provided the

reactor MLSS < 3,5 g/ℓ; the higher the reactor concentration above 3,5 g/ℓ, the lower the permissible overflow rate below 1 m/h and vice versa. For bulking sludges (DSVI > 150 mℓ/g) the 1 m/h IWPC criterion is no longer adequate and the design should be based on an expected DSVI (or $SSVI_{3,5}$) using the procedures discussed in the paper.

7. From a design point of view, sufficient understanding of secondary settling tank behaviour has been developed to produce reliable designs. The emphasis should be focussed on practical application of the design procedures discussed in this review. The problems still to be resolved lie in determining the causes of bulking and developing methods for ameliorating this; however, bulking is a problem of the activated sludge process itself, not the settling tank.

8. In South Africa, it is recommended that design of settling tanks always should provide for bulking sludges until the causes for bulking and remedies to control these on a permanent basis have been established. In the interim, attention should be given to the current methods for controlling bulking by appropriate process configuration design and where a bulking problem needs to be overcome in the short term, this can be done by appropriate dosing of chlorine (see Jenkins et al., 1985).

9. Hydraulic considerations were not discussed in detail in this review but a consistent pattern emerges from the literature viz (a) with double sided overflow launders, solids loss always occurs sooner than with single sided launders; with the former, sludge is scoured by a horizontal flow between the bottom of the launder and the sludge blanket whereas with the latter, the blanket must rise to within 0,2m of the weir level before solids loss occurs; with the former the tank depth, and hence sludge storage volume, is effectively reduced by 0,6 to 0,8m. In consequence, it is recommended that the IWPC 8,3 $m^3/h/m$ weir discharge flow should fall away and to provide always a single peripheral effluent weir on which there is not flow rate per unit length limitation (Stofkoper and Trentelman, 1982; Stukenberg et al., 1983), (b) although there were good resons for hydraulic suction sludge collection systems (fast sludge return, elimination of sludge

movement to the central collection hopper), research indicates that these systems are no more effective than the conventional scraper collection systems. Furthermore the suction collection system has a number of disadvantages: it tends to collect preferentially the more dilute concentrations and causes hydraulic disturbance of the symmetry of flow due to the rotating suction arm; this effect is particularly adverse under high recycle rates (1:1 on ADWF) common to nutrient removal plants in South Africa where deliberate denitrification is included in the plant. It is recommended to design deep settling tanks (3,5-5,0m) (Parker, 1983; Pitman, 1984) with scraper collection (Stukenberg et al., 1983; Pitman, 1984) instead of shallow tanks (2-3m) with hydraulic suction collection systems.

5.9 Recommendations for research

The literature review above indicates that a large body of research information is available on the behaviour of secondary settling tanks. A significant proportion of this research was undertaken on full scale tanks and was directed specifically at developing design procedures that recognize sludge settleability. These procedures were shown to give a good correlation with observed behaviour of full scale settling tanks. The procedures have not been adopted for design in South Africa. Consequently, it is more appropriate at present to upgrade the currently used hydraulic design criteria which disregard sludge settleability, by making available the design procedures and full scale experience (appropriately modified where necessary) developed in Europe and England, rather than conduct further full scale research. In other words, a lot of research has been done; it is time it is put into practise in South Africa. This need will be filled by three approaches:

(i) writing an information document for distribution to municipal and consulting engineers and plant operators giving guidance for the design and operation of secondary settling tanks, based on the above review,

(ii) writing a series of technology transfer papers for publication in IMIESA or "Water, Sewage and Effluent" highlighting important aspects for design and operation, and

(iii) writing a series of scientific papers for Water SA detailing original contributions by the writers of this review.

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