THE EFFECT OF SLUDGE AGE ON DECOMPOSITION OF SLUDGE IN BATCH AEROBIC DIGESTION OF ACTIVATED SLUDGE ACCLIMATED TO GLUCOSE AND PEPTONE

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Experiments on batch aerobic digestion in continuous aeration were carried out by using activated sludges acclimated to synthetic wastewater of glucose and peptone at various sludge ages. As sludge age decreased, *VSS* decreased quickly with the progress of digestion and the ratio of maximum *VSS* reduction to initial *VSS* increased, but *VSS/SS* was kept constant. The decomposition rate of sludge was proportional to the biodegradable *VSS*, and its proportional constant (rate constant of decomposition) increased as sludge age decreased. The oxygen uptake rate of sludge was related to the decomposition rate of sludge by using a reaction model where the composition of activated sludge cell was $C_5H_7NO_2$. Moreover, the *SVI* of sludge increased with the progress of digestion, but the final *SVI* was within the range of good settleability.

Introduction

An important problem is how to dispose the excess activated sludge produced in the activated-sludge process, which is used widely to treat many kinds of organic wastewaters. The aerobic digestion process is considered to be suitable for disposal of the excess activated sludge from small-scale wastewater plants on a solitary island or other remote place, because the process is simple and cheap in construction, easy to maintain and free from nuisance odors.

The authors[2, 5-7] experimented on a batch aerobic digestion using the excess activated sludge produced at a municipal wastewater treatment plant. However, the results for the percentage of maximum decomposition of the sludge and the rate constant of decomposition varied somewhat among the experiments. This depends on the fact that the characteristics of the activated sludge used in these experiments changed with the season when the sludge was collected.

It is thought that sludge age has a strong influence on the characteristics of the sludge. Reece *et al.*[9] and Krishnamoorthy *et al.*[4] reported the effect of sludge age on the rate constant of decomposition under aerobic digestion, but their conclusions are different from each other. In addition, no one has reported the effect of sludge age on oxygen uptake rate (*OUR*) and settleability of aerobically digested sludge.

In this paper, the authors experimented on batch aerobic digestions of activated sludges acclimated to a synthetic wastewater of glucose and peptone at various sludge ages, and discuss the effect of sludge age on the percentage of maximum decomposition of sludge, rate constant of decomposition, *OUR* and settleability of the sludge.

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1. Experimental

1.1 Experimental apparatus

The apparatus for the acclimation and the aerobic digestion of activated sludge was the same as that used previously[2] for aerobic digestion. The cylindrical digestion tank (25 cm in diameter and 35 cm in height) was made of transparent vinyl chloride and was kept at 30°C. A porous diffuser was fixed at the bottom of the tank, and air was blown into the tank at a flow rate of 0.003 $m^3 \cdot min^{-1}$. The sludge in the digestion tank was constantly stirred by a paddle agitator (120 rpm), so that all the sludge solids were kept in suspension.

1.2 Acclimation of activated sludge

The acclimation of activated sludge was performed by the batch activated-sludge process (one cycle = one day). Seed sludge used in this acclimation was collected from the return activated-sludge line at the municipal wastewater treatment plant in Matsuyama, and was acclimated to the synthetic wastewater where glucose and peptone were dissolved as substrate in the tap water. **Table 1** shows the weight fractions of components in the synthetic waste-water.

The sludge (0.01 m^3) mixed with synthetic wastewater was aerated for 23 hours. Just before the aeration was stopped, the proper volume (= 0.01 m^3/sludge age) of the mixed liquor was drawn from the tank to provide activated sludge of the desired sludge age (5-40 days). After the sludge in the tank was settled calmly for one hour, the supernatant was drawn until the remaining

Table 1. Composition of synthetic wastewater

Component	Percentage [wt%]
Glucose	42.6
peptone	42.6
$Na_2HPO_4 \cdot 12H_2O$	7.5
NaCl	3.1
$CaCl_2 \cdot 2H_2O$	1.8
KCl	1.4
$MgSO_4 \cdot 7H_2O$	1.0

BOD : N : P = 100 : 8.2 : 1.5

Table 2. Results of acclimation of activated sludge

Sludge age [d]	5	7.5	10	15	20	30	40
Glucose supplied [$g \cdot d^{-1}$]	8	6	4.3	3	2.7	1.9	1.85
peptone supplied [$g \cdot d^{-1}$]	8	6	4.3	3	2.7	1.9	1.85
F/M ratio [$g\text{-BOD} \cdot g\text{-SS}^{-1} \cdot d^{-1}$]	0.36	0.31	0.18	0.14	0.11	0.10	0.09
Growth yield [$g\text{-SS} \cdot g\text{-substrate}^{-1}$]	0.42	0.38	0.42	0.36	0.32	0.26	0.20
SS [$g \cdot m^{-3}$]	3370	2988	3582	3261	3680	3049	3080
VSS/SS [-]	0.855	0.882	0.859	0.850	0.882	0.891	0.888
pH [-]	8.30	7.09	6.68	6.43	7.19	6.65	6.94
*TOC** [$g \cdot m^{-3}$]	11.7	10.3	5.5	3.3	5.2	2.6	2.4
OUR [$g\text{-}O_2 \cdot m^{-3} \cdot d^{-1}$]	305	266	222	186	187	209	183
SVI [$ml \cdot g\text{-SS}^{-1}$]	42	28.1	17.1	24	24.1	41	40

* *TOC* is the concentration of supernatant.

volume of the sludge reached 0.005 m^3. After that, 0.005 m^3 of synthetic wastewater was fed into the tank and aeration was started again. *MLSS* was measured every day and the quantity of substrate in the synthetic wastewater was controlled according to the difference between the measured *MLSS* and 3000 $g \cdot m^{-3}$, which was selected as the concentration of activated sludge that would maintain aerobic and suspended conditions in the tank. This operation was continued for about two months, and then the sludge in the tank reached steady state and the measured *MLSS* was kept at 3000 $g \cdot m^{-3}$ at a constant feed rate of substrate for more than 10 days. And the acclimation of activated sludge was achieved.

1.3 Batch aerobic digestion

The experiments in batch aerobic digestion were performed under an air-flow rate of 0.003 $m^3 \cdot min^{-1}$, using activated sludge acclimated at various sludge ages. The dissolved oxygen concentration (*DO*) in the tank was always maintained above 4.0 $g \cdot m^{-3}$. Before sampling the sludge from the tank, the sludge solids adhering to the tank wall were scraped away and returned into the sludge in the tank. At the same time, tap water was poured into the tank until the volume of the entire sludge reached just 0.01 m^3 to compensate for evaporated water. After that, pH, *DO*, total organic carbon concentration (*TOC*), *SS*, *VSS*, sludge volume index (*SVI*) and *OUR* were measured.

2. Results of Acclimation of Activated Sludge

The results of acclimation of activated sludge by batch activated-sludge process are shown in **Table 2**. The quantity of substrate per day, *F/M* ratio and growth yield, which is the ratio of the mass of cells formed to that of substrate consumed, tend to decrease as sludge age increases. The decrease in growth yield may be due to the rise in the rate of substrate consumed for life maintenance of activated sludge cells with increasing sludge age. *VSS/SS* values are constant between 0.85 and 0.90 regardless of sludge age. pH, *TOC* and *OUR* of the acclimated sludge fall as sludge age increases. The sludge volume index (*SVI*), which represents the settleability of activated sludge, is less than 50 $ml \cdot g^{-1}$ for all sludge ages, and so their settleability is excellent. *SVI* for a sludge age of 10 days is lowest.

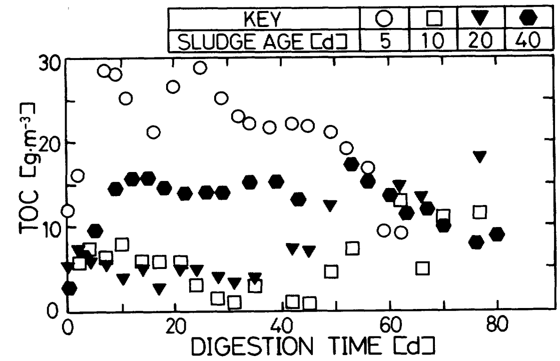

Fig. 1 Change in total organic carbon concentration (*TOC*) during batch aerobic digestion

3. Results and Discussion of Batch Aerobic Digestion

3.1 *TOC*

If the activated sludge in the digestion tank is allowed to be aerated without substrate, the organic matter in the cell is released into liquid by decomposition of some microorganisms, and is preyed upon by other microorganisms. The value of *TOC* in the digestion tank is dependent on relative rates of release and prey of the organic matter.

Figure 1 shows the change of *TOC* with digestion time. *TOC* for a sludge age of 5 days increases rapidly at the start of digestion and then decreases slowly. *TOC* for sludge age of 10 and 20 days decreases slightly until the 40 th day of digestion and then increases. *TOC* for a sludge age of 40 days increases until the tenth day, after which it becomes constant, and then decreases slowly after the 60 th day. Thus *TOC* for intermediate sludge age is lowest throughout digestion time.

3.2 *VSS/SS*

Figure 2 shows the change of the ratio of volatile suspended solid (*VSS*) to suspended solid (*SS*) with digestion time. *VSS/SS* for every sludge age is constant at about 0.9 during digestion time. This means that fixed suspended solid (*FSS* = *SS* – *VSS*) is decomposed at the same rate as *VSS* during digestion. This result agrees with the reports of Randall *et al.*[8], Reece *et al.*[9] and Judkins *et al.*[3]. On the other hand, *VSS/SS* for excess

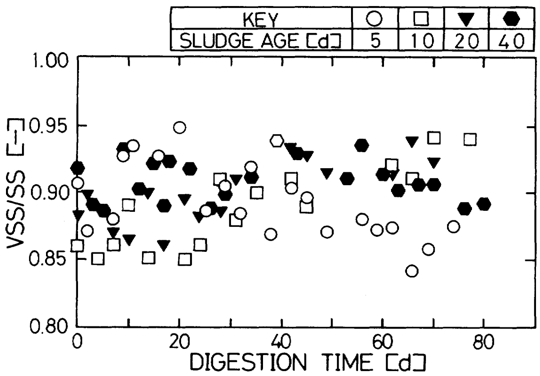

Fig. 2 Change in *VSS/SS* during batch aerobic digestion

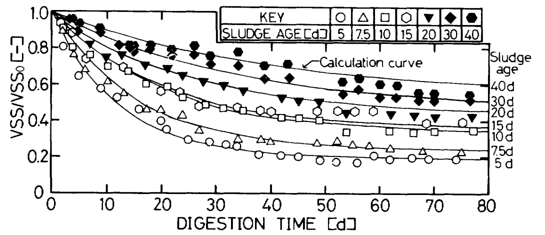

Fig. 3 Change in VSS/VSS_0 during batch aerobic digestion

activated sludge collected from the municipal wastewater treatment plant in Matsuyama changed from 0.7 to 0.84[2], depending on the season when the sludge was collected. Moreover, *VSS/SS* decreased gradually with the progress of aerobic digestion of the sludge[2]. This means that there is inorganic matter other than microorganisms in the excess activated sludge from the municipal wastewater treatment plant.

3.3 Decomposition of activated sludge solids

Figure 3 shows the observed values of VSS/VSS_O during digestion (VSS_O is initial *VSS*). VSS/VSS_O decreases with the progress of digestion. This means that microorganisms in activated sludge are decomposed with digestion time. VSS/VSS_O rises as sludge age increases, and the slope in Fig. 3 is steepest at the beginning of digestion, then becoming gradually more gentle. The decomposition rate slows as sludge age increases.

At every sludge age, VSS/VSS_O becomes constant after 40-70 days' digestion and the digestion becomes complete. This period (40-70 days) is longer than that (20-30 days[2]) for the digestion of activated sludge produced at a municipal wastewater treatment plant. When the activated sludge acclimated to synthetic wastewater is digested under aerobic condition, part of the *VSS* (VSS_N) cannot be decomposed and remains at the end of digestion.

The ratio of maximum *VSS* reduction ($VSS_O - VSS_N$) to VSS_O is shown in **Fig. 4**, and decreases from 0.82 to 0.45 as sludge age increases. The data of Reece *et al.*[9] and Krishnamoorthy *et al.*[4], plotted in Fig. 4, are smaller than the data in this work. This reason seems to be that the digestion did not finish perfectly in their works because their digestion period was only 20 days. On the other hand, $(VSS_O - VSS_N)/VSS_O$ of excess activated sludge produced at the municipal wastewater plant in Matsuyama was in the range of 0.50-0.70[2]

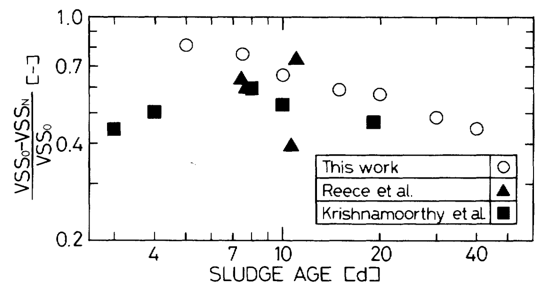

Fig. 4 Relationship between the ratio of maximum *VSS* reduction to initial *VSS* and sludge age

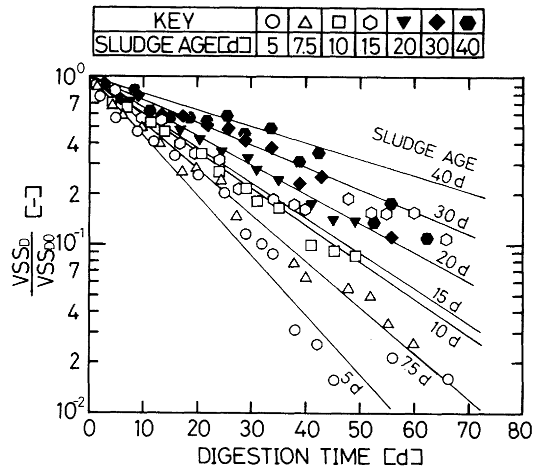

Fig. 5 Correlation of biodegradable *VSS* with digestion time based on Eq. (2)

3.4 Rate constant of decomposition

As mentioned above, after the activated sludge is decomposed for a long time by aerobic digestion, VSS_N remains. Biodegradable *VSS*, $(VSS - VSS_N) = VSS_D$, is considered to correspond to the net quantity of microorganisms.

Adams *et al.*[1] proposed Eq. (1) where the reduction rate of *VSS* was proportional to VSS_D.

$$\frac{-d\,(VSS_D)}{dt} = k \cdot VSS_D \qquad (1)$$

It was ascertained that this equation could be applied to excess activated sludge produced at the municipal wastewater treatment plant[2]. Equation (1) is integrated as follows.

$$\frac{VSS_D}{VSS_{D0}} = e^{-kt} \qquad (2)$$

The observed values of VSS_D/VSS_{DO} for the sludges acclimated to the synthetic wastewater of glucose and peptone at various sludge ages are plotted in **Fig. 5**, based on Eq. (2). Although the observed values are scattered, the plots for each sludge age are linear. The rate constant of decomposition (k) for each sludge age is decided from the slopes of these lines in Fig. 5, and the values of k are plotted against sludge age in **Fig. 6**. The

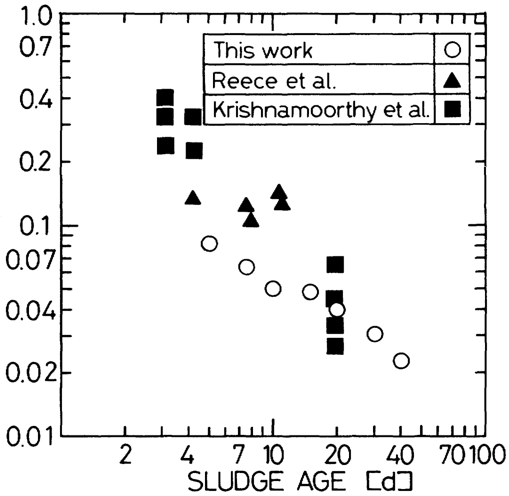

Fig. 6 Relationship between rate constant of decomposition and sludge age

rate constant decreases greatly from 0.08 to 0.02 d^{-1} as sludge age increases. The data of Krishnamoorthy *et al.*[4] and Reece *et al.*[9] are plotted in Fig. 6. *k* of Krishnamoorthy *et al.* decreases as in this work as sludge age increases, but *k* of Reece *et al.* is constant regardless of sludge age.

On the other hand, the authors[2] have reported that the average value of *k* of the excess activated sludge produced at the municipal wastewater treatment plant was 0.11 d^{-1}, which is larger than *k* of activated sludge acclimated to the synthetic wastewater of glucose and peptone. This is explained as follows. In microscopic observations, the number of kinds of microorganism in the excess activated sludge is more than that in the sludge acclimated to the synthetic wastewater of glucose and peptone in this study, because various organic matters are contained in municipal wastewater. Therefore it is conjectured that the aerobic digestion of the excess activated sludge progresses quickly.

Equation (2) is rewritten as follows.

$$\frac{VSS}{VSS_0} = \frac{VSS_N}{VSS_0} + \left\{1 - \frac{VSS_N}{VSS_0}\right\} e^{-kt} \tag{3}$$

The values of VSS/VSS_O calculated by substituting k, VSS_O and VSS_N into Eq. (3) are shown by solid lines in Fig. 3. They agree with the observed values.

3.5 Oxygen uptake rate (*OUR*)

Since the composition of activated sludge cells is generally represented as $C_5H_7NO_2$, it is considered that the reaction of aerobic digestion progresses as follows.

$$\underset{(1)}{C_5H_7NO_2} + \underset{(1.42)}{5O_2} \rightarrow 5CO_2 + 2H_2O + NH_3 \tag{4}$$

When the ammonia produced is oxidized to nitrate, Eq. (4) changes to Eq. (5).

$$\underset{(1)}{C_5H_7NO_2} + \underset{(1.98)}{7O_2} \rightarrow 5CO_2 + 3H_2O + NO_3^- + H^+ \tag{5}$$

$C_5H_7NO_2$ in the reaction equations (4) and (5) corresponds to the degradable biomass, namely, biodegradable *VSS*, VSS_D. When 1 g of the activated sludge cell ($C_5H_7NO_2$) is oxidized, 1.42 g and 1.98 g of oxygen are consumed in Eqs. (4) and (5), respectively. Therefore, the relationship between the decomposition rate of activated sludge, $-d\,(VSS_D)/dt$, and *OUR* for decomposition of activated sludge is expressed as follows:

$$\frac{OUR}{(1.42 \text{ or } 1.98)} = \frac{-d\,(VSS_D)}{dt} = k \cdot VSS_D \tag{6}$$

where 1.42 is used when the nitrogen in the sludge changes to ammonia and 1.98 when the ammonia produced is further oxidized to nitrate. According to the analysis of various forms of nitrogen, about 30 % of the nitrogen which was released into the liquid changed to nitrate for low sludge ages, the percentage of the nitrogen which was oxidized to nitrate increased as sludge age increased, and all of the nitrogen changed to nitrate for sludge ages above 30 days.

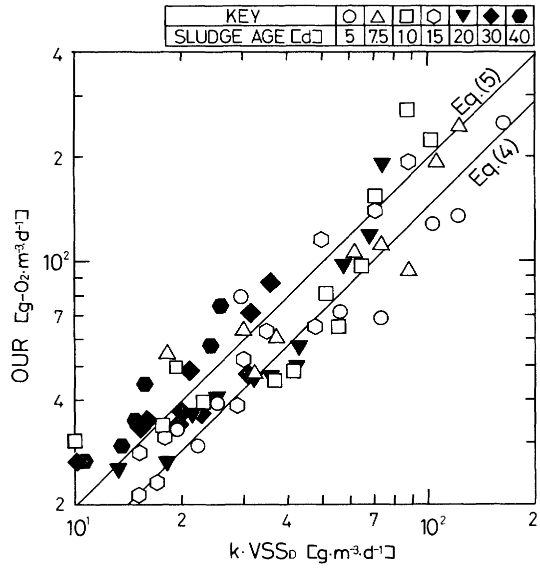

Fig. 7 Relationship between oxygen uptake rate (*OUR*) and decomposition rate of sludge

OUR is plotted against $k{\cdot}VSS_D$ in **Fig. 7** based on Eq. (6). The data are scattered but agree roughly with Eqs. (4) and (5). Therefore, it is confirmed that the aerobic digestion of activated sludge progresses according to Eqs. (4) and (5).

3.6 Sludge volume index (*SVI*)

Figure 8 shows the change of *SVI*, which represents the settleability of sludge, with digestion time. At the beginning of aerobic digestion, *SVI* is smallest for sludge age of 10 days, and increases in the order of 20 days, 7.5 days and 40 days. *SVI* at every sludge age increases after the start of digestion, and the slope of *SVI* decreases as sludge age increases. *SVI*, however, is less than 75 ml·g^{-1} even when the aerobic digestion is completed, and generally speaking, the sludge has good settleability during aerobic digestion.

Figure 9 shows the change in SV_{30}, which is the percentage of the settled sludge volume after 30 minutes

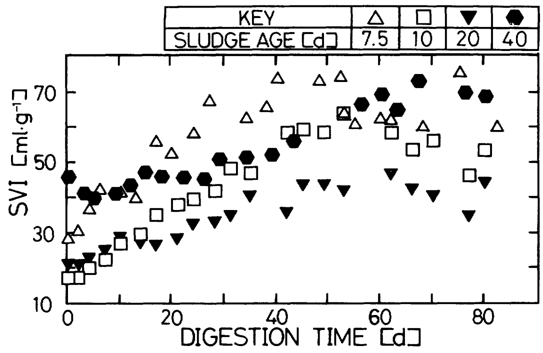

Fig. 8 Change in sludge volume index (*SVI*) during batch aerobic digestion

sedimentation and is important in practical solid-liquid separation. SV_{30} for every sludge age decreases by aerobic digestion.

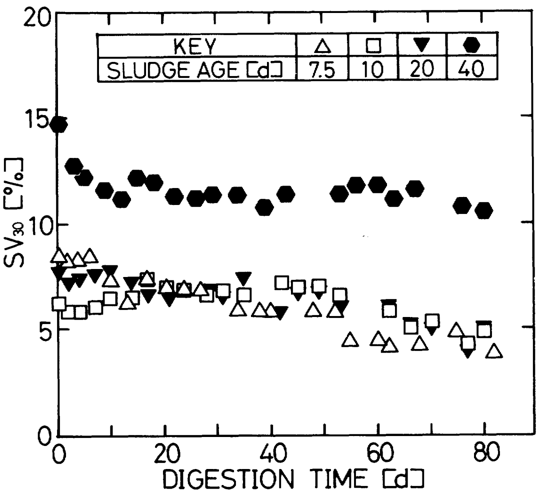

Fig. 9 Change in SV_{30} during batch aerobic digestion

Conclusion

Experiments in batch aerobic digestion were made, using activated sludge acclimated to a synthetic wastewater of glucose and peptone at various sludge ages, and the following results were obtained.

(1) The value of *VSS/SS* of activated sludge remains constant throughout aerobic digestion.

(2) As sludge age decreases, *VSS* decreases quickly at the beginning of digestion, and the ratio of maximum *VSS* reduction to initial *VSS* increases.

(3) The decomposition rate of sludge is proportional to the biodegradable *VSS*, and its proportional coefficient (rate constant of decomposition) decreases as sludge age increases.

(4) The oxygen uptake rate (*OUR*) of sludge is related to the decomposition rate of sludge by using a reaction model where the composition of activated sludge cell is $C_5H_7NO_2$.

(5) *SVI* of sludge increases during aerobic digestion, but the final *SVI* is within the range of good settleability. SV_{30} of all sludges decreases with aerobic digestion.

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Nomenclature

DO	=	dissolved oxygen concentration	[g·m^{-3}]
FSS	=	fixed suspended-solid concentration	
	=	*SS* – *VSS*	[g·m^{-3}]
k	=	rate constant of decomposition	[d^{-1}]
OUR	=	oxygen uptake rate	[g-O_2·m^{-3}d^{-1}]
SS	=	suspended-solid concentration	[g·m^{-3}]
SV_{30}	=	percentage of settled sludge volume after 30 minutes' sedimentation	[%]
SVI	=	sludge volume index	[ml·g^{-1}]
t	=	digestion time	[d]
TOC	=	total organic carbon concentration	[g·m^{-3}]
VSS	=	volatile suspended-solid concentration	[g·m^{-3}]
VSS_D	=	biodegradable $VSS = VSS - VSS_N$	[g·m^{-3}]
VSS_{DO}	=	initial biodegradable $VSS = VSS_O - VSS_N$	[g·m^{-3}]
VSS_N	=	non-biodegradable *VSS*	[g·m^{-3}]
VSS_O	=	initial *VSS*	[g·m^{-3}]

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