Sealed Storage of Bag Stacks: Status of the Technology

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Abstract

The potential of permanent sheeting for long-term storage of bag-stacks has been suggested for many years, but practical experience with the technique has not always matched expectation. A simple and reliable system of bag-stack sealing previously reported was tested for reliability at several locations in Southeast Asia. These tests have demonstrated that the technique makes it possible to reliably store dry grains for long periods after a single initial treatment with either carbon dioxide or phosphine. Grain quality was never any worse and normally better than that stored using conventional bag-stack methods. Data from these trials have provided the basis for implementing the method with carbon dioxide, and a set of preliminary recommendations for its use with phosphine. The enclosure must be sealed to give a pressure halving time of >10 min and ideally >15 min. A single dose of 1.5 kg CO_2 per tonne will then give a concentration >35% CO_2 for >15 days, the concentration regime needed to kill all insects. With phosphine, the dosage requirements are harder to define. However, in weakly sorptive grains such as milled rice and maize, a dosage of about 1 g PH_3 per tonne appears to be adequate for a complete disinfestation. The phosphine dosage required to disinfest potentially sorptive commodities, such as paddy, may have to be determined on the basis of the observed phosphine concentration and redosing if necessary. Using the recommendations on sealing and dosing it is possible to routinely and reliably maintain dry bagged grains for long periods in a good condition.

THIS paper gives a brief review of the development of sealed bag-stack technology from its early use to its current form, and discusses the current status of the technique. The review highlights recent developments and experience with the technique, and shows how it has changed in status from being somewhat unreliable, to a standard pest and quality control procedure ready for routine use.

The first extensive use of sealed bag-stack technology in Australia, and possibly in the world, was in the period 1917–1919. By modern standards the technique was cumbersome. The enclosures were made of wooden sheeting and sealed with bituminous materials. Low oxygen atmospheres were piped into the enclosures from a coke-fired producer gas plant (Winterbottom 1922). While these treatments were at least partly successful, they were in no way reliable (Ratcliffe et a203. 1940).

It was not until the second world war that further extensive sealed stack treatments were again carried out. These treatments, in enclosures of soldered flat iron, were with carbon bisulphide, ethylene chloride/trichloroethylene and, experimentally, with methyl bromide (Wilson and Gay 1946). They reported success in reducing the number of insects but not in eliminating infestations. In these early studies the level of sealing was not tested and it is likely that there were still many leaks in the 'gastight' enclosures. Neither a perfect disinfestation nor insect-proof storage was possible because of these leaks.

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A new impetus was given to sealed stack technology when the gaseous fumigants methyl bromide and phosphine became widely used with advent of more convenient plastic gas-proof sheeting. Initially, the sole reason for sheeting was to retain gas for long enough to kill insects, not to form an insect proof barrier. In fact, immediately after fumigation the sheets were removed, either to minimise the number of sheets needed or due to concern that sheeting would lead to excessive moisture migration. The process became widely used and known as 'fumigation under gas-proof sheets'. In this process, a more-or-less defined procedure could be followed to give a high-degree of insect kill (e.g. Brown (1954) and, more recently, Anon. (1974)).

Later. it was realised that, because of the high level of kill achieved, if the sheets were left in place, the commodity should remain free from infestation for a long period without further treatment. Several workers (Anon. 1959; Prevett 1962; Hyde and Kockum 1963; Halliday et al. 1968; McFarlane 1980) tried to make use of this. The practical results, however, did not match the theoretical expectation. Generally, these workers found that the procedure was not reliable; reinfestation occasionally occurred and moisture migration to the stack surface appeared to be encouraged. The reasons for these problems were hard to identify, but the four most likely causes were:

1. inadequate gas retention, thereby allowing some insect survival
2. incomplete barrier to reinfestation
3. excessive moisture migration caused by localised heating due to the metabolic heat of insects that are progeny from 1 or 2 above
4. excessive initial moisture content.

The first three of these possibilities could be eliminated if the enclosures were totally sealed.

Development of controlled atmosphere (CA) technology for bulk grain led to systematic studies on the causes of gas loss from large sealed structures. The increased knowledge of gas processes from these studies was used in the formulation of recommendations for the use of CA for the storage of bulk grains (Banks and Annis 1977) and for recommendations concerned with upgrading the practice of phosphine fumigation in Australia (Winks et al. 1980; Williams et al. 1980). An important aspect of these sets of recommendations is that a high standard of gas-tightness is essential to ensure reliable treatment. This was true also for phosphine, a fumigant formerly considered suitable for use in unsealed or partially sealed systems.

It has since been shown that treatments based on these recommendations work reliably when: sealing had passed a pressure test; correct dosage had been applied; and problems with distribution of gas had been overcome (e.g. Banks and Annis 1984). In many commercial treatments it became clear that the high level of gastightness also conferred a substantial degree of 'insect-proofness' on the enclosure (Banks et al. 1980).

Initial attempts to reproduce this in sealed bag-stacks failed, because the enclosure used for 'fumigation under gas-proof sheeting' (see Anon. 1959) produced neither a reliable nor a testable seal. The method of sealing to the floor, using sand-snakes or similar means, could not survive pressure testing. It was therefore impossible to assess the level of sealing objectively before gas addition. The only methods of assessing sealing were by measuring gas concentration during the treatment period or indirectly by observing the level of mortality in bioassay of naturally occurring insects. Concentration measuring was rarely carried out and it is extremely difficult to interpret insect mortality as a quantitative measure of sealing. In the few papers where there were adequate concentration data to be able to calculate a gas-loss rate, the rates calculated would have been too high for carbon dioxide treatment (Annis et al. 1984), and were often too high for effective phosphine fumigation (e.g. Cogburn and Tilton 1963). A plastic floor-sheet used in conjunction with various ad hoc sealing methods, such as self adhesive tapes and rolling sheets together, was also unsatisfactory (Annis and Graver 1986).

The problem of overcoming the unreliability of sealing and producing a sealed bag-stack enclosure that could be pressure tested was overcome by fabricating a PVC cover sheet tailored to fit closely to the stack and sealing this to a PVC floor-sheet with a PVC cement. This type of enclosure was used as the basis for assessing the feasibility of using carbon dioxide treatment as a preliminary to long-term sealed storage of bag-stacks in sealed enclosures. These trials, carried out in Australia, Indonesia and Papua New Guinea (Annis and Graver 1986), along with independent work in China using polyethylene sheeting (reported by Rånnfelt 1980), showed that the method was technically feasible and could be economical over a range of conditions. The Indonesian workers proceeded with further trials and subsequent commercial treatments with milled rice, and their experiences have been reported previously (Anon. 1984) and elsewhere in these proceedings (Nataredja and Hodges 1990).

Australian workers, in collaboration with others in Malaysia, Thailand and the Philippines, further investigated the technique to test its reliability and range of applicability. These trials form the basis for the rest of this paper. Several specific aspects of this work have been reported previously elsewhere.

Method

Bag-stacks of milled rice, paddy and maize were treated with carbon dioxide in sealed plastic enclosures using the method of Annis et al. (1984). Some stacks were treated with phosphine using a modification of this method, by the technique described by Sabio et al. (1990). Treatments were carried out in a range of sites in Malaysia, the Philippines, and Thailand. The treatments are summarised in Table 1. During these trials, specific attention was directed at pressure testing, gas concentration, insect numbers, and changes in quality. Specific methodologies for measurement of quality and insect infestation are given elsewhere (Annis et al. 1987; Esteves et al. 1988; Gras et al., in press). The results of quality and insect data will be reported in only general terms. The main discussion here will be on the pressure test and gas concentration results.

Pressure testing was carried by observing the time for a negative pressure difference, with respect to atmospheric, to decay from approx. 200 Pa to half the initial value. In several cases this was much longer than an hour. On these occasions, an extrapolation of a logarithmic pressure decay curve was used to approximate the halving time. Applied CO_2 doses were measured by difference weighing of the gas supply cylinders. On most occasions, gas was added until the carbon dioxide concentration at the top of the stack was at least 70%. However, a few stacks were dosed at a predetermined low dosage rate of about 1.0 kg per tonne. The phosphine treated stacks were dosed with 1–4 g PH_3 per tonne.

Gas concentration measurements were made from at least two parts of the stack; one near the top and the other near the bottom. These were taken at appropriate intervals; daily at the start of the treatment and reducing to weekly towards the end. Carbon dioxide concentration was estimated using Dräger carbon dioxide detector tubes. A diluting chamber was used when concentrations were above 60%. Phosphine concentrations were measured directly with Drager phosphine detector tubes.

Regression analysis of concentration with time was carried out on both logarithmic and reciprocal transformed average carbon dioxide concentration (Annis et al. 1984, Appendix 2) give the rationale for these transformations]. The regression equation for the transformation of best fit was used to calculate the concentration at 15 days. The concentration at 15 days was then fitted as a function of pressure test and dose using a generalised linear model computer package GLIM.

Table 1. Sources of data from sealed bag-stack treatments referred to in this paper.

Country/ commodity	Treatment	Stack size	Number of treatments	Storage period
Malaysia				
Milled rice	CO_2	215 t	15	3–13 months
	PH_3		3	
Philippines				
Milled rice	CO_2	290 t	5	3–12 months
	PH_3		2	
Paddy	CO_2	190 t	17	3–12 months
	PH_3		6	
Maize	CO_2	240 t	10	3–12 months
	PH_3		2	
Thailand				
Milled rice	CO_2	70 t	9	3–6 months
	PH_3		4	
Previously reported comparable trials:				
Indonesia				
Milled rice	CO_2	177 t	4	1–4 months
Australia				
Milled rice	CO_2	108 t	1	1 month
Totals	CO_2		61	
	PH_3		17	
Grand total			78	

In the case of phosphine concentrations, only two statistics were calculated: the regression analysis of the decay curve and calculation of the concentration at 10 days.

Results

Quality and Insect Infestation

Results from these trials are very extensive and will be presented in detail elsewhere when full statistical analysis is complete. Results from the work on maize stored in the Philippines have been presented both for carbon dioxide (Gras et al., in press) and for phosphine (Sabio et al. 1990), as have results for milled rice in Thailand (Sukprakarn et al. 1990). The most detailed analysis has been completed on the results of the carbon dioxide treated stacks.

In summary, the quality results indicated that, over a wide range of quality parameters, long-term storage in sealed bag-stacks produced a better commodity at out-turn than conventional storage for the same period. However, quality deterioration was not totally arrested by this form of storage and some 'ageing' of the product occurred. Some moulding was found in one stack in Malaysia, in which there was also some degradation of quality. The data so far analysed from the phosphine treatments indicate that quality preservation of the commodity is equivalent to that obtained from carbon dioxide treatment.

Insect control was always good: in no case was a stack more than very lightly infested at the end of the storage period. Ten stacks in the Philippines contained very low numbers of *Sitophilus zeamais, S. oryzae,* and *Rhyzopertha dominica,* almost certainly the result of insects seen boring into the stacks (Sabio and Graver 1986). One stack in Thailand contained a few psocids close to a small hole in the seal at ground level. One stack in Malaysia had a single bag infested with *Sitophilus* spp. This bag was next to a known leak at the top of the stack. All the phosphine-treated stacks have so far demonstrated excellent insect control, i.e. there were no apparent survivors and there has been no reinfestation.

Pressure Tests

A wide range of pre-treatment pressure-test results were observed. These varied between pressure halving times of 6 and 270 minutes. A minimum of 10 minutes was the target. This was easily exceeded with new sheets, but as sheets were re-used, greater sealing and inspection efforts were required to achieve this target.

Concentration Decay Rates

Carbon dioxide. The logarithm and the reciprocal of concentration were always well correlated with time ($r^2 > 0.8$) and it was usual for one of the correlations to be better than the other, sometimes very much so. The best correlation, based on the highest r^2, was used to calculate the carbon dioxide concentration at 15 days.

Of the treatments so far analysed, 42 retained concentrations of 35% or more at 15 days and 12 less than 35% at 15 days. A calculation of the concentration axis intercept needed to give a concentration of 35% carbon dioxide at 15 days gave an intercept of close to or above 100% for 6 of the treatments not meeting the 15 day > 35% target.

Phosphine. The course of phosphine concentration decay with time was very much like that of carbon dioxide, except the loss rates were both higher and much more variable between types of commodities (see Table 2) and, in the case of paddy, with either time after harvest or the number of fumigations.

Table 2. Loss rate of phosphine from sealed stack fumigations.

Commodity	Date treated	Loss rate per day	S.D.
Paddy	Dec 1987	0.538	0.074
	Mar 1988	0.254	0.039
	Jun 1988	0.178	0.023
Milled rice	Feb 1988	0.037	0.002
	Jun 1988	0.072	0.021
Maize	Jun 1988	0.125	0.062

The concentration target for phosphine fumigation for commodity above 25°C is 7 days > 100 mg/m^3 (Annis 1990). A concentration of > 100 mg/m^3 at 10 days was used to assess these trials to allow for the release rate of phosphine from the phosphide preparation and to ensure distribution throughout the enclosure. Calculation of the concentration at 10 days gave values of less than 100 mg/m^3 for 7 stacks of more recently

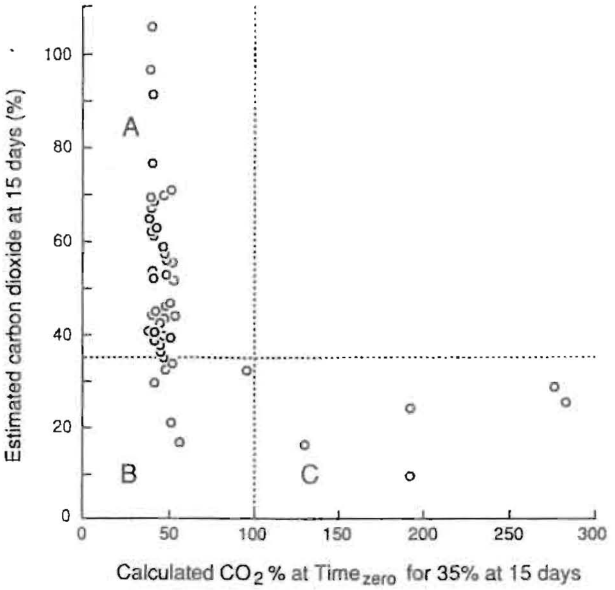

Fig. 3. Estimated CO_2 concentration at 15 days compared with the calculated concentration required at the start of treatment to give a concentration of 35% CO_2 at 15 days. Data from the CO_2 treatments referred to in Table 1.

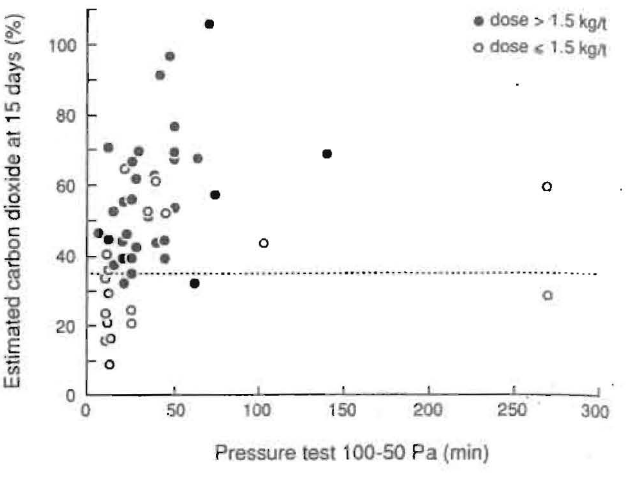

Fig. 4. Estimated CO_2 concentration at 15 days compared with pressure tests showing the influence of high and low dose rates. Data from the CO_2 treatments referred to in Table 1.

where C_{15} is the carbon dioxide concentration at 15 days, P is the pressure test halving time, in minutes, for 200–100 Pa, and D is the applied dose in kg per tonne. A plot of this equation (Fig. 5) shows this relationship over a range of useful values. It is clear that doses below 1.0 kg per tonne are not useful and it is only over 1.5 kg per tonne that the required pressure test is reasonably easy to obtain (average pressure test in this study 40.9 min). The data of Annis et al. (1984) imply a value of 1.48 m^3 per tonne for the ratio of gaseous volume to mass in a sealed sheeted bag-stack of milled rice (this includes the billowed volume of the newly purged enclosure). At 30°C this is the equivalent of 2.56 kg of pure carbon dioxide per tonne of commodity at the start of the treatment. On the basis of the average concentration decay observed in these trials, an average initial concentration of 45.96 ± 4.83% CO_2 was required to give an average concentration of 35% in 15 days. This is the equivalent of 1.18

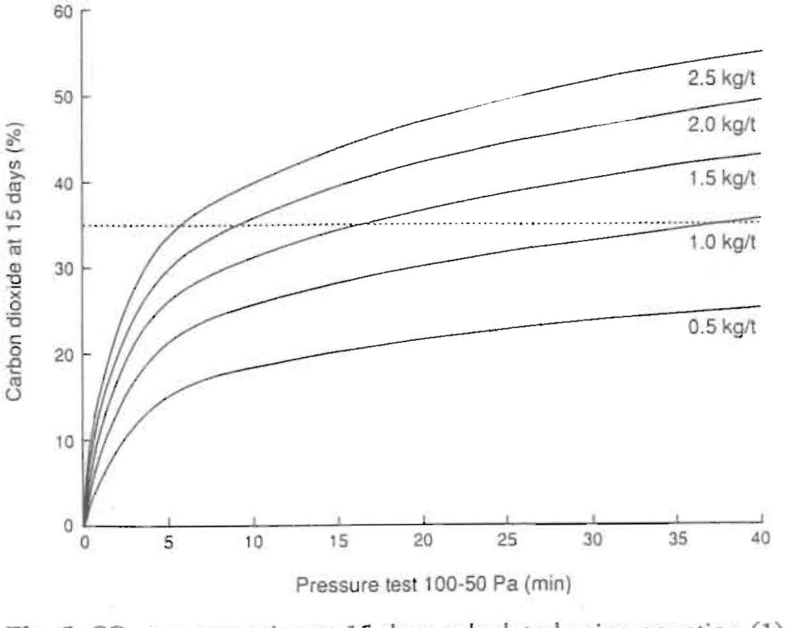

Fig. 5. CO_2 concentration at 15 days calculated using equation (1) to show the combinations of pressure tests and dosages needed to give the required concentration of 35% CO_2.

kg per tonne, a value very close to that derived from Figure 1 for a pressure test of 40 min.

The practical implications of these results are that, in the case of treatments with carbon dioxide, there can be some trade-off between the amount of gas added and pressure test achieved, but this is only true within small limits. Equation 1 is based on tonnes of commodity. Dosage rates based on an enclosed volume are sometimes preferred. However, it is very difficult to estimate the true gas volume within a sheeted stack that changes its volume with gas addition, whereas the mass of grain in a stack is almost always known. Calculations based on mass are both easy to make and useful for economic evaluation of the method.

Equation 1 gives only a best estimate of the dosage rate required and is useful for planning and analysis of results. The actual dosage of carbon dioxide in any treatment has to be established during that treatment by observing the concentration at the top of the stack during gas addition. Carbon dioxide addition is continued until the concentration at that point exceeds approximately 70% CO_2.

Dosage levels with phosphine are not nearly as well established and there are no simple initial concentration criteria. It is clear that, with weakly sorptive commodities (milled rice, and to a lesser extent maize), a dosage of 1 g PH_3 per tonne is more than adequate for sealed stack fumigation. In the case of paddy, there is no easy answer. From the data, paddy appears to be both highly and variably sorptive, particularly when first fumigated or recently harvested (see also Banks 1990). On the basis of the observed concentrations dosages of up to 10 g PH_3 per tonne may be required. It appears that at present the only way of ensuring a sound phosphine fumigation of paddy is an a posteriori method: that is, treat the paddy, measure the concentration, then if necessary treat again with the dosage appropriately adjusted.

Conclusions

After an initial disinfestation with either carbon dioxide or phosphine, sealed bag-stacks can provide safe insect-proof storage for long periods. This can be carried out in a plastic sheet enclosure sealed to an achievable pressure test (goal > 15 min, minimum 10 min halving time). Paddy, milled rice, and maize require a dose in the range 1.5 to 2.0 kg of carbon dioxide per tonne. To some extent, lower levels of sealing can be tolerated but at the expense of higher dosages. It is not possible to establish a unique phosphine dosage, as it appears that this is determined by both the commodity type and its provenance. However, a dose of 1.0 g per tonne should be enough for non-sorptive materials, although this may well eventually be found to be excessive in some cases.

There appears to be no quality, technical, or scientific reason to prevent sealed-stack storage now being considered a routine treatment option when used with carbon dioxide, dry commodities and indoor storage. Outside these three restrictions, its use must be still considered a developmental technique. While not enough is known about phosphine dosage requirement to give the same status to this kind of treatment, its use is bound to be a great improvement on current practice and further development of the technique should be encouraged.

There is nothing magical about sealed stack storage. It will be subject to failures, but if adequate care is taken these should be few and far between. In order to operate sealed-stack storage to its maximum advantage, good housekeeping, hygiene and rodent control remain important. Indeed, they become more important but perhaps easier to carry out.

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