

Biomass accumulation patterns for removing volatile organic compounds in rotating drum biofilters

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Abstract A rotating drum biofilter (RDB) with multi-layered foam media was developed for the improvement of current biofiltration technology. The biofilter was used to investigate the effects of organic loadings and influent volatile organic compound (VOC) concentrations on VOC removal efficiency and biomass accumulation. These effects were evaluated using diethyl ether and toluene separately as model VOCs at an empty bed contact time (EBCT) of 30 s. When the toluene loading increased from 2.0 to 4.0 and 8.0 kgCOD m⁻³ day⁻¹, toluene removal efficiency of the biofilter decreased from over 99% to 78% and 74%, respectively. The biomass distribution was found to be more even within the medium when removing toluene than when removing diethyl ether. Higher organic loading also resulted in the more even distribution of the biomass. The ratios of biomass accumulation rates in the medium of the outermost, middle and innermost layers ranged from 1:0.11:0.02 when removing diethyl ether at 2.0 kgCOD m⁻³ day⁻¹ to 1:0.69:0.51 when removing toluene at 8.0 kgCOD m⁻³ day⁻¹. Review of these ratios revealed three biomass accumulation patterns: surface pattern, in-depth pattern and shallow pattern. Different patterns represent different removal mechanisms in the biofiltration process. Improved biofilter design and operation should be based on the biomass accumulation pattern.

Keywords Biofiltration; biomass accumulation pattern; diethyl ether; rotating drum biofilters; toluene; volatile organic compounds

Introduction

Biofiltration is becoming an established technology for the control of volatile organic compounds (VOCs) and odor emissions from waste gas streams. A biofilter is a bioreactor that biodegrades VOCs and odors using biofilms attached on support media. The biofilm is primarily composed of bacteria and/or fungi. Nutrients are amended to the biofilter in order to stimulate VOC degradation by the microorganisms.

Existing biofilters are usually classified as conventional biofilters and biotrickling filters (or trickling biofilters) based on the movement of the water phase (Baltzis, 1998; Devinny *et al.*, 1999). The advantages of existing biofiltration technology include the low cost and environmental friendliness when compared to conventional methods such as incineration and carbon adsorption. However, biofiltration technology has not yet reached its full potential. More research and innovative biofilter designs are needed to make biofiltration technology competitive, especially when biofilters are employed for the treatment of waste gas streams with high organic loadings.

A general problem for existing biofilters is the highly uneven distribution of the VOC loading, nutrients, water and biomass in the biofilter medium (Kim, 2001; Yang *et al.*, 2002). Biomass is a critical factor in a biofilter system. It is the biomass that biodegrade the VOCs and odorous compounds. In the biofiltration process, biomass accumulates and decays. Therefore, biomass distribution is an indirect index of where VOC and odor degradation is taking place within the biofilter, and different biomass accumulation patterns are a possible indication of different removal mechanisms. At the same time, excess biomass in

biofilters often results in deterioration in the performance. Alonso *et al.* (1997) investigated the minimum necessary quantity of biomass using dynamic mathematic models.

Biofiltration is usually considered to be a technology most suitable for removing VOCs from waste gas streams that have high flow rates and low concentrations (Leson and Winer, 1992; Hwang and Tang, 1997). Cost-effectively expanding the range of application of biofiltration technology to the treatment of high concentrations of VOCs under high loadings is also a research focus (Smith *et al.*, 1996; Yang *et al.*, 2002).

Uneven distribution of biomass in the biofilter was considered to be one of the major factors responsible for certain operational problems such as clogging and excessive head loss, especially at high VOC concentrations and high VOC loadings. Clogging of the voids in the biofilter and difficulty with uniform distribution of the contaminated air stream, nutrients, and oxygen to the biomass resulted in channel formation and uneven distribution of the air and water streams in the medium (Kim, 2001).

Usually periodic removal of excess biomass is necessary to maintain the performance of trickling biofilters working at high removal efficiency for longer durations, and backwash with water or a nutrient solution weekly has proved to be effective (Smith *et al.*, 1996, 1998; Rihn *et al.*, 1997; Sorial *et al.*, 1997; Zhu *et al.*, 1999). Moe and Irvine (2000) also developed a method for the removal of excessive biomass by squeezing out excess biomass from the foam media in a trickling biofilter. Rupert (1995) reported a biofilter having a horizontal cylindrical vessel that is rotated periodically, e.g. weekly, for several rotations in order to mix the filter materials, break up compacted materials, and collapse fissures. However, fundamental investigations on this kind of biofiltration process and other innovative biofilter developments are still needed.

Owing to the importance of biomass distribution in biofilters, two critical questions consequently exist for innovative biofilter development. One is how to distribute VOC loading and biomass more evenly in the medium so that biofilters can effectively operate for larger periods of time with little maintenance and cost, even at high VOC loadings. The other question concerns the specific location of biomass accumulation in the medium and how to control this excess biomass.

An innovative biofilter, the rotating drum biofilter (RDB), was therefore developed in order to address these questions. In this study, the main objectives are to investigate the effects of different VOC loadings and influent concentrations as well as different VOCs on biomass accumulation among the different layers of the RDB. VOC removal efficiency under different conditions is another important aspect of this research. These investigations are necessary for the elucidation of biofiltration mechanisms and therefore to properly design and operate RDBs.

Materials and methods

Multi-layered rotating drum biofilter

A multi-layered RDB was developed and used in this research. The biofilter consists of a closed stainless steel chamber enclosing a stainless steel drum frame with impermeable end plates at both ends. A schematic diagram of the biofilter system is illustrated in Figure 1. A set of four concentric layers of spongy foam media is mounted on the drum frame. The media of all layers have an axial length of 15.2 cm (6.0 inches), and the pore size is 10 pores per inch (about 4 pores per cm). The outer diameters of the four layer medium are 43.2, 33.0, 22.9 and 12.7 cm, respectively; the corresponding inner diameters are 35.6, 25.4, 15.2 and 5.08 cm; and the medium volume of the four layers are 7.18, 5.33, 3.48 and 1.62 litres, respectively.

The lower portion of the biofilter chamber is filled with a nutrient solution where the media are partially submerged. About 43% of the media is submerged in the liquid phase in the biofilter's chamber. The media are rotated at 1 rpm with continuous submerging and

emerging cycles. The liquid model VOC is injected via syringe pump into the air stream where it is vaporized, and enters the biofilter through a distribution tube. When the waste gas stream enters the biofilter housing, it fills the space between the housing and the media and passes through the media containing the biofilm, nutrients, and water. As contaminants contact the biofilm, they are biodegraded. The purified gas stream exits through the shaft of the drum.

The nutrient-enriched solution is fed with a peristaltic pump and feeding rate control system. With the rotation of the drum, the liquid phase in the biofilter is mixed, and nutrients are delivered to the microorganisms. Some metabolites and biomass are released into the liquid which is discharged by a peristaltic pump.

Materials

Reagent grade diethyl ether ($C_2H_5OC_2H_5$) and toluene (C_7H_8) were chosen as the model VOCs in this research. Biofiltration of diethyl ether and toluene from waste gas streams had been investigated by trickling bed biofilters in this laboratory, and some comparisons were possible when evaluating this biofilter (Smith *et al.*, 1996; Alonso *et al.*, 1997; Zhu *et al.*, 1999).

The nutrient solution for the biofilter consisted of macronutrients (including nitrate and phosphate), micronutrients and vitamins. Sodium bicarbonate was used as a buffer for the nutrient solution, sodium nitrate as the sole nitrogen source, and sodium phosphate monobasic as the sole phosphorus source. VOC concentration is the only rate-limiting factor in this investigation. When VOC loading was doubled, all nutrient feed concentrations were also doubled to keep the feeding mass ratios of VOC to nutrients constant.

Concentrated activated sludge was taken as bacterial seeds. The sludge was collected from a secondary sedimentation tank at the Sycamore Creek Wastewater Treatment Plant, Metropolitan Sewer District of Greater Cincinnati, Cincinnati, Ohio, U.S.A.

Analytical methods

Measurements for the gas phase include headloss, influent and effluent concentrations of diethyl ether, toluene and carbon dioxide. Measurements for the liquid phase include

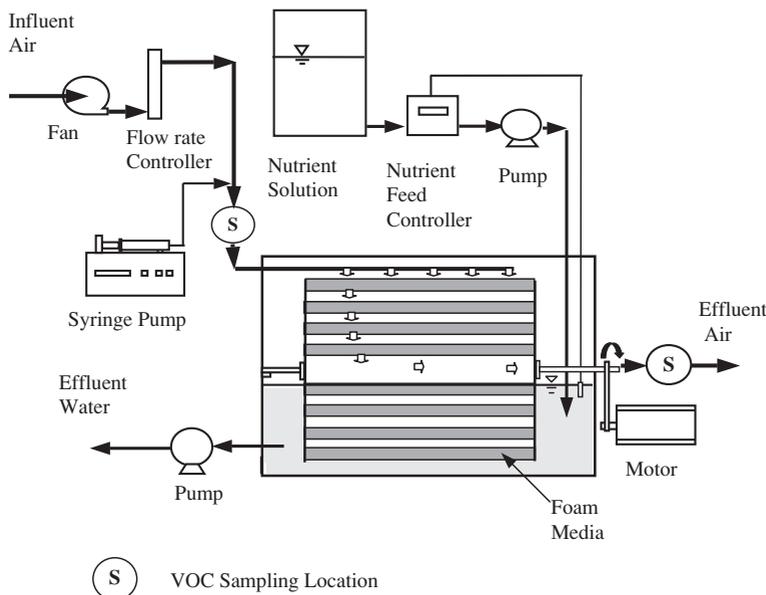


Figure 1 Schematic of the rotating drum biofilter

influent and effluent concentrations of nitrate, dissolved inorganic carbon, dissolved total carbon, volatile suspended solids (VSS), pH and dissolved oxygen. Liquid phase measurements also included effluent concentration of VSS, diethyl ether and toluene and nutrient flow rate. The headloss measurement is used to help monitor the operation of the bioreactor and the accumulation of biomass in the foam media.

Gas samples for VOCs and carbon dioxide analysis were collected with gas tight syringes (Hamilton Co., Reno, Nevada, U.S.A.) through low bleed and high puncture tolerance silicone GC septa (Supelco Co., Bellefonte, Pennsylvania, U.S.A.). Analysis for VOC concentrations was carried out using a gas chromatograph (GC) (HP 5890, Series II, Hewlett-Packard, Palo Alto, California, U.S.A.) equipped with a flame ionization detector (FID) (Hewlett-Packard Co., San Fernando, CA, U.S.A.). Nitrate was analyzed using a diode array spectrophotometer (Model 8452A, Hewlett Packard, Palo Alto, California, U.S.A.). VSS analysis was carried out in accordance with Method 2540 G of Standard Methods (American Public Health Association, 1992). The pH values were measured using an Orion pH meter (Model 720A, Orion Research Co., Boston, Massachusetts, U.S.A.). Dissolved oxygen in the liquid was determined using a DO meter (Corning Co., Corning, New York, U.S.A.). The pressure in the tank was measured with a manometer (Dwyer Instruments, Mich. City, Indiana, U.S.A.).

Results and discussion

Effect of organic loading and influent concentration on removal of toluene

Startup of the biofilter. The rotating drum biofilter was operated during startup at a toluene feed rate of 0.542 mL hr^{-1} and a gas flow rate of 1.25 SCFM ($51 \text{ m}^3 \text{ day}^{-1}$). The corresponding organic loading was $2.0 \text{ kg COD m}^{-3} \text{ day}^{-1}$ (based on the medium), the influent toluene concentration was 221 mg m^{-3} , and the EBCT was 30 s. The nutrient solution was fed at a flow rate of 4.2 L day^{-1} with a nitrate influent concentration of 100 mgN L^{-1} , and the discharge rate was 3.4 L day^{-1} . The drum rotating speed was set at 1.0 rpm, and the system temperature was maintained at $23 \text{ }^\circ\text{C}$. Before this startup, the biofilter was used to biodegrade diethyl ether, and the medium was not changed. The medium was washed to remove biomass, but still contained some microorganisms. The activated sludge from a municipal wastewater treatment plant was also added to increase the diversity of the structure of the biofilms. Toluene removal efficiency exceeding 99% was achieved within 4 days.

Effect of toluene loading and influent concentration on VOC removal. After the successful startup of the biofilter, the effect of the organic loading and influent VOC concentration on toluene removal efficiency of the multi-layered biofilter was investigated. The organic loading rates investigated were 2.0, 4.0 and $8.0 \text{ kg COD m}^{-3} \text{ day}^{-1}$ sequentially. The corresponding influent toluene concentrations were 221, 442 and 884 mg m^{-3} . When the organic loading was doubled, the concentrations of the components in the nutrient solution were also doubled to keep the mass ratio of the VOC to nutrients constant. All other operational parameters remained unchanged.

Figure 2 shows the performance of the biofilter at the different toluene loadings and influent concentrations. The average toluene removal efficiency decreased from over 99% to 78% and 74% when the toluene loading increased from 2.0 to 4.0 and $8.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$, respectively.

Effect of organic loading and influent concentration on removal of diethyl ether

RDB performances including ether removal efficiencies and biomass accumulation in the medium by visual observation have been reported (Yang *et al.*, 2002). Ether removal efficiency exceeding 99% was achieved by the RDB at an EBCT of 30 s when the influent ether

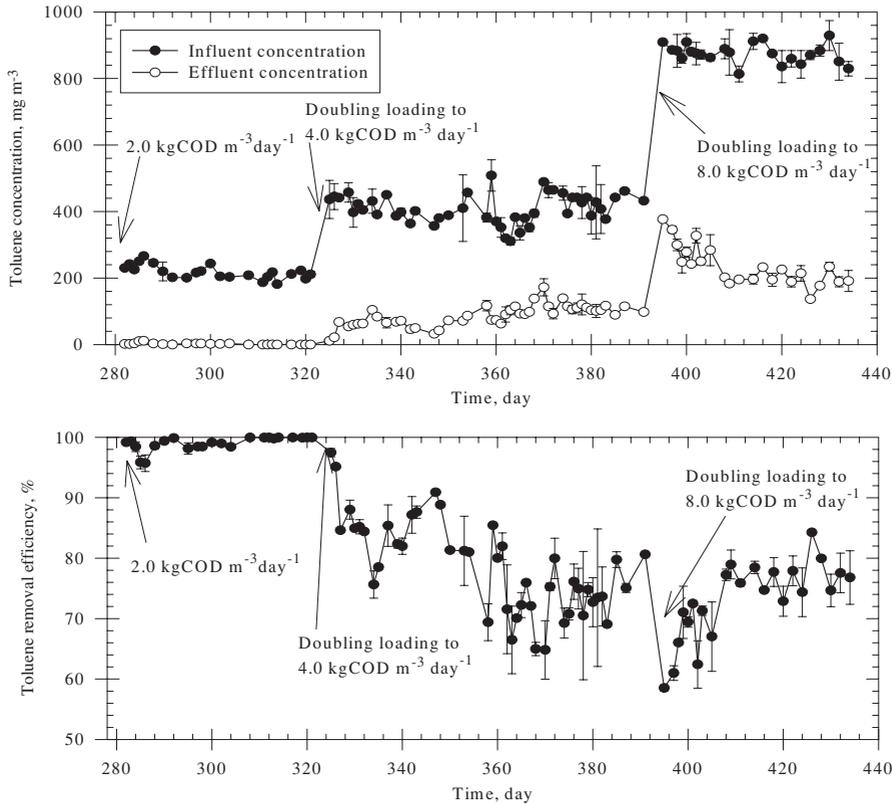


Figure 2 Biofiltration of toluene by the multi-layered RDB at different organic loadings

concentrations were 266, 532 and $1,064 \text{ mg m}^{-3}$. The corresponding organic loadings were 2.0, 4.0 and $8.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$. When ether influent concentration was further increased to $2,128 \text{ mg m}^{-3}$ and the loading to $16.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$, ether removal efficiency dropped to about 43%.

Biomass accumulation rates and patterns

Visual observation showed that biomass distribution was highly uneven in the radial depth of the medium and the distribution changed with organic loadings in the single-layered RDB when removing ether. These phenomena were further demonstrated in the multi-layered RDB when removing ether and toluene, and were able to be quantified.

In the multi-layered RDB, biomass from different layers was removed and measured separately. The frames of the third and fourth layers (inner layers) are connected tightly, and thus it is difficult to separate the layers without mixing the biomass in the two layers, so these two layers are considered as the inner layers when investigating the biomass distribution. The biomass removal and measurement were conducted weekly at different organic loadings when removing toluene in the multi-layered biofilter.

When removing the biomass in the media by squeezing the media in water manually, most of the biomass was removed from the media into the water solution. In order to minimize the effect of the unevenness when removing the biomass manually, the weekly mass of the biomass in each layer was separately summed over the entire period of the run at an organic loading rate. Biomass accumulation rates were then calculated as the overall biomass produced per day per unit volume of the medium in the layer. Figure 3 shows the biomass accumulation rates when removing toluene at the organic loadings of 2.0, 4.0 and $8.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$, and Figure 4 shows the biomass accumulation rates when removing

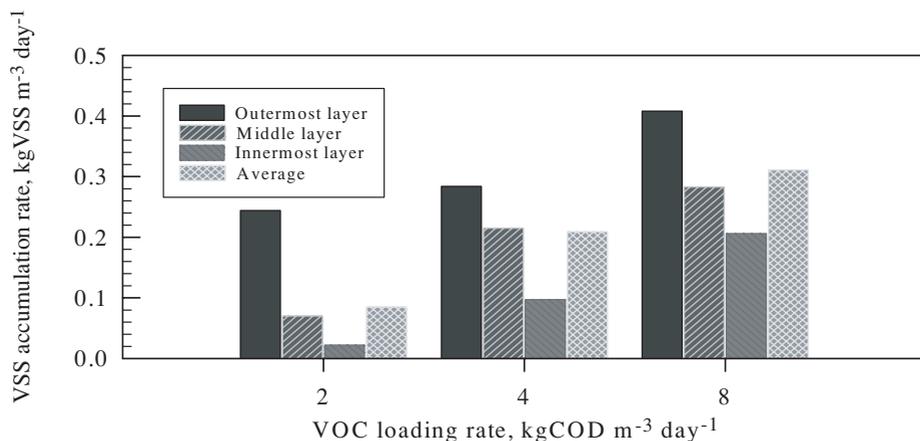


Figure 3 Biomass accumulation rates in the medium layers when removing toluene

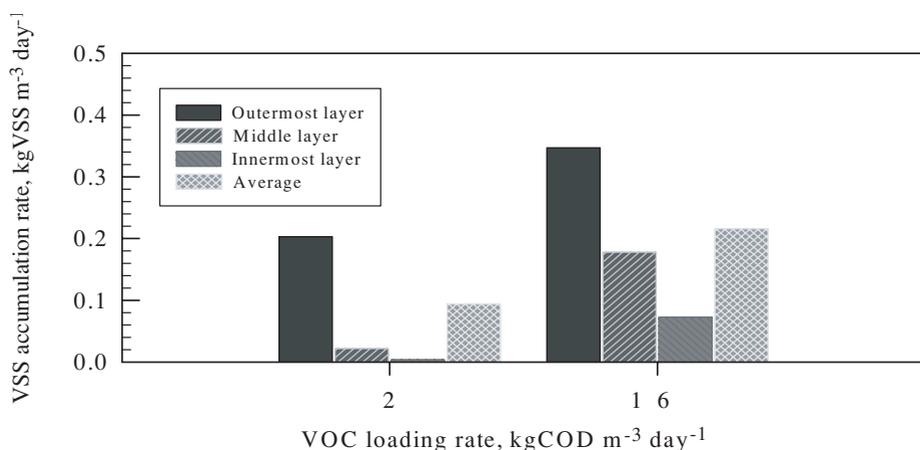


Figure 4 Biomass accumulation rates in the medium layers when removing diethyl ether

diethyl ether at the organic loadings of 2.0 and 16.0 kgCOD m⁻³ day⁻¹. All these experiments were conducted at an EBCT of 30 s except for the experiment when removing ether at 2.0 kgCOD m⁻³ day⁻¹.

The experiment conducted for the removal of diethyl ether at 2.0 kgCOD m⁻³ day⁻¹ lasted 34 days. In the first week, ether removal efficiency quickly increased from 72% to 96% at the EBCT of 30 s. In the following 10 days, ether removal efficiency increased to above 99% at the EBCT of 30 s. During the last 15 days, ether removal efficiency remained above 99% at an EBCT of 60 s. When treating ether at the EBCT of 60 s, the influent ether concentration is higher, and the gas stream remains in the outer part of the medium where there is more biomass for a longer period of time, therefore a more uneven biomass distribution than the data in Figure 4 is possible at the organic loading of 2.0 kgCOD m⁻³ day⁻¹.

The ratios of biomass accumulation rates in the medium of the outermost, middle and innermost layers can also be used to express the biomass distribution. The ratios are 1:0.29:0.09, 1:0.76:0.34 and 1:0.69:0.51 respectively when removing toluene at 2.0, 4.0 and 8.0 kgCOD m⁻³ day⁻¹, respectively. When removing ether at 2.0 and 16.0 kgCOD m⁻³ day⁻¹, the ratios were observed to be 1:0.11:0.02 and 1:0.51:0.21 respectively. From Figure 3 and Figure 4 and from these ratios it can be seen that the biomass tends to distribute more evenly at a higher organic loading rate. The biomass distribution was also observed to be more uneven when removing diethyl ether than when removing toluene.

According to the characteristic of the biomass concentration-depth profile in the medium, three different biomass accumulation patterns may be speculated. These are surface pattern, in-depth pattern and shallow pattern. In the surface pattern most of the biomass is distributed on the outer surface of the medium. In the in-depth pattern, biomass is distributed deeply throughout the medium. All cases between these two scenarios are classified as shallow pattern.

Biomass distribution in the medium is an indicator where VOCs are biodegraded, and different biomass accumulation patterns may represent different mass transport phenomena and removal mechanisms. Therefore, methods of design and operation of any biofilter should be different for different biomass accumulation patterns. In a surface pattern, most VOCs are removed at the surface of the medium, consequently the most important factor is maximizing the surface area of the medium when designing a biofilter. Operating parameters such as VOC loading and EBCT should also be selected to facilitate the surface pattern so that excess biomass accumulation can be controlled by methods for surface pattern, such as replacing or cleaning the surface medium.

Experimental results have shown that which particular biomass accumulation pattern dominates is related to organic loadings and influent concentration as well as the properties of the VOC. Other parameters such as EBCT, biodegradability and Henry's law constant also play an important role. After further investigations in this field, it will be possible not only to predict which biomass accumulation pattern will dominate a biofiltration process, but also to control, to a certain extent, which biomass accumulation pattern will dominate, by adjustment of some design and operating parameters such as VOC loading and EBCT.

Conclusions

This study has demonstrated that the rotating drum biofilter efficiently biodegrades VOCs from waste gas streams. Diethyl ether can be removed more efficiently than toluene, however, toluene removal efficiency of 99% is also achieved at an organic loading of $2.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$ and an EBCT of 30 s.

VOC removal efficiency decreases with the increase of the organic loading and influent VOC concentration in the biofilter. Toluene removal efficiency decreases from over 99% to 74% when the organic loading increases gradually from 2.0 to $8.0 \text{ kgCOD m}^{-3} \text{ day}^{-1}$ at an EBCT of 30 s.

Biomass is very highly unevenly distributed when comparing different radial depths of the foam medium in the biofilters, although is almost evenly distributed within the same depth. With an increase in organic loading, the biomass distribution along the medium depth is more even. The biomass distribution along the medium depth is also more uneven when removing diethyl ether than removing toluene.

Review of the biomass accumulation rates among different layers at different operation conditions revealed three biomass accumulation patterns. One is surface pattern in which most biomass was accumulated in the outer surface of the medium. The other extreme was the in-depth pattern, in which biomass is almost evenly distributed along the depth of the medium. A biomass accumulation pattern between these two cases was termed as shallow pattern. The VOC concentration profile along the depth of the medium determines which pattern dominates. Different biomass accumulation patterns represent different VOC removal mechanisms.

The dominant biomass accumulation pattern in a rotating drum biofiltration process can be predicted and can, to a certain extent, be controlled. Methods to design and operate RDBs are different for different dominant removal mechanisms, such as methods of selecting loading rate, EBCT, and biomass control strategies. Proper design and operation of RDBs should consider these new findings.

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