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ACTIVE FUMIGATION SYSTEMS: BETTER WAYS TO FUMIGATE GRAIN

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ABSTRACT

Although for many years phosphine (PH_3) has been used to fumigate grain in unsealed storages with static methods, such usage is not an acceptable option in any on-going fumigation strategy. In these methods, the source of PH_3 is simply added to the fumigation enclosure or admixed with the commodity, and the gas generated is allowed to permeate through the commodity naturally. At best, such methods will lead to an illusion of success by killing the mobile stages; at worst, they will promote the selection for PH_3 resistance. Other methods, such as "trickle-flow" or regular "top-up" of concentrations in storages that are not sealed, are equally unacceptable.

The development of SIROFLO®, an active fumigation technique designed for both sealed and unsealed storages, has brought into focus the question of fumigation strategies and the problem of whether or not some storages should be sealed. The choice of fumigation strategy can now be between static methods in sealed storages (other than vertical silos) and active methods in storages that are not gastight. An understanding of both the behaviour of gases and the factors that give rise to gas loss is of primary importance in examining this question. Other factors that will influence the choice include the geometry of the structure and the costs of the available options.

A new manifolded recirculation system called SIROCIRC™, that uses the engineering principles of SIROFLO® and achieves balanced airflows in silos that are less than gastight, is described, together with data obtained from recent trials. The relative merits of the alternative strategies are discussed.

INTRODUCTION

The fundamental requirement of fumigation is the provision an adequate concentration of fumigant for a sufficient period of time, a time that, in principle, will achieve a dosage or concentration × time product (Ct) that will kill all stages of all species present. This is a simple concept, but it is difficult to achieve, largely because most structures in which fumigations are carried out are not gastight. Although all recommendations for fumigation clearly state that the enclosure should be gastight, the great majority of fumigations worldwide are conducted in structures or enclosures that fall well short of the standard of gastightness that ensures dosages sufficient to kill all stages of all species present in an infested commodity (Winks *et al.*, 1980). Tablets or pellets that produce a peak phosphine (PH_3) concentration in about 1.5 d, and decay to zero in about 5 to 7 d, are used for many if not most PH_3 fumigations around the world. These parameters, however, are typical of concentration profiles in quite leaky storages in which the most that can be expected is a cosmetic fumigation giving the illusion of success. The susceptible adults and larvae may be killed, but the more tolerant eggs and pupae survive; within a relatively short time, the infestation returns to its prefumigation level. At this stage the fumigator, farmer or store manager, simply fumigates the commodity again, in the process selecting the population for resistance to PH_3. This constitutes the greatest threat to the continued use of this valuable fumigant (Winks, 1986; Winks and Ryan, 1990).

The most obvious approach to sound fumigation practice is to achieve a standard of gastightness that will retain the gas long enough to kill all stages of insects, including the more tolerant eggs and pupae. Banks and Annis (1984) among others have done much both to define standards of gastightness aimed at achieving this objective and to describe how such standards may be achieved in a variety of storages. However, these standards are not always sufficient. In themselves they do nothing to ensure adequate distribution of fumigant throughout the fumigation enclosure, and thus, in some situations, they fail to eliminate pockets of low concentration. This is because of the forces that give rise to gas loss, most importantly air ingress, and the forces that influence distribution.

This paper describes the forces that affect gas behaviour and fumigant distribution in grain storages and the benefits of active fumigation systems; it also describes a new fumigant recirculation method.

FORCES THAT AFFECT FUMIGATION OF GRAIN

The principal forces that give rise to air ingress are the chimney effect and wind. The forces that influence distribution are convection, diffusion and sorption. In this paper the chimney effect, wind and convection are discussed. Molecular diffusion is a minor force in terms of gas loss and distribution (Banks and Annis, 1984), and although sorption can be very significant in the fumigation of some commodities it is outside the scope of this paper.

The chimney effect

The "chimney effect" occurs as a result of temperature differences between the grain and the atmosphere surrounding a silo (Winks and Russell, 1994). In a silo in which the intergranular air is at a higher temperature than the air surrounding the silo, the lower density of the intergranular air creates a potential for the air within the silo to rise. This potential generates a pressure difference between the inside and the outside of a silo and in this case, with warmer intergranular air, the pressure at the base of the silo would be negative with respect to the outside of the silo. If the intergranular air was colder than that surrounding a silo, a positive pressure would be generated at the base of the silo.

To measure, or even observe, the maximum chimney pressure, a silo needs to resemble a bucket, either upright or inverted. In this case, there is measurable pressure but no flow, i.e. no ingress of air. In a real silo with cracks, etc., around the base and at the top, the temperature difference between the grain and the atmosphere surrounding the silo will determine the chimney potential, and the size of the cracks will determine the amount of flow into and out of the silo, i.e. the amount of air ingress. In turn, this determines the size of the pockets of low concentration in which insect survival can occur.

An example of the chimney effect is evident in data obtained by the pest control staff of the NSW Grain Corporation during the attempted fumigation of a number of sealed vertical bins at a site in southern New South Wales. PH_3 was "dumped" from cylinders into the base of the bins with fan assistance to drive the gas to the top of the bins; the fans were then shut off and the balance of the contents of the cylinders added to the base of the bins to try to compensate for the chimney effect. It is clear from Table 1 that there was either little or no gas in the bottoms of these bins within a few days, and the fumigation would thus have failed.

The sealing would need to be absolute to stop the ingress of air altogether by sealing cracks, etc. This is virtually impossible to achieve. Anything less for a given temperature difference will simply determine the size of the pocket of low concentration. When the grain temperature is consistently greater than (or less than) the temperature of the surrounding atmosphere, there will be a constant and significant ingress of air. There is thus a high probability of insect survival in the affected zones, either at the top or bottom of a silo depending on the direction of the chimney. An alternative to storage-sealing is application of positive pressure equal to the chimney effect (Winks and Hunter, 1994). The site referred to in Table 1 has been equipped with SIROFLO® which, because of the positive pressure it generates, has overcome the problems evident from the earlier data.

TABLE 1
The influence of the chimney effect on PH_3 concentrations (ppm) at the bottom of sealed bins at Wallendbeen following the dump method with cylinders of PHOSFUME

Bin no.	Day 3 (6 May 1991)	Day 4 (7 May 1991)	Day 6 (9 May 1991)
3	2100	1500	0
4	1350	1200	0
5	5[1]	1	0
6	0[1]	4000	0

[1]More gas added.

Wind

In substantial structures such as fixed silos, sheds, squat bins, farm bins, etc., wind is a relatively minor force in the context of fumigant loss or air ingress. It is more significant in temporary structures, such as bag-stacks and bunkers. From numerous field trials of SIROFLO® in which wind speed and wind direction were monitored, it would appear that wind would be a problem only if it causes air disturbance in the head space and turbulence in the surface layers of grain (Winks and Russell, unpublished data). This disturbance or turbulence is not difficult to prevent or overcome.

Convective distribution

Without the imposition of mechanical systems, air movement occurs within a grain mass as a result of thermal convection driven by temperature gradients throughout the grain mass (e.g. Nguyen, 1985). Simply put, warm air rises while cold air sinks. When grain is loaded into a silo, e.g. from trucks, it is to be expected that the loads will vary in temperature and this may lead to layers or pockets of different temperatures within the grain mass. These differences may be sufficient to induce movement of air within localized cells in the grain mass. In addition to this, the variations in temperature near walls and roofs will also induce convective movement of air within the grain mass. In sheds and squat bins it is commonly found that during the cool night hours the air in the grain adjacent to the walls will drop in temperature and, because of the higher density, will start to move downwards. At the same time the warmer air in the center of the grain mass, with its lower density, will start to move upwards. In a sealed bin the warm air rising out of the surface of the grain will be cooled against the roof above and drawn back into the grain in the area adjacent to the walls. This creates efficient convective movement of the air within the bin and relatively rapid distribution of fumigant. However, in a bin that has a leaky roof this same process is simply a variation of the chimney effect and it will cause loss of fumigant from the headspace through the roof, draw cool air from outside the silo down the walls of the structure and thus rapidly dilute the fumigant concentration.

Convective distribution can be eliminated or substantially reduced if the temperatures within the grain mass are evened out and the differences eliminated or substantially reduced. Cases have been documented in Australia which clearly demonstrated this phenomenon. In both cases the grain in large squat bins had been aerated which evened out the temperatures, and when fumigant was added to the headspace it largely remained there.

While most of the time convective distribution can be expected to provide the mechanism for effective distribution in sealed sheds, squat bins and farm bins, it cannot always be relied upon. The only methods currently available that can provide both consistent fumigant distribution and an acceptable probability of success are those based on active or forced distribution systems. In vertical storages, forced distribution is the only viable approach to effective fumigation. All other methods provide a lower probability of success and, usually, little more than a cosmetic fumigation and effective selection for resistance.

ACTIVE FUMIGATION SYSTEMS

The term “active fumigation system” is used here to describe any system in which another process is superimposed on natural gas distribution processes in order to improve distribution of fumigant or to overcome the ingress of air, which causes reduction of fumigant concentration, into the enclosure. By contrast, “static fumigation systems” are those in which the fumigant is simply added to the enclosure; the success of the treatment thereafter depends on natural processes, such as convection and diffusion, to distribute effective concentrations of fumigant throughout the enclosure. Static fumigation processes include both ‘one-shot’ and ‘multiple-shot’ (or top-up) techniques as well as those using simple ‘trickle flow’ from cylinders.

Active fumigation methods include recirculation and SIROFLO® (Winks, 1992). SIROFLO® is a pressurised distribution system aimed at overcoming the chimney effect. It has been implemented over the last 8 years in a wide range of storages, ranging from small farm bins to large horizontal or vertical storages, in Australia. While SIROFLO® is effective in poorly sealed units, including open-topped bins, and can overcome the chimney effect, conventional recirculation (Fig. 1) is effective only in sealed bins. Even then, success depends on the way the system is operated. For example, if conventional recirculation is carried out by operating the fans only to mix the fumigants, whereupon they are switched off, there is a high probability of the chimney effect’s producing pockets of low concentra-

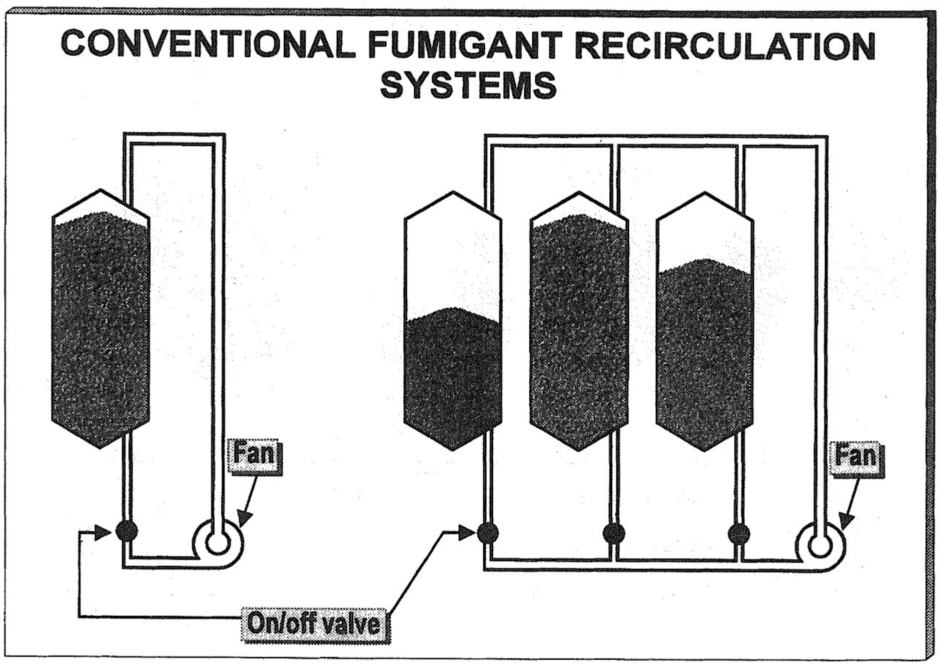

Fig. 1. Conventional fumigant recirculation in single bins or multiples of bins manifolded together.

tion in different parts of the bin, which part depending on the relationship between the grain temperature and that of the surrounding atmosphere. In sealed bins conventional recirculation can be effective if it is based on a continuous low-flow system. This implies flows, or recirculating fans, that will generate only low pressure differentials within the bin. If large fans, such as those traditionally used with methyl bromide recirculation systems (Bond, 1984), i.e. fans that produce an air change in a few hours, are used, the excessive pressures generated within the bin are likely to lead to fumigant loss and air ingress.

SIROCIRC™

A new recirculation method, called SIROCIRC™, has been developed. It employs the engineering principles of SIROFLO® and is designed for use in manifolded systems in which multiples of capped bins in any combination are fumigated concurrently (Fig. 2). Earlier methods of recirculation with manifolded systems (Fig. 1) are capable of achieving balanced airflows only in very symmetrical systems in which there are uniform back-pressures through each bin.

It seemed possible that the new method would allow for a degree of leakiness in addition to achieving a balanced flow through multiples of bins. To examine this

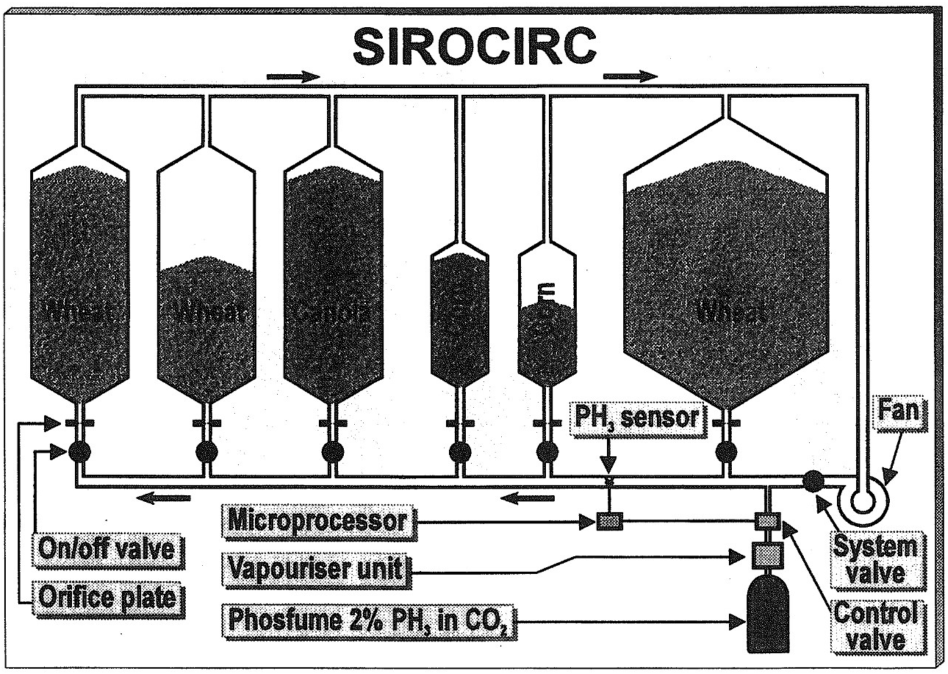

Fig. 2. SIROCIRC™, an active fumigation system, applies a balanced air flow to multiple bins manifolded together. Bins are not constrained by size, shape, commodity or bin-fill ratio.

possibility, a number of trials were carried out in three 50-t riveted-steel bins, purchased as gastight units, in which a pattern of leaks was established and the effects evaluated.

MATERIALS AND METHODS

During these trials temperature and pressure were monitored automatically at a number of locations within each of the bins and, in addition, ambient temperature together with wind velocity and direction were recorded. In the latter part of these trials, a PH_3 concentration was established and its decay rate monitored using a gas chromatographic method with an automated sampling procedure which took samples from all points within the grain of each bin and compared the response of a flame photometric detector to those with the response to samples drawn from a cylinder containing a reference PH_3 concentration. The detector responses for PH_3 were stored electronically and graphically on a chart recorder, and the electronic records were subsequently extracted into a Microsoft Excel spreadsheet.

For the most part, the input of PH_3 into the fumigation system was controlled using a newly-developed micro-processor control unit. The aim of these trials was both to examine how effectively a concentration could be maintained throughout these bins with different patterns of leaks and to examine the distribution of these concentrations through the bins. Leakiness was established progressively by ranging from no leaks in any of the three bins to the worst pattern of leaks tested (a 148-mm diameter hole in the top plus a 100-mm hole in the bottom of each bin).

The concentration of PH_3 was monitored in the inlet duct, the head space and at three depths within each of the bins. In addition, in one of the bins, PH_3 concentration was monitored at several locations around the periphery about 150 mm in from the wall.

RESULTS

PH_3 concentrations in all trials were found to be evenly distributed throughout the bins. The results obtained for the worst pattern of leaks are shown in Figs. 3 and 4. The fluctuations observed at points within the bins mirrored the fluctuations in the inlet concentration. Comparing the concentration profiles for sampling points within the grain shows that the distribution throughout each of the bins was remarkably constant and, more importantly, that the leaks created had little or no effect on either the concentration or the distribution of the PH_3. The leaks did, however, affect the rate at which PH_3 was introduced into the system. Even with the worst-case situation, however, there was only 72.3% of the usage rate for SIROFLO®. The usage rate for other leak patterns decreased with the magnitude of the leaks; with no introduced leaks in the bins, it dropped to 9% of the SIROFLO® rate.

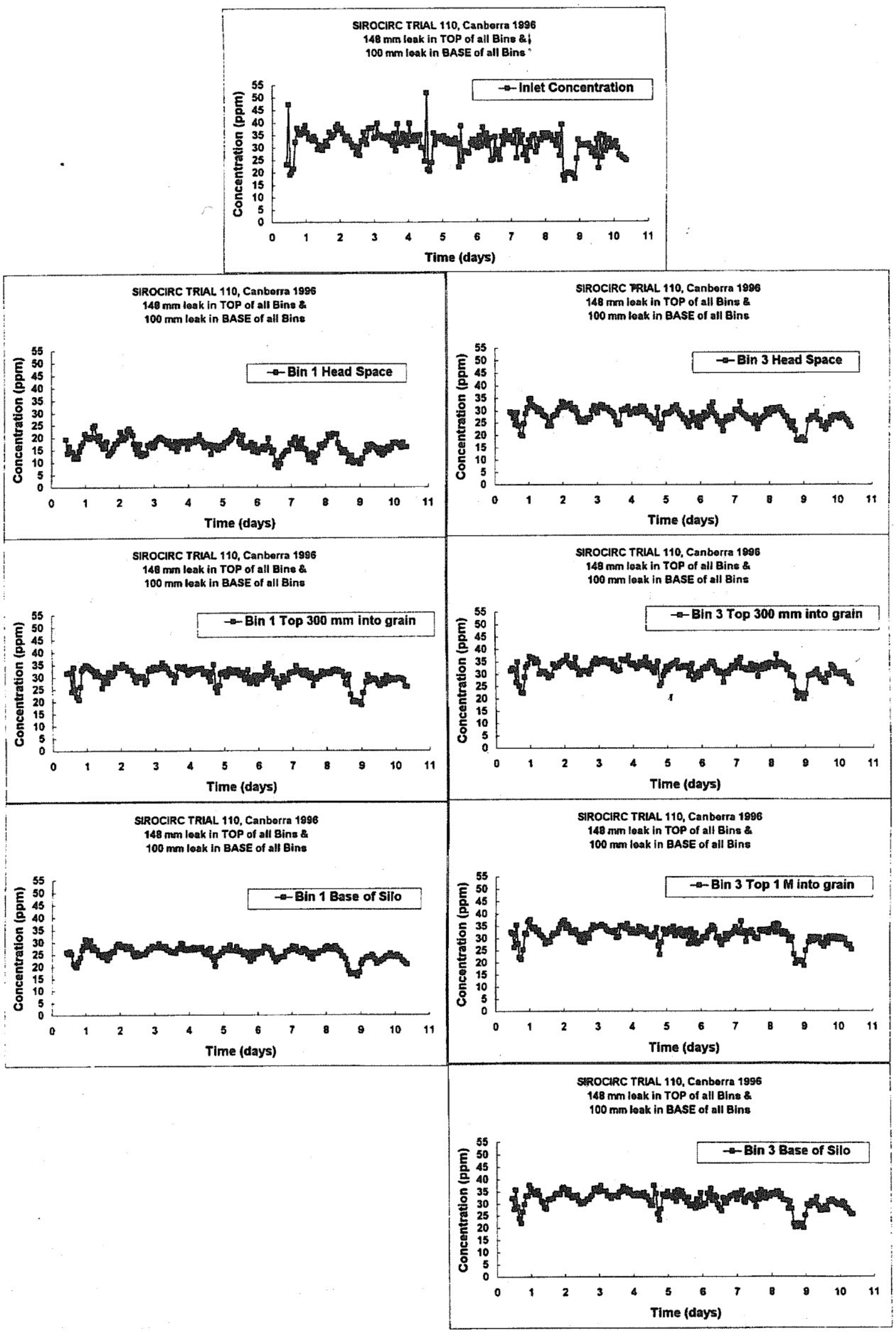

Fig. 3. PH_3 concentration profiles in bins 1 and 3, SIROCIRC™ Trial 110, Canberra, 1996.

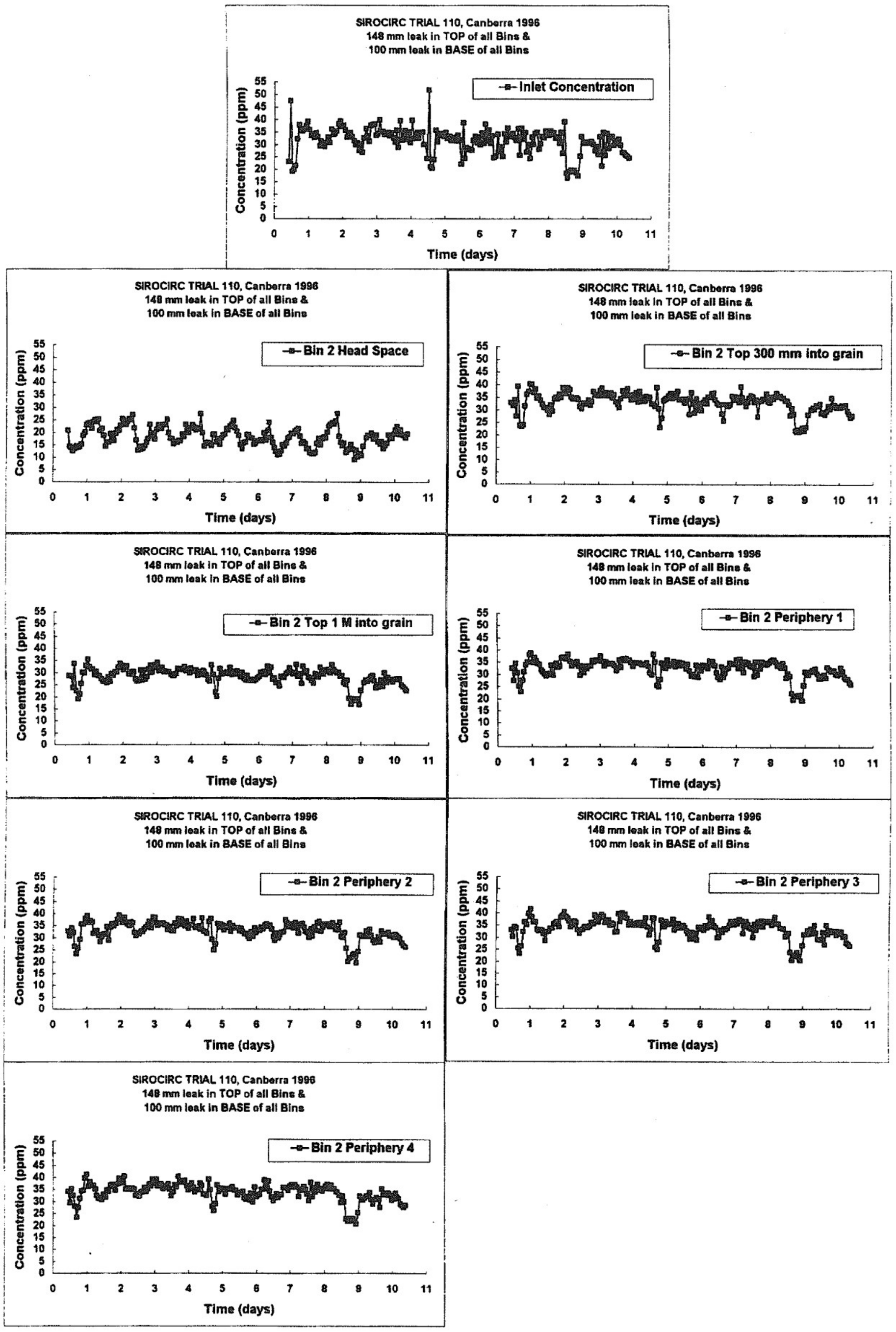

Fig. 4. PH_3 concentration profiles in bin 2, SIROCIRC™ Trial 110, Canberra, 1996.

DISCUSSION

SIROCIRC™ appears to provide an effective recirculation system in capped bins that fail to meet the gastightness standard. Compared with SIROFLO®, a substantial saving in gas can be achieved. In a 2,000-t vertical bin, the lowest usage rate achieved in these trials was equivalent to a cost of less than A$0.03/t. A further benefit of the system is that it substantially reduces gas emissions into the environment. It should be noted, however, that even with SIROFLO®, which is a flow-through system, emission levels are substantially below those currently set by any known environmental protection agency.

SIROCIRC™ has now been installed in a 25,000-t silo block at the GRAINCO grain export terminal at Gladstone, Queensland.

CONCLUSION

Because of the importance of the chimney effect on the effectiveness of fumigation and other gas processes, there is little doubt that active fumigation systems offer a higher probability of achieving efficacious fumigations in a wide range of storage structures. Moreover, this may be achieved in structures that are less than gastight with SIROFLO® and SIROCIRC™.

Static fumigation processes have an acceptable probability of success only in gastight structures, and then only in bunkers, sheds, squat bins and low-profile farm bins. In structures that are not gastight, and in all vertical silos, static fumigation can not be recommended as a means of achieving efficacious fumigation, and any such usage may significantly threaten the long-term usefulness of PH_3 by increasing selection for resistance.

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