J. ENVIRONMENTAL SYSTEMS, Vol. 27(1) 71-83, 1999

A POSSIBLE APPROACH FOR ACTIVATED SLUDGE FOAMING CONTROL USING DISSOLVED AIR FLOTATION

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ABSTRACT

The principles of dissolved air flotation (DAF) which could potentially be applied to solve activated sludge foaming problems are discussed in the relevant context. Modification of existing Activated Sludge Plants (ASP) by incorporating a DAF facility in parallel with the aeration basin conceptually holds much promise as an alternative solution to foaming problems. A modeling approach with a summary simulation study of a real-world foaming problem has been presented for the purpose of exploring the conceptual feasibility of the DAF approach. It is proposed that this approach to foaming control that merits further laboratory and plant studies with a view to potential wide-scale applications.

INTRODUCTION

Foaming is a recently recognized operating difficulty in Activated Sludge Plants (ASPs) [1]. Recent surveys conducted at ASPs in the United States, France, South Africa, and Australia all reveal the severe extent of the foaming problem. For instance, some 50 percent of the ASPs surveyed in Australia experience foaming problems [2]. Of the 6000 ASPs surveyed in France, 20 percent are affected by foaming [3]. In South Africa, the incidence of foaming was reported to be present in about 40 percent of the ASPs, while in the United States, about 66 percent of the ASPs surveyed had this problem [4, 5].

Foaming is caused primarily by an over-abundance of hydrophobic filamentous micro-organisms such as *Nocardia* spp., *Microthrix parvicella* and Type 1863 [6]. The hydrophobic nature of the cell surfaces of these organisms results in the formation of flocs that tend to attach themselves with air bubbles and float to the surface of the aeration basin. The presence of branched hyphae in *Nocardia* spp. and the extended lengths of *M. parvicella* further enhance foaming by forming a net that traps air/gas bubbles and oil droplets [7].

Foaming often disrupts the smooth and successful operation of ASPs. In the aeration basins with subsurface withdrawal mechanisms to the secondary clarifiers, foam accumulates to such an extent that it overflows the aeration basin free-board and covers the walkways, thereby creating hazardous conditions for operating personnel. When foam overflows to the secondary clarifiers, some of it may exit the plant with the secondary effluent, thereby increasing treated effluent TSS and BOD content.

Foam is a dispersion of air in a liquid (water) forming a two-phase system with a clear liquid-air interface [6]. Surface-active agents can stabilize the foams by having their molecules strongly bind the liquid-air interface. The presence of micro-organisms associated with foaming further enhances the stability of the foams by binding themselves across the interface.

The formation of activated sludge foams resembles the process of Selective Flotation [8, 9]. Selective Flotation is a technique that is used in the mining industry to purify ores and also in water and wastewater treatment for TSS removal. In water and wastewater treatment, TSS removal in secondary clarification is sometimes brought about by Dissolved Air Flotation (DAF), a particular case of Selective Flotation [9, 10, 11]. The three major factors necessary for effective Selective Flotation are (i) the presence of biologically derived surface-active components, (ii) the presence of hydrophobic elements, and (iii) the presence of rising air bubbles [7, 12]. All these are present in a foaming activated sludge. Therefore, if the principles of DAF could be applied, in the relevant context of activated sludge foaming, it may be possible to separate foaming organisms from the activated sludge very rapidly by enhancing the selective flotation of these organisms. In this fashion, it could be possible to flush out these organisms from the system in a short time and thereby eliminate or minimize foaming by reducing further reseeding of foaming organisms in the mixed liquor. Such a DAF facility could possibly be placed to draw mixed liquor from and return it back to the aeration basins removed of foams.

In this article, a desk study has been made to delineate:

1. the relevant principles of DAF that could efficiently eliminate the foaming organisms from the activated sludge;
2. the operating protocol for foaming control by incorporating a DAF facility in parallel with the aeration basin and the secondary clarifier;

3. a modeling approach to the dissolved air flotation technique with respect to activated sludge foaming; and
4. optimization and simulation of the model behavior for a real-world case-study of a foaming affected activated sludge plant to explore the conceptual feasibility of the DAF approach.

Realizing that control strategies for foaming can often be contradictory and lack a rational basis [5], this article hopes to introduce the subject of DAF for foaming control and propose further work at establishing DAF as a viable method for foaming control.

PRINCIPLES OF DAF: ANALOGIES TO FOAMING

The major treatment steps in a DAF facility are:

(i) coagulation and flocculation prior to flotation;
(ii) bubble generation by releasing pressurized water;
(iii) bubble floc collision and attachment in a mixing zone; and
(iv) rising of bubble-floc agglomerates in a flotation tank.

Foaming in ASPs resembles more closely the process of selective flotation than the typical scum forming mechanism [6]. The step (i) identified above generally takes place in foaming-affected ASPs early in the foaming event. Due to their hydrophobic nature, *Nocardia* spp. and *M. parvicella* tend to floc among themselves. In DAF, step (i) is achieved through charge neutralization by the addition of a coagulant.

Bubble Generation

Small air bubbles up to 100 µm diameter are formed in a flotation tank by the release of pressurized recycled water using a specially-designed nozzle or needle valves [13]. A bubble is formed in two steps: (i) nucleation and (ii) growth. The critical diameter of a bubble (d_b) in meters is given by,

$$d_b = \frac{4\sigma}{\Delta P} \tag{1}$$

where,
σ = surface tension of water (N/m)
ΔP = pressure change across the nozzle (N/m^2).

To ensure small bubbles (® 100 µm diameter, a pressure difference of 400 kPa to 600 kPa is generally recommended for water and wastewater purification [13]. Additional bubble growth may occur as the bubbles rise in the flotation tank due to the decrease in the hydrostatic pressure, but this is said to have little overall effect on small bubbles formation in DAF [14]. In the ASPs, although foaming has been observed with coarse Bubble diffusers [15], Hiraoka and Tsumura [16] have reported that fine bubbles are essential to cause severe foaming problems.

Bubble Floc Collision, Attachment, and Rising

The most widely accepted mechanism for bubble floc collision, which is also the most relevant in the context of activated sludge foaming, is the mechanism where particles collide and then adhere to preformed bubbles [13].

Figure 1 shows the two zones in a DAF tank where the mechanism of bubble-floc collision and attachment takes place.

If the DAF principles are to be applied to foaming control, then laminar flow conditions (Stoke's Law) would need to be assumed in DAF tank. As a rule of thumb, 0.44 mL of air is required to float 1 g of sludge (dry wt.) in the aeration tank [7]. This would imply that a 100 µm diameter bubble can attach itself about 10 mg of hydrophobic sludge (dry wt.).

There exist different schools of thought as to how exactly the mechanism of bubble-floc interaction is brought about. There is, however, universal agreement that a hydrophobic nature is necessary for the particle to adhere to the preformed bubbles [13]. This is important to note because if DAF principles are to be applied to the rapid flotation of foaming organisms such as *Nocardia* spp. and *Microthrix parvicella,* their hydrophobic nature, due to presence of mycolic acid in their cell walls [17], would be a key to success of the technique.

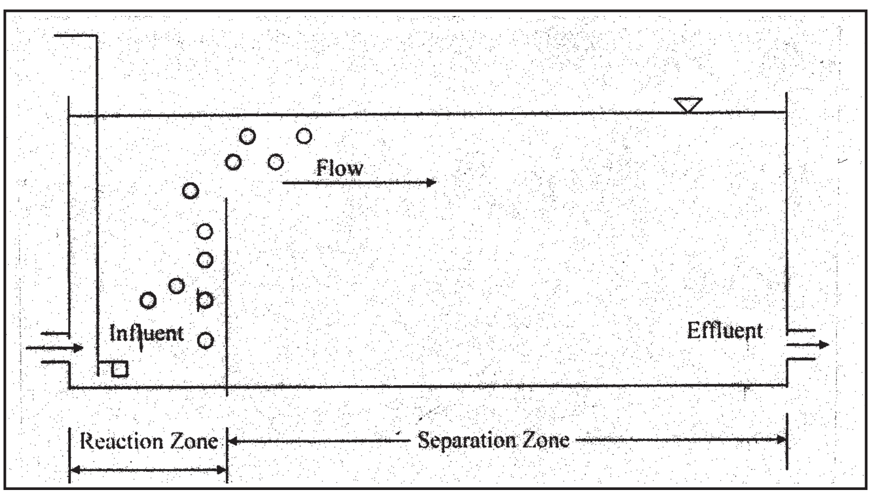

Figure 1. Schematic diagram of a DAF tank showing the reaction and separation zones.

Supply of Bubbles

Measures which can be used to quantify the supply of air bubbles include: (i) mass or concentration, (ii) air-bubble volume, and (iii) bubble numbers. The **Recycle Ratio, R_r**, is commonly used to express the supply of bubbles for a given pressure difference.

$$R_r = \frac{Q_r}{Q_o} \tag{2}$$

where,

Q_r = Recycle Flow
Q_o = Influent Flow

This recycle ratio R_r is important for the DAF process, as it equates to a given concentration of bubbles at a given temperature for a given efficiency of dissolving air.

AN OPERATING PROTOCOL FOR USING THE DAF FOR FOAMING CONTROL

It is proposed that a DAF tank could be installed in parallel with the aeration tank and the secondary clarifier. Figure 2 shows the schematic diagram of such an arrangement.

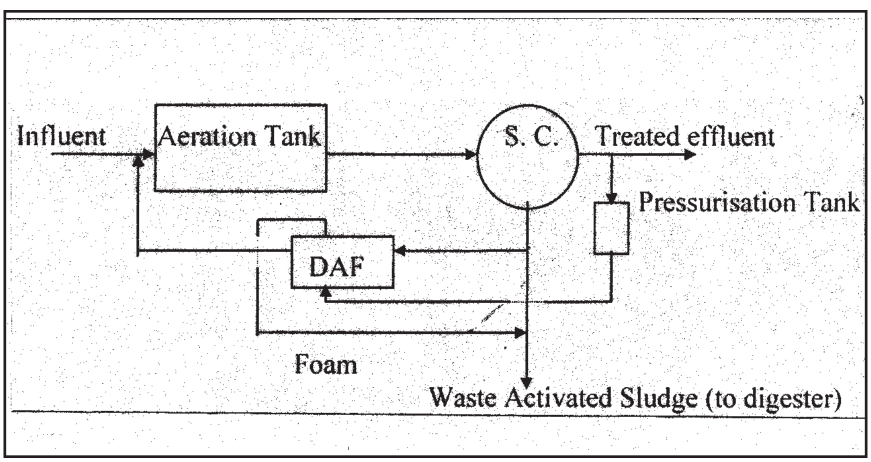

Figure 2. Schematic diagram of an ASP fitted with a DAF tank.

Stepwise Operation Using the DAF

1. When *Nocardia* or *M. parvicella* foams start to appear on the surface of the aeration tank, the return activated sludge is passed through the DAF.
2. Pressurized recycle (from the effluent) is fed to DAF tank.
3. Foaming organisms get rapidly floated to the surface by selective flotation. Two layers are formed in the DAF tank: (i) a subnatant containing only the active biomass, and (ii) a clear float (supernatant) concentrated in foaming organisms.
4. The float is scraped from the DAF tank and is wasted (to digesters).
5. The MLSS (i.e., subnatant), now rid of foaming organisms, is fed to the aeration tank again.
6. Through continual operation of the DAF tank, the aeration tank is rapidly flushed of foaming organisms.
7. The dissolved air flotation is stopped as soon as foaming in the aeration tank reduces to tolerable limits.
8. The whole process of flushing out foaming organisms from the mixed liquor takes very little time, as the time scale for each flotation process is under 1 second [18].

ASSUMPTIONS TAKEN

1. The foaming organisms are the major hydrophobic elements present in the biomass of a foaming MLSS, and therefore only these get selectively floated.
2. Conditions in the DAF tank are laminar (Stoke's Law is obeyed).
3. The whole process of flushing out foaming organisms takes very little time, and therefore, treatment variables like HRT and SRT are not changed.
4. The DAF process does not damage the bio-stability of the active biomass (active biomass indicates mainly the fast-growing organotrophs that rapidly remove BOD from the MLSS). Use of polymers and coagulants may be used to ensure (4).

A MODELING APPROACH

As shown in Figure 1, the DAF flotation tank has two zones: Reaction Zone and Separation Zone. The removal efficiency (R) of particles by a single bubble in the reaction zone is expressed as:

$$R = \alpha_{pb}\, \eta_{\mathrm{T}}\, (100\%) \tag{3}$$

where,

α_{pb} = adhesion efficiency of particle on bubble
η_T = total single collector (bubble) efficiency

η_T describes the particle transport to bubble surface and can be further broken down as,

$$\eta_T = \eta_D + \eta_I + \eta_S + \eta_{IN} \tag{4}$$

where,

η_D = efficiency due to diffusion = $0.9\,(kT / \mu\, d_p\, d_b\, U_b)^{2/3}$
η_I = efficiency due to interception = $3/2\,(d_p / d_b)^2$
η_S = efficiency due to sedimentation = $(\rho_p - \rho_w)\, g\, d_p^2\ (18\, \mu\, U_b)$
η_{IN} = efficiency due to inertia = $(g\, \rho_w\, d_b\, d_p^2\ ) / (324^2)$

and,

k = Boltzmann constant = 1.38×10^{-23} J/°K
T = Temperature in Kelvins (°K)
d_p = particle diameter (m)
ρ_p = particle density (Kg/m^3)
μ = (N.s/m^2) and ρ_w (Kg/m^3) are the water viscosity and density respectively
U_b = bubble rise velocity (m/s)
g = acceleration due to gravity = 9.81 (m/s^2)

Under optimum conditions of coagulation, flocculation, and pH (nearing 8), the α_{pb} can be assumed to be 1 while for bubbles of up to 100 μm η_{IN}, due to inertia, the α_{ph} can be ignored [13].

Rearranging terms of equation 3 by substituting the relevant terms with mathematical manipulation and realizing that $\rho_w >> \rho_b$, the removal efficiency (R) can be expressed as,

$$R = \frac{2.146789 \times 10^{-23}\ T}{d_b^2\ d_p\ \rho_w} + \frac{3d_p^2}{2d_b^2} + \frac{(\rho_p - \rho_w)d_p^2}{\rho_w\ d_b^2}\ (100\%) \tag{5}$$

A CASE STUDY OF THE SENBOKU TREATMENT PLANT

The Senboku wastewater treatment plant had been reported to be affected with *Nocardia* foaming problem in 1984 [16]. The *Nocardia* presence caused about 60 m^3 per day of foam to be produced in the aeration basins [16]. Based on the preceding information on foaming, 60 m^{3}day of foam equated to the requirement of at least 1.848 m^3/day of dissolved air for the selective flotation of the foam (assuming 100% removal efficiency R). Microscopic photography revealed that the air bubble diameter was generally 65 μm while the bubble-particle diameter was around 100 μm [16].

MODEL OPTIMIZATION AND SIMULATION OF PARAMETER SENSITIVITY

With the case study presented as above, and assuming state of the art foaming conditions as known from the literature, the conceptual feasibility of the DAF approach was tested by:

1. optimizing the model in equation 5 to maximize R.
2. deriving the optimized parameter values, T, d_p, d_b, and ρ_p.
3. deriving the supply of bubbles required per day, the pressure change needed for the required size of the bubbles and the recycle ratio.
4. analyzing the sensitivity of T, d_p, *and* d_b, and ρ_p against R.

i) Model Optimization

The programming problem was formulated as follows:

Maximize R (eq. 5)
subject to:
$288°K < T < 308°K$ (from 15°C to 35°C)
$30\ \mu m < d_p < 60\ \mu m$ (based on the Senboku case [16])
$0\ \mu m < d_b < 100\ \mu m$ (model assumption)
$1010 < \rho_p < 1050$ (Kg/m^3) (typical for *Nocardia* foams)

Furthermore, the density and surface tension of water were expressed as linear functions of T (⊃K) (by linear regression of viscosity and density data from [19].

$$\rho_w = 1119.339858 - 0.417604T \quad (Kg/m^3) \tag{6}$$

$$\sigma = 0.122574 - 0.00017T \text{ (N/m)} \tag{7}$$

The direct search algorithm for systematic reduction of size of search region by Luus and Jaakola [20] was used for model optimization (see Appendix).

ii) Optimized Model Parameters

A hypothetical R of 100 percent removal efficiency was simulated against the requirement of the following criteria for the DAF,

$$T = 290.2°K\ (17.2°C),\ \ d_p = 59.8\ \mu m,\ \ d_b = 74\ \mu m,\ \ \rho_p = 1030\ Kg/m^3$$

The above parameters are all within the viable range of operation for the Senboku plant.

iii) Supply of Bubbles, Pressure Change, Recycle Ratio

The supply of bubbles, N_b, required for the DAF to combat the Senboku wastewater treatment plant foaming was calculated as,

$$N_b = 2.07 \times 10^5/\text{mL}$$

Pressure change required (from equation 1) for the size of bubbles,

$$\Delta P = 4000 \text{ Pa (which is very nominal for a DAF)}$$

A recycle ratio R_r, ranging from 10 to 15 percent was noted from operating charts that could produce the required bubbles in required quantities [13]. Indirectly, that corresponded to 6300 m^3/day of pressurized influent required for the DAF at the Senboku wastewater treatment plant, which was treating 42,000 m^3/day. This recycle ratio and the requirement of influent for dissolved air appears to be viable for the Senboku plant.

iv) Sensitivity of T, d_p, d_b ρ_p against Removal Efficient R

As part of the sensitivity analyses, the optimized sets of parameter values necessary to ensure a certain limiting removal efficiency R ranging from 100 percent to 50 percent for the given constraints were derived using the direct search algorithm [20].

Figure 3 depicts the computer-simulated sensitivity of the parameters, T, d_p, d_b. The parameter ρ_p was observed to be insensitive to changes of R for the given parameter constraints. There appears no specific trend of increasing or decreasing sensitivity of the parameters T (temperature), d_p (particle diameter), and d_b (bubble diameter) with the removal efficiency R in the simulation analysis.

DISCUSSION ON THE DAF APPROACH

1. The first question often raised about this proposal would be that disposal of foaming sludge in the digester could create problems as it can float in the digester. Hence, the problem normally encountered in digesters due to foaming sludge is not solved by the DAF facility. However, it must be remembered that the DAF facility creates safe operating conditions in the aeration tank and secondary clarifiers by preventing outflow of foams into the walkways. The effluent quality is not degraded as foams cannot spill over to the effluent channels. There is also no basic need to constantly scrape the surface of the aeration tank for foams. Furthermore, the amount of foaming sludge being fed to the digester would be less, as the periodic use of DAF would prevent reseeding of the foaming micro-organisms in the MLSS.

2. The DAF process of foaming sludge is treated as highly theoretical. Experimental values from bench-scale or pilot scale plants are not available to validate the idea. Therefore, satisfying performance requirements may not be fulfilled. However, the optimization and simulation study performed for the Senboku treatment plant reveals that the DAF parameters required for clearing the foam are within the feasible range.

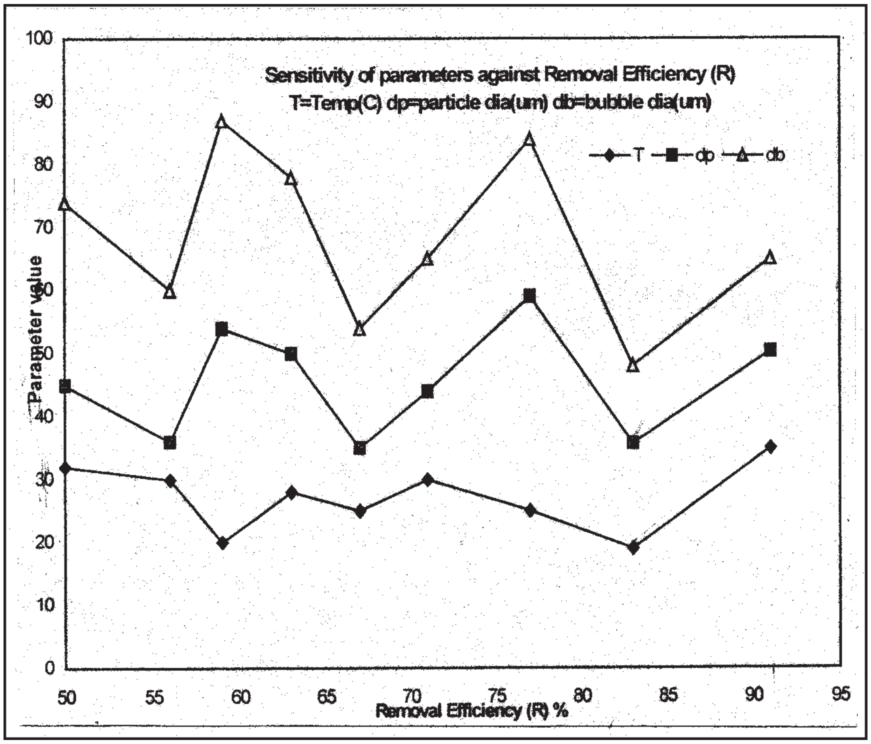

Figure 3. Parameter sensitivity of *T, dp, db* against *R.*

3. The foaming organisms may not be the major hydrophobic elements present in the biomass of the MLSS. However, the DAF facility would be used when ASPs are severely foaming. Under such circumstances, literature reveals that 70 to 95 percent of *Nocardia* filaments get transferred to the foam [21].

4. DAF is a very rapid and efficient technique and therefore allows rapid flushing out of foaming organisms.

5. The DAF process can be applied at short notice when foaming starts to exceed tolerable limits in the aeration tank.

6. A rational basis is provided for the control of activated sludge foaming.

RESEARCH NEEDS

Having proposed the use of DAF techniques as above, the following areas that should be researched in the context of foaming:

1. Bubble formation and attachment to foaming organisms—*Nocardia, M. parvicella;*
2. Modeling study on a pilot-scale to modify existing DAF models for foaming control; and
3. Operational problems encountered in ASPs during the DAF process.

CONCLUSION

DAF technique could be an alternative for the long-term solution of foaming problems in activated sludge plants. It shows promise as a technique which could be put into or withdrawn from service on relatively short notice. Such short response times would allow the technique to be applied when foaming is determined to be serious. Use of the DAF in this manner would be further enhanced by the technique's anticipated fast removal of foaming organisms. Conceptual feasibility, involving modeling, optimization, and simulation of model parameter sensitivity, has been shown for a real world foaming example. The temperature has been found to be fairly invariable between ranges of 15 to 35°C, while bubble diameter played a very important part in removal efficiency of *Nocardia* elements. The pressure change required for the given size of bubbles and the recycle ratio have been found to be within feasible limits. Accordingly, further study of this technique is warranted. A potential drawback could be the difficulties associated with disposal of the foam collected by the DAF. While it is acknowledged this could indeed be a problem in the short term, application of the DAF could see a progressively rapid decline in foaming organisms, as they are expected to be selectively removed from the activated sludge. Many activated sludge plants already have a DAF facility in place for sludge thickening. Hence, for many plants, the DAF could be an attractive option to explore, as the capital cost involved would be minimal.

APPENDIX
Direct Search Algorithm

The algorithm of direct search by Luus and Jaakola (1973) is outlined below:

1. Take initial values for x_1, x_2, ... x_n and initial range for each variable; denote these by $x_1^{o\,(0)}, x_2^{o\,(2)}, \mathrm{K\ K\ K}, x_n^{0\,(0)}$ and by $r_1^{(0)}, r_2^{(0)}, \mathrm{K\ K\ K}, r_n^{(0)}$. Set iteration index j to 1.
2. Read in a sufficient number of random numbers (say 500) between –0.5 and +0.5. Denote these by y_{ki}.
3. Take pn random numbers from 2 and assign these to x_1, x_2, ...x_n so that we may have p sets of values, each calculated by

$$x_i^{(j)} = x_i^{o(j\backslash 1)} + y_{ki}\, r_i^{(j\backslash 1)} \qquad i = 1, \ldots\ldots\ldots\ldots, n$$
$$k = 1, \ldots\ldots\ldots\ldots, p$$

4. Test to find if the constraints are satisfied and calculate a value of the objective function with each admissible set.
5. Find the set which minimizes the objective function given. Write out the minimum value of the function and the corresponding $x_1^{o(j)}$, $i = 1, \mathrm{K\ K\ K}$, n. Increment j by 1 to $j + 1$.
6. If the number of iterations has reached the maximum allowed, end the problem. For example the maximum number of iterations may be set as, say, 1000, depending on how the minimum value converges.
7. Reduce the range by an amount ε
   $r_i^{(j)} = (1 - \varepsilon) r_i^{(j\backslash 1)}), \quad \varepsilon > 0$
   For example, we may choose $\varepsilon = 0.05$
8. Go to step 2 and continue.

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