Activated primary tanks for phosphate removal

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Abstract

Primary and secondary release of phosphates, i.e. release in the presence and absence of acetate takes place in the anaerobic zones of Phoredox plants. Secondary release leaves the cells with no energy for subsequent uptake and should be minimized. Prolonged anaerobic retention times enhances secondary release and for plant optimization, fermentation for the production of acetates should be separated from the anaerobic contact stage which should be minimized. Fermentation is possible in primary sedimentation and thickening tanks by recycling thickener underflow to the primary sedimentation tank (PST), thus maintaining an aerobic sludge blanket in these units and elutriating the acetates in the primary, hence the concept of *activated primary tanks*. Surplus sludge is passed to the anaerobic digester. The volatile fatty acid concentration is proposed as a measure of phosphate removal ability of the plant.

Introduction

While many research papers have attempted to explain the phenomenon of phosphate removal in activated sludge plants there remained certain anomalies. An attempt will be made to propose an optimized process for reliable removal of phosphates to low concentrations.

Theory of phosphate release and uptake

Fuhs and Chen (1975) attributed most of the phosphate uptake in activated sludge plants to one specific organism, an obligate aerobic bacterium which uses acetate as feedstock, and which is similar to *Acinetobacter Lwoffi*, except that it accumulated poly-β-hydroxybuterate (PHB). This organism which they isolated from activated sludge from the Baltimore plant was responsible for most of the uptake of phosphates.

Most significantly, Fuhs and Chen (1975) released phosphates in the presence of acetates and carbon dioxide. Apparently these authors did not relate the essential release of phosphates to uptake in the aeration zone but pointed out that the reduced substances in foul sewage would contain sufficient concentrations of acetates to sustain them. However, they also noted that release during anaerobiasis was followed by uptake during aeration.

According to Fuhs and Chen (1975), the presence of acetate in the influent of the plant should result in the growth of the correct organisms and the removal of phosphates through uptake into the cells, which would then explain the removal of phosphates in plug-flow plants such as the one at Baltimore. This neither explained the observed need for the activated sludge to pass through an anaerobic basin nor the role of nitrates on phosphate removal (Barnard, 1974), nor the selection of Acinetobacter above other less specialized organisms that also metabolize acetate readily. Fuhs and Chen (1975) concluded that some questions remained with regard to the release of phosphates from the cells and stated that low pH (sometimes resulting from accumulated CO_2), addition of a carbon source and unidentified substances from fermented sewage were more effective than anaerobiasis for releasing phosphates. Also the death of Acinetobacter and the consequent release of orthophosphate during autolysis could not be ruled out.

Nicholls and Osborn (1979) studied the work of Dawes and Senior (1973) and others and concluded that certain organisms, especially Acinetobacter, while being strict aerobes and therefore expected to be at a disadvantage in an aerobic zone, had the ability to transport acetates through the cell wall and accumulate PHB in the cell, using stored poly-phosphate as energy source. Sludge from the Johannesburg plants that removed phosphates effectively, contained high percentages of poly-phosphates and PHB, (Nicholls and Osborn 1979). Thus when passing activated sludge containing Acinetobacter through an aerobic zone, they could use stored energy in the form of poly-phosphate to transport food across the cell membrane, storing it as PHB until the cell reaches the aerobic section of the plant where the stored PHB is metabolized for the formation of adenosine triphosphate (ATP) and used for energy for replenishing the phosphate pool.

When the sewage is fresh, the anaerobic stage must fulfil two functions, firstly, that of fermentation of complex organic compounds by facultative organisms for the production of volatile fatty acids, specifically acetic acid and secondly, for allowing the phosphate accumulating bacteria to sequester available acetates. The problem facing the designer is how to optimize the anaerobic basin to best achieve these two separate goals.

Full-scale observations relating to phosphate removal mechanism

The operation of full-scale plants soon indicated that better and more reliable phosphate removal was possible when the influent sewage was septic, but this could be explained in terms of ease of creating anaerobic conditions. For example, sewage is pumped through a 3 km forced main to the Klerksdorp plant having a nominal anaerobic retention time of only one hour. The concentration of volatile fatty acids in the sewage at the plant varies between 360 and 1 700 mg/ℓ. Consistent phosphate removal of between 90 and 99 % was observed, based on analyses done by the South African Bureau of Standards (SABS) over a period of three years, while the Northern Works of Johannesburg and the Baviaanspoort plant in Pretoria with the same retention times in the anaerobic zones could not be operated to remove phosphates according to the municipal officials. Information obtained from the municipal laboratories indicated that the Windhoek plant by contrast released up to 70 mg/ℓ of phosphates as P, all of which could not be re-absorbed through aeration leaving on balance the effluent concentration at about 60% of the influent concentration.

Figure 1 shows a typical ortho-phosphate profile through the various zones of the existing five stage plant at Randfontein as

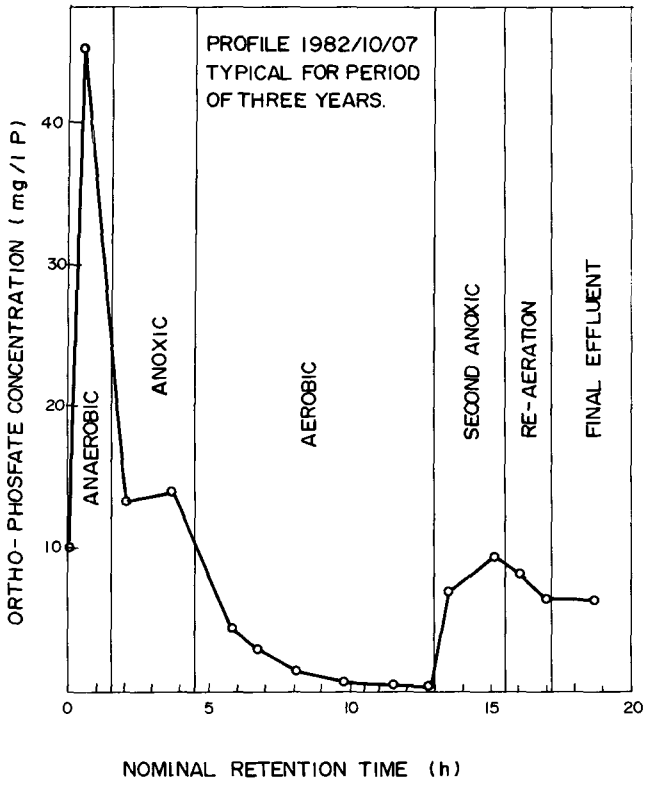

Figure 1
Profile of ortho-phosphate through Randfontein plant (as measured by the municipal laboratories)

measured consistently over a period of about three years by the municipal laboratories. Almost without exception the soluble phosphate concentration in the aeration basin just before recycling to the first anoxic basin was less than 0,1 mg/ℓ as P. Even though 60 % of the flow to the plant was humus tank effluent, complete nitrification and denitrification were observed in the aeration basin such that less than 0,1 mg/ℓ of nitrates was discharged to the second anoxic zone. Orthophosphate released to the liquid in this stage could not be taken up again such that not once during a period of three years could the phosphates in the effluent be reduced to below 1 mg/ℓ. This seemed to contradict the findings by Wells (1969) as shown in Figure 2.

Similar releases of phosphates in second anoxic zones were observed at two plants in Witbank (Uys, 1984) and at a plant in Canada (Stevens, 1983).

Release of phosphates in the presence and absence of acetates

Since Fuhs and Chen (1975) found that bubbling carbon dioxide through sludge that removed more phosphates than is needed for cell growth, resulted in large releases of phosphates even when no source of acetate was added, it is postulated by the author that there are two types of release that take place in activated sludge plants. The first release of phosphates results from the uptake of acetates which could later serve as an energy source for uptake of the phosphates. This will be referred to as *primary release*. The second release may result, amongst other, from carbon dioxide production in the gently stirred anaerobic or anoxic basins. This release is not associated with energy intake that would be

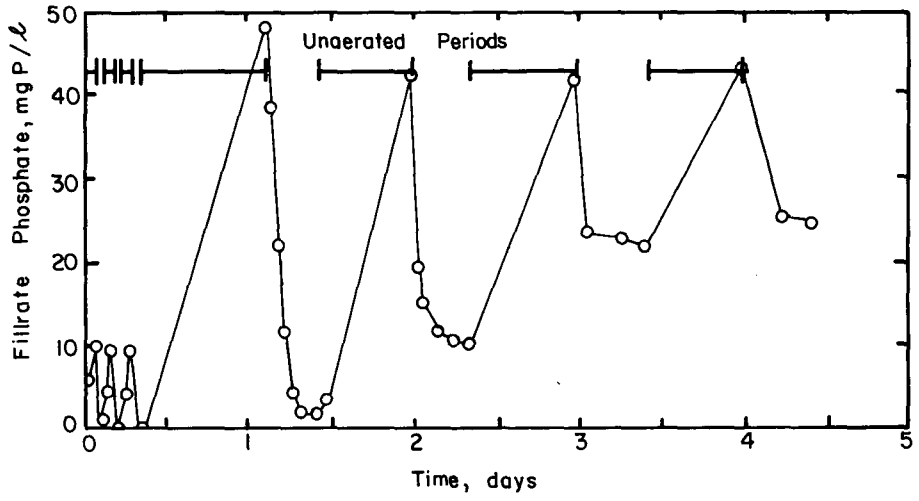

Figure 2
Uptake and release of phosphates after Wells (1969)

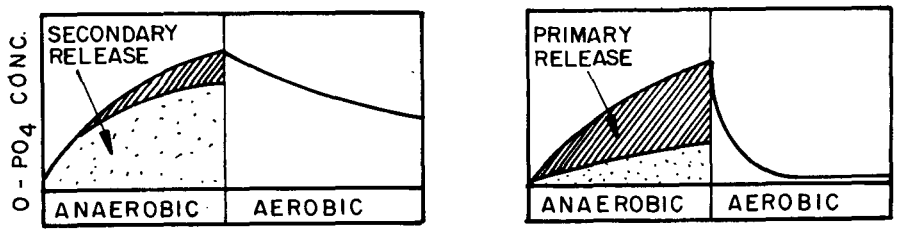

Figure 3
Diagrammatic presentation of primary and secondary release and uptake of phosphates.

available for uptake of released phosphates. This will be referred to as *secondary release* (Figure 3).

If most of the release is secondary, with only a small release resulting from the intake of acetate by the Acinetobacter, a slow uptake will follow which might not be completed by the end of the aeration basin (See Figure 1). If on the other hand a sufficient release were due to the intake of acetates, sufficient energy will be available in the aeration zone for the uptake of all released phosphates, including secondary releases. The actual fraction of the primary release for a total uptake will need further investigation.

The inability of some plants to remove phosphates in spite of a substantial release of phosphates in the aerobic basin could be explained if most of the release is secondary. This has been experienced in the Witbank plants (Uys, 1984) where the sewage enters both plants in a fresh state and the anaerobic basins were too small to allow for good fermentation to take place. An attempt was made to improve the situation by switching off the stirrers in the anaerobic basin. Phosphate release increased to between 30 and 50 mg/ℓ but little improvements in the overall removal of phosphates was observed. Without the stirrers, insufficient agitation would result in a slower removal of carbon dioxide which may then cause excessive secondary release. As mentioned before, secondary release in the second anoxic zone did not result in an phosphate uptake in the re-aeration basin.

At the Kelowna plant in British Columbia, Canada, (Figure 4, process design by author), primary settled sludge is passed to a thickener with a long retention time which incidentally serves as an acid fermenter and the supernatant is returned to the primary sedimentation tank (PST), the effluent of which contained between 10 and 20 mg/ℓ volatile fatty acids (VFA), (Stevens, 1983). Good P removal was observed at 8 °C mixed liquor temperatures with a release of about 9 mg/ℓ of phosphates as P in the anaerobic basin. When an attempt was made to further improve the situation by switching off the stirrers in the anaerobic basin, the release increased to about 18 mg/ℓ. However, uptake in the aeration basin could only reduce the phosphate in the filtrate to about 7 mg/ℓ indicating clearly that while the acetate in the influent was just sufficient to ensure that phosphates released could be taken up, little additional acetate was produced in the anaerobic basin while secondary release took place probably due to the increased carbon dioxide content of the mixed liquor. Upon restarting the stirrers, the release of phosphates to about 9 mg/ℓ was restored and the uptake was again down to less than 1 mg/ℓ.

Gerber (1983) found that retention times in the anaerobic basin of up to 12 h resulted in very good and reliable phosphate removal. It is assumed that during this time the contents of the basin was stirred which would limit the size of the secondary release.

The activated primary concept

The above observations clearly indicate that plants could be optimized when secondary releases in either the anaerobic basin or the anoxic basins are minimized. Such secondary releases are minimized when the retention time is short and the basin contents stirred. The required retention time in the anaerobic basin is reduced when excess acetates are present in the feed and there is no need to generate acetates in this basin. Some experimentation would be required to determine the optimal retention times, but judging from the short anaerobic retention times in the plug-

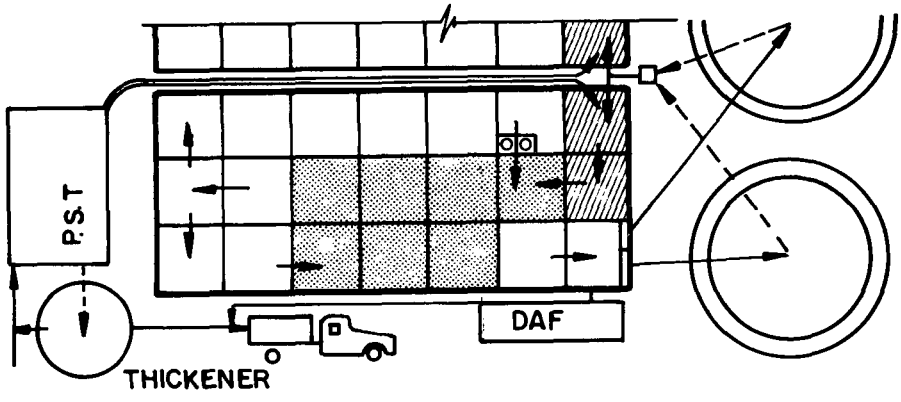

Figure 4
Lay-out of the Kelowna plant, B.C. Canada.

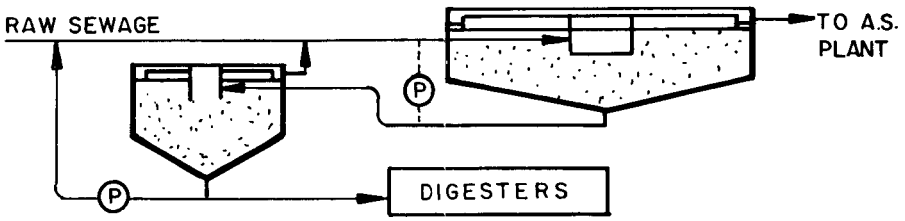

Figure 5
The activated primary sedimentation tank

flow plant in the USA (Barnard, 1974) that removed phosphates, as well as the success with plants such as Klerksdorp, Goudkoppies and recently also Baviaanspoort, a nominal retention time of 1 h is ample and may even be reduced.

The fermentation would then have to take place in a special fermenter leading to a treatment sequence that could be described as fermenation/anaerobic/anoxic/aerobic. The fermentation step could take the form of an activated anaerobic sludge plant, using the primary as the clarifier. However, it woud be more economical to make use of the existing units in the treatment plant and by a simple recycle loop, produce the fermentation products and elutriate them for use in the shortened anaerobic basin. For example, by discharging the underflow of the PST's to a gravity thickener and recycling some of the thickener underflow back to the PST's such that a sludge blanket is maintained in the PST's, the capacity of these units would be available for fermentation (Figure 5). The recycling has the dual purpose of maintaining the sludge blanket and elutriating the acids. Sludge should be removed from the system to the anaerobic digesters only when the sludge blanket is close to the surface of the PST's. One could control the production of the acetates to that required for the optimal operation of the plant by control of the recycle rate of sludge from the thickener to the PST. Under mild temperature conditions, no further fermentation would be required and if the production of VFA's is excessive, the sludge blanket could be lowered since this would return less additional COD to the activated sludge plant.

In the absence of a thickener, or in the case of Dortmund type tanks which serve as combined PST and thickener, a simple recycle of the underflow of the tank to the influent may be sufficient. The VFA concentrations in the underflow of a number of PST's are shown in Table 1.

TABLE 1
VFA CONCENTRATIONS IN THE UNDERFLOW OF PST's*

Plant	Volatile fatty acid concentration (mg/ℓ)
Vereeniging	2 300
Pretoria Daspoort East	2 100
Pretoria Daspoort West	1 900
Verwoerdburg	2 700
Olifantsfontein	1 800
Witbank	1 700

*i.e. of sludge discharge to digester, normally about 2 % of flow.

The COD:TKN ratio

Ekama *et al.*, (1984) used this ratio and the models developed at the University of Capetown (UCT) to show that under normal operating conditions, it would be most improbable to achieve phosphate removal in Bardenpho type plants of the ratio did not exceed 14:1 when the easily degradable COD of the influent is 20 % of the total COD. This was based on laboratory work and since phosphate removals to less than 1 mg/ℓ have been observed in many full-scale plants at ratios as low as 7:1 but seldom as high as 14:1, it is clear that what happens in real plants was not simulated by the laboratory units. The following plants achieve an effluent phosphate concentration of less than 1 mg/ℓ as P: Kelowna, Canada (Stevens, 1983); Palmetto, Florida USA (Digregorio, 1983); Goudkoppies (Osborn, 1983); Klerksdorp (Author); Potchefstroom (Nel, 1984); Harare – Firle (Marks, 1983); Harare – Growborough (Cox, 1984); Mutare – Zimbabwe (Marks, 1983); Bulawayo – Zimbabwe (Marks, 1983).

The five-stage Bardenpho plant in Kelowna (Stevens, 1983) treats primary effluent to which the supernatant from the thickener is returned. The following operational characteristics are typical.

	Influent	Effluent
COD (mg/ℓ)	270	25
Total nitrogen	30	2,5
Total P	4,5*	0,43*
Sludge age	25 to 30 days	
Minimum mixed liquor temp.	8 °C	

*Annual weighted average

The UCT model (Ekama *et al.*, 1984) when applied to the inputs to the Kelowna plant showed that it should be most improbable to remove all the nitrates to the levels that would be required to ensure that sufficient anaerobic conditions could be maintained, even at relatively high temperatures of 14 °C.

Experimentation at the Kelowna plant (Stevens, 1983), indicated that supernatant from the gravity thickener contained between 200 and 300 mg/ℓ VFA which enabled the plant to remove nitrates and phosphates even though the COD:TKN ratio was well below 10:1. The relatively low ratio could be overcome by converting some of the COD to the correct form of easily degradable fatty acids even if some of the COD is lost in the fermenting process.

Thus instead of using a long anaerobic retention time for mixed liquor, a similar retention time could be substituted by a

fermenting zone, followed by a short anaerobic zone for the mixed liquor. Furthermore, the reduction of the COD:TKN ratio by primary sedimentation is not important if in the process of doing so, fatty acids are produced, provided that the ratio does not drop below approximately 7:1.

The emphasis on high COD:TKN ratios led to the practice of feeding raw sewage to the nutrient removal plants resulting in high energy consumption and the production of about twice the amount of secondary sludge which is difficult to dewater. It is safe to design for primary sedimentation, provided that provision is made for feeding sufficient volatile fatty acids to the anaerobic basin of the plant.

The Pho-strip process

In the Pho-strip process (Levin *et al.*, 1972) reliance is placed on endogenous respiration for producing the necessary acetates for the growth of the phosphate removing organisms. Since the process is applied essentially to high rate systems, there should be sufficient absorbed organic matter to ensure that fermentation could take place provided that the anaerobic retention time is sufficient. However, in the process of producing acetates, the prolonged anaerobic conditions without stirring, result in massive secondary releases that cannot always be removed by uptake alone, hence the necessity for removing some of the phosphates through decanting of the supernatant, reducing the concentration to a level that could be taken up by the bacteria. The stripping and decanting and subsequent chemical treatment could all be eliminated if the secondary release could be reduced.

Easily biodegradable material vs volatile fatty acid concentration

In the fermentation process, the intermediate products are short chain fatty acids of which up to 70 % may be acetic acid. In the determination of the requirements for phosphates removal, Ekama *et al.*, (1984) suggested measuring easily biodegradable COD in the influent to the anaerobic basin as a means of predicting the ability of the plant to remove phosphates. Upon accepting the concept of a separation of the fermentation and anaerobic functions for phosphate removal, there is little incentive for using a parameter such as easily degradable material when there are routine tests such as for VFA concentration that could be performed in most laboratories. This would allow for the correlation between plant performance and VFA content of the influent.

Future plant lay-outs

During the early seventies power costs were so low that extended aeration plants seemed very attractive, even for large scale applications. Since then the cost of power has risen so steeply that shorter aeration times and primary sedimentation are again becoming economically attractive. In most parts of the country, one can safely design the activated sludge plant on a combined anoxic and aerobic solids retention time (SRT) of about 10 to 12 days and still ensure good nitrification in winter. When this is combined with a COD removal of about 35 % in the primary sedimentation tank, the aeration cost could be reduced by about half.

Futher optimization of the process

The effect of activated primary tanks on the dentrification rates need further study. While acetates are incorporated in the Acinetobater cells and would not be available for denitrification in the following anoxic basin, other intermediate products would be available and the time required for denitrification should be drastically reduced. If sufficient VFA's are produced in the primary tank, it may be advantageous to divert some of the settled sewage directly to the anoxic zone to improve denitrification.

The author is presently investigating the optimal removal of nitrogen and phosphates by bleeding a small fraction of the acetate rich influent to the second anoxic basin where these exist. If the theory is correct, a relatively small fraction will be sufficient to ensure that secondary release in these basins will be taken up in the re-aeration basin.

Summary and conclusions

- Observations seem to indicate two types of phosphate release mechanisms under anaerobic conditions, the primary release being due to acetate uptake and conversion in the cell to Poly-β-hydroxybuterate, and the secondary release being caused possibly by carbon dioxide developement, cell lysing or diffusion out of the cells.
- Only the primary release will result in the subsequent uptake of phosphates and although more phosphates will be taken up than released, the energy available to the cells may not necessarily be sufficient to take up all the primary and secondary released phosphates.
- It is therefore essential to limit the secondary release to a minimum and this could only be done by limiting the time that the return sludge is subjected to anaerobic conditions. However, this opposes the requirement for longer anaerobic periods for acetate fermentation.
- It is therefore suggested that the acetates be formed in a prefermenter in order that the anaerobic retention time for the activated sludge could be minimized.
- The preferred sequence for good phosphate removal in nitrification plants is therefore fermenter/anaerobic/anoxic/aerobic.
- *The activated primary sedimentation tank* is proposed, consisting of a simple recycle of PST or thickener underflow to the influent in order to build up an anaerobic sludge blanket in either or both of the tanks. The recycle will simultaneously elutriate the acids formed in the sludge blanket. The fermenting sludge, pumped back to the primary sedimentation tank, will 'activate' it in a somewhat similar way as recycled secondary sludge activates the main reactor. The level of the sludge blanket is controlled by wasting sludge to the anaerobic digester such that sludge is not spilled over the weirs to the main reactor.
- In existing full-scale plants, a survey by the author indicated that the volatile fatty acid concentration in the underflow of the primary sedimentation tanks range from 800 to 3 000 mg/ℓ, depending on the degree of thickening that is practised. In the Boviaanspoort plant, calculations by the author show that a solids retention time of more than 40 days can be accomodated in the existing Dortmund tanks.
- Observations in full-scale plants seem to indicate that the COD:TKN ratio is not important provided that there is a sufficient concentration of VFA in the influent to the anaerobic basin.

- The need for stripping in the Pho-strip process as opposed to Phoredox type processes arise from the massive secondary releases that take place when subjecting the activated sludge to prolonged anaerobic conditions. The acetate take-up is not sufficient for the removal of all the released phosphates and decanting is required to ensure the removal of all the phosphates.
- The activated primary allows the normal use of primary sedimentation tanks and anaerobic sludge digestion and unless the plant is quite small, there is no need for feeding primary sludge to the aeration basin. In a period of increasing energy cost, this reverts the process to very nearly the same footing as conventional activated sludge plants in terms of operating and construction costs.
- Current investigations of full-scale plants include the following:

  conversion of a number of full-scale plants to the activated primary concept (this information will be published as soon as it becomes available);

  the minimum requirements for anaerobic retention time for contacting the activated sludge with the acetate rich influent in order to minimize secondary release in this basin;

  the need to discharge a small fraction of the acetate rich supernatant to second anoxic basins for optimal nitrogen and phosphate removal in the light of even stricter standards for phosphates; and

  the optimal arrangement for maximum phosphate and nitrogen removal.

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