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THE USE OF ON-SITE GENERATED ATMOSPHERES TO TREAT GRAIN IN BINS OR FLOOR STORES

C.H. BELL, S.T. CONYERS AND B.E. LLEWELLIN
Central Science Laboratory,
Sand Hutton, York, UK

ABSTRACT

A system available for on-site generation of low-oxygen (O_2) atmospheres for application to typical storage structures is described. The performance of a propane burner in generating and maintaining an atmosphere lethal to stored-grain pests has been evaluated in three bins and one small floor-store. Under reasonably calm conditions, a flow rate of 4.5 m^3/h was required to maintain an atmosphere of 1% or less O_2 in a bin containing 290 t of grain, compared with flow rates of 11.5 m^3/h for a bin loaded with 810 t of barley and 12 m^3/h for a bin containing 1,150 t of wheat. The 100-t bulk of floor-stored grain was held under a 1% O_2 atmosphere by a maintenance flow rate of 9 m^3/h. The results are discussed in the contexts of sealing problems and the effects on maintenance flow rates and application costs of both bin size and interruptions caused by windy weather or wide temperature fluctuations. A provisional dosage schedule, based on the current and previous work, is presented.

INTRODUCTION

Grain in the UK is stored mostly in either free-standing bolted metal bins or on the floor in barns constructed of either brick or galvanised steel. The proportion of grain admixed with pesticides at harvest has in recent years fallen to less than a third of the total; most grain is dried and cooled to reduce the incidence of spoilage and infestation. Phosphine fumigation of grain is carried out if an infestation is discovered and the nature of the storage structures used can cause gas-retention problems. Modified atmospheres (MA's) offer an alternative to both fumigation and pesticide-admixture strategies for insect control in stored grain. They can be easily integrated into present strategies of drying and cooling and could thus play an important role in the protection of grain, particularly where residue-free *in-situ* treatments are needed (Banks *et al.*, 1991).

Insects are susceptible to both high levels of carbon dioxide (CO_2) and very low levels of oxygen (O_2), although long exposures are required (Annis, 1987; Bell and Armitage, 1992; Banks and Fields, 1995). For MA's based principally on nitrogen (N_2) to work effectively, it is important to maintain the O_2 level below 1%, though Bailey (1955) and Reichmuth (1987) considered 2% O_2 a workable upper limit for the efficacy of MA's against most species. It is also important that the quality of the stored grain not be adversely affected by exposure to MA's. In this respect a N_2-based atmosphere is generally regarded as safer than CO_2. Neither germination nor end-use properties of wheat, rice and barley were affected by continuous storage in N_2 for one year (Ouye, 1984).

Propane combustion is a cost-effective method of producing an O_2-deficient atmosphere. It has the advantage of providing continuous on-site generation of gas, a vital aspect for treatment of most storage structures, but there is a disadvantage: the initial capital cost. Trials have been conducted for some years (Bell *et al.*, 1991, 1993a, b) with a self-cooling combustion unit, and an alternative system is also available in the USA (Storey, 1980a, b; McGaughey and Akins, 1989). Because the UK system does not require an energy-hungry electric compressor to run the cooling system, it is cheaper to operate. The unit needs only a 13-amp electrical supply and is therefore easily used in farm situations. Uncertainties still remain concerning the degree of modification required to render an enclosure suitable for MA's, the required gas supply rate and the full economic potential of the MA's (Banks and Fields, 1995). The results of our recent trials with MA's generated by propane combustion are here presented.

MATERIALS AND METHODS

The sites

Three grain silos of different sizes located on different silo complexes, plus a 100-t floor-store bay, were chosen for the trials. The bins were all constructed from curved sections of corrugated, galvanised steel. The sheets were bolted together using sealant at the joints, and then the sheets were mounted on a concrete base. Each base incorporated a series of aeration ducts (either hexagonal or a set of fingered ducts) fed by a single inlet and an auger. The latter was fed from a central opening and emerged from the silo base diametrically opposite to the aeration duct. The down pipe from the auger to the main conveying system was disconnected. A gastight polythene sheet was wrapped around the auger tube and drive motor and then taped to provide a leak-proof seal. This polythene sheet was then anchored to the side of the silo.

The tested bins were of 290-, 810- and 1,150-t capacity.

The propane burner

A propane-fueled inert atmosphere generation system, originally constructed by Aerogen Ltd., Alton, Hants, and modified at CSL, was used for these trials. The unit burned a calibrated premix of propane and air, with an optimal fuel to air ratio of 1:25 (v/v), in a closed combustion chamber. The resulting mixture of gases (primarily N_2, water vapour, CO_2 and O_2) was passed via a tightly coiled piping system through a water-based condenser, where it was cooled.

The condenser coolant which contained 50% ethylene glycol was cooled by an absorption refrigerator driven by waste heat from the combustion process. Most of the water vapour was removed as liquid. It was possible to control the amount of cooling required with a secondary heat exchanger fitted in the water-glycol circuit between the refrigerator and the condenser. This exchanger was fan-driven and the air was blown over radiator vanes. The air was sucked, via a large duct, from one side of an open-ended box placed over the warm exhaust draft from the refrigerator. Shutters in the sides of the box provided a means of control over the amount of warm air drawn in by the fan.

The generator was mounted on a road trailer 3 × 1.5 m. It was covered by a tarpaulin stretched over a frame to protect it from the weather and was open at the ends to allow good circulation of the surrounding air. Fuel gas was supplied from two banks of four 47-kg cylinders connected by an automatic change-over valve. The empty cylinders were changed as required to give an uninterrupted supply.

The generator was adjusted to give an output gas stream of less than 1% O_2, 12–13% CO_2 and <40 ppm CO, at about 50% relative humidity (r.h.), at each of the flow rates used in the trials. The maximum output of this low-O_2 atmosphere was about 20 m^3/h. The cool, dry gas mixture was fed to the silo, assisted by a small fan to overcome the back pressure of the grain, via a 5-cm-diameter flexible hose connected to the aeration duct of the silo. For this purpose a plate, featuring a central spigot to receive the flexible hose, was made to fit the dimensions of each duct opening. The output was measured by a flow meter which had to be read manually.

Monitoring the gas constituents and preparations for atmosphere application

All gas monitoring of the generator effluent content and the atmosphere within the enclosures was carried out using 2-mm nylon sampling lines. These were inserted into the grain by interconnecting 1-m lengths of rod in two columns, one at the bin centre and the other 0.5 m from the silo wall below the roof entrance hatch. The lines were located, in a cross pattern determined by the hatch's position, at 1-m intervals from a depth of 6 m to the surface and also at the sides on the surface. Lines in the floor-store covered various points and depths along a transept across the bulk. A line was also attached to the generator outlet and, in some of the trials, to the aeration duct.

Type T thermocouples were inserted into the grain to record temperatures throughout the trials. Attached to rods, they were pushed into the grain as close to the sampling profiles as possible. A further thermocouple attached to the mobile laboratory recorded the ambient temperature. The gas lines and thermocouples, fed out of the silos through the roof hatch, ran down to the mobile laboratory where they were attached to the analytical and recording equipment.

The grain surface was covered with a 70-micron-thick plastic sheet, the edges of which were buried in the grain (at the silo or bin wall) to improve gas retention. Wind was an important cause of generated atmosphere loss in trials carried out in silos in the open. Wind speed and direction were measured throughout these trials by an anemometer (Vector Instruments, Rhyl, Clwyd) which was mounted on a walkway above the silo or on the silo itself. The floor-store bulk was protected from the weather by being set up in the centre of a large shed, and wind speed was not monitored in this trial.

An automatic sampling system, which could be programmed to move through each of the sampling lines at a pre-set time interval (every 8 min) using a Psion Organiser II (Model LZ64), was used. A complete set of data from each position could be completed every 2 h. The samples were drawn down the lines using a diaphragm pump and were passed through a bank of instruments contained in the mobile laboratory. To allow the readings to stabilise, there was a 2-min delay before the data were recorded. The instruments were connected in series and consisted of a Series 1400 paramagnetic O_2 analyser, a Series 1400 infra-red CO_2 analyser, a Type 1490 infra-red carbon monoxide analyser and a Type 1491 nitrous oxide analyser coupled to a Model 1000D thermal oxidiser (all instruments by Servomex Ltd.). The data from each sample were collated using a HR2300 Hybrid recorder (Yokogawa Electric Corporation, Tokyo, Japan).

Assessment of the MA generation results

Every 2 h during the initial purge, and thereafter at least every 6 h, a record was made for each trial from each line and for each environmental condition. The efficacy of the flow in lowering O_2 levels was then assessed to produce a suitable purge rate and an achievable maintenance rate for each enclosure in relatively calm conditions. The maintenance rate calculation was made by taking a mean O_2 value from the beginning and end of each flow rate period and then subtracting the latter from the former. In order to achieve a more representative result, these calculations were made after the O_2 level of the generator output had been subtracted. These values were then plotted against the flow rate and a regression line fitted. A value for the maintenance rate was identified as the flow rate which produced no change in the O_2 level.

RESULTS

Micheldever (810 t malting barley)

For the initial purge, a rate of 15.6 m^3/h was used. The O_2 levels dropped rapidly, starting at the positions in the centre (1.5% O_2/h) and followed by those at the sides (0.6% O_2/h) opposite the aeration duct entrance and therefore furthest from the point of gas entry. There was no change in the rate of O_2 decrease at the side positions. However, following an initial O_2 decrease, at the centre there was a rapid increase. This increase in the central positions was then followed by another decrease, and over time a large oscillating cycle developed, particularly at the 6-m depth.

The source of this influx of O_2 was the cool, relatively dense night air pushing into the centre of the silo through the auger pipe. The atmosphere within the silo was very warm relative to the ambient air (Table 1). This large differential was caused by the warm,

TABLE 1
Temperatures and wind speed in the trials in free-standing grain bins

Conditions	Location Hursley (290 t)	 Micheldever (810 t)	 Linton (1,150 t)
Grain temperature (°C)	16.9 (16.2–17.7)	22.7 (22.4–22.8)	9.1 (6.9–9.8)
Ambient temperature (°C)	4.9 (–6.9–12.7)	10.6 (4.3–15.5)	6.5 (–2.8–13.2)
Wind speed (m/s)	4.0 (0.0–17.6)	3.0 (0.0–8.7)	8.0 (0.0–20.0)

post-harvest weather which had given little opportunity for the grain to cool. The lower density of the warm atmosphere within the grain facilitated its displacement. This occurred at night when the temperature difference was greatest. Sealing the auger more thoroughly after the first week removed this problem. However, the atmosphere in the silo had already dipped below the 3% O_2 level by this time and this extended period at the start meant that an accurate purge time could not be calculated.

Lower post-purge flow rates were tried to determine the maintenance rate which would hold the silo at a constant 1% O_2. The results from the O_2-content data at each of the flow rates showed that the maintenance rate for this silo was 10.8–12 m^3/h with a best estimate of 11.5 m^3/h.

Hursley (290 t wheat)

The purge started with a gas flow rate of 15 m^3/h. The smaller diameter and lower height of this silo meant that the MA reached the 6-m centre position almost immediately. However, analysis of the purge revealed that there was a slow decline in the entire silo, and the target of 1% O_2 was not achieved throughout the silo for a further 52 h (6.9 atmosphere changes). This was longer than expected and indicated that there was ingress of air from some source. Again the auger was implicated as the problem area and attempts were made to improve the seal.

After the initial purge further flow-rate adjustments were performed to find a suitable maintenance rate for the low-O_2 atmosphere. This was hampered by occasional increases in the wind speed which affected the collection of results obtained under otherwise calm conditions. Ambient temperature was also a factor which influenced the trial, as below-freezing temperatures were recorded which caused large temperature differentials (Table 1) and resulted in an increase in the O_2 content within the silo, particularly near the grain surface. The final phase of the trial assessed the rate at which O_2 increased in the silo after the flow was turned off. The maintenance rate was estimated as 4.5 m^3/h.

Linton (1,150 t wheat)

The initial purge-flow was 19.2 m^3/h. The 1% O_2 level was reached after 72 h, meaning 2.4 total changes of atmosphere within the silo.

Further changes were made in flow rate, starting with 15.6 m^3/h, to discover a maintenance rate. The lowest flow rate tested was 12 m^3/h. After 36 h, representing 0.75 atmosphere replacements at this flow rate, there was no change in O_2 levels at any point. This indicated that the maintenance rate was lower than this value. However, because subsequently a very high level of wind was experienced during the trial, this was the best estimate of the maintenance rate for this silo (Table 1). As the mean wind speed rose towards 15 m/s, the O_2 level at the sides of the silo rose rapidly.

Sevenhampton (100 t wheat in a small floor-store bay)

The purge to less than 1% O_2 throughout the bulk was achieved within 48 h by a flow rate of 14 m^3/h (6–7 atmosphere changes of the enclosure). The atmosphere was adequately maintained by a flow rate of 9 m^3/h of burner gas containing 0.6% O_2.

Relating the required maintenance flow to silo size

Figure 1 shows the three values for maintenance flows for 1% O_2, produced by the three above-described silo trials, compared with three others from past work with MA generators (Bell *et al.*, 1991; 1993a, b). A regression line (solid line, Fig. 1) fitted to these data gave an R^2 value of 0.824 with a slope of 0.522, as compared to 0.757 ($R^2 = 0.956$) for the above three bins. This would imply that the maintenance flow rate required for the bins can be related to their surface area rather than to their volume. The predicted maintenance rate for a 100-t bin from the regression line was 3.55 m^3/h, and for a 1,000-t bin, 11.8 m^3/h.

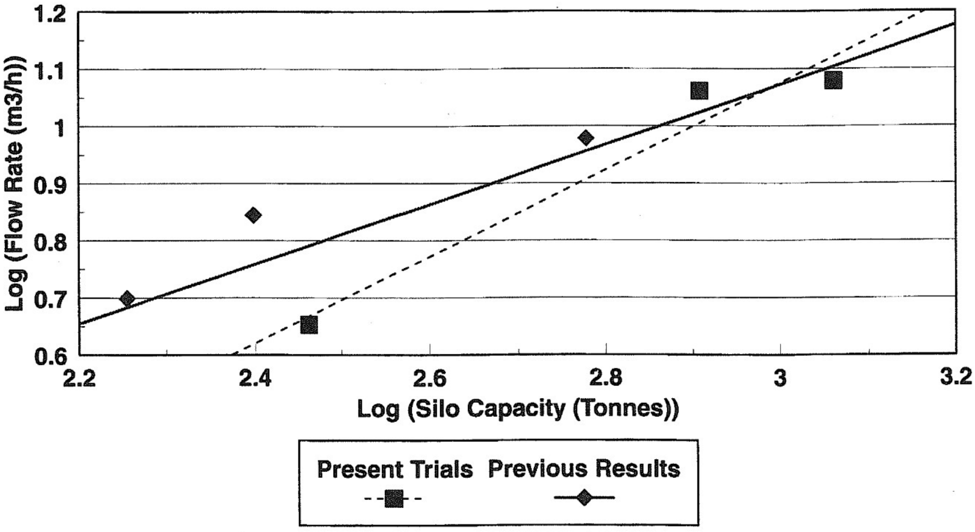

Fig. 1. Relationship between silo capacity and maintenance flow rate to hold a low O_2 atmosphere.

DISCUSSION

It has been shown before that for an efficient purge in MA applications, it is important to have as high a flow rate as possible (McGaughey and Akins, 1989; Bell *et al.*, 1993a). The present results showed that any source of leaks could greatly extend purge times. As far as ingression of air was concerned, the auger inlet to the silo was found to be an area of weakness during the purging operation. The best result was obtained with the 1,150-t bin at Linton, purged at 19.2 m^3/h, which needed only 2.4 atmosphere changes to achieve 1% O_2 at all points.

The results from the floor-store indicated that a low-O_2 atmosphere could be maintained by a flow rate which approximated that necessary to hold an equivalent level in a silo of about 5 times its capacity. Such treatments would of course be more costly than those for bins, but the enclosure volume in this initial trial was increased by the need to sheet over the high grain walls, creating dead spaces amounting to about 25% of the total volume, which reduced purge and maintenance efficiency. In other situations, the volume treated, and hence treatment costs, could be substantially reduced.

Although maintenance flow rates for retaining MA's in grain bins are affected radically by any changes in the prevailing weather conditions, the size of the grain bulk is also important. Because of the relation between volume and surface area, it can be expected that, for maintenance of a low-O_2 atmosphere, doubling bin volume will increase surface area, and hence the flow rate to counteract leakage, by 1.59 times (Bell *et al.*, 1993a). The four-fold difference in volume between the bins at Hursley and Linton indeed gave almost the expected two-and-a-half times increase of the maintenance flow rate needed to maintain 1% O_2. The maintenance rates required as silo size increased from 290 to 810 to 1,150 t represent 0.75, 0.60 and 0.51 changes in atmosphere per day, providing further support for the theory that maintenance flow rates become more economic as silo volume increases.

Comparison with earlier work (Bell *et al.*, 1991, 1993a, b) indicated that some improvement had been achieved in the seal level obtained on the bins at Hursley and Linton; the points lay below the fitted regression line for maintenance flow rates in the bins tested to date (Fig. 1). The outlying value of 7 m^3/h for a 250-t silo was extrapolated from the data generated by that trial (Bell *et al.*, 1993b) which was, in fact, carried out on a similar silo at the same site as the present 290-t silo trial. Therefore, the extrapolated flow rate may have been set too high. However, differences in the effectiveness of joint seals in different silos may alter the maintenance rate attainable even in two silos of similar size.

The gradient obtained for the regression line fitted to data from six bins sealed with differing degrees of success was lower than that expected for a volume surface area relationship, and in fact was intermediate between this value ($b = 0.6691$) and that expected for a volume linear dimension relationship ($b = 0.3346$). This provides some evidence that having restricted the potential sites of leakage as much as possible by the sheet edges buried in the grain around the perimeter of the bins, the potential minimum maintenance flow rates required were more closely related to a linear dimension, such as bin circumference or diameter, than to surface area.

The decreasing number of per-day atmosphere changes with increasing silo size is reflected in the cost per t for the treatment. Taking a treatment purge at maximum flow rate and a 4-week run under the estimated maintenance flow for each silo, the expected UK£ cost per t in terms of propane consumed would be 36, 24 and 17 pence (actual consumption 0.35, 0.90 and 0.94 kg propane/h) for the three sites, in ascending order of tonnage, plus a small, constant electricity cost for running the burner. However, these figures may over-estimate the minimum costs per t because the results for both the Hursley and Linton trials were maximum estimates of the required maintenance rates.

The cost results presented are estimates for calm weather conditions and do not take into account the possible changes in conditions which might cause a rise in the O_2 level. Some interruptions can be withstood without the need to increase exposure times beyond those normally required to produce 100% mortality in certain grain-pest species (Conyers and Bell, 1997), although further work is necessary to define the critical length of such interruptions.

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