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Sealing a farm silo for insect control by nitrogen swamping or fumigation

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Summary—A bolted galvanized iron silo (21.5 t) was sealed using a polyvinyl resin formulation (1624 White) sprayed onto joints from the inside. Gastightness was assessed by pressure decay and static pressure tests. The silo was loaded with wheat into which cages of insect-infested wheat, thermocouples and gas sampling lines, were introduced. Oxygen levels were reduced to <1% by purging with nitrogen, and similar levels were then maintained by a slow nitrogen bleed for 35 days, after which the silo was emptied. All adult insects were dead but, as expected, some immatures survived since the maintenance period was too short to ensure complete kill at the observed grain temperatures (generally <15°C). The silo was reloaded, resealed and tested again for leaks. Some leaks were found and sealed with silicon rubber. Gastightness was not as good as before, though the silo would still be suitable for fumigation. Further sealing would be required however, if nitrogen were to be used efficiently (maintenance rate of 0.2 $m^3 t^{-1} day^{-1}$).

Sealing achieved was sufficient to permit use of nitrogen or fumigants but sealants cost $132 and labour a minimum of $280, representing an overall cost of $19.16 t^{-1}. This would still be cheaper than buying a new silo of suitably gastight construction at a cost of at least $28 t^{-1}.

The incidence of resistance of stored grain insects to maldison and development of cross resistance to other insecticides has now reached the stage where there is an urgent need for the Australian grain industry to adapt existing storages to enable grain fumigants and physical control methods to be used effectively. Grain protectants that may be substituted for maldison for admixture with grain can be expected to prove effective only in the short-term.

Many farmers use aluminium phosphide tablets for phosphine fumigation of infested grain in silos. Usually little or no attempt is made to seal silos for fumigation and this results in only partially effective fumigations and exposure of insects to sub-lethal doses of phosphine, which may lead to development of resistance (Bell *et al.* 1977; Bond and Upitis 1973).

Problems of sealing a small silo for fumigation or for physical control techniques are greater than for a large silo, for a leak equivalent to a given hole size has a greater overall effect in a small silo. If an effective and economical technique can be developed to seal a small farm silo, it will be of considerable benefit to farmers and may also be of use to bulk grain handling authorities when considering the technical problems to be overcome in sealing large storages.

An experiment was therefore carried out at the Rutherglen Research Station, north-east Victoria, to determine if a farm silo could be sealed effectively and, if so, whether nitrogen swamping in such a sealed silo would be an economic technique for disinfesting grain under these conditions. The duration of the experiment was limited by a prior commitment to sell the grain.

Materials and methods

A farm silo was sealed and pressure tested to determine the level of gastightness achieved. It was then loaded with wheat containing caged insects for bioassay. Gastightness of the silo of wheat was measured and oxygen levels reduced to < 1% by purging with nitrogen, and similar levels were maintained by a slow nitrogen blend for 35 days after which the silo

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was emptied. It was then reloaded and pressure tested to assess effects of grain transfer on the sealing. An identical silo was left unsealed and untreated, but loaded with wheat and caged insects to provide a control for comparison.

Silos and sealing procedure

Two 21.5 t silos, each of bolted galvanized iron with welded cone bases, were used in the study. There were numerous gaps between the metal sheeting, the largest being between the roof and walls, and around the roof hatches. One silo (control) was left in this condition, while the other (experimental) was sealed using the material 1624 White, a polyvinyl resin spray. The formula of 1624 White consists of a mixture of polymerised vinyl resins mixed with several solvents and plasticisers, including dioctylphthalate, methylisoleutylketone and acetone. The resin manufacturer (Union Carbide) claims that when used under correct conditions the resins and solvents would not become a component of food, nor cause vinyl chloride monomer to become a component of food, and they would conform with all existing and proposed FDA food additive regulations.

Prior to sealing, any loose rust along internal bolted or welded joints was removed, and any large gaps between the wall sheets were filled with plaster. At the top of the silo there was an iron cylinder in the centre of the roof to which the roof sheets were attached and through which grain could be loaded into the silo. Bolts were welded to this cylinder so that a steel plate incorporating a pressure release valve, gas sampling lines and thermocouple cables, could be attached. Fitted into the basal cone of the silo for introduction of nitrogen was a ring shaped copper manifold (18 mm i.d.) with 37 holes (2.4 mm diameter at 203.2 mm centres along its underside).

Joints inside the silo were sprayed with successive coats of 1624 White. Incorporation of a webbing compound with the sealant enabled the gap (max. width 25 mm) between the roof and walls to be sealed. The gap between the iron cylinder at the top of the silo and the roof could not be sealed in this manner. Instead, a collar of nylon reinforced PVC sheeting (750 μ thick) was used to bridge the gap and sealed in position using the sealant. Two manholes in the roof, closed by loose fitting metal covers, were covered with PVC sheeting on the inside and sprayed with the sealant. A bagging chute on one side of the silo was sealed on the inside with a metal plate secured to the wall, and sprayed with sealant. The auger chute at the base of the silo was covered on the outside with nylon reinforced PVC sheeting and sealed in position.

Once sealing was completed, the steel plate containing a pressure release valve (set for 1500 Pa) was bolted to the top of the silo and sealed with Silastic silicon rubber.

Gastightness was then measured, the steel plate was then removed and the silo loaded with wheat containing insect cages and gas sampling lines. The plate was resealed into position and gastightness again assessed before the nitrogen treatment commenced. After 35 days the silo was opened and emptied of wheat. Later the outloading chute was resealed with the PVC sheeting and 1624 White applied with a paint brush. The silo was loaded with wheat, the steel plate at the top replaced, and gastightness tests carried out to determine how well the sealing materials had withstood the abrasive and other forces involved during loading and emptying. Gastightness was considerably reduced and soap solution was used to detect leaks. A few minor leaks were found in the silo walls and sealed with silicon rubber. Major leaks were detected around the roof hatches which had been sealed on the inside with PVC sheeting and 1624 White. The metal hatch covers were removed and the roof to PVC joints sealed with silicon rubber and the hatches replaced. These leaks probably resulted from workers climbing over the roof while sampling grain and operating taps on gas sampling lines.

Tests for gastightness

Gastightness of the silo was first assessed by a static pressure test (Banks and Annis 1977) by using a centrifugal fan connected to a linear flow meter and thence to the gas manifold of the silo. The air intake of the fan was restricted to give different flow rates which were measured by the linear flow meter, and different static pressures in the silo measured using an inclined manometer. When this test was completed the steel plate at the top of the silo removed, the wheat augered in until only about 1.6 m^3 of headspace remained. The plate was then resealed in position and the gastightness of the silo assessed by a pressure decay test (Banks and Annis 1977). The silo was pressurised to 900 Pa using nitrogen from a cylinder and the rate of pressure decay observed using an inclined manometer. The test was repeated three times. A static pressure test was not carried out after the silo was loaded because the equipment required for this test was not available by the time loading was complete. Both types of pressure test were used to assess durability of the silo sealing materials after the nitrogen treatment trial.

Measurement of oxygen levels and temperatures in the silo

To enable oxygen concentrations and temperatures to be measured, holes were drilled in the walls of the silos and gas taps (to which sampling lines were attached) and thermocouples inserted (figure 1 and table 1). Any gaps around the taps and thermocouples were sealed with silicon rubber. Gas piping attached to the taps protruded about 10 mm into the silos and the pipe ends were covered with wire gauze to prevent grain from entering the sampling lines. The gas lines and thermocouples were led into a monitoring shed where the gas samples were periodically assessed using a Thermo-lab electrolytic oxygen analyser and the thermocouples linked to a multipoint recorder that operated continuously during the experiment.

Bioassays

Ten calico bags, each containing 1 kg of wheat infested with all stages (some of which were dead) of *Rhyzopertha dominica* (F), *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst), were introduced into different regions of both silos during loading. A dowelling pole (3.25 m × 0.013 m × 0.013 m) with attached gas lines, thermocouples and 5 wire gauze cages containing 4 g of wheat infested with adults of a strain of *R. dominica* (CRD 118) resistant to maldison and dichlorvos, was pushed down the centre line of each silo. Locations of gas lines, thermocouples, bioassay bags and cages are shown in figure 1 and table 1.

After 35 days storage the wheat was emptied from both silos, the bioassay bags and cages were retrieved, and their contents sieved for adult insects, which were assessed as living or dead. Wheat from the bags and cages was retained and incubated at 27±1°C and 65–70% R.H. for 10 weeks, after which it was sieved for adult insects that had developed from immature stages in and amongst the wheat grains.

Nitrogen generation and purging

Nitrogen purging was carried out from a road tanker and 52.1 m^3 of nitrogen was introduced into the experimental silo over a period of 3 hours. The silo gas manifold was then connected to a nitrogen maintenance system designed to maintain oxygen levels below 1%, as advocated by Banks and Annis (1977). Nitrogen from a portable liquid container, holding 88 kg of liquid nitrogen giving 103 m^3 of gas at NTP was passed through a vapouriser and thence

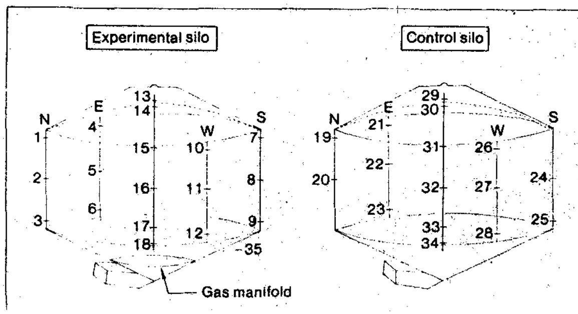

Figure 1—Location of observation points in experimental and control silos.

TABLE 1

Testing equipment located at observation points in the experimental and control silos.

Observation points	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35†
Thermocouple	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*					*		*					*	*
Gas sample line	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*			*	*	*			*	*	*	*		*				
Insect bag	*	*			*			*	*		*		*		*	*		*	*	*		*		*	*		*		*		*	*		*	
Insect cage															*	*	*	*												*	*	*	*	*	

† The Thermocouple at observation point 35 measured ambient air temperatures.

to the silo. The system was required mainly to compensate for gas loss resulting from diurnal temperature variation in the headspace. During the experiment excessive amounts of nitrogen were used, due to numerous leaks which had developed in the vapouriser. Subsequently the vapouriser was by-passed and it was found that the system could still operate successfully.

Results and discussion

Gastightness measurements

Results of pressure testing of the experimental silo are given in table 2 (static pressure tests) and figure 2 (pressure decay tests). In table 2 values for the slope (n) and the intercept (b) were calculated from the log flow (Q) and log pressure (P) according to the equation given by Sharp *et al.* (1976). Correlation coefficients (r) are also given. Gastightness data obtained after the silo was sealed and before loading commenced (August 9, 1976) were too variable to enable a line to be fitted, as indicated by the low r value, but it is nevertheless clear that the greatest degree of gastightness was achieved at this time. In the second pressure test on November 23, 1976, after the silo had been loaded, emptied and reloaded with wheat, gastightness was considerably reduced. After leak testing and further sealing with silicon rubber the gastightness was improved (November 24, 1976), but not to the same level as originally obtained.

TABLE 2

Leakage rates of experimental silo calculated from static pressure tests. See text for explanation of symbols.

Test	$Q = b\,P^n$ $10^6 \times b$	n	$10^3 \times$ air leakage rate at 125 Pa	Correlation coefficient (r)
			$m^3\,s^{-1}$	
Aug. 9, 1976 Before loading	0.00596	1.845	0.044	0.797
Nov. 23, 1976 Loaded, roof hatch leaks undetected	12.17	0.853	0.746	0.999
Nov. 24, 1976 Loaded, roof hatch sealed	2.25	1.060	0.376	0.995

Results of the pressure decay tests (figure 2) were inconclusive. The level of gastightness of the silo was greater after it was first loaded with wheat and resealed (August 10, 1976) than after subsequent loading (November 23, 1976), although the differences in pressure decay rates were not significant at $P < 0.5$. The pressure decay rates before (November 23, 1976) and after additional sealing (November 24, 1976) were almost identical.

It is not possible to compare directly the results of the static and pressure decay tests for gastightness obtained in August 1976 with those in November 1976, since the relative gastightness of the silo on August 10, 1976 after filling with wheat and final sealing is not known.

Nitrogen treatment

Physical conditions within the silos during nitrogen swamping are shown in table 3. The higher grain temperatures in the control silo were attributed to an infestation of *R. dominica* known to be present in the grain.

Nitrogen consumption during purging was 2.4 $m^3\,t^{-1}$, which is higher than the 1.1 m^3 estimated by Banks and Annis (1977) to be sufficient. The faulty vapouriser undoubtedly resulted in considerable nitrogen leakage during both the purge and maintenance phases (table 3), resulting in considerably more nitrogen being used than expected. Nonetheless, the

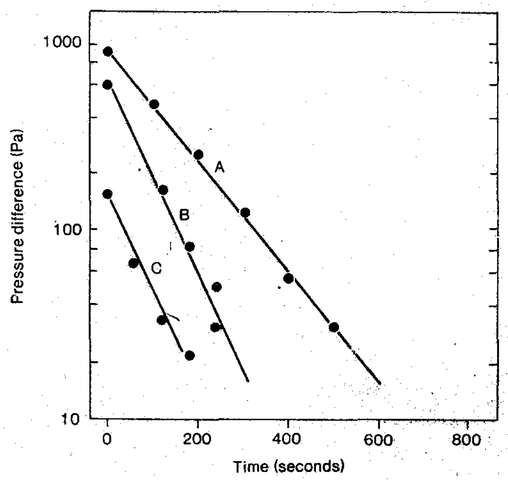

Figure 2—Results of pressure decay tests on experimental silo after sealing and loading with wheat. A. *Silo of wheat, August 10, 1976.* B. *Silo after emptying, reloading with wheat and resealing, November 11, 1976.* C. *Silo after additional sealing of roof hatches, November 11, 1976.*

TABLE 3

Physical conditions occurring during nitrogen swamping of a 21.5 t silo filled with wheat.

Variables	Silo			
	Control		Experimental	
Silo volume (m^3)	28.9		28.9	
Headspace volume (m^3)	1.6		1.6	
Gas volume after filling† (m^3)	13.9		13.9	
Grain moisture content (% *wet basis*)	12.5		12.5	
Temperature range (°C)				
Ambient temperature	−2.5	20.0	−2.5	20.0
Silo periphery‡	2.0	22.0	−3.6	37.7
Silo headspace	−2.5	41.7	−2.1	36.2
Silo centre	20.0	21.5	11.0	13.5
N_2 consumption (m^3)				
Purge phase			52.10	
Maintenance phase			226.73§	
Total consumption			278.83	
Duration of phases				
Purge phase (*hours*)			3.0	
Maintenance phase (*days*)			35	
O_2 after purge (range) (%)				
Silo periphery	20.0	21.9	0.1	1.30
Silo centre	20.0	21.9	0.1	1.10

† Interstitial gas volume taken as 45% of volume occupied by wheat.

‡ Excluding headspace.

§ Initially maintenance N_2 supplied via leaky vapouriser (14 days at 9.67 m^3 day^{-1}); thereafter vapouriser by-passed (21 days at 4.35 m^3 day^{-1}).

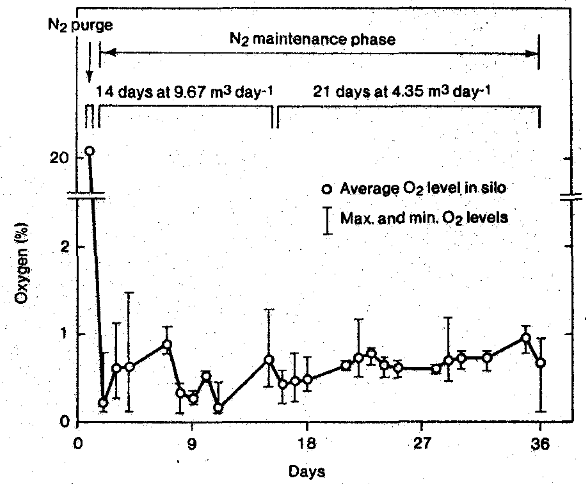

Figure 3—Oxygen levels in experimental silo during nitrogen swamping trial.

desired level of 1% oxygen in nitrogen was probably reached within the 3 hour purge time, with oxygen levels at most locations (figure 1) being held below 1% during the maintenance phase (figure 3).

Bioassays

The trial period had to be limited to 5–6 weeks because of prior commitment for sale of the wheat. This period would be expected to be long enough for the treatment to kill the test insects at temperatures of 20°C (Bailey and Banks 1975; Lindgren and Vincent 1970; Storey 1975). Wheat temperatures in the experimental silo (table 3) were, however, much lower than 20°C, and the relatively stable temperatures at the centre of the bulk (11.0–13.5°C) were so low that exposure for >24 weeks would be required to eradicate insects (Banks and Annis 1977).

Bioassay results (table 4) were of particular interest because of the low temperatures, for no study has been published on effects of oxygen depletion on insects at temperatures as low as those encountered in this experiment. Most grain bulks are not thermally homogeneous and it is useful to have some knowledge of effects to be expected if the temperature of part of the bulk falls below that on which the exposure period is based.

Adults of all three species, *R. dominica*, *S. oryzae* and *T. castaneum* exposed to the nitrogen treatment were all dead (table 4), a result which might be expected on the basis of extrapolation of data obtained by Harein and Press (1968) for *T. castaneum* and by Lindgren and Vincent (1970) for *S. oryzae*.

Some immature insects survived the treatment as was expected, for it is known that most immature stages are more tolerant of low oxygen levels than are adults and that tolerance of adults, and hence probably immature stages, is greatest at low storage temperatures (Bailey and Banks 1975; Lindgren and Vincent 1970; Storey 1975). Incubation of bioassay wheat resulted in very few *T. castaneum* adults being reared from immature stages in either silo, but for *R. dominica* and *S. oryzae* the number of adults reared from immatures in the experimental treatment was far lower than in the control (table 4).

TABLE 4

Effects on stored grain insects of exposure to an atmosphere of 0.1 to 1.3% oxygen in nitrogen for 3 days at an average temperature of approx. 12.3°C†.

Measurement	Bioassay cages (4 g)				Bioassay bags (1 kg)			
	R. dominica (CRD118)		*R. dominica*		*S. oryzae*		*T. castaneum*	
	Silo		Silo		Silo		Silo	
	Experimental	Control	Experimental	Control	Experimental	Control	Experimental	Control
Total no. adult insects at end of experiment	257	218	538	855	3697	4367	513	601
No. alive	0	85	0	446	0	1528	0	270
Total no. adults emerging from wheat after 10 wks incubation	15	286	54	2555	591	3242	2	1
No. alive	11	262	20	1939	499	2331	0	1

† Bioassay cages and bags contained wheat infested with all stages of the insect pests used; some dead insects were present in this wheat at the start of the experiment.

Cost effectiveness of sealing and nitrogen treatment

This study has demonstrated that a small farm silo can be sealed, using 1624 White and silicon rubber, to a degree of gastightness sufficient to permit the use of controlled gas atmospheres for insect control. The level of gastightness achieved would also be expected to be adequate to permit very effective use of fumigants.

The estimated costs for sealing the silo, and for the nitrogen used for the controlled atmosphere storage of wheat in the silo, are given in table 5.

The costs of the sealant 1624 White and the labour for its application are very high at \$19 t^{-1}. If the farmer provided the unskilled assistance and the costs were discounted over several years (accepting that some resealing would be required annually at minimal cost), there would be some reduction, but the cost would still remain high. Although the material made a good seal, costs involved make it unlikely to be used as a general commercial treatment for bolted metal farm silos unless a system can be devised to enable the farmer to do all the application work himself and discount labour costs. However, if in the future it were essential for effective fumigation or controlled atmosphere treatment to be carried out on a farm, e.g. if the farm were quarantined because of a persistent grain insect infestation, then sealing an existing silo in this way would be much cheaper than purchasing a new suitably gastight silo, made of either welded steel plates or of galvanised iron with the joints filled with sealant during manufacture; estimated cost being at least \$28 t^{-1} for a 21.5 t silo.

The reduction in gastightness observed after the silo was subjected to loading, emptying and reloading with wheat indicates the need to test for leaks before carrying out a fumigation or controlled atmosphere treatment. The level of gastightness achieved on November 24, 1976 after such leak testing and sealing with silicon rubber was suitable to allow effective fumigation, but further treatment with 1624 White or silicon rubber would probably be required to permit nitrogen to be used at the rate of 4.35 m^3 day^{-1} (as achieved in the experiment) during the maintenance phase.

The cost (*ca* \$5 t^{-1}) of the nitrogen treatment was higher than expected due to the excessive wastage of gas from the faulty vapouriser. Improvements in the gas introduction system would clearly reduce the amount of nitrogen lost and thereby lower costs. The most economic maintenance rate achieved in the trial required use of 4.35 m^3 of nitrogen per day at a cost of \$1.74. The maintenance phase would need to last for 2–3 weeks under favourable conditions with grain temperatures of 26°C or above; longer exposure periods would be required at lower temperatures (Banks and Annis 1977).

It is clear that the nitrogen technique is far more expensive than fumigation, and would probably be

TABLE 5

Costs (1977) for sealing a bolted galvanized iron farm silo (21.5 t), for controlled atmosphere storage of grain using nitrogen.

Factor	$
Sealing	
Materials	
1624 White	118.00
Nylon-reinforced PVC sheeting, silicon rubber;	14.00
Labour†	280.00
1 trained operator and 1 unskilled assistant	
Total cost	412.00
Cost t^{-1}	19.16
Nitrogen	
Hire of portable liquid container (PLC) of 88 kg capacity on annual basis	41.20
Basic N_2 cost m^{-3}	0.40
Delivery charge for PLC (metro Melb.)	8.50
Nitrogen for purge phase (52.1 m^3)	20.84
Nitrogen for maintenance phase	
14 days at 9.67 m^3 day^{-1}	54.15
21 days at 4.35 m^3 day^{-1}	36.54
Total cost of N_2 (excluding PLC hire)	111.53
Cost t^{-1}	5.19

† Cost of labour for sealing includes no allowance for travelling or possible accommodation charges.

used only if there were serious objections to fumigant residues in the grain or if fumigant resistant strains of insects developed. The recommended rate of aluminium phosphate tablet application for a bolted steel silo is six tablets/tonne, and the cost of tablets to fumigate the experimental silo at this rate would be $17.50 (a tube of 30 tablets costs $3.50). The recommendation for bolted steel silos assumes a lesser degree of gastightness than in the experimental silo, which would be at least equivalent in gastightness to a welded steel silo and would thus require only two tablets/tonne at a total cost of $7.00. Thus, the sealing procedure though costly, should ensure good conditions for effective fumigation.

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