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LONG TERM SEMI-UNDERGROUND HERMETIC STORAGE OF GRAIN

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ABSTRACT

Two trials, here called the Cunningar and Narrabri trials, were carried out to investigate the feasibility of long term (> 10 yr) storage of grain in underground and semi-underground structures. In the Cunningar trial 104 tonne of wheat, about 12.5% moisture content (w.b.) was held for 10 yr in a specially constructed, semi-underground, sealed concrete storage. The design was modelled on the semi-underground Argentinian stores constructed in the 1940s. In the Narrabri trial 160 tonne of wheat, about 9.3% m.c., were held in a polyethylene-lined, earth-covered semi-underground bunker for 34 yr. No infestation was found at outturn in either trial, but insects were added in one trial (Cunningar) to assist reducing the interstitial oxygen content rapidly to insecticidal levels and in the other (Narrabri) the grain was initially treated with malathion and later with phosphine.

Oxygen, carbon dioxide, temperature and relative humidity were recorded during the storage and at final outturn. In the Cunningar trial, oxygen levels fell to <2% after addition of infested grain as an oxygen absorber. Carbon dioxide levels remained low (<3%), presumably because the new concrete in the bins absorbed the metabolic CO_2. In the Narrabri trial, oxygen levels fluctuated from about 8 to 18% over most of the trial, but were low (<2%) at outturn. The low oxygen level was associated with water ingress late in the trial. This also resulted in some grain loss (30 tonne contaminated out of 160 tonne load).

Acceptable loaves could still be baked from the wheat after 10 yr of storage, but not after 35 yr. Falling number values were very high (>900 s) and the grain was not viable.

Key words: postharvest systems, long term grain storage, non-chemical alternatives, hermetic storage, modified atmospheres.

INTRODUCTION

Two long term grain storage trials are described here – the Cunningar and Narrabri trials. Both systems were intended to operate as hermetic stores. The first trial, the Cunningar trial, was initiated by S.W. Bailey. He was concerned over the use of chemical treatment of grain even at that time (the late 1950s) and sought to apply the basic knowledge of the mechanism of hermetic storage that he (Bailey, 1955, 1956, 1957, 1965) and Oxley and Wickenden (1963) had gained, to give a modern, functional and 'non-chemical' method of grain preservation. The second trial, the Narrabri trial, was carried out to determine the suitability of the then recently-developed, Australian earth-covered bunker system for long term storage of grain.

Neither trial provides a true example of pure, dry grain, hermetic storage, as in both cases there was intervention that altered the system. In the Cunningar trial, insects were intentionally added to accelerate the removal of oxygen. In the Narrabri trial, the wheat used was treated on inloading with malathion and the bunker was later fumigated with phosphine after mechanical damage to the seal was detected. Oxygen levels in this trial were not sufficiently low (i.e., <2%) to cause rapid elimination of insect pests. However, both trials provide data on oxygen loss and trends in quality changes during long term storage in systems that could probably be used for true hermetic storage. There is very little good contemporary information on this subject, apart from the studies of Burrell (1980) and Pixton (1980).

THE CUNNINGAR TRIAL

Background

Bailey's studies (1955, 1956, 1957, 1965) had shown that insect pests of stored grain could be killed by atmospheres containing less than 2% oxygen and, furthermore, that such atmospheres could be generated by holding infested grain in gastight systems under laboratory conditions. He also showed that it was the lack of oxygen and not, as then believed, the elevated CO_2 levels which eliminated the pests. He also noted that the quantity of product consumed and damage caused by the insects under fully sealed conditions was very small, with about 500 g of wheat starch per tonne of wheat stored metabolised to create the insecticidal conditions.

S. W. Bailey had constructed in 1960 an airtight silo approaching the size of commercial operations to investigate hermetic storage at a scale greater than under laboratory conditions. Storages incorporating the hermetic storage principle have been used in many parts of the world for centuries (e.g., Sigaut, 1980). Of particular interest at the time were the storages installed by the Ministry of Agriculture in Argentina (see Hyde et al., 1973), in which cereals had been stored successfully for periods in excess of 6 yr. These partly subterranean pits consisted of concrete walls up to ground level with an arched brick cover and were fairly easily rendered airtight. A design based on the Argentinian stores was chosen for construction of the store at Cunningar, NSW.

Design and gastightness of the storage

The storage contained two cells each of about 50 tonne wheat capacity, constructed of sprayed, reinforced concrete, and covered with an airtight seal, consisting of four layers of bituminised felt, each sealed to the next with hot bitumen, then a further coverage of sprayed concrete. The two cells had an ovoid cross section with an arched roof and had a common wall separating them (design shown in Fig. 1).

The effectiveness of the door seals and level of gastightness of the cells was checked using a tracer technique. About 3 m^3 medical oxygen was released into each empty cell, raising the oxygen level therein above atmospheric. Regression analyses on oxygen concentration with time showed leakage rates for the western (Near) and eastern (Far) bins of 1.9 and 4.2% d^{-1}, respectively, showing the Near bin to be well sealed, but the Far bin to be somewhat more leaky.

After modifications to reduce condensation problems on the metal inloading hatches, pressure tests for both the Near and Far bins for 500-250 Pa decay was 2 min 5 s.

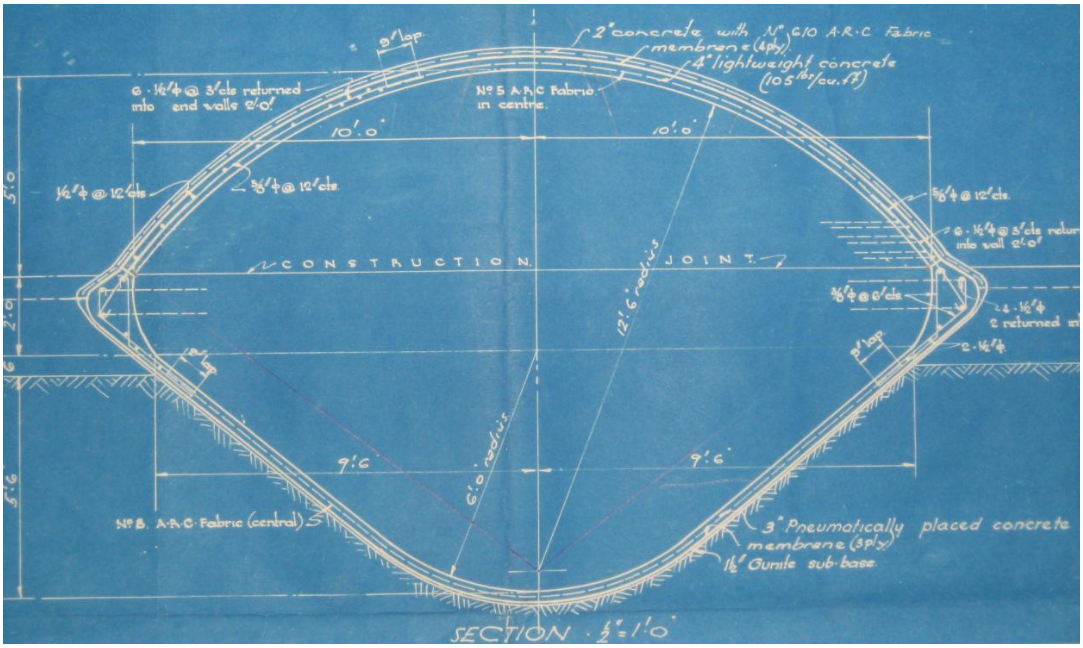

Fig. 1- Cross section of the Cunningar hermetic storage pit. From original 1960 construction blueprint.

The two cells were filled with 56 and 48 tonne FAQ wheat, probably at around 12% m.c, for the Near bin and Far bin, respectively. The two cells were sealed at 4:30 p.m. on 10 January 1962, soon after filling and conditions within the two cells were monitored during the subsequent 10 yr period of storage.

RESULTS

Oxygen concentration and infestation levels

The initial low rate of oxygen loss suggested that insects were either absent from the mass or were present in very low numbers. As the complete absence of insects could prolong the investigation unnecessarily and render the experiment unconvincing in terms of insect control, it was decided to open the bins and introduce a population of insects into one bin.

Approximately 100 kg of wheat in nylon gauze bags, heavily infested with all stages of several insect pests, primarily of *Sitophilus granarius* (L.) and to a lesser extent with *S. oryzae* (L.), *Rhyzopertha dominica* F., *Oryzaephilus surinamensis* (L.) and *Tribolium castaneum* (Herbst), were placed in the Near bin 251 days after the cell was originally sealed. The bags allowed the insects to escape but prevented the admixture of the heavily damaged culture grain.

The oxygen concentration in the Near bin was reduced much more rapidly after the addition of the insects, falling from atmospheric to 8.2% in the next 10 weeks, while during the same period the levels in the Far bin fell from 16.5% to 13.3%. The oxygen levels in the Near bin continued to fall over the succeeding weeks reaching a minimum of 1.8% on 30 January 1963 (4.5 months). The Far bin oxygen concentrations also continued to fall during this period, suggesting that either there was a leak between the two cells or there was a low infestation in the grain that did not develop substantially until the grain warmed up after winter but then increased rapidly, depleting the oxygen to a similar level to that in the Near bin. The oxygen content in the Far bin reached a minimum of 2.7%. Oxygen concentrations in both cells then tended to even out and gradually increase to between 9 and 10% by the following autumn, peaking in October 1963 then dropping again during January and February 1964 to between 4 and 5%. This trend indicated that the contractors had been unable to achieve a sufficiently good seal to prevent ingress of some atmospheric oxygen. At no time since the sealing of the cells had the oxygen concentrations remained low enough for sufficiently long periods, i.e. <2% for several weeks, to ensure that all insects had been killed. To check this, the Near bin was again opened in June 1964 and samples taken. Visual examination showed the grain was still in a sound condition but 17 live *S. granarius* were found on the walls above the grain surface indicating a light general infestation. On further inspection a small patch consisting of 1-2 kg of damp grain was found at the lower edge of the hatch cover. This grain contained a few hundred adult *S. granarius.* The patch had become damp due to condensation on the inside of the steel hatch cover.

The Far bin was opened in September 1965 for inspection and modification. The grain was examined for insects and for condition. Samples were taken for culturing to check for presence of live immature stages and for milling, baking and germination tests. On the surface of the bulk fair numbers of dead *S. granarius* and a few dead *O. surinamensis* were found. No live or dead insects were recovered from the samples drawn from depth. Examination of the bin walls revealed one moribund *S. granarius* which died a few hours later. A small patch of mouldy grain was found at the lower edge of the loading hatch, resulting from condensation on the metal hatch cover. Examination of this grain in the laboratory revealed one live *S. granarius* adult.

The conditions inside the two cells continued to be monitored; the oxygen concentrations fluctuating in a cyclic manner generally reaching a yearly high around 5% in September/October and reducing to a minimum of between 1 and 2% in summer, around February/March.

Carbon dioxide levels

Only after 29 months of storage (June 1964) were appreciable (>0.1%) CO_2 concentrations observed. Presumably the alkaline freshly formed concrete structure of the cells was absorbing any CO_2 as it was produced. After 29 months, CO_2 levels ranged between 0.25 and 1%. Low concentrations were again detected in April 1966 reaching less than 0.5% in the Far bin and 2.5% in the Near bin. From November 1967 regular analyses were made. Concentrations in the Far bin remained fairly constant between 1 and 3.5% to the end of the experiment in May 1972. In the Near bin more CO_2 was found ranging between 3 and 7.2% with the peaks in CO_2 corresponding with the troughs in oxygen concentration.

Temperatures and relative humidities

There was an overall cooling of the grain from the time it was placed in the storage throughout the 10 yr of the experiment. The maximum average temperature of the grain in the Near bin was 26°C soon after filling, with yearly maxima falling progressively to 19.6°C after 10 yr storage. Minimum temperatures usually observed ranged from 13.2 to15.4°C in 1963 and 1964, but then fell steadily back to 13.4°C in 1971.

The average r.h. was 58% in the Near bin and 54% in the Far bin at the commencement of the storage period corresponding to moisture contents of about 12.7 and 12.0%, respectively. The r.h. also showed a tendency to fluctuate, reaching the highest each year around February and March and dropping around August. A gradual increase was recorded over the 10 yr storage period to r.h. corresponding to final moisture contents of 14.6 and 12.6%, respectively.

As the construction of the cells incorporated a gas tight membrane, it is unlikely that moisture was gained from the surrounding earth or the atmosphere, so is probably associated with the increased metabolic activity. The Near bin had received an additional substantial quantity of living insect material, while the Far bin did not. Apart from this metabolic activity there was evidence of mycological activity.

Milling, baking and germination characteristics

Milling and baking tests on samples of the stored grain are provided in Table 1.

Germination of the grain after the 10 yr storage period was very low, the Near bin giving a figure of 1.25% of grains giving normal seedlings (5 grains in 400) and a further 0.5% (2 in 400) showing some germination activity. The Far bin fared worse, with 0.25% giving normal seedlings (1 in 400) and no other grains (0 in 400) showing activity. The operator conducting the germination tests noted an unusually heavy fungal infection developed on the grains during the tests.

THE NARRABRI TRIAL

Background

The design of the Cunningar trial storage was capital intensive and logistically inflexible. However, consideration of the fundamentals of its design and operation contributed substantially to the concept of the earth-covered bunker for emergency storage of grain. The first modern examples of this storage construction type were semi-underground and of a similar cross section shape to the Cunningar pit. A long pit was excavated and lined with polyethylene sheeting. After filling, the grain bulk was first covered with polyethylene and then some of the soil obtained from the excavation. The remainder of this soil was used to build the storage walls. Similar pits were recommended for storage of dry grain in South Australia in the 1930s (Spafford, 1939).

A prototype storage containing 1888 tonne of wheat was constructed at Narrabri, NSW in December 1975 (McCabe 1976). This prototype performed well, despite exceptional rainfall and flooding during the storage period, with a loss of about 31 tonne through water damage. Experience gained with the store indicated that earth-covered bunkers could be suitable for long term protection of dry grain.

The results of a trial to evaluate the system for long term preservation of grain are described below.

Storage construction

The storage for the trial was constructed at Narrabri, NSW essentially as described by Champ and McCabe (1983). The storage pit was excavated below ground level to a depth of 3 m. It was 2.4 m wide and 9 m long at floor level tapering out to 4.2 m x 12 m at ground level. The walls were built up to a further 0.6 m above ground level and the pit was lined with 150 μm black polyethylene sheeting. After filling, the grain bulk was covered with 150 μm polyethylene sheeting and then a further cover of double-coated 16 x 16 m woven polyethylene (Canvacon). These sheets were overlaid with 100 mm of river sand to facilitate the removal, at completion of the trial, of the nominal 900 mm of top cover of soil. A cross-section of the pit, showing construction details, is given in Fig. 2.

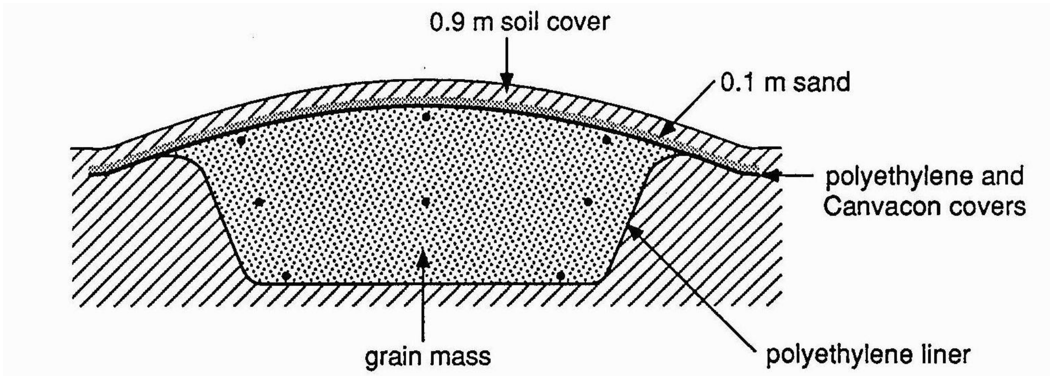

Fig. 2- Cross section of semi-underground Narrabri storage pit, showing construction detail.

Experimental design

The storage was filled in June 1976 with 160 tonne of Northern Hard 1 wheat. The wheat used had an initial moisture content of 9.0% and a temperature of 15°C. It had been treated with a grain protectant (malathion) at the nominal rate of 18 ppm one month prior to being placed in the storage and had a residual malathion content of 5.2 ppm at the time of sealing.

The storage was instrumented with thermocouples, humidity sensors (PCRC-11) and gas sample lines during filling. Relative humidity readings were converted to equivalent moisture contents using the wheat isotherm of Pixton and Warburton (1971).

Samples of grain were taken at the time of loading and also from time to time throughout the 34 yr storage for milling and baking tests.

RESULTS

Oxygen and CO_2 concentrations

The oxygen concentrations within the storage atmosphere fell steadily over the first 15 months to 14%, then tended to fluctuate between 9.6% and 17.7% before settling down around 14%. They dropped again between September 1985 and May 1987 after about 10 yr of storage to an average of 8.4% and in June 1991 were measured at 8.0%.

Carbon dioxide values fluctuated between 2.8% and 7% for three years of storage then tended to even out around 4%. An average value of 12% was observed after 15 years of storage (June 1991) after a three-year break in the series of readings.

The relative decrease in oxygen content and increase in CO_2 observed in 1991 would generally indicate some increase in metabolic activity in the bulk, but the five 10 kg samples of grain taken at the time disclosed no reason for the increase.

At outloading after 34 yr of storage, oxygen levels were <1%, with CO_2 levels at 20%.

Moisture content

The samples of grain taken in June 1991 had moisture contents (oven method) ranging from 9.1 to 9.8%, average 9.4%. These values compare with samples tested with a capacitance meter (Marconi model TF933A, St Albans, UK) at the time of loading which indicated an average of 9.0% and values deduced from readings from the r.h. sensors (PCRC-15) in the bulk which indicated a range of 8.8% to 9.4% during the first 15 yr storage.

Temperatures

The grain was loaded into the bunker in winter and had an initial temperature of 15°C. Thermocouple readings at each visit to the site showed that grain temperatures near the surface fluctuated seasonally between 9°C and 34°C following winter and summer trends in temperature. Temperatures at the bottom of the store varied to a lesser degree, between 1 9°C and 25°C with a seasonal lag of about six months.

Grain quality

A comparison of milling and baking test results are shown in Table 2 for samples taken during the trial.

Table 1. Milling and baking test results for wheat samples from the Cunningar trial.

	Near bin			Far bin		
Test date	Nov 62	Oct 64	Aug 72	Nov 62	Nov 65	Aug 72
Storage period (yr)	0	1.9	9.8	0	3.0	9.8
Wheat						
Test weight (kg hL^{-1})	71.1	73.6	72.3	72.3	70.8	72.3
Moisture content (% w.b.)	13.2	14.8	14.3	12.2	14.6	14.1
Wheat protein (N x 5.7,%)	9.8	9.9	11.4	12.3	12.1	11.8
Acidity (mg KOH/100 g d.b.)	-	43	62	-	65	74
Flour						
Farinograph						
Water absorption (%)	55.0	53.0	57.4	60.5	58.4	59.2
Development time (min)	0.75	2.5	8.0	4.0	5.5	6.0
Diastatic activity (% maltose)	-	1.85	1.51	-	1.67	2.02
Extensograph (135 min)						
Length (cm)	19.1	18.5	18.3	22.9	19.8	15.6
Height at 5 cm (BU)	125	195	395	255	430	530
Maximum height (BU)	130	225	-	385	-	-
Area (cm^2)	39	62	45	123	166	144
Alveograph						
Stability	32	34	57	51	46	61
Strength	7	16	28	38	42	34
Extensibility (cm)	7.6	11.3	8.7	15.2	14.5	8.5
L/P	2.62	3.60	1.67	3.30	3.45	1.55
Baking test						
Score (%)	61	61	65	76	80	58
Volume (mL)	(Fair)	-	600	(Fair+)	770	550

After 34 yr of storage, most of the wheat, about 135 tonne of the initial 160 tonne, was recovered in good condition. It was free running, had no mouldy or other off-odours, was free of infestation and quite dry. A poor loaf could be baked from the grain and the grain was sold for stockfeed. The main change observed in storage was a toughening of the gluten and an increase in Falling Number as expected from the low final α-amylase value.

Caked grain, in most cases containing a white mould, and also blackened grain was present on the base of the store and also particularly at the western edge of the store at ground level. In both cases it was clear that some water had been able to leak into the store. Two years prior to outloading, the top cover had suffered unauthorised damage, allowing rainwater to enter.

GENERAL CONCLUSION

Both the Cunningar and Narrabri trials, described above, demonstrate that long term storage of dry grain is feasible in some semi-underground or underground structures under conditions typical of the Australian wheat growing regions over 10-15 yr, but with some changes to wheat baking quality and also loss of germination. Insect infestation can be expected in freshly harvested grain as delivered to the central bulk handling system. This normally becomes easily detectable in untreated grain within 3 months of storage. In both trials, the grain at outturn after storage in excess of 10 yr was pest free. However, in neither case were insects eliminated by pure, unassisted hermetic storage. In one case insects were added to assist the process (Cunningar) and in the other (Narrabri) the grain was pesticide-treated before storage. The continued low oxygen content (<3%) maintained over a long period in the face of leakage of air into the system in the Cunningar trial indicates a significant level of metabolism. This may have resulted from the metabolism of damp grain but is more likely to be from the continued presence of a population of *Sitophilus* at a level below that normally detectable at outturn.

The grain in the Cunningar trial was initially at quite high moisture content, about 13%. This increased to over 14% during the 10 yr storage (Table 1).

Such an increase is to be expected as a result of the metabolic activity apparent from the continuing low oxygen levels and CO_2 production. Although a satisfactory loaf could be baked from the grain from this trial after storage there was a marked off-odour in the bread, possibly associated with the very high free fatty acid content.

In the Narrabri trial the grain was taken in very dry, with a moisture content of about 9%. Its quality was well maintained during the first 15 yr storage period. In contrast to the Cunningar trial, there was evidence that metabolic activity within the bunker was low, with oxygen levels generally being about 12%.

The maximum moisture limit for long term storage of wheat in systems such as used here is probably about 11.5% (see Annis and Banks, 1993, for discussion). This is low enough to have little metabolic activity and sufficient margin to allow for some moisture generation during storage without reaching a moisture content where rapid metabolism and mould activity can become a problem.

With correct control of moisture content, both systems described here appear promising for long term grain storage.

Underground bunkers similar to the Narrabri trial bunker were extensively used in Victoria during the late 1970s and were constructed in Iraq for long term storage of wheat. The design was the forerunner of the modern Australian plastic-covered bunker system. Use of the earth cover has been discontinued, though it may still be useful where very long term storage of grain is required, as it will provide the insulation needed to reduce moisture migration. Moisture migration can be a significant problem during long term storage in plastic-covered systems.

Table 2. Milling and baking test results for wheat samples from the Narrabri trial.

Test date	Jun 76	Oct 78	Aug 83	Jun 91	Sep 10
Storage period (yr)	0	2.3	7.2	15.0	34.3
Wheat					
Test weight (kg hL^{-1})	80.7	81.0	80.6	82.2	-
Protein (%)	13.3	13.5	13.5	13.5	12.9
Fat acidity (mg KOH/100 g d.b.)	10.4	17.5	27.2	-	-
Falling number (s)	527	553	810	1426	991
Milling yield (%)	77	75	76	74	78
Flour					
Protein (%)	12.8	12.3	12.5	12.5	12.3
Diastatic activity (mg)	225	182	195	-	-
Farinogram					
Water absorption (%)	67.1	62.0	66.5	67.5	64.3
Development time (min)	4.4	5.4	3.9	3.6	3.6
Extensogram (135 min)					
Extensibility (cm)	21.6	17.9	21.0	16.3	11.0
Maximum resistance (BU)	330	410	500	640	640
Viscogram					
Peak viscosity (AU)	520	750	783	-	-
Baking test					
Loaf score (%)	81	79	79	-	19
Loaf volume (mL)	860	840	775	693	438

Since these trials were initiated there have been many attempts to design and commercialise systems that truly work on hermetic storage principles. Some of these are described by Villers et al. (2008).

ACKNOWLEDGEMENTS

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