STORAGE OF GRAIN IN EARTH-COVERED BUNKERS

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Abstract

Storage of grain in plastic-lined earth-covered bunkers has been demonstrated to provide a low-cost method for maintaining quality in grain held for long periods. Various designs of bunker have been evaluated in Australia and the most satisfactory has been based on an above-ground structure with permanent earth side walls and end built on a slight slope to facilitate drainage. The walls and base are covered with a thin layer of sand and lined with polyethylene sheeting. After filling and trimming, the grain is covered with a woven polyethylene fabric, a layer of sand spread over the cover sheets to protect them, and then soil placed over the structure to a total depth of 1 metre. The method has been used commercially in Australia with bulks of wheat up to 25 000 tonnes at total storage costs averaging A$6.72 per tonne. The concept of storage in earth-covered bunkers is discussed and its use throughout the world reviewed.

INTRODUCTION

Grain has been stored underground in many parts of the world almost since time immemorial, particularly in the Mediterranean, Middle East and North and West Africa. As well as having a role in subsistence economies, such storage of grain underground has potential in commercial operations for low-cost emergency applications and in buffer stock control systems. In recent years, a range of systems has been developed, for example in Argentina, the large underground storage complexes in China, and small-scale farm storages elsewhere. There are also reports of use of caves such as in limestone caves near Kansas City.

The need for this type of storage comes from a variety of situations. Any long-term storage system ideally requires a low capital investment in the storage structure but a high degree of security from losses during storage. This applies particularly to planned maintenance of buffer stocks or other strategic stockpiling of grain. However, there are the situations that do not arise from deliberate planning. Thus, the situation frequently arises when production in particular areas is more than the available permanent storage capacity. This may result from storages being full at times of over-supply of grain on world markets, difficulties in moving grain to alternative storage sites, shortage of adequate storage capacity particularly in expanding areas of production, or from abnormally high yields in areas where such occurrences are not at frequencies that would justify provision of additional permanent storage capacity. If the grain cannot be moved from the district to other stores, some emergency storage must be provided to protect the grain from deterioration through weather and pests. Ideally, the method should provide the option for long-term safe protection of the grain so that the time in storage can be open-ended.

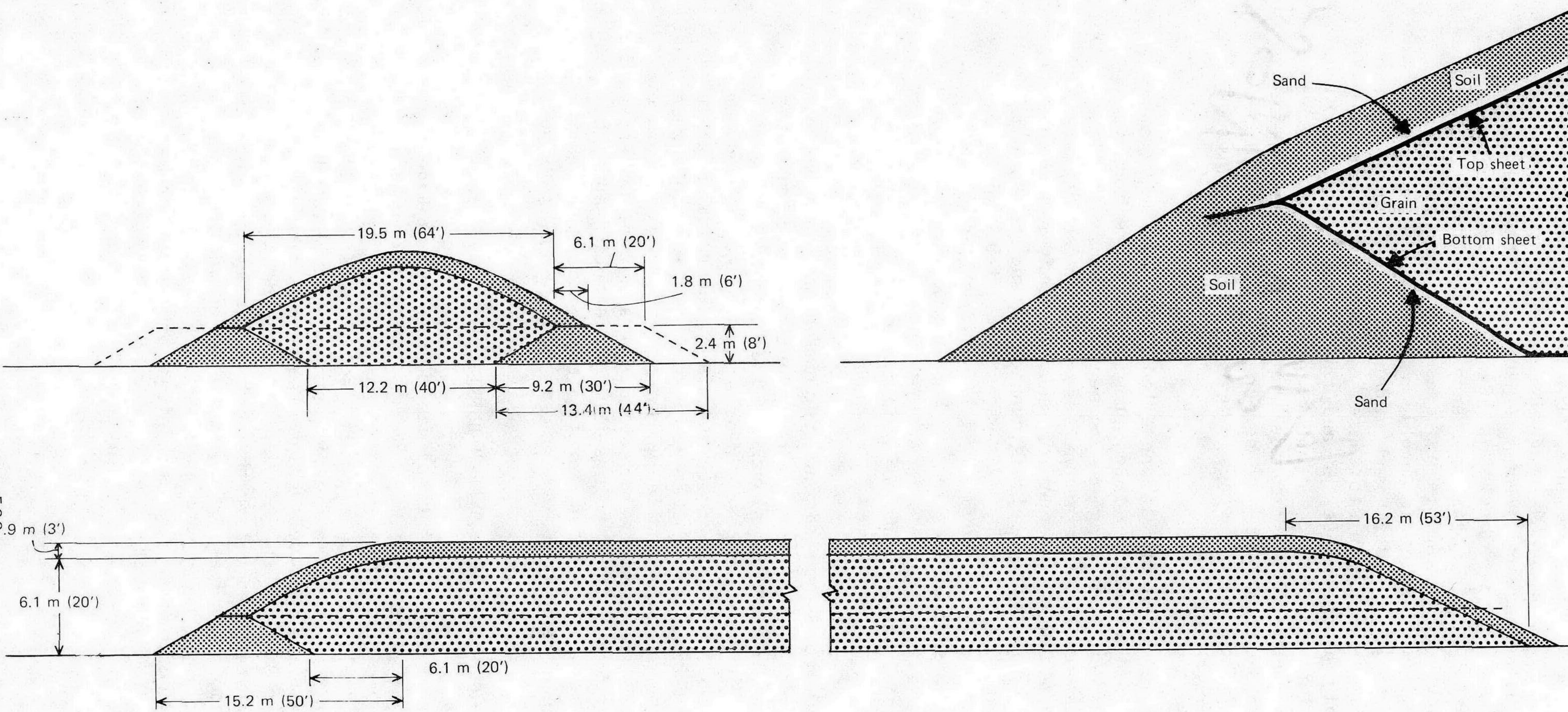
In Australia, the need for emergency storage has been greatest in New South Wales (N.S.W.), although recently expanding acreages and increased yields in Queensland and Victoria have resulted in acute storage problems in those States also. The Grain Handling Authority of N.S.W. has been most active in the emergency storage field. This authority previously depended on "A" frame stores built from timber and corrugated iron. These had inherent problems in providing little protection against weather, insects, and rodents; they were also susceptible to flood damage. Grain stored in "A" frame stores for long periods invariably became infested and there was considerable difficulty in disinfesting it. More recently, plastic-covered earth-walled stores have been used. These provide short-term protection for the grain until it can be transferred to permanent storage or shipped out, but neither method, however, provides long-term safe protection of grain over periods of years.

The experiences in Argentina and elsewhere indicated that storage in plastic envelopes enclosed in soil offered promise for safe long-term storage. The option of soil covering was chosen to enhance the long-term security of the system. A trial was carried out at Narrabri, N.S.W., in 1975/76, in which 1888 tonnes of wheat were stored for six months in a bunker partly excavated below ground level and partly built above the ground (McCabe 1976). The pit was lined with 150 micron polyethylene, filled with wheat, covered with polyethylene sheeting, and then overlaid with 1 m of soil. This trial indicated promise for the method as a means of excluding moisture and pests, although difficulty was experienced in removing the soil cover.

Subsequently, trials were carried out to develop an improved form of earth-covered bunker store to overcome the problems associated with the earlier type of below-ground storage. These trials comprised firstly an evaluation of the improved design of bunker based on monitoring conditions and insect infestation, and determining grain quality by milling and baking tests after storage. Similar trials were then carried out to determine the applicability of bunkers for storage of pesticide-free grain, and finally to estimate grain quality after long-term storage in bunkers. The findings from these trials and their application in Australia are reported herein, the concept of earth-covered bunkers discussed, and their use on a world scale reviewed.

EVALUATION OF AN ABOVE-GROUND EARTH-COVERED BUNKER

From October 1977 to July 1979, a trial was carried out at Boggabri, N.S.W., using an improved form of earth-covered bunker store based on an above-ground structure as proposed by Woolcock and Amos (1977). This design enabled normal handling equipment to be used for loading and unloading the grain and overcame drainage problems associated with below-ground operations. The improved design also incorporated stronger cover sheets and a layer of sand over the sheets to prevent soil adhering to them and to facilitate removal of the soil by acting as a lubricant between the soil and the cover. The sand also acted as a visual indicator of the location of the cover and was readily and completely removed by sweeping. Sections through a typical bunker are shown in Fig. 1. With bunkers of different size, the cross-sectional geometry remains the same and the length is varied to the capacity required.



Sand thickness · 0.1 m (4")
Top sheet - 25 m x 12 m (12 x 12 DS Canvacon)
Overlap - 1 m. Fasten with 25 mm double-sided adhesive tape
Bottom sheet - 25 m x 6 m (250 μ black polythene)
Overlap - 1 m. Fasten with 50 mm single-sided PVC adhesive tape.

Figure 1. Section through a grain storage bunker of nominal 10,000 tonnes capacity. A bunker of this capacity would have a length of 192 metres.

Details of storage design and construction are given in McCabe and Champ (1981).

Filling of the bunker with wheat commenced at 0800 h on October 13, 1977 using grain throwers. ASW grade wheat of approximately 9% moisture content was used. It had been treated with 1 ppm bioresmethrin and 12 ppm DDVP on intake in December 1976 and had been fumigated with phosphine two weeks before filling. Samples sieved during the filling operation produced some insect fragments and one live Rhyzopertha dominica adult was observed on the clothing of an operator.

Filling was completed on the afternoon of October 14, when a total of 2014 tonnes had been loaded into the bunker. After placing the cover sheets, the sand and soil overlay was placed with a tracked hydraulic excavator with a boom length of 8.5m. This operation was completed at 1500 h, on October 16.

The storage was left in place for 21 months. Uncovering of the bunker commenced on the afternoon of Wednesday, July 4, 1979 also using a hydraulic excavator but with a bucket without teeth. Removal of the soil and sand was completed by 1200 h on Friday, July 6. There was minimal tearing of the cover sheets during the operation and no significant admixture of soil and sand with the grain. Removal of the grain with sweepers and drag chain elevators commenced at 1600 h on Thursday, July 5 and was completed at midday on Saturday, July 7.

Condition of the grain during storage and at recovery

Grain temperatures at filling ranged between 23.8 and 25.8°C and the average moisture content was 9%, ranging between 8.5 and 9.5%.

The atmosphere in the storage was monitored throughout the storage period. For this purpose, a gas sample line and a thermocouple were inserted to a depth of about 2.4 m at the midpoint of the storage during December 1977. The oxygen content of the intergranular air decreased to 8.8% and carbon dioxide increased to 8.4% indicating that a good seal had been achieved but that the atmosphere conditions in the bunker were not themselves insecticidal. Grain temperatures ranged from 26.6°C in December 1977 to 22.5°C at the time of opening the storage bunker in July 1979 (Table 1).

Table 1 - Grain temperatures during storage.

Time in storage (months)	2	5	9 (July)	11	12	21 (July)
Temperature (°C)	26.6	26.2	25.8	23.8	23.0	22.5

During a routine visit to the bunker in October 1978, fissures were noticed in the soil cover caused by drying of the heavy black soil. It was suspected that mice might have gained entry through some of these cracks but exploratory digging failed to find evidence of rodent attack.

While the bunker was being opened two mouse holes were found in the cover sheet on the lower end of the bunker. These were close to where the cracks had been noticed in October 1978. Mice had been feeding on the wheat beneath one of the holes and about 2 kg of grain had been consumed or damaged. The mice had not established in the grain and damage was not significant. Two further mouse holes were found close together at the top end of the bunker. Here a localised infestation of Sitophilus oryzae was present. Grain in a sharply delineated space approximately 0.5 m diameter and 0.1 m deep had been completely destroyed. The grain remnants were badly discoloured and no live insect was detected in a detailed examination of the grain. Many dead insects, however, were present. Sampling of the surrounding grain also did not reveal any live insects or show evidence of damaged grain. Subsequent incubation of samples revealed an incipient infestation of Sitophilus oryzae, Rhyzopertha dominica, and Cryptolestes ferrugineus. It is presumed that the infestation gained access through a soil crack and the mouse hole. Spread of the infestation was limited by the low moisture content of the grain and possibly the pesticide residues present in the grain.

Frequent samples (100 x 500g) were taken during unloading both on site and by operators at the inloading of the grain to the nearby silos to which the grain was transferred. Sieving failed to find any live insects.

The grain was cool and free running with moisture content averaging 9.6%. A sample was taken from each truck load which, after bulking and division, was submitted to the Bread Research Institute of Australia for milling and baking tests for comparison with similar tests done at the time of filling (Table 2).

Table 2 - Comparison of milling and baking tests.

	Before storage	After storage
Fat acidity (mg KOH)	13.3	17
Diastatic activity (mg)	222	241
Extensibility (cm)	19.9	21.8
Extensogram maximum resistance (E.U.)	279	295
Viscogram peak viscosity (A.U.)	650	570
Loaf volume (cm^3)	660	760
Loaf score (%)	67	79

The test concluded "This wheat is in remarkably fresh condition, the fat acidity being quite low for a sample which has been stored for 21 months. We are at a loss to explain the greater dough extensibility now, than when the inloading samples were tested in April 1978: the change is usually in the other direction, as it is with the peak hot paste viscosity (Viscogram). Suffice it to say this wheat has changed very little in quality during storage, and it is possible such changes as we have noted, are due to moisture and milling effects in part".

Samples were analysed for residues of the bioresmethrin applied in December 1976. These averaged 0.1 g/t of bioresmethrin ranging from 0.05 to 0.16 g/t.

Table 3 - Construction costs * ($ Australian) for the below-ground storage at Narrabri in 1975, for the current trial, and for an equivalent 10,000 tonne bunker.

	Narrabri 1975 1888 tonnes	Boggabri 1977 2014 tonnes	Equivalent for a 10,000 tonne bunker
Clearing of site	-	400	-
Construction of walls & placing sand & soil cover	1700	3910	11400
Plastic liners+	960	365	1200
Plastic covers	-	1995	8500
Sand for cover protection	-	1000	3500
Hire of equipment	-	270	-
	$2660	$7940	$24600
	$1.41/tonne	$3.94/tonne	$2.46/tonne
Uncovering costs	$ 700	$1063	$19000

* These costs do not include labour costs for sheeting and unsheeting or costs of loading and unloading of the grain.

\+ The Narrabri storage used polyethylene sheets for both lining and covering.

Comments

The trial successfully demonstrated the potential of the above-ground earth-covered bunker for storage of grain in Australia. The heavier and stronger cover sheets used in the improved design together with the layer of sand prevented damage to the sheets during covering operations and greatly facilitated the removal of the soil cover.

Construction of the storage at ground level required more soil for the walls but obviated any entry of ground water. Moreover, the storage, when empty, could not fill with water creating an environmental hazard. The soil removed from the cover was replaced on the outside of the walls and the site was available for re-use with minimal preparation. Some damage was done to the cover sheets but it appeared that most of this damage could be repaired and the sheets used again.

The grain remained in very good condition throughout the 21 months storage period and was clean and free of live insects. The absence of detectable infestations containing living insects and mice, together with evidence that localised infestations had been suppressed, suggest that the method will prevent general infestations becoming established. The low moisture content of the grain is the most plausible cause but the interrelations of depressed oxygen levels and high carbon dioxide contents with the low grain moisture contents as well as the low levels of pesticide residues may also have contributed to the lack of detectable infestation. Nevertheless, there appeared to be potential for pesticide-free storage at least at low grain moisture contents.

Costs for construction of this bunker, for an equivalent bunker of 10,000 tonne nominal capacity, and for the original below-ground storage of McCabe (1976) are given in Table 3. Bunker storage, thus is a cost effective method for storing grain.

BUNKER STORAGE WITHOUT PESTICIDES

Low moisture grain

Following the success of the 1977-79 bunker storage trial conducted at Boggabri, a similar trial was carried out at the same site from January 1980 to February 1981 to determine if grain could be stored without use of insecticides. This trial was designed also to demonstrate re-use of a bunker site and re-use of the cover sheets.

The bunker was filled with 2000 tonnes of untreated wheat with an average moisture content of 9.0±1.1% (24 samples). Eighty samples (500 g each) of the wheat were taken during inloading and examined for insects. Three live insects were detected - 1 *Sitophilus oryzae*, 1 *Rhyzopertha dominica*, and 1 *Tribolium confusum*. Forty-four cages of test insects (all developmental stages of *S. oryzae*, *R. dominica*, *Tribolium castaneum*, and *Cryptolestes ferrugineus*) were distributed throughout the bulk. Temperature and humiditysensing devices and gas sampling lines were inserted at 18 positions on a grid pattern, so that conditions in the bulk could be monitored periodically.

The first readings of conditions within the bunker were made in March 1980 (2 months storage) when the oxygen content of the intergranular air had dropped to an average of 6.6% (Table 4). Carbon dioxide content averaged 6.3% and temperatures were high, averaging 29±3°C. The grain remained in the dry condition in which it had been put in store. By January 1981 (12 months storage), the oxygen content had steadily risen to an average of 14% and the CO_2 level, after a brief rise to 7.4% after 3 months storage, had dropped to 3.7%. Temperatures fell during the winter months and rose slightly with the warmer summer conditions. The grain remained dry.

During unloading, samples (500 g) were taken from the grain face, sieved, and examined for insects. Of 75 samples taken, 35 contained live insects comprising *R. dominica* (30), *Cryptolestes ferrugineus* (10), *Tribolium castaneum* (2), and *Oryzaephilus surinamensis* (2). A further 13 samples contained dead insects. Most samples contained few insects - *R. dominica*, mean number per sample 14, range 1-150; *C. ferrugineus*, 3, 1-10; *T. castaneum*, 5, 1-8; *O. surinamensis* 1.

Table 4 - Content of oxygen and carbon dioxide in the interstital atmosphere of a 2000 tonne bunker containing untreated wheat.

	Time in storage (months)				
	2 (Mar)	3 (Apr)	6 (Jul)	8 (Sept)	12 (Jan)
Oxygen %	6.6±1.9*	8.2±0.9	11.3±1.5	12.1±2.1	14.0±1.3
Carbon dioxide %	6.3±1.8	7.4±0.4	5.9±0.8	4.8±0.7	3.7±1.3

* Sample standard deviations. These are used throughout the text and tables.

Samples were also taken during delivery of grain from the bunker to nearby silo storage. Of samples examined from 52 truckloads, 12 contained live insects and 11 contained dead insects. The highest number of live insects detected in any one sample was 3.

The cages of test insects were recovered and most showed extensive grain damage. The prolonged storage period (13 months) in the low moisture (9.0%) grain bulk had favoured the Cryptolestes particularly and to a lesser extent the T. castaneum. There was no survival of S. oryzae which would be expected at the low moisture content. Few R. dominica were present.

Grain at 11% moisture content

At the same time as the Boggabri trial was in progress, two bunkers at Watchem (10,967 tonnes) and Lillimur (6800 tonnes) in Victoria were filled with untreated wheat at a higher moisture content (approximately 11%) delivered directly from farms. The grain remained in storage for 6 months. Temperatures and contents of oxygen and carbon dioxide in the interstital air were monitored at 12 locations in each store during the final 4 months of storage. In the Watchem bunker, the mean grain temperature was 22±4°C, the oxygen level decreased from 13.3±2.2% to 9.4±1.7%, and the carbon dioxide level was stable at 5%(4.8±2.3 to 5.1±0.7). In the Lillimur bunker, the grain temperature fell from 27±5°C to 24±3°C but both oxygen and carbon dioxide were relatively stable over the period of observations at 8.5% and 7.4% respectively (oxygen 8.5±1.2% to 8.5±1.1% and carbon dioxide 6.9±1.4% to 7.8±11%). On unloading, infestations of T. castaneum and R. dominica were detected in both bunkers as well as large numbers of C. ferrugineus and O. surinamensis in the Lillimur bunker.

Comments

The grain from the untreated bunker at Boggabri was not as heavily infested as expected if it had been stored for the same period in conventional structures in the same area. The grain in the Watchem and Lillimur bunkers was more heavily infested than that at Boggabri despite lower storage temperatures. The lower moisture content of the Boggabri bunker with possibly some contribution from the altered contents of oxygen and carbon dioxide in the storage together with temperature appeared to be responsible.

The experience with the Victorian bunkers indicated that the storage conditions alone would not suppress infestation present in grain stored at the insect-compatible moisture content of 11%. The condition at outturn of the relatively low moisture content grain (9% m.c.) from the untreated bunker at Boggabri confirmed this for much of the range of moisture contents (9-11% m.c.) usually encountered in Australian wheat.

LONG TERM STORAGE AND GRAIN QUALITY

A necessity for storage of grain in earth-covered bunkers is the maintenance of quality. The only real assessment of this can be made from long-term storage trials under practical conditions.

In June 1976, McCabe (1976) established at Narrabri, N.S.W., a small earth-covered bunker partly excavated below-ground level and of similar design to the 2000 tonne bunker described in that report. The pit was lined with 150μm black polythene and the grain mass covered with woven, coated polyethylene and a layer of soil nominally 1 metre deep. The bunker contained 159 tonnes of Northern Hard 1 wheat which, at inloading, had a moisture content of 9.0%, a temperature of 15°C, and a malathion residue content of 5.2 ppm. Temperature and humidity sensors and gas sampling lines were located at 8 monitoring points near the bottom, middle, and surface of 3 transects along the bunker. Storage conditions were monitored 21 times over the 7 year period until the most recent assessment in August 1983.

Grain temperatures during storage fluctuated between 9° and 34°C in the surface layers following a winter, summer cycle, and between 19°C and 24°C at the bottom of the storage again with an annual cycle but with lowest temperatures in summer.

The moisture content has remained almost constant. Samples of wheat taken at inloading showed 9% moisture using a capacitance meter. Readings taken 10 days later at the first monitoring using the *in situ* sensors gave an average moisture content of 9.8% and subsequent readings have not exceeded 10.1% (Table 5).

The content of oxygen in the storage atmosphere fell gradually during the first year to approximately 14% and has remained of that order subsequently (Table 5). The content of carbon dioxide has fluctuated between 2% and 7% but now appears relatively stable about 5%.

Grain quality was determined by the Bread Research Institute, Sydney after 28 and 73 months storage. Their estimates are compared in Table 6 with corresponding tests carried out at the start of the trial. Germination tests were made on the 73 month sample by the Brisbane Seed Testing Laboratory of the Queensland Department of Primary Industries. These tests gave a 7 day count of 86% normal seedlings, 9% abnormal seedlings, and 5% dead seeds.

The wheat stored well in terms of its milling and baking quality and its germination capacity. Insect infestation was not a problem and the grain was undoubtedly of higher quality than it would have been if held under the normal storage conditions in current use in the industry.

The trial is being continued indefinitely.

Table 5 - Grain moisture levels and contents of oxygen and carbon dioxide in the long-term bunker trial at Narrabri, N.S.W. (June 1976 to August 1983).

%	Time in storage (months)						
	0.3	2	5	8	15	17	20
Moisture content	9.8±0.2	9.8±0.2	9.8±0.2	10.0±0.2	10.1±0.1	9.9±0.3	9.9±0.2
Oxygen	17.6±0.5	16.1±0.9	16.2±1.4	14.8±1.4	14.0±0.9	15.6±0.6	15.1±0.4
Carbon dioxide	-	-	-	-	-	-	6.8±0.6
	24*	26	27	36	42	44	45
Moisture content	9.8±0.1	9.9±0.1	9.9±0.1	9.8±0.1	10.1±0.3	10.1±0.2	9.9±0.2
Oxygen	17.7±0.7	12.6±0.8	12.6±1.0	13.6∓0.6	10.1±1.6	9.6±0.9	12.7±0.8
Carbon dioxide	3.1±1.0	4.7±1.4	7.0±0.8	5.8±0.7	2.8±1.2	3.0±1.1	5.2±0.8
	48	50	54	55	62	66	73
Moisture content	10.0±0.2	10.0±0.2	-	10.0±0.2	-	10.0±0.3	10.1±0.2
Oxygen	13.6±0.7	13.3±1.0	13.9±0.5	12.7±0.7	13.6±0.6	14.1±1.4	14.1±1.0
Carbon dioxide	4.7±0.6	3.4±0.9	5.2±0.7	4.9±0.2	3.4±0.6	4.6±0.4	4.6±0.4

* Following heavy rain and erosion of the soil cover, a small split was observed in the top sheet of the bunker. This was sealed after spot treatment with phosphine for insects observed at the surface of the grain at the split. This breaking of the seal presumably explains the changes in oxygen and carbon dioxide at this time.

Table 6 - Quality estimates of wheat stored for 7 years in an earth-covered bunker at Narrabri, N.S.W.

	Jun. 1976	Oct. 1978* (1)	Aug. 1983+ (2)
<u>Wheat</u>			
Test weight (kg/hl)	80.7	81	80.6
Protein % (11% moisture basis)	13.3	13.5	13.5
Fat acidity (mg KOH/100 g d.b.)	10.4	17.5	27.2
Particle size index	13	15	13
Falling number (sec.)	527	553	810
Milling yield %	77	75	76
<u>Flour</u>			
Protein %	12.8	12.3	12.5
Diastatic activity (mg)	225	182	195
Farinogram			
Water absorption %	67.1	62.0	66.5
Development time (min.)	4.4	5.4	3.9
Extensogram (135' pull)			
Extensibility (cm)	21.6	17.9	21
Maximum resistance (EU)	330	410	508
Viscogram			
Peak viscosity (AU)	520	750	783
<u>Baking test</u>			
Loaf score %	81	79	79
Loaf volumes (ml)	850	840	775

* The higher fat acidity and dough stability (development time and resistance to stretching) coupled with some sacrifice of baking quality are normal. So too is the loss of enzyme activity, giving lower diastatic activity and higher paste viscosity (viscogram). The extensograph dough became very sticky during the test.

\+ The higher falling number and higher viscogram peak indicate a further decline in alpha amylase activity since the previous sampling. The higher extensograph resistance indicates a further toughening of the protein, as is normal. The baking figures indicate that the sample is capable of producing acceptable bread, although inferior to that at the time of the earlier tests. The fat acidity figures are approaching the level where off flavours could be noticed but they are still remarkably low for wheat stored for seven years.

DISCUSSION

Development of underground storage.

Much has been written on the storage of grain underground. The use of traditional underground pits in subsistence economies has been reviewed extensively for the Mediterranean area, the Middle East, and many parts of Africa (Hall *et al*. 1956; Gilman and Boxall 1974; Gast and Sigaut 1979), and for India (Ramasivan *et al*. 1966). Various styles of containers and systems of storage have been used for grain of both high (greater than 12%) and low moisture content. Use of pits for high moisture grain has been recorded from the Iron Age in England (Hill *et al*. 1983) but most applications of pit storage in antiquity and since, concern comparatively dry grain and generally dry climates where problems with high water tables do not occur. These pits can be quite large as with the Maltese "fossae" which vary from 50-500 tonnes (Hyde and Daubney 1960).

The major attributes of these systems are that they require locally-available resources only and that they offer varying degrees of protection against pilferage, damage from insects (excluding termites) and rodents, and extremes of climate. The requirement for airtightness has been developed independently in many of the systems in response to the observation that the changes in the storage atmosphere of the sealed containers , if sufficient, would delay deterioration of wet grain, and be lethal to insects in infested grain. This has been extended to artificial manipulation of storage atmospheres. This review concerns the concept of underground storage and its attributes as a storage medium *per se* and only peripherally the wider fields of airtight storage and alteration of storage atmospheres.

The development of modern commercial sized underground storages for bulk grain began in the 1820s with the underground silos of Ternaux in France (Sigaut 1979). These flask-shaped structures, the largest of which held approximately 150 tonnes, resemble the smaller of the modern underground silos of Yuan Shimin (Anon. 1980) in Henan Province in China. These Chinese stores vary from spherical brick structures holding 500 tonnes of grain to much larger stores holding up to 4000 tonnes of grain. The brick fabric of these silos was sealed with bitumen to proof the structures against ingress of moisture and to render them substantially airtight. The location underground reduced temperature fluctuations and was suitable for long-term storage of reserve grain stocks.

Problems with exporting grain from the Argentine during World War II and the need for a system of buffer stock storage prompted an intensive development of subsurface pit storages in that country. These storages were originally trenches with the earth spoil used to cover a waterproof lining over the filled store, progressing to use of the spoil to provide side walls for added capacity, and finally to concrete-lined structures with either permanent or removable roofs (Anon 1949; Hall *et al*. 1956). Wheat and maize have been stored successfully for up to seven years in these structures despite a hot, moderately dry climate. Use of this type of store followed in Paraguay, Venezuela, and Uruguay, and interest generated in the British Colonial Office resulted in construction of larger permanent subsurface facilities in Cyprus and then in Kenya as well as experimental studies in Tanzania, Malawi, Zimbabwe, Ghana, Nigeria, and the Sudan.

In Australia, the trials carried out in 1975/76 at Narrabri, N.S.W., of earth-covered bunkers partly excavated below ground level and the evaluation of an improved design based on an above-ground structure as described earlier in the text have provided the basis for a commercially viable storage system.

Commercial storage in Australia

During the 1978/79 season, the Grain Elevators Board of Victoria adopted a standardised design for an above-ground bunker of 10,000 tonne nominal capacity (McCabe and Champ 1981) and constructed a total of 6 of these containing a total of 72,773 tonnes of wheat. Construction costs averaged \$5.83/tonne, including earthworks (\$2.37), lining materials (\$1.21), freight on materials (10c), travelling and plant hire (4c), cartage (\$1.02), wages (93c), and seeding for soil stabilisation (16c). Costs for individual storages ranged from \$4.54/tonne to \$7.64/tonne. In the 1979/80 season, 43 bunkers were prepared of which 39 were used but only 32 completed with a soil covering. These 32 bunkers contained 324,082 tonnes of wheat at an average cost to the covered stage of \$4.86/tonne. This included construction earthworks (\$1.43), lining materials (\$1.10), plant hire (18c), cartage (94c), wages (76c), and covering (45c). Costs for individual storages ranged from \$3.37 to \$7.28/tonne. Recovering the grain cost \$1.86/tonne including uncovering (45c), delivery of grain to the silo (65c), and labour and supervising staff (76c). The total cost of storage averaged \$6.72/tonne. Losses of grain were minimal and were usually from rain during loading in and out. Most wetted grain was recovered. There was no significant loss from accidental admixture of soil with the grain.

The bunker system of storage thus provided satisfactory emergency storage capacity during the record harvest of 1979/80. Moreover, the sites were available for re-use as the need arose. Many of the covering sheets also would be reusable considerably reducing costs to the covering stage. Re-use of the bunker and undamaged cover sheets in the Boggabri trials reduced the costs for sheets and earthworks from \$3.94/tonne when the bunker was first built in 1977 to approximately \$1.00/tonne in the trial with pesticide free grain.

Most emergency storage in Australia has been relatively short-term, that is within a single season, and there has been a rapid development of structures similar in design to the earth-covered bunkers but using heavier PVC covering sheets without a soil overlay. Lower earth walls spaced further apart have been used and nominal capacities increased to 50-60,000 tonnes. More recently, movable concrete blocks have been used to construct the retaining walls and solid asphalt bases prepared (Yates and Sticka, in press). These PVC covered stores are considerably more expensive (Yates and Sticka *op. cit.* quote \$22.50/tonne construction costs and \$7.82/tonne actual storage costs) than the earthcovered bunkers particularly in their present form in which they are part of the permanent storage system and must be used continuously to offset the capital costs. The PVC covered stores, however, require less skills of supervisory and operating staff and are operationally easier to manage during loading and unloading provided specialised large scale equipment is available. Insect infestation remains a problem. The storage atmospheres appear similar to those of earth-covered bunkers (based on observations on two PVC covered stores at Cootamundra, N.S.W. and on a similar store in Israel as reported by Navarro *et al.* 1982) and do not suppress infestations to acceptable levels. The reinfestation potential is high and although fumigation techniques are available which will contain infestations (Banks and Sticka 1981), holding grain in PVC covered stores appears appropriate for the short-term only. It is the preferred technique under the circumstances of short-term storage which prevail in much of Australia. If the option for long-term storage is required in the system, the earth-covered bunker is preferable. The same bunkers can be used for short-term storage also by substituting heavier cover sheets and not covering with soil as has been done by the Grain Elevators Board of Victoria for emergency storage.

Farm storage

The underground storage technique has been extended into smaller scale farm storage in developed countries. This has been particularly so in dry areas such as inland Australia where underground pits have been found to be a cheap, practical way of storing grain as a fodder reserve for droughts and as a buffer against the uncertainty of export markets. Storage capacities have ranged up to 80 tonnes, the pits have been lined with moisture limiting barriers and the grain masses covered with similar barriers and a layer of soil. The method has been found effective in South Australia using malthoid liners for storing and disinfesting insect infested wheat. It is used also in New South Wales and Queensland,where, using polyethylene liners, it is officially recommended for storing reserve stocks of oats and other grains (Tiller 1971). Although early reports warned of possible harm to germination of seed grain probably resulting from storage of initially damp grain or ingress of moisture, Bourne (1977) described satisfactory storage of barley which gave a 97% test for germination and a good strike on sowing after 3 1/2 years underground. He placed a 10% moisture content upper limit for grain for storage. In Western Australia, wheat of 10.4% moisture content stored satisfactorily in a pit for 6 years based on unimpaired germination and grain quality assessed by milling and baking tests (Anon. 1976). This pit was lined with opened plastic fertiliser bags and covered with corrugated galvanised iron before covering with soil.

In Israel, barley, with a moisture content varying between 9% and 12%, has been stored for 15 months in a polyethylene lined pit without loss of quality (Donahaye *et al*. 1967). The light insect infestation present was supressed presumably by the initial fall in oxygen tension to 1.3% and the rise in CO_2 content to 18% despite extensive rodent damage to the liner.

In Brazil, maize of approximately 11-12% moisture content has been stored underground in small polyethylene lined pits for up to 8 months without significant loss of quality or germination (Sartori and Costa 1975; Ferriera *et al*. 1979).

Insect infestation in bunker storage.

The degree of sealing achieved in practice in many plastic-lined earth-covered stores, particularly in the larger bulks, is not such that sufficiently anaerobic conditions can be achieved for complete suppression of insects and fungi. Table 7 illustrates the changes in oxygen and carbon dioxide levels observed in 5 bunkers constructed in Victoria in 1979. There is considerable variation between storages but none of the atmospheres could be regarded as acutely insecticidal.

It must be assumed that variations will occur also in the composition of the atmosphere within storages depending on the uniformity of the grain mass but it seems that the damping by the earth-cover of diurnal temperature changes and wind effects could minimise this.

Table 7 - Conditions* during storage in 5 earth-covered bunkers located in Victoria, Australia.

Location and Capacity		Time in storage (months)					
		7 (Sept)	10 (Dec)	13 (Mar)	15 (May)	18 (Aug)	19 (Sept)
Dunolly 18500 t	Surface temp.°C	13	27	27	15	-	13
	Bulk temp.	26 ±1.1	23 ±0.7	22 ±0.0	22 ±0.7	-	22 ±0.0
	" m.c.	10.8±0.4	10.8±0.3	10.9±0.3	10.8±0.1	10.6±0.2	10.5±0.1
	" O_2	5.0±0.7	6.3±1.8	7.3±0.4	7.8±1.1	6.0±0.0	4.5±0.0
	" CO_2	7.6±0.2	6.9±0.6	6.0±1.4	8.3±1.1	8.0±0.7	8.8±0.4
Hunter 10728 t	Surface temp.°C	14	25	25	16	-	
	Bulk temp.	25 ±2.9	23 ±2.0	24 ±0.8	25 ±1.0	-	Empty
	" m.c	10.7±0.3	10.4±0.4	10.7±0.4	10.6±0.7	10.6±0.6	
	" O_2	14.0±0.0	13.0±0.0	13.5±0.5	15.3±0.7	15.0±0.5	
	" CO_2	2.3±0.2	0.9±0.2	1.3±0.3	3.4±0.9	3.3±1.0	
Murtoa 12500 t	Surface temp.°C	13	20	23	18		
	Bulk temp.	23 ±0.6	20 ±1.0	20 ±1.0	22 ±0.6	Empty	Empty
	" m.c.	9.7±0.1	9.5±0.1	9.4±0.1	9.3±0.0		
	" O_2	15.7±0.6	15.9±0.4	18.3±0.3	20.5±0.5		
	" CO_2	0.7±0.3	0.1±0.1	0.5±0.5	0.7±0.3		
Mitiamo 11500 t	Surface temp.°C	15	25	28	18		
	Bulk temp.	27 ±0.9	25 ±0.9	22 ±0.6	25 ±0.6	Empty	Empty
	" m.c.	10.7±0.1	10.5±0.2	10.6±0.1	10.3±0.2		
	" O_2	13.3±0.6	13.3±0.6	13.0±0.5	15.2±0.8		
	" CO_2	2.5±0.5	3.0±0.5	1.5±1.3	4.2±0.6		
Waaia 12397 t	Surface temp.°C	15	26	28	18	-	
	Bulk temp.	28 ±0.3	25 ±0.0	23 ±0.3	24 ±0.8	-	Empty
	" m.c.	11.1±0.4	11.4±0.1	11.4±0.3	11.2±0.2	11.3±0.2	
	" O_2	9.5±2.8	6.3±1.5	7.2±0.3	8.6±0.5	7.5±0.5	
	" CO_2	6.7±2.1	6.4±0.7	8.0±0.3	8.0±0.5	8.2±0.8	

* Measurements in the grain mass were made at 3 points approximately 5 m below the surface and radiating from a single entry point on the ridge of the bunker.

With low moisture grain, fungi are not a consideration and the insect populations appear sufficiently stressed that populations, irrespective of their initial density, may be reduced to light infestations only. Typically, there is a sharp initial drop in oxygen content and rise in carbon dioxide content, the extent of which is dependent on the moisture content of the grain and the level of infestation. The changes are then reversed, presumably from suppression of the infestation, and, depending on the degree of sealing of the plastic envelope, the gas contents remain relatively constant or gradually revert towards normal atmospheric levels. If, however, the grain is disinfested before storage, the changes in oxygen and carbon dioxide levels are lessened as has been shown with wheat in the first Boggabri trial and with maize in Brazil by Ferriera et al. (1979).

In most documented trials, the storage periods are limited and the long-term trends are not available for contents of gases in the atmosphere of the store or for levels of pest infestation. Moreover, the long-term exposure effects are not known when oxygen and carbon dioxide levels are altered within non-acutely toxic levels and interact with temperature and low grain moisture contents. In practice, the changes in atmospheric composition in bunkers will not completely suppress infestations but the lower the moisture content, the lighter the infestation that survives. If additional stresses are placed on the insects such as by fumigation before or after inloading, or by use of a residual grain protectant, infestations are reduced below detectable levels at least in recorded storage trials. This was the experience in the two Boggabri trials where, in the first trial, an initial fumigation and grain protectant residues were associated with a bunker apparently free of infestation at unloading, compared with the second trial at the same site where, with pesticide -free grain, a significant infestation was recorded. Assuming that insect infestation is always present in grain being loaded into underground stores, some pretreatment or treatment in storage is desirable. Without such extra stress, the infestations will not be suppressed.

Reinfestation is not significant in properly-constructed earth-covered bunkers because of the physical barrier presented by the covering of earth.

With high moisture grain, suppression of insect populations can be achieved readily in the sealed enclosures by the atmospheres altered by the insects themselves, the microflora, and respiration of the grain. The level of sealing required, however, to create atmospheres that prevent growth of fungi is much more critical and difficult to attain particularly in large bulks. The problem is compounded by the possible occurrence of mycotoxins and the accelerated reduction in quality, attractiveness, and germinability that are associated with any mould growth in grain. The temperature of the grain is a dominant factor affecting the rate at which changes occur particularly at these high moisture contents. Thus, damp grain may store safely in sealed plastic enclosures in the cool climates of Europe but such storage could be disastrous in the tropics.

In summary, storage of grain has been shown to be a viable and cost-effective option for long-term storage of grain at safe moisture content. Some supplementary treatment, however, is necessary if the grain is to be kept free of infestation.

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