FS-BIO-009

TECHNOLOGY FACT SHEETS
FOR EFFLUENT TREATMENT PLANTS
ON TEXTILE INDUSTRY

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR (UASB)

SERIES: SECONDARY TREATMENTS

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UASB REACTOR (FS-BIO-009)

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1. INTRODUCTION

The upflow anaerobic sludge bed reactor (UASB) was developed in the Netherlands in the early seventies (Lettinga *et al.*, 1980). Most of these full scale reactors are used for treating agro-industrial wastewater, but its application for wastewater from chemical industries and sewage is increasing. Figure 1 shows a schematic representation of a UASB reactor. Examples of UASB reactors of the major anaerobic system manufacturers are shown in Figure 1.

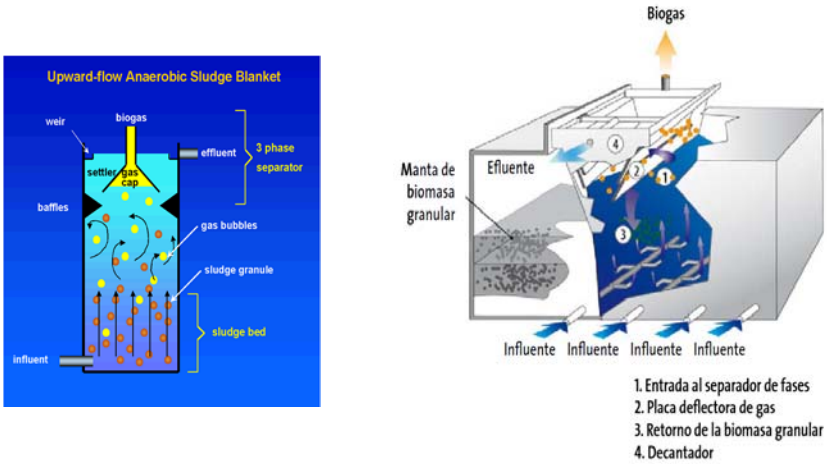

Figure 1.- UASB reactors of the major anaerobic system manufacturers: (A) Paques, B.V. and (B) Biothane B.V.

The anaerobic process through UASB reactors presents several advantages in relation to conventional aerobic processes. In these situations, a system can have the following main characteristics:

- compact system, with low land requirements
- low construction and operating costs
- low sludge production
- low energy consumption (just for the influent pumping station, when necessary)
- satisfactory COD and BOD removal efficiencies, amounting to 65 to 75%
- high concentration and good dewatering characteristics of the excess sludge

Although the UASB reactors present many advantages, there are still some disadvantages or limitations:

- long time interval necessary for the start-up of the system
- need for a post-treatment stage

The start-up of the system can be slow (4 to 6 months), but only in situations in which seed sludge is not used. In the past few years, with the use of well-based start-up methodologies and the establishment of appropriate operational routines, significant progresses were achieved towards reducing the start-up period of the systems and minimizing the operational problems in this phase. In situations in which small amounts of seed were used (less than 4% of the reactor volume), the start-up period was reduced to 2 or 3 weeks. In any case, the quality of the biomass to be developed in the system will depend on an appropriate operational routine and, consequently, on the stability and efficiency of the treatment process.
The design of UASB reactors is very simple and does not require the installation of any sophisticated equipment or packaging medium for biomass retention.

2. PROCESS PRINCIPLES

The reactor is initially inoculated with sufficient quantities of anaerobic sludge, and its low-rate feeding is started soon afterwards, in the upflow mode. This initial period is referred to as *start-up* of the system, being the most important phase of the operation of the reactor. The feeding rate of the reactor should be increased progressively, according to the success of the system response. After some months of operation, a highly concentrated *sludge bed* (40 to 100 g TS/L) is developed close to the bottom of the reactor. The sludge is very dense and has excellent settling characteristics. The development of sludge granules (diameters from 1 to 5 mm) may occur, depending on the nature of the seeding sludge, on the characteristics of the wastewater and on the operational conditions of the reactor.

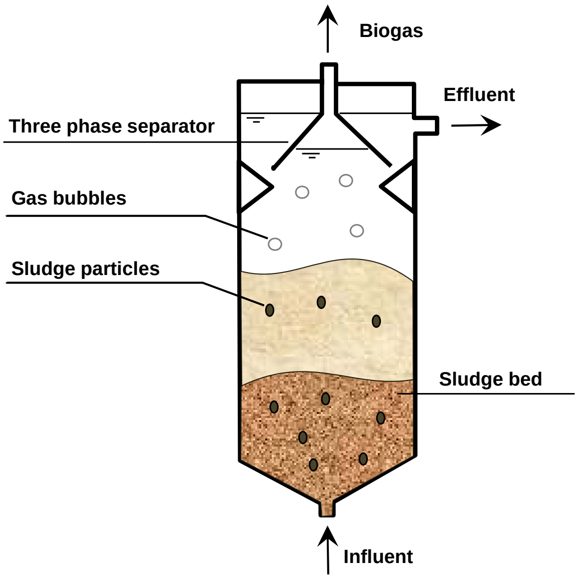

Figure 2.- Schematic drawing of a UASB reactor.

An area of more dispersed bacterial growth, name *sludge blanket*, is developed above the sludge bed, with solids presenting lower concentration and settling velocities. The concentration of sludge in this area usually ranges between 1 and 3%. The system is self-mixed by the upflow movement of biogas bubbles and by the liquid flow through the reactor. During the start-up of the system, when the biogas production is usually low, some form of additional mixing, such as by the recirculation of gas or effluent, may become necessary. Substrate is removed throughout the bed and sludge blanket, although removal is more pronounced at the sludge bed.

The sludge is carried by the upflow movement of the gas bubbles, and the installation of a *three-phase separator* (gases, solids and liquids) in the upper part of the reactor is necessary, to allow sludge retention and return. There is a sedimentation chamber around and above the three-phase separator, where the heaviest sludge is removed from the liquid mass and returned to the digestion compartment, while the lighest particles leave the system together with the final effluent (see Figure 2).

The installation of the gas, solids and liquid separator guarantees the return of the sludge and the high retention capacity of large amounts of high-activity biomass, with no need for any type of packing medium. As a result, UASB reactors present high solids residence time (sludge age), much higher than the hydraulic retention times, which is a characteristic of the high rate anaerobic systems. Sludge ages in UASB reactors usually exceed 30 days, leading to stabilization of the excess sludge removed from the system.

3. DESIGN CRITERIA

One of the most important aspects of the anaerobic process applying UASB reactors is its ability to develop and maintain high-activity sludge of excellent settling characteristics. For this purpose, several measures should be taken in relation to the design and operation of the system.
The main design criteria for reactors treating organic wastes are presented below. Specific criteria should be adopted for certain types of industrial effluents in view of the concentration of the influent wastewater, the presence of toxic substances, the amount of inert and biodegradable solids and other aspects.

3.1. Volumetric hydraulic load and hydraulic retention time

The volumetric hydraulic load is the volume of wastewater applied daily to the reactor, per unit of volume. The hydraulic retention time is the reciprocal of the volumetric hydraulic load,

$$VHL = \frac{Q}{V}$$

where:

VHL = volumetric hydraulic load ($m^3/m^3.d$)
Q = flowrate (m^3/d)
V = total volume of the reactor (m^3)

$$t = \frac{1}{VHL}$$

where:
t = hydraulic retention time (d)

$$t = \frac{V}{Q}$$

Experimental studies demonstrated that the volumetric hydraulic load should not exceed the value of 5.0 m^3/m^3.d, which is equivalent to a minimum hydraulic retention time of 4.8 hours.
The design of reactors with higher hydraulic loading values (or lower hydraulic retention times) can be detrimental to the operation of the system in relation to the following main aspects:

- excessive loss of biomass, that is washed out with the effluent, due to the resulting high upflow velocities in the digestion and settling compartments
- reduced solids retention time (sludge age), and a consequently decreased degree of stabilization of the solids
- possibility of failure in the system, once the biomass residence time in the system becomes shorter than its growth rate

Thus, knowing the influent flowrate and assuming a certain design hydraulic retention time, the volumen of the reactor can be calculated as follows:

$$V = Q.t$$

3.2. Organic loading rate

The volumetric organic load is defined as the amount of organic matter applied daily to the reactor, per volume unit:

$$L_V = \frac{Q \times S_0}{V}$$

where:
L_v = volumetric organic loading rate (kg COD/m^3.d)
Q = flowrate (m^3/d)
S_o = influent substrate concentration (kg COD/m^3)
V = total volume of the reactor (m^3)

Hence, knowing the flowrate and the concentration of the influent wastewater, and assuming a certain design volumetric organic load (L_V), the volume of the reactor can be calculated as follows:

$$V = \frac{Q \times S_0}{L_V}$$

3.3. Biological loading rate (sludge loading rate)

The biological or sludge loading rate refers to the amount of organic matter applied daily to the reactor, per unit of biomass present:

$$L_S = \frac{Q \times S_0}{M}$$

where:

L_S = biological or sludge loading rate (kg COD/kg VS.d)
Q = average influent flowrate (m^3/d)
S_o = influent substrate concentration (kg COD/m^3)
M = mass of microorganisms present in the reactor (kg VS/m^3)

It is recommended that the initial biological loading rate during the start-up of an anaerobic reactor should range from 0.05 to 0.15 kg COD/kg VS.d, depending on the type of effluent being treated. These loads should be gradually increased, according to the efficiency of the system.
The maximum biological loading rate depends on the methanogenic activity of the sludge.

3.4. Upflow velocity and reactor height

The upflow velocity of the liquid is calculated from the relation between the influent flowrate and the cross section of the reactor, as follows:

$$v = \frac{Q}{A}$$

where:

v = upflow velocity (m/hour)
Q = flow (m^3/hour)
A = area of the cross section of the reactor, in this case the surface area (m^2) or alternatively, from the ratio between the height and the HRT:

$$v = \frac{Q \times H}{V} = \frac{H}{t}$$

where:
H = height of the reactor (m)
The maximum upflow velocity in the reactor depends on the type of sludge present and on the loads applied. For reactors operating with flocculent sludge and organic loading rates ranging from 5.0 to 6.0 kg COD/m^3.d, the average upflow velocities should amount to 0.5 to 0.7 m/hour, with temporary peaks up to 1.5 to 2.0 m/hour being tolerated for 2 to 4 hours. For reactors operating with granular sludge, the upflow velocities can be significantly higher, amounting to 10 m/hour.

3.5. UASB reactor efficiencies

The COD and BOD removal efficiencies are substantially affected by the hydraulic retention time of the system, ranging from 40 to 70% for COD removal and from 45 to 90% removal. The COD and BOD concentrations in the final effluent can be estimated as follows:

$$C_{effl} = S_0 - \frac{ExS_0}{100}$$

where:

C_{effl} = effluent total COD or BOD concentration (mg/L)
S_0 = influent total COD or BOD concentration (mg/L)
Ex = COD or BOD removal efficiency (%)

The concentration of suspended solids in the final effluent from UASB reactors depends on a series of factors, including:

- the concentration and the settling characteristics of the sludge present in the reactor
- the sludge wastage frequency and the height of the sludge bed and blanket in the reactor
- the velocities through the apertures to the sedimentation compartment
- the presence of scum baffles in the sedimentation compartment
- the efficiency of the gas, solids and liquid separator
- the loading rates and the hydraulic retention times in the digestion and sedimentation compartments

It can be estimated the concentration of solids using the following equation:

$$SS = 102xt^{-0.24}$$

where:

SS = effluent suspended solids concentration (mg/L)
t = hydraulic retention time (hour)
102 = empirical constant
0.24 empirical constant

3.6. Influent distribution system

To obtain a good performance from UASB reactors, it is essential that the influent substrate is evenly distributed in the lower part of the reactors, to ensure a close contact between the biomass and the substrate. For that purpose and so that the maximum advantage is taken from the biomass present in the reactors, it is essential that preferential pathways (hydraulic short circuits) are avoided through the sludge bed as much as possible. That is particularly important when the process is used in the treatment of low-concentration and/or low-temperature wastewater, once in those situations the biogas production can be very low to allow appropriate mixing within the digestion compartment. Other potential risks for the occurrence of short circuits are:

- short height of the sludge bed
- small number of influent distributors
- occurrence of very concentrated sludge with very high settling velocities

Distribution compartments
An even distribution of the influent is very important in UASB reactors, to ensure a better mixing regime and a reduced occurrence of dead zones on the sludge bed. Thus, the equal division of the influent flow to the several distributing tubes should be done by small compartments (boxes) fed by weirs. Each box feeds a single distribution tube extending to the bottom of the reactor. These compartments, installed in the upper part of the reactor, ensure the uniform distribution of sewage throughout the bottom of the tank, besides enabling the visualization of occasional increments in the head loss, in each distributor. Once an increased head loss is detected in a distributor, the tube can be easily unblocked by using appropriate rods. Examples of influent distribution structures in UASB reactors are presented in Figure 3.

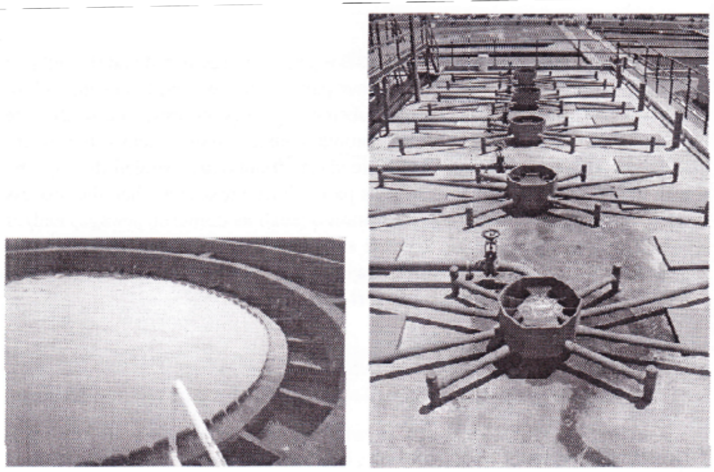

Figure 3.- Influent distribution structures in: (a) a circular reactor (left side) and (b) a rectangular reactor (right side).

Distribution tubes
Wastewater is routed from the distribution compartments to the bottom of the reactor through distribution tubes. The main requirements for these tubes are as follows:

- the diameter should be large enough to enable a descending wastewater velocity lower than 0.2 m/s, so that the air bubbles occasionally dragged to inside the tube can go back upwards (opposite the direction of the wastewater). The introduction of air bubbles in the reactor should be avoided for the following reasons: (i) they may cause the aeration of the anaerobic sludge, harming methanogenesis; and (ii) they may cause a pontentially explosive mixture with the biogas accumulated close to the three-phase separator.
- the diameter should be small enough to allow a higher flow velocity at its lower end (bottom of the reactor), which favours good mixing and greater contact with the sludge bed. Besides that, a higher velocity helps avoid the deposition of inert solids close to the discharge point of the tube. The requirement is somehow incompatible with the previous ones, once a reduced diameter of the tube hinders the upward movement and the release of air bubbles, besides increasing their possibilities of

blocking. A solution that can be adopted is the reduction of the tubing section just close to its lower end, thus keeping an area large enough to avoid blockage. There are two options, to make nozzles or to make apertures (windows) on the side ends of the distribution tubes. These devices are illustrated in Figure 4.

The number of distribution tubes is determined according to the area of the cross section of the reactor and the influence area adopted for each distributor, as follows:

$$N_d = \frac{A}{A_d}$$

where:
N_d = number of distribution tubes
A = area of the cross section of the reactor (m^2)
A_d = influence area of each distributor (m^2)

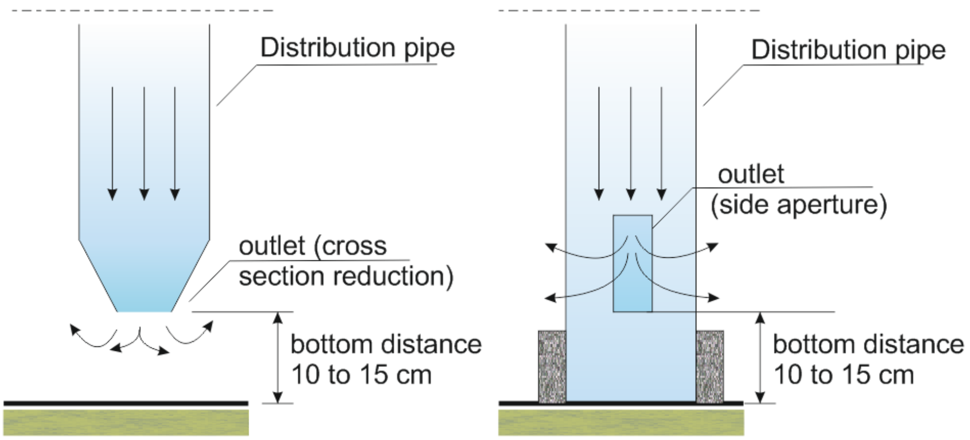

Figure 4.- Examples of distribution tube ends.

3.7. Three-phase separator

The gas, solids and liquid separator (three-phase separator) is an essential device that needs to be installed in the upper part of the reactor. The main objective of this separator is to maintain the anaerobic sludge inside the reactor, allowing the system to be operated with high solids retention time (high sludge age). This is initially achieved by separating the gas contained in the liquid mixture, enabling as a consequence, the maintenance of optimal settling conditions in the settling compartment. Once the gas is effectively removed, the sludge can be separated from the liquid in the settling compartment, and then returned to the digestion compartment.

Separation of gases
The design of the gas, solids and liquid separating device (three-phase separator) depends on the characteristics of the wastewater, the type of sludge present in the reactor, the organic load applied, the expected biogas production and the dimensions of the reactor. Aiming at avoiding sludge flotation and the consequent biomass loss from the reactor, the dimensions of the separator should be such that they allow the formation of a liquid-gas interface inside the gas collector sufficient to allow the easy release of the gas entrapped in the sludge. The biogas release rate should be high enough to overcome a possible scum layer, but low enough to quickly release the gas from the sludge, not allowing the sludge to be dragged and consequently accumulated in the gas exit piping. It is recommended a minimum release rates of 1.0 m^3 gas/m^2.hour and maximum rates from 3.0 to 5.0 m^3 gas/m^2.hour. The biogas release rate is established by the following equation:

$$K_g = \frac{Q_g}{A_i}$$

where:
K_g = biogas release rate (m^3 gas/m^2.hour)
Q_g = expected biogas production (m^3/hour)
A_i = area of the liquid-gas interface (m^2)

Evaluation of the biogas production

The biogas production can be evaluated from the estimated influent COD load to the reactor that is converted into methane gas. The portion of COD converted into methane gas can be determined as follows:

$$COD_{CH_4} = Q \times (S_0 - S) - Y_{obs} \times Q \times S_0$$

where:
COD_{CH_4} = COD load converted into methane (kg COD_{CH4}/d)
Q = average influent flow (m^3/d)
S_0 = influent COD concentration (kg COD/m^3)
S = effluent COD concentration (kg COD/m^3)

Y_{obs} = coefficient of solids production in the system, in terms of COD (0.11 to 0.23 kg COD_{sludge}/kg COD_{appl})
The methane mass (kg COD_{CH4}/d) can be converted into volumetric production (m^3 CH_4/d) by using the following equations:

$$Q_{CH_4} = \frac{COD_{CH_4}}{K(t)}$$

where:
Q_{CH_4} = volumetric methane production (m^3/d)
$K(t)$ = correction factor for the operational temperature of the reactor (kg COD/m3)

$$K(t) = \frac{P \times K_{COD}}{R\ x\ (273 + T)}$$

where:
P = atmospheric pressure (1 atm)
K_{COD} = COD corresponding to one mole of CH_4 (64 g COD/mol)
R = gas constant (0.08206 atm.L/mole.K)
T = operational temperature of the reactor (ºC)

Once the theoretical methane production is obtained, the total biogas production can be estimated from the expected methane content.

Separation of solids
After the separation of the gases, the liquid and the solid particles that leave the sludge blanket have access to the sedimentation compartment. Ideal conditions for sedimentation of the solid particles occur in this compartment, due to the low upflow velocities and the absence of gas bubbles. The return of the sludge retained in the sedimentation compartment to the digestion compartment does not require any special measure, as long as the following basic guidelines are met:

- installation of deflectors, located immediately below the apertures to the sedimentation compartment, to enable the separation of the biogas, and allow only liquid and solids to enter the sedimentation compartment
- construction of the sedimentation compartment walls with slopes always higher than 45º adoption of depths of the sedimentation compartment ranging from 1.5 to 2.0 m

3.8. Effluent collection

The effluent is collected from the reactor in its upper part, within the sedimentation compartment. The devices usually used for the collection of effluent are plates with V-notch weirs and submerged perforated tubes.

3.9. Gas system

The biogas produced in the reactor should be collected, measured and, later, either used or burnt. The biogas removal system from the liquid-gas interface inside the reactor consists of:

- collecting piping
- sealed compartment with hydraulic seal and biogas purge
- biogas meter
- biogas reservoir

When the biogas is not used, the gas reservoir is replaced by a security valve and a gas burner, preferably located at a safe distance from the reactor, as illustrated in Figure 5.

3.9. Sludge sampling and discharge system

The design of the reactor should comprise a group of valves and piping that allows both sampling and discharge of the solids present in the reactor.

The sampling system usually consists of a series of valves installed along the height of the digestion compartment, to enable the monitoring of the growth and quality of the biomass in the reactor. One of the most important operational routines in the treatment system is the evaluation of the amount and activity of the biomass present in the reactor, by means of two basic mechanisms:

- determination of the solids profile and mass of microorganisms present in the system
- evaluation of the specific methanogenic activity of the biomass

The sludge discharge system is intended for the periodical removal of the excess sludge produced in the reactor, also allowing the removal of inert material that may accumulate at the bottom of the reactor. At least two sludge withdrawal points should be planned, one close to the bottom of the reactor and another approximately 1.0 to 1.5 m above the bottom to allow a higher operational flexibility.

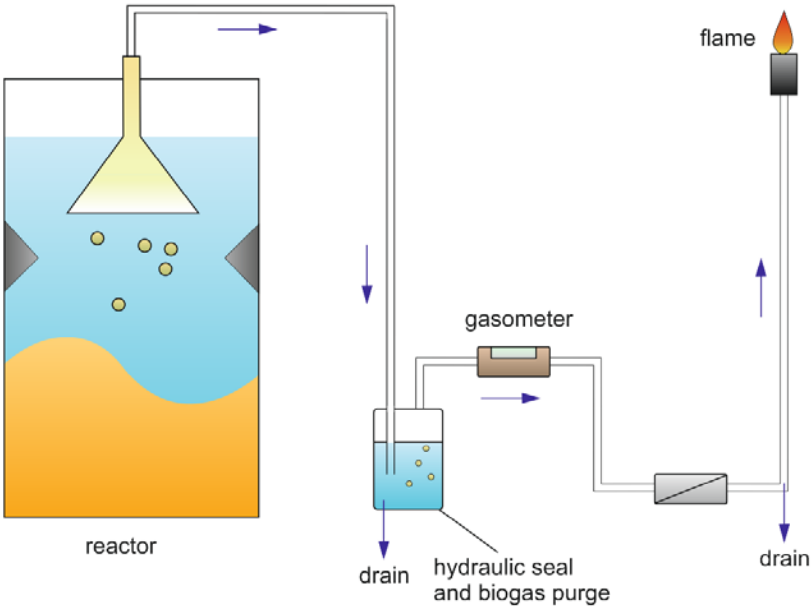

Figure 5.- Diagram of a gas system in UASB reactors with a hydric seal.

4. SLUDGE PRODUCTION

The solids accumulation rate depends essentially on the type of effluent being treated and is greater when the wastewater has a higher concentration of suspended solids, especially non-biodegradable solids.
In the case of treating soluble effluents, the production of excess sludge is very low and generally few problems are found in the handling, storage and disposal of the sludge.
The estimation of the mass production of sludge in UASB reactors can be done through the following equation:

$$P_S = Y \times COD_{app}$$

where:
P_S = production of solids in the system (kg TSS/d)
Y = yield of solids production coefficient (kg TSS/ kg COD_{app})
COD_{app} = COD load applied to the system (kg COD/d)

The values of Y reported for the anaerobic treatment of domestic sewage are in the order of 0.10 to 0.20 kg TSS/kg COD_{app}.

The estimation of the volumetric sludge production can be done by the following equation:

$$V_S = \frac{P_S}{\gamma \times (\frac{C_S}{100})}$$

where:
V_S = volumetric sludge production (m^3/d)
γ = sludge density
C_S = solids concentration in the sludge (%)

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